CHALMERS

Application of fibre reinforced polymer materials in road bridges – General requirements and design considerations

Master of Science Thesis in the Master's Programme Structural Engineering and Building Technology Master's programme name

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Department of Civil and Environmental Engineering
Division of Structural Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2014

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ABSTRACT

The work in this thesis is carried out in collaboration with Swedish Transport Administration on preparation for the first fibre reinforced polymer composite bridge in Sweden. This is an important step for Sweden to be regarded as an innovative country in terms of civil engineering applications. Fibre reinforced polymer composites have many advantages such as light weight, high strength, fast assembly and durable which makes them suitable for infrastructure applications.

The main aim of this thesis is to provide Swedish Transport Administration with background information on using fibre reinforced polymer materials in bridge construction. In addition the thesis aims to increase the awareness of the benefits enabled with fibre reinforced polymer materials and to investigate the competitiveness of fibre reinforced polymer composite materials in comparison with conventional materials.

An extensive literature study was performed in order to get a holistic perspective of fibre reinforced polymer composites. The studied subjects consisted of the structure of fibre reinforced polymers, manufacturing methods, properties, existing bridges, advantages and limitations, testing methods and design considerations. Subsequently a two lane road bridge, located in northern Sweden, was chosen as a case study where firstly an optimised cross-section was designed in Abaqus and verified with hand calculations. The optimized cross-section was analysed in terms of a life cycle cost and compared to a conventional steel-concrete bridge.

The results from the finite element modelling showed that the requirements regarding the ultimate limit state and serviceability limit state of the optimized cross-section was fulfilled. It was furthermore noted that the deflection requirements was decisive in design due to the low stiffness exhibited by fibre reinforced polymer composites. The life cycle cost analysis of the optimized cross-section indicated that the initial cost was slightly higher than for the conventional bridge, the total cost was however lower.

Key words: FRP composites, Road Bridge, LCC analysis, optimized cross-section, FE analysis

Applikationer för fiberarmerade plast material inom trafikbroar – allmänna krav och designhänsynstaganden

Examensarbete inom Structural Engineering and Building Technology

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SAMMANFATTNING

Arbetet bakom examensarbetet har tagits fram i sammarbete med Trafikverket med syftet att förbereda för den första fiberarmerade plast trafikbron i Sverige. Detta är ett viktigt steg för att Sverige ska anses som ett innovativt land med hänsyn till infrastruktur projekt. Det finns många fördelar med fiberarmerad plast såsom låg vikt, hög hållfasthet, snabb montering samt hållbar vilket gör dem attraktiva som byggnadsmaterial.

Huvudmålet med examensarbetet är att ge Trafikverket en helhetsbild av användandet av fiberarmerade plast kompositer inom brokonstruktioner. Syftet är även att öka medvetenheten om fördelarna med fiberarmerade plast kompositer samt undersöka konkurrensförmågan i jämförelse med konventionella byggnadsmaterial.

En utförlig litteraturstudie har genomförts för att skapa en helhetsbild av fiberarmerade plast kompositer. Ämnena som studerades var uppbyggnaden av fiberarmerad plast, produktionsmetoder, materialegenskaper, befintliga fiberarmerade plastbroar, fördelar och begränsningar, testmetoder samt hänsynstaganden inom design. En bro med två körfält belägen i norra Sverige valdes ut som fallstudie, där tvärsektionen bestående fiberarmerad plast optimerades och därefter analyserades i finita elementprogrammet Abaqus. Efter verifiering med handberäkningar, jämfördes den optimerade bron med en konventionell stål-betong bro med hänsyn till livscykelkostnaden.

Resultaten från Abaqus visade på att kraven gällande brottsgränstillstånd och bruksgränstillstånd uppfylldes för den optimerade tvärsektionen. På grund av att fiberarmerade plast kompositer har en låg styvhet vilket resulterade i att nedböjningen är avgörande i designen. Livscykelkostnads analysen påvisade att fiberarmerade plast kompositer har en något högre initial kostnad, men den totala kostnaden är lägre på grund av att det krävs mindre underhållsarbete.

Nyckelord: FRP kompositer, trafikbro, LCC analys, optimerad tvärsektion, FE analys

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Preface

This thesis was written at the Department of Civil and Environmental Engineering, division of Structural Engineering, at Chalmers University of Technology during the spring of 2014. The thesis was formulated in collaboration between Chalmers and Trafikverket.

We would firstly like to thank our supervisor Reza Haghani Dogaheh for his guidance and support and who have helped us tremendously during our work. We would also like to thank Mohsen Heshmati for his help with Abaqus and Valbona Mara for her assistance with the LCC part of the project.

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Emma Friberg

Jenny Olsson

List of abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ADT	Average daily traffic
AE	Acoustic emission testing
AFRP	Aramid fibre reinforced polymer
APC	Advanced Polymer Composites
ASTM	American Society for Testing and Materials
ATH	Alumina trihydrate
AVK	Industrievereinigung Verstärkte Kunststoffe
BMC	Bulk moulding compound
BPA	Bisphenol-A
CCM	Continuous compression moulding
CFM	Continuous filament mat
CFRP	Carbon fibre reinforced polymer
CO	Carbon monoxide
CO_2	Carbon dioxide
CSM	Chopped strand mat
CTE	Coefficient of thermal expansion [10^{-6}/°C]
DMC	Dough Moulding Compound
EMPA	Swiss Federal Laboratories for Material Science and Technology
FE	Finite element
FRP	Fibre Reinforced Plastic
GRP	Glass Reinforced Plastic
GFRP	Glass fibre reinforced polymer
HCL	Hydrochloride
HCN	Hydrogen cyanide
HDT	Heat Distortion Temperature
HM	High modulus
HRR	The heat release rate
HT	High tenacity
IPA	Isophtalic acid
ISO	International Organization for Standardization
KFRP	Aramid fibre reinforced polymer
LCA	Life cycle assessment
LCC	Life cycle cost

LOI	Limiting oxygen index
MR&R	Maintenance, rehabilitation and repair
NDE	Non-destructive evaluation
NDI	Non-destructive inspection
NDT	Non-destructive testing
NO_x	Nitrogen Oxides
NPV	Net present value
PEEK	Polyetheretherketine
PET	Polyethylene Terephthalate
PG	Propylene Glycol
PHRR	Peak heat release rate
PMC	Polymer Matrix Composites
PMI	Polymethacrylimides
PP	Polypropylene
PPS	Polyphenylene sulfide
RIM	Resin infusion moulding
RTM	Resin transfer moulding
SEA	Specific Extinction Area
SM	Standard modulus
SMC	Sheet Moulding Compound
SO_2	Sulfure Dioxide
Tg	Glass transition temperature
T_m	Melting point
QA	Quality assurance
QC	Quality control
ULS	Ultimate limit state
UT	Ultrasonic testing
UV	Ultra-violet
VARTM	Vacuum assisted resin transfer moulding
V_f	Fibre volume fraction [%]
VT	Visual testing
WOL	Whole of Life
WR	Woven roving

Notations

Upper case letters

A_a	The accident rate during construction
A_n	The normal construction rate
C_a	The cost per accident
C_n	The cost incurred in year n
E_c	Compressive modulus of elasticity
$E_{c(char)}$	Compressive modulus of elasticity of the char region
E_f	Flexural modulus of elasticity
$E_{f(0)}$	Original value of flexural modulus of elasticity
E_t	Tensile modulus of elasticity
$E_{t(0)}$	Original value of tensile modulus of elasticity
EI	Stiffness
I	The second moment of area
N	The number of days of roadwork
N_f	Number of cycles to failure
P_c	Euler buckling load
P_f	The flexural failure load
R_m	Tensile strength

Lower case letters

d	The discount rate [%]
r	The hourly vehicle operating cost
w	The hourly time value of the drivers
γ_{CK}	Creep conversion factor

1 Introduction

1.1 Background

The general state of the existing infrastructure in Europe, Canada, United States and other developed areas is comprised by an accelerated deterioration, as a result of systematic neglect and overuse (Bisby 2006). Canada, for example, is facing a serious situation since more than 40% of the bridges are older than 50 years and are in need of rehabilitation, strengthening or replacement (Bisby 2006). The number and age of the road- and railway bridges managed by the Swedish Transport Administration (Trafikverket) can be seen in Figure 1. It can be concluded that a considerable amount of the existing road bridges in Sweden are 40 years and older, and will require maintenance during their existing life span.

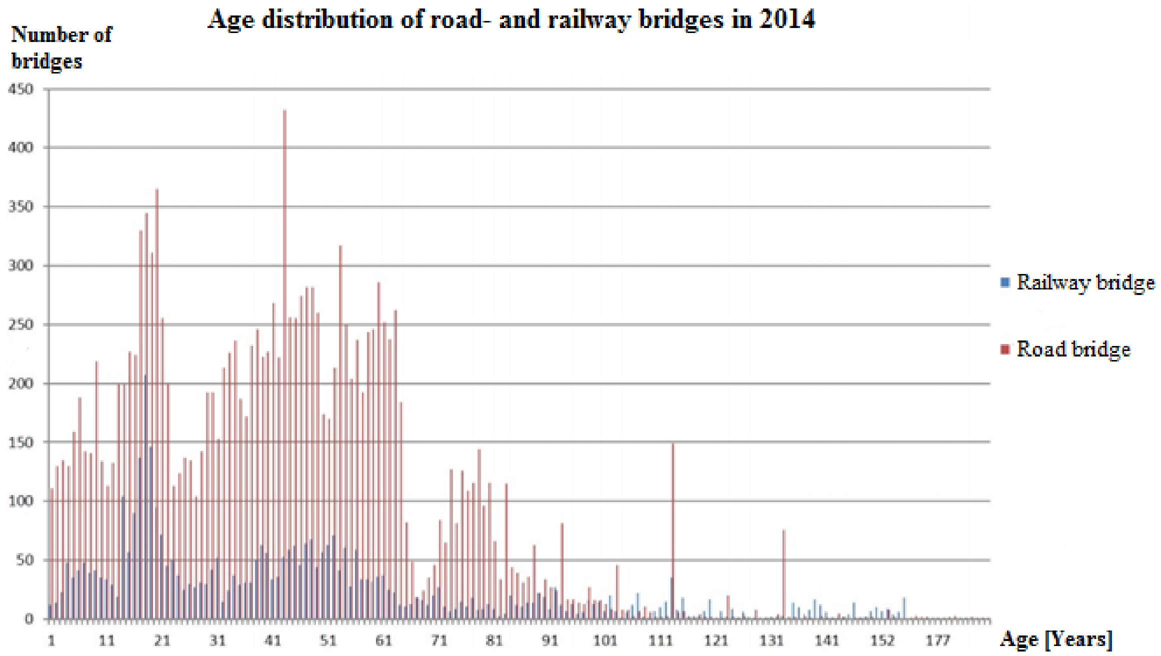

Figure 1 Number and age of bridges maintained by the Swedish Transport Administration in 2014 (Trafikverkets hemsida)

The main source of the deterioration of the bridges is corrosion of the reinforcing steel in the concrete (Bisby 2006). Common problems induced by deterioration are delamination, loss of tensile reinforcement, spalling of concrete and ultimately failure (Bisby 2006). Other factors that contribute to the global infrastructure crisis are increased loads and design requirements, corrosion of steel structures as well as aging (Bisby 2006). Fibre reinforced polymer composites (FRP) is a promising alternative to the conventional materials steel and concrete since they are non-corrosive, non-magnetic, lightweight, versatile and have high tensile strength (Bisby 2006; Tang & Podolny 1998).

FRP is a composite material that consists of a polymeric matrix which is reinforced with fibres (Potyrala 2011). The definition of a composite is a mixture of at least two different materials which are combined to get a finish product with better properties than what the materials have separately (Potyrala 2011). FRP materials have been used in civil engineering applications for roughly 30 years which mainly is due to their advantageous mechanical, chemical and physical properties (Tang & Podolny 1998). They are desirable in many applications such as repairing of existing and construction of new structures (Tang & Podolny 1998; Muniz & Bansal 2009). Today bridges (both vehicular and pedestrian) can be built as hybrid- or all-composite versions. The focus has previously been on hybrid materials, where conventional materials are combined with FRP composites. Today however the all-composite structural elements are expanding due to the development of FRP deck systems for construction of bridges (Hollaway 2010). The available markets today of FRP composites are mainly FRP decks and externally bonded FRP repair (Leo, Chakrabortty & Khennane 2010).

There has previously been little progress in highway structures and in the 1990's there was only a dozen all-composite FRP bridges available. The demand of FRP composites have however increased, which have resulted in that in 2003 the number of available pedestrian bridges comprised more than 160 and the corresponding value for vehicular bridges was 175 (Chlosta 2012; Mostostal Warszawa S.A. et al. 2012). This rapid increase in number of bridges was mostly due to a growing recognition of the advantageous properties of the material (Mostostal Warszawa S.A. et al. 2012). Today there are a large number of FRP road bridges in the world; however there are no such bridges constructed in Sweden. For this reason the Swedish Transport Administration in collaboration with Chalmers will conduct a feasibility study if the bridge concept is appropriate in Sweden. This is an important step for Sweden to be regarded as an innovative country in terms of civil engineering applications.

There is a need today for alternatives to the conventional construction materials steel and concrete. This is due to that they consists of finite raw materials and have many disadvantages such as being sensitive to alkaline environments and in general environmentally unfriendly. FRP composites are relatively new materials used in infrastructure applications and there is a need to further increase the awareness and demonstrate the benefits enabled with the material. In order for FRP composites to establish a status as a prominent and promising building material it is crucial to compare the properties with the conventional building materials.

In this thesis an extensive literature study has been performed in order to get a holistic picture of FRP composites. An optimized cross-section for an all-composite FRP road bridge was designed with Finite Element (FE) software with regard to ultimate limit state (ULS) and serviceability limit state (SLS) requirements. The optimized all-composite road bridge was finally compared to a conventional road bridge with regard to the life cycle cost (LCC).

1.2 Aim and Objectives

The aim of the report is to gather information about FRP composite material for the purpose of road bridge construction in Sweden. The objectives are to compare FRP composites with the conventional construction materials steel and concrete, analysing the behaviour of an optimized FRP composite bridge cross-section in FE software and finally performing a LCC analysis.

1.3 Method

The first and main part of the thesis consisted of performing a literature study where subjects such as the structure, manufacturing techniques, properties, advantages and limitations, existing bridges, testing methods and design considerations were studied.

In the second part an optimized cross-section of an all-composite road bridge was designed based on the study case Rokån Bridge. Preliminary hand calculations of the design were performed and verified to the FE analysis performed through Abaqus. The capacity of the cross-section was verified by analysing ULS and SLS requirements. Finally a LCC analysis was conducted and compared to the results of a corresponding concrete- and steel road bridge.

1.4 Limitations

The structure of the literature study is very holistic and a large range of subjects was considered. Hence few limitations were made, such as only covering FRP road bridges.

During the FE modelling only the software Abaqus was used. The LCC analysis was limited to the study case Rokån Bridge which had a fixed width and length of 7x12m.

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2 The Structure of FRP Composites

2.1 Materials

FRP composites are a subgroup to a class of materials called composites (Bisby 2006). The FRP composite is mainly made up of the two materials: high-strength fibre reinforcement and a liquid polymer which creates a solid, inhomogeneous and anisotropic building material (Chlosta 2012; Bisby 2006). Figure 2 illustrates the main components of FRP composites. FRP composite furthermore consists of additives, which main purpose is to provide a protective surface of the composite towards environments that are corrosive, wet or fire-hazardous (Chlosta 2012).

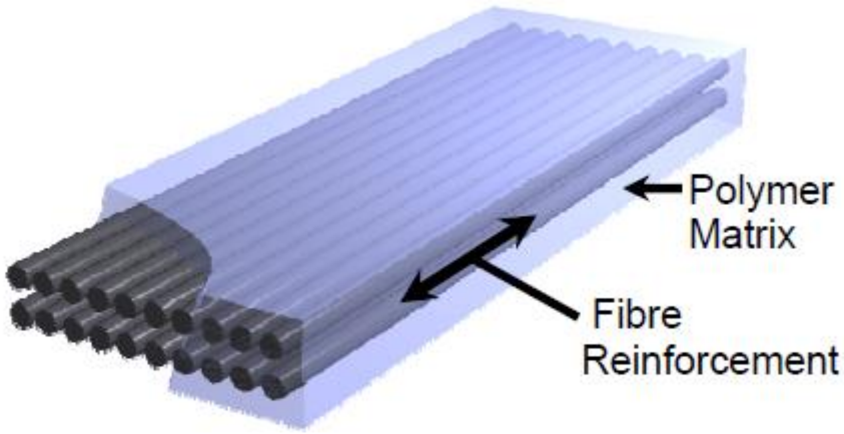


Figure 2 Schematic of reinforcement and matrix forming a FRP composite (Bisby 2006)

2.2 Reinforcement

There is a large variety of reinforcement materials available such as unidirectional (rovings for glass fibres and tow for carbon fibres), chopped fibre mats, woven fabrics and non-crimp fabrics (Clarke 1996; Cytec n.d). These types have been developed with regard to both ease of manufacture and mechanical properties (Clarke 1996).

2.2.1 Fibres

A fibre is a long filament made out of a single material (Potyrala 2011) such as glass, aramid or carbon. The main purposes of the fibre are to provide a sufficient strength and stiffness (Clarke 1996; Bisby 2006), be able to carry the applied load and generate thermal stability etc. (Potyrala 2011). For this to be achieved the fibre must fulfil some properties such as to have a sufficient modulus of elasticity and ultimate strength, little variation of strength, stability of fibres during handling as well as a uniformity of diameter of the fibres (Potyrala 2011; Bisby 2006). The properties of the fibre are governed by both the backbone of the fibre and the structure of the molecule (Clarke 1996). In addition the fibres should provide a sufficient aspect ratio in more than one direction i.e. provide a reinforcing function in both the longitudinal and transversal direction (Halpin, Hastak & Hong 2004).

The diameters of the fibres are generally in the range of 6-15 µm (Potyrala 2011; Clarke 1996). Suppliers however are today moving towards larger fibre diameters ranging from 20-30 µm (Clarke 1996). If the diameter is greater than that there is a risk of surface defects (Potyrala 2011) and decreased strength (Clarke 1996). The advantages with larger diameter fibres are that they are less expensive, easier to impregnate and more health and safety beneficial (Clarke 1996). The advantage of using small diameter fibres are that the risk of inherent flaws is reduced (KAW 2005). This phenomenon also applies for steel members where the strength of a plate is in the range of 100 ksi (689MPa) and a wire has strength of 600 ksi (4100MPa) (KAW 2005). The relation between strength and diameter of the fibre can be seen in Figure 3. The fibre diameter also has an impact on the toughness and ductility of the composite, since these parameters are related to the size of the fibre-matrix interface, where the size of the fibre-matrix is inversely proportional to the diameter of the fibre (KAW 2005). During manufacture it is important that the fibres don't break which consequently requires bendable fibres (KAW 2005). The fibres bendability is measured as flexibility which increases with decreasing diameter (KAW 2005). Furthermore the diameter of the fibre also has an impact on the stress transfer (Chlosta 2012). This is related to that a smaller diameter aids the stress transfer since the smaller diameter provides a larger surface area of fibre per unit weight (Chlosta 2012). The aspect ratio between diameter and length range from approximately 1000 to near-to- infinity, resulting in that they generally are considered continuous (Potyrala 2011; Bisby 2006). The highest performing composites are achieved by choosing unidirectional and isotropic fibres with aspect ratios that are near-to infinity (Chlosta 2012). In general the lowest mechanical properties are achieved by choosing short fibres and inserting them anisotropic (Chlosta 2012).

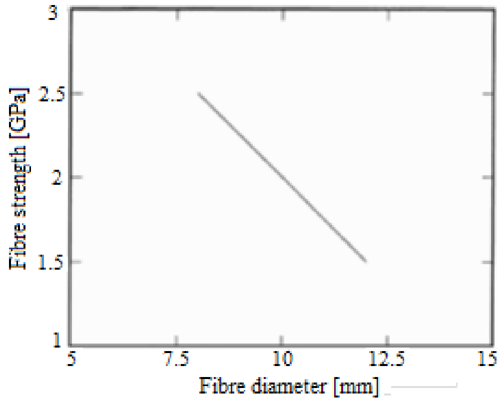


Figure 3 Fibre strength as a function of fibre diameter for carbon fibres (KAW 2005)

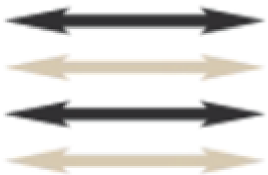
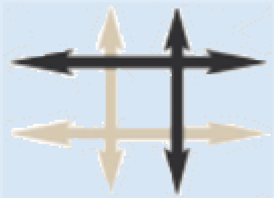
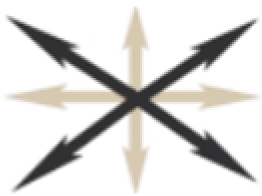
The fibres generally represent about 30-70% of the volume and 50% of the weight depending on the manufacturing technique (Potyrala 2011). The volume fraction is a function of the manufacturing process and the form of the reinforcement (Clarke 1996; ZRMK et al. 2013). In Table 1 a comparison of different fibre volume fractions achieved with the most common manufacturing techniques is displayed. The strength and stiffness of a FRP composite is governed by the volume fraction of fibres in the section of the composite, the choice of matrix resin and the direction of the fibre in respect of the applied load as well as the properties of the fibre (Clarke 1996; Muniz & Bansal 2009; ZRMK et al. 2013). The fibres used in FRP composites show very good performance when subjected to tension, however their performance under pressure or flexure is generally poor (Chlosta 2012).

Table 1 Fibre volume fractions achieved with hand lay-up, pultrusion respective Vaccum assisted resin transfer moulding (VARTM) process (Mara 2014)

	Hand lay-up	Pultrusion	VARTM
Typical fibre volume fractions	up to 30%	up to 65%	up to 60%

The fibre arrangement can be assigned into three main categories which are unidirectional, bidirectional and random (Clarke 1996). Unidirectional is referred to the case when all fibres are arranged in one direction (Clarke 1996). Bidirectional is when fibres are arranged in two directions either as 0° and 90° or ±45° (Clarke 1996). This is performed with woven or non-woven fabrics (Clarke 1996). For the arrangement termed random, which also is referred to as multidirectional fibre direction, the fibres are randomly distributed (Clarke 1996). In Table 2 the different categories of fibre arrangement is displayed. In general better mechanical performance is achieved of the composite if continuous fibres are used instead of chopped fibres (Clarke 1996).

Table 2 Different fibre directions (MFG n.d, p. 6)

Unidirectional fibre orientation		**Reinforcement types:** Continuous strand roving **Processes:** Continuous pultrusion, compression moulding
Bidirectional fibre orientation		**Reinforcement types**: Continuous strand roving, woven fabrics, woven roving's **Processes**: Filament winding, compression moulding, hand lay-up
Multidirectional fibre orientation		**Reinforcement types**: Chopped strands, continuous chopped strand mat, tri-axial fabric **Processes**: Compression and injection moulding, spray-up, pressure bag, preform

During the manufacture of the FRP composite the performance of the composite is often decreased (Clarke 1996). Glass fibres are an example related to this, where the fibres have the disadvantage of being very sensible towards even small defects which can cause a great reduction in strength (Muniz & Bansal 2009). A measure to prevent this is through controlling and thus eliminating flaws during the production process (Clarke 1996). However the fibre modulus is not affected during manufacture, which generates an accurate prediction of the modulus (Clarke 1996). The production of fibres is either by drawing from a melt as for glass fibres or as precursors by spinning of extrusions for chemical or thermal conversion as for carbon fibres (Clarke 1996).

The three types of fibres that are most common in civil engineering applications are: glass, aramid and, to a lesser extent, carbon fibres (Potyrala 2011; Muniz & Bansal 2009). They are suitable for different types of applications depending on requirement of factors such as strength, stiffness, cost, durability and availability (Bisby 2006). Glass fibres are the most used fibres in civil engineering application (Clarke 1996; Chlosta 2012) mainly due to their low cost (Bisby 2006). They are common in application where there are no requirements regarding weight, which is due to that glass is the heaviest of the fibre types and when larger deflections are permitted which is the result of the low modulus of elasticity (Bisby 2006). However a shift towards carbon fibres has been observed due to the increasing need for stronger and stiffer parts (Chlosta 2012). Carbon fibres have better properties than glass fibres in terms of strength, stiffness and modulus of elasticity (Bisby 2006). Furthermore they have advantages in terms of resistance against thermal, chemical and environmental effects (Bisby

2006). The applications of carbon fibres are common when there are requirements regarding weight and/or modulus (Bisby 2006). Examples of applications are pre-stressing tendons and structural wraps (Bisby 2006). Glass- and carbon fibre are regarded as non-combustible fibres and aramid and also polyethylene fibres are regarded as combustible (Gibson, Mathys & Mouritz 2006). A larger amount of non-combustible reinforcement in a FRP composite result in less material to be burned (Clarke 1996). A composite with either uni- or bidirectional fibres have better performance during fire. This is due to that these fibre arrangements allow a higher fraction of fibres (Clarke 1996). Both glass, aramid and carbon fibres have low densities which provides the polymer with an excellent strength/stiffness to weight ratio (Chlosta 2012). Furthermore the three types have similarities in their behaviour until breakage which is of a quasi-elastic manner (Chlosta 2012). Carbon fibres are however lighter and stiffer than the other fibre types which have resulted in it being the preferable choice in the high performance applications such as the transport industry (Chlosta 2012).

2.2.1.1 Glass Fibre

Glass fibre is the most common reinforcement in FRP composites where it stands for approximately 90% of the market (Chlosta 2012). Glass fibres are a processed form of glass, and consist of a number of oxides (largest extent of silica oxide) and raw materials (such as limestone, fluorspar, boric acid, clay etc.) (Potyrala 2011). Due to that glass fibres contain silica they are in general very sensitive to alkaline environments (Hollaway 2010; Bank 2006). Studies from civil engineering applications have however shown that the attack have generally been moderate (Hollaway 2010).

The glass fibres are manufactured by drawing the melted oxides through filaments (Potyrala 2011). The melt is formed at a temperature of approximately 1400°C in a refractory furnace (KAW 2005). The melt is then drawn through approximately 250 nozzles that are heated to form a filament with a specified size at a general speed of 25m/s (KAW 2005). For the fibres to be able to be packed in strands they are sprayed with an organic sizing solution that is a mixture containing of binders, lubricants as well as coupling and antistatic agents (KAW 2005). The glass manufacturing scheme can be seen in Figure 4.

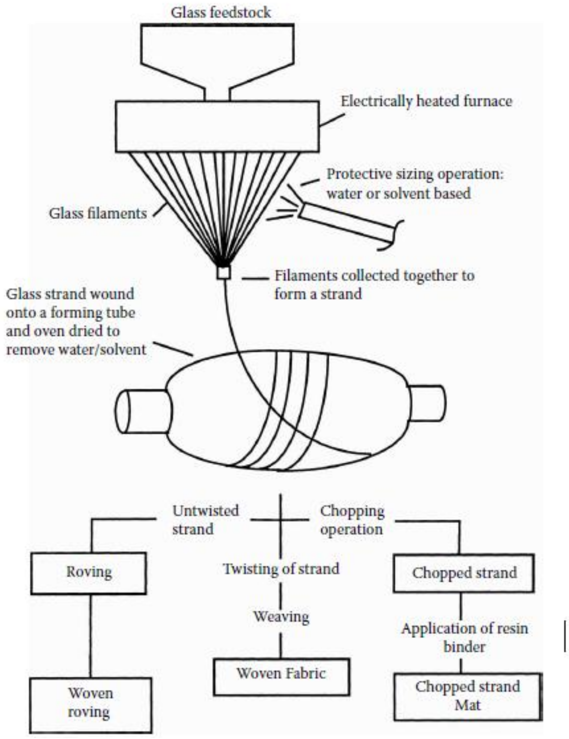


Figure 4 Manufacturing scheme of glass fibres and available glass forms (KAW 2005)

The existing forms of glass fibres can be seen in Figure 4 and are: chopped fibres, chopped strands, chopped strand mats, woven fabrics and surface tissue (Potyrala 2011). The most common forms in civil engineering applications are the glass fibre strands and woven fabrics (Potyrala 2011). A picture of glass fibre fabric can be seen in Figure 5.

Figure 5 Glass fibre fabric (Potyrala 2011, p. 9)

An advantage with glass fibres compared to other fibres is that they are inexpensive (Potyrala 2011; Clarke 1996; Cytec n.d). In addition they have good processing characteristics and properties (Clarke 1996). Glass fibre also has the advantage of being a suitable reinforcement for all the available manufacturing processes (Clarke 1996). In comparison with other fibres, glass fibres have higher resistance against impact due to a high strain to failure (Clarke 1996). See Figure 6 and Table 9 for comparison of stress-strain relations for different fibres. In Figure 6 the carbon type 1 is related to the stiffest carbon fibre and type 2 related to the strongest carbon fibre.

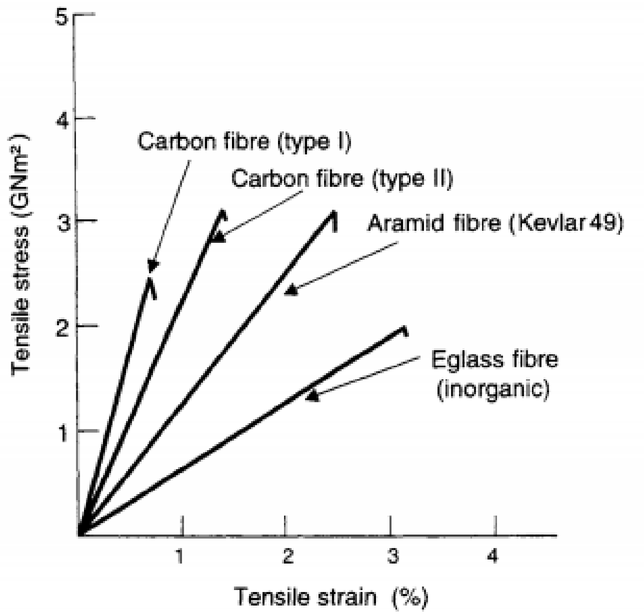


Figure 6 Comparison of stress-strain relation between different fibres (Hollaway 2001, p. 24)

The down sides with glass fibre are that they have a relatively low Young's modulus (KAW 2005), low humidity and alkaline resistance as well as low long-term strength due to stress rupture (Potyrala 2011). In addition glass fibres are denser and have lower strength and stiffness than carbon and fibres (Cytec n.d). If glass fibres are subjected to alkaline environments with pH much higher than 7 there is a risk of severe degradation of the fibres due to mechanisms such as pitting, hydrolysis, leaching and hydroxylation (Hollaway 2010). Examples of alkali salts are sodium hydroxide, potassium hydroxide, calcium hydroxide and magnesium hydroxide (Reichhold 2009). In Table 3 the composition of glass types E, C and ECR are specified.

Table 3 Indicative composition of E-, C- and ECR glass fibre (Clarke 1996)

Components	E-glass	C-glass	ECR-glass
Silicon oxide	54	65	54
Aluminium oxide	15	4	15
Calcium oxide	17	13	21
Magnesium oxide	5	3	5
Sodium oxide	< 1	8	< 1
Potassium oxide	1	2	< 1
Boron oxide	8	5	0
Barium oxide	-	1	0

Another disadvantage regarding glass fibres is that they are sensitive to abrasion which can result in that the handling and weaving of glass fibres can cause a reduction in strength (Clarke 1996; KAW 2005). In addition glass fibres are very susceptible to ingress of moisture which can lead to microcracks in the fibre which ultimately can reduce the tensile strength (Hollaway 2010). Due to that glass fibres in general have a high ratio of surface area to weight there is a larger risk of chemical attack (Hollaway 2010). Furthermore glass fibres have low fatigue strength, adhere poorly to polymers and have a high specific gravity which can be seen in Table 9 (KAW 2005). The specific gravity is larger than for aramid and carbon but are however smaller than the conventional building materials steel and aluminium which is displayed in Table 4.

Table 4 Comparison of specific gravity for glass, steel and aluminium (Clarke 1996)

Material type	Specific gravity [-]
Glass	2.5
Steel	7.8
Aluminium	2.8

There are many types of glass fibres with different characteristics for example E, C, E-CR, R and S2 glass (Clarke 1996) as well as Z-glass (Hollaway 2010). The glass types mainly used in applications are E and S glass (KAW 2005). The glass fibre types E, C and ECR have a modulus of elasticity of about 70GPa relatively low strength. Typical properties of E, C and E-CR glass can be seen in Table 5. The glass types R and S2 have a modulus of elasticity of 85GPa with higher strength (Clarke 1996).

Table 5 Typical properties of glass fibres E, C and ECR (Clarke 1996)

Properties	Unit	E-glass	C-glass	ECR-glass
Specific gravity	-	2.54	2.5	2.71
Tensile strength	N/mm^2	3400	3000	3300
Tensile modulus	kN/mm^2	72	69	72
Elongation	%	4.8	4.8	4.8
Coeff. of thermal expansion	$10^{-6}/°C$	5.0	7.2	5.9

2.2.1.1.1 E-glass

The “E” in E-glass stands for electrical since it was initially developed for electrical application (KAW 2005). E-glass is the most common fibre in composite application and is the best choice of fibre type if the highest strength as well as electrical and thermal resistance is strived for (Clarke 1996). The reason E-glass has good electrical resistance is due to that it has a low alkaline content (Clarke 1996). In addition due to a high devitrifying temperature of 675°C E-glass is relatively insensitive to temperature effects (Clarke 1996). The polymeric part of the FRP composite however has in general a low devitrifying temperature and will be the limiting factor in design (Clarke 1996). Other advantages with E-glass are good overall mechanical and physical properties, easy availability, versatile and little degradation of water over time (Clarke 1996)

E-glass is very sensitive to both physical and environmental damage with a result in decreased strength (Clarke 1996). A measure to avoid physical damage is through awareness in the manufacture of both the fibre and especially the composite that is extra sensitive (Clarke 1996). With regard to environmental damage E-glass is insensitive towards most chemicals except for mild alkalis and acids (Clarke 1996). If E-glass is subjected to chloride ions the surface of will be dissolved (Hollaway 2010). In addition, if E-glass fibres are exposed to distilled water for 100 days the remaining short-term tensile strength is approximately 65%, which can be compared with 75% for R-glass fibres (Clarke 1996).

If using E-glass fibres, only composites with relatively low moduli can be produced due to that E-glass itself has a low modulus (Clarke 1996). The modulus of elasticity of the composite if using unidirectional E-glass fibres with a fibre fraction of about 75% is in the range of 45 to 50GPa (Clarke 1996). However for the transverse direction the modulus of the composite is in the range of 4GPa which is approximately the modulus of the resin (Clarke 1996).

2.2.1.1.2 C-glass

The "C" in C-glass stands for corrosion (KAW 2005) and should be chosen if high chemical resistance is needed, however the strength is lower than of E-glass (Clarke 1996). C-glass is often used if E-glass is unacceptable for an application and the main area of application is surface layers of laminates (Clarke 1996). Since C-glass has a higher alkaline content the electrical resistance is lower than that of E-glass (Clarke 1996).

2.2.1.1.3 E-CR-glass

E-CR-glass is boron-free and can be chosen as a substitute for E-glass since they have similar properties. In comparison with E-glass, ECR-glass also has higher chemical resistance especially in acid environments (Clarke 1996).

2.2.1.1.4 S2- and R- glass

The "S" in S-glass glass indicated that the silica content is high (KAW 2005). S2- and R-glass are mainly used in high-performance applications such as aerospace and have compared to E-glass approximately 40% more strength and 20% higher stiffness (Clarke 1996). In addition they provide better resistance towards elevated temperature (Clarke 1996) and have higher fatigue strength (KAW 2005). However S2- and R-glass fibres are more expensive than E-glass fibres which are justified due to considerable higher strength and stiffness (Clarke 1996). Another disadvantage of S2- and R-glass is that they are only compatible with some resin systems compared to E-glass that are more flexible since they are compatible with all available resin systems (Clarke 1996).

Due to a high modulus of elasticity of the S2- and R-glass fibres, high modulus of elasticity for the composite in the range of 60GPa can be achieved if unidirectional reinforcement is used and 25GPa for non-crimp bidirectional material (Clarke 1996).

2.2.1.1.5 Comparison of different Glass Fibres

Table 6 displays a comparison between different types of glass fibre. From the table it can be concluded that the glass fibre types R and S provides best performance to the composite, since it has both the highest tensile strength and tensile modulus. The second best option is the E glass fibre. The compared glass fibre types show similar fracture strain which is low if compared to steel that has a fracture strain in the range of 10%. It can thus be concluded that glass fibres are brittle and that they show less ductile behaviour than steel (Chlosta 2012).

Table 6 Comparison between E, C, EC-R and R glass fibres (Chlosta 2012, p. 28)

Type	Unit	E	C	EC-R	R & S
Specific gravity	-	2.6	2.52	2.72	2.53
Tensile strength					
- Filament	N/mm^2	3400	2400	3445	4400
- Roving	N/mm^2	2400	-	-	3600
Tensile modulus	kN/mm^2	73	70	73	86
Fracture strain	%	4.8	4.8	4.8	4.8
Softening points	°C	846	750	882	985

2.2.1.2 Carbon Fibres

Carbon fibre is one of the two types of high-performance fibres used in civil engineering application (Potyrala 2011). The use of carbon fibres is increasing and between the years 1998 and 2010 the worldwide use of carbon fibres doubled to an amount of 30.000 tons annually (Chlosta 2012). Carbon fibres are generally used when high strength and stiffness is required and where a lower weight justifies the higher cost (Cytec n.d). Carbon fibres are furthermore considered to be the most durable fibre type (Bank 2006).

The production of carbon fibres, in comparison with glass fibres, has higher energy consumption and is more complicated (Chlosta 2012). The manufacturing technique can be seen in Figure 7 and consist of a controlled pyrolysis and crystallization of organic precursors at as high temperatures as 2.000°C-2.400°C (Potyrala 2011; Hollaway 2010).

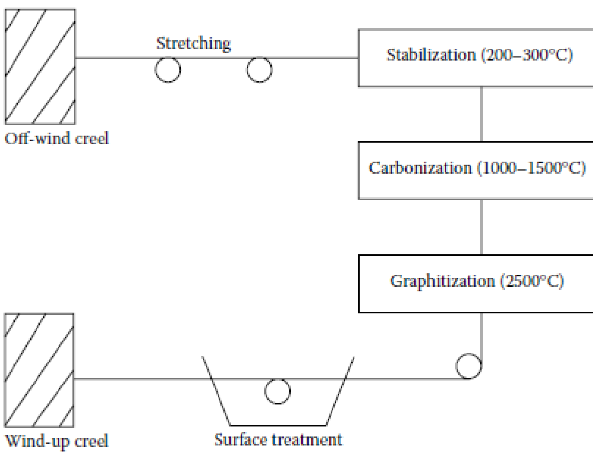


Figure 7 Manufacturing pf carbon fibres based on PAN precursors (KAW 2005)

There are two different production processes generally related to the production of carbon fibres which are separated depending on the precursor used (Chlosta 2012). At present there are three kinds of precursors used for the manufacture of carbon fibres which are: rayon, polyacrylonitrile (PAN) and pitch precursors. The most commonly used precursor today is PAN, and has the advantage that it yields at approximately 50% of original fibre mass (Potyrala 2011). Pitch precursors have the same characteristics of high carbon yield for a low cost (Potyrala 2011). See Figure 8 for a scheme of the production process of carbon fibres with PAN and pitch precursors.

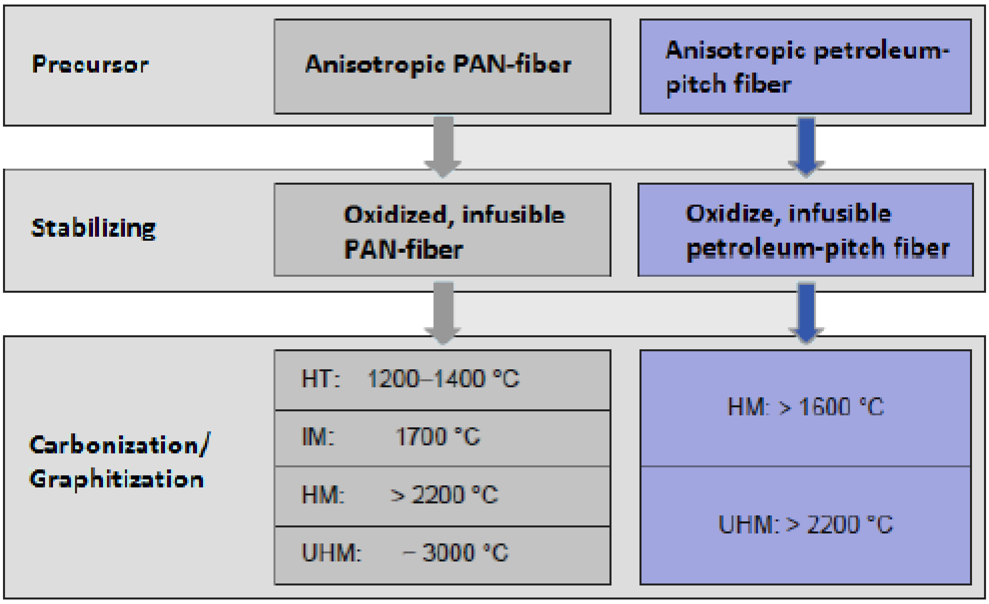


Figure 8 Scheme of the two production processes of carbon fibres (Chlosta 2012, p. 32)

Carbon fibres are available as high modulus fibre, ultra-high modulus fibre and high strength fibre (Hollaway 2010). The high modulus carbon fibre have a stiffness of 240GPa and a tensile strength of 400MPa indicating a high strain to failure ratio (Hollaway 2010). The ultra-high modulus fibre has stiffness of approximately 400GPa and with a tensile strength of 1800MPa which indicates a low strain to failure ratio (Hollaway 2010). Typical strength for the high strength carbon fibre is 4400MPa and a modulus of the fibres of 200GPa (Hollaway 2010). The fibre termed T300 is the most common carbon fibre (Clarke 1996). The cost of the T300 fibre in relation to the performance makes it a valid option for commercial applications (Clarke 1996). T1000 is a carbon fibre used for more high-performance application; however the cost high and applications are rarely justified (Clarke 1996). A picture of carbon fibre fabric can be seen in Figure 9.

Figure 9 Carbon fibre fabric (Potyrala 2011, p. 9)

The advantages with carbon fibre compared to glass fibre are a higher modulus of elasticity and fatigue strength (Potyrala 2011; Bank 2006). Some studies also suggest that carbon fibre compared to both aramid and glass fibre have a better service life (Potyrala 2011). Carbon fibres are resistant to ingress of alkalis and solvents since they cannot absorb liquids (Hollaway 2010; Bank 2006). In addition the use of carbon fibres contributes to FRP composites with high strength and stiffness (Clarke 1996). The stiffness of carbon fibres in comparison with glass fibres are sometimes up to four times as large (Clarke 1996). The specific modulus, also referred to as the stiffness-to-weight ratio, is property that is advantageous for carbon fibres in comparison with both steel and E-glass fibres (Clarke 1996). Another benefit with carbon fibres are that they have a low coefficient of thermal expansion in the longitudinal direction resulting in a high dimensional stability (Bank 2006). In Table 7 the specific modulus for the carbon composite Torayca M46 with fibres in uni- and bidirectional as well as E-glass and steel is compared. It can be noted that the modulus of elasticity for M46 is 255GPa and for steel is 210GPa (Clarke 1996).

Table 7 Specific modulus for carbon fibre, glass fibre and steel (Clarke 1996)

Material	Specific modulus
M46 unidirectional composite	160
M46 bi-directional composite	70
E-glass unidirectional composite	23
Steel	27

The disadvantages with carbon fibres are that the fibres are anisotropic in themselves and that the manufacture of carbon fibres is both relatively expensive and with a high energy consumption (Potyrala 2011; Bank 2006) where the heat treatment temperature increase with the modulus of the fibres (Hollaway 2010). In addition FRP composites with ultra-high carbon fibres have a very low strain to failure compared to other fibres which indicates limited ability to absorb impact without being damaged (Clarke 1996; Hollaway 2010). This behaviour can however be improved by adding fibres with higher strain to failure such as glass- and aramid fibres (Clarke 1996). Carbon fibres are furthermore both thermally and electrically conductive which can be problematic (Bank 2006).

2.2.1.3 Aramid Fibres

Aramid fibres are the second of the two types of high-performance fibres used in civil engineering (Potyrala 2011). The fibre is manmade and organic and is used in many civil engineering applications (Clarke 1996) and is made of carbon, hydrogen, oxygen and nitrogen (KAW 2005). The characteristics of aramid fibres are a relatively high tensile strength, low density and medium modulus of elasticity (Clarke 1996) as well as high resistance towards impact and low cost (KAW 2005; Cytec n.d). Furthermore they provide very good resistance towards abrasion (Cytec n.d). The main disadvantages regarding aramid fibres are the low compressive strength and the sensitivity towards sunlight (KAW 2005; Cytec n.d). In Figure 10 a single fibre and aramid fibre fabric is displayed.

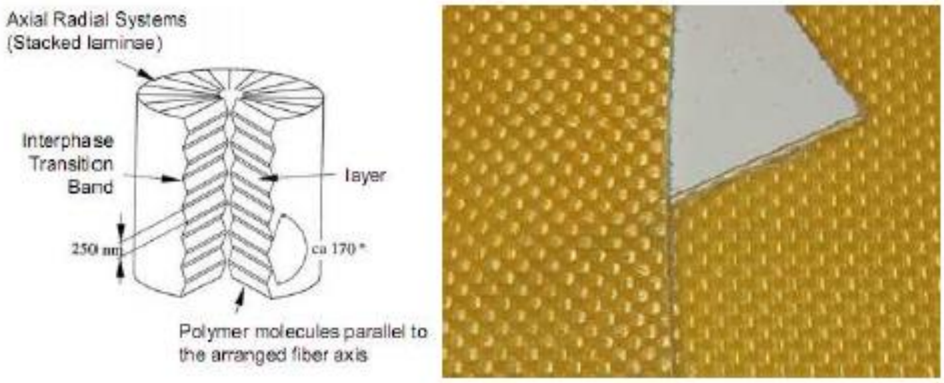


Figure 10 Single aramid fibre and aramid fabric (Potyrala 2011, p. 10)

When manufacturing aramid fibres a solution of aromatic polyamide is extruded at temperatures between -50°C and -80°C and then put into a cylinder with a temperature of 200°C (Potyrala 2011; KAW 2005) and are thereafter washed and left to dry on spools (KAW 2005). Aramid fibres are mainly oriented in the longitudinal direction due to that the residual fibres from the evaporation process are stretched and thus increasing strength and stiffness (Potyrala 2011; KAW 2005).

Aramid fibres can be divided in two types Kevlar 29® and Kevlar 49®. Both types have similar ultimate tensile strength, specific gravity and coefficient of thermal expansion but they differ however in modulus of elasticity (KAW 2005). Kevlar 29® is characterized by having a modulus of elasticity in the range of 60-70GPa which is similar to glass-fibre (Clarke 1996). They are commonly used when high strain to failure is required (Clarke 1996). Kevlar 49® has a modulus of elasticity that is the double of that of Kevlar 29® (Clarke 1996). The type Kevlar 49® is the most widely used of the two types and the main applications are the aircraft industry and in bulletproof vests, ropes and cables (Clarke 1996; KAW 2005). An advantage with Kevlar 49 is that it is relatively stable towards chemicals, especially neutral chemicals (Clarke 1996). However they are sensitive towards strong acids and bases (Clarke 1996). The company Teijin has overcome this problem and the product is called Technora® (Clarke 1996). In Table 8 typical properties of Kevlar 29® and Kevlar 49® are displayed.

Table 8 Typical properties of Kevlar fibres (KAW 2005)

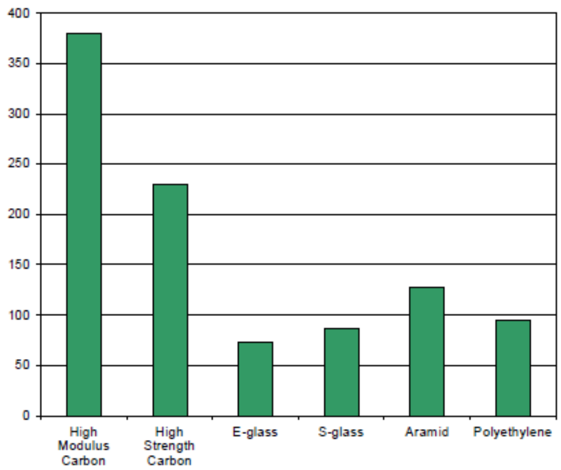
Property	**Unit**	**Kevlar 29**	**Kevlar 49**
Specific gravity	-	1.44	1.48
Modulus of elasticity	kN/mm^2	62.05	131.0
Ultimate tensile strength	N/mm^2	3620	3620
Coeff. Of thermal expansion	$10^{-6}/°C$	-2	-2

Advantages encountered with aramid fibres are that they have a high impact, static and dynamic strength (Potyrala 2011; Clarke 1996). In addition they provide good insulation towards both heat and electricity (Clarke 1996). They also have the ability to resist organic solvents, lubricants and fuels (Clarke 1996). Aramid, glass and carbon fibres behave in a ductile manner (Clarke 1996). For both groups the behaviour to failure is linear in tension (Clarke 1996). In compression the failure stress is lower than for compression and the behaviour to failure is non-linear (Clarke 1996). Aramid has a lower specific gravity than glass- and carbon fibres; hence the strength to weight and stiffness to weight is higher than for the other fibre types (Clarke 1996).

One of the downsides with aramid fibres is that it has a very low longitudinal compressive strength of about 500-1000 MPa (Potyrala 2011; Clarke 1996; Muniz & Bansal 2009) which is almost one fourth of the tensile strength (Clarke 1996). If aramid fibres are subjected to an alkaline environment there can be some reduction in the tensile strength (Hollaway 2010). The compressive and tensile properties of aramid fibres are ranked in Table 10 in comparison with carbon and glass fibres, aramid fibres provide the lowest strength with regard to loads applied transversally to the fibre direction (Muniz & Bansal 2009). It can be concluded that in terms of applications aramid fibres are not a valid option in flexural or compressive situations (Clarke 1996). As for the case of glass fibre, aramid fibres have a low long-term strength due to stress rupture (Potyrala 2011). Another negative aspect with aramid fibres is that during manufacture problems arise whit cutting and machining of the fibres (Potyrala 2011). Also worth mentioning is that aramid fibres are sensitive to ultra-violet (UV) radiation (Potyrala 2011) as well as high creep rate, much higher than for carbon- and glass fibres (Clarke 1996). In addition aramid fibre is more expensive than glass fibres (Clarke 1996).

2.2.1.4 Comparison of Fibres

The main factors that separate the different fibre types are the modulus of elasticity, tensile strength and elongation (Chlosta 2012). The specific gravity for glass is higher than aramid and carbon (Clarke 1996). Typical properties of glass-, aramid- and carbon fibres can be seen in Table 9. As can be seen in the table and Figure 11 glass and aramid fibres have the highest ultimate tensile strength if compared with carbon fibre, however a lower modulus of elasticity (Potyrala 2011; Clarke 1996; Muniz & Bansal 2009). On the other hand glass fibres have the disadvantage of being very sensible towards even small defects which can cause and great reduction in strength. Due to this the ultimate strength of FRP composites with incorporated glass fibres can have much lower strength than a composite with carbon fibres (Muniz & Bansal 2009). Indicative values of compressive strength and stiffness of carbon, fibre and aramid are hard to predict since experimental testing are difficult due to differences in boundary conditions, weight of composite and volume fraction of fibres (Muniz & Bansal 2009). Aramid, glass and carbon fibres behave in a ductile manner (Clarke 1996). Carbon and glass fibres have also the advantage of not suffering to creep in ambient temperature (Muniz & Bansal 2009). Aramid fibres have the lowest resistance towards loads applied transversally to the fibre direction (Muniz & Bansal 2009).



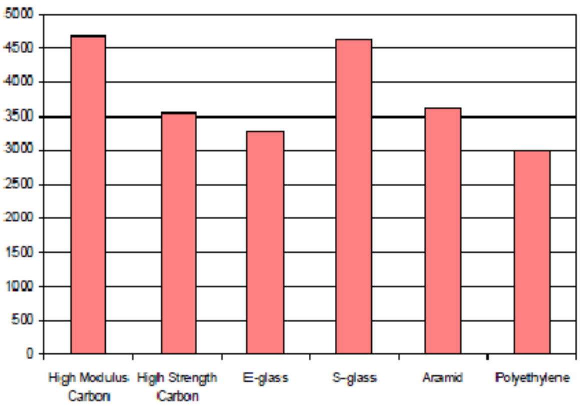


Figure 11 Comparison of properties for different fibres for Left: Modulus of elasticity [GPa], Right: Tensile strength [MPa] (Cytec n.d. p. 10)

Table 9 Comparison mechanical properties of carbon, aramid and glass fibres (Potyrala 2011; Clarke 1996; Muniz & Bansal 2009; ZRMK et al. 2013)

		Fibres								
		Glass				Aramid			Carbon	
Property	**Unit**	**E**	**S2**	**R**	**ECR,C**	**Kevlar 29**	**Kevlar 49**	**Teijin Technora**	**HS**	**HM**
Density	g/cm^3	2.6	2.5	2.4-2.6	2.4-2.6	1.44	1.44	-	1.8	1.9
Modulus of elasticity	GPa	72	85-90	86	69	83-100	115-130	70	215-235	370
Tensile strength	MPa	3450	4600	4400	3030	2750	2750	3000	3530	4400
Strain	%	4.8	5.7	-	4.4	4	2.4	4.4	1.4-2.0	0.5-0.9
Specific gravity	-	2.54	2.47	2.55	2.49	1.44	1.44	1.39	1.77	1.77
Heat transfer coefficient	W/m^2K	long: 6 to 10, trans: 19 to 23				long: -6 to -2, trans: 60 to 80			long: -1 to 0, trans: 22 to 50	
Coeff. of thermal expansion	$10^{-6}/°C$	5				-			7.2	

Note: HS – high strength HM – high modulus

The difference in density for the differnet fibres can be seen in Figure 12.

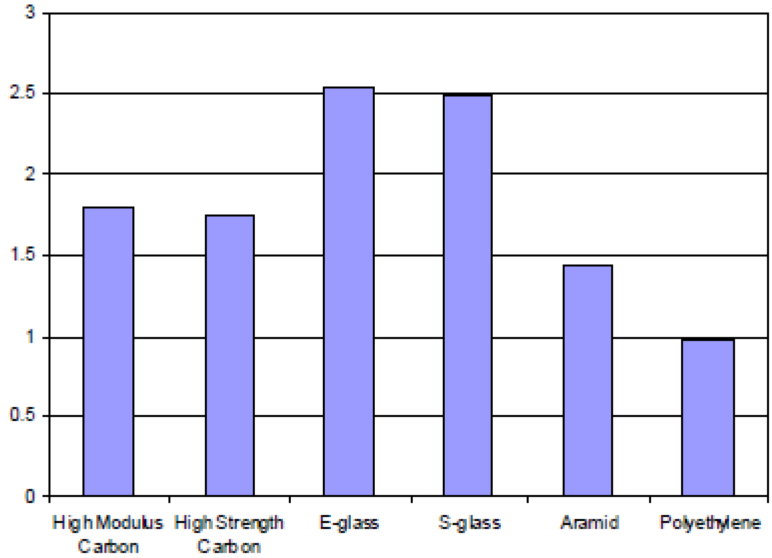


Figure 12 Comparison densities of different fibres (Cytec n.d, p. 8)

Table 10 include a quantitative rating of the different fibre types where different criterias have been weighted. Carbon fibres got the highest ranking, followed by aramid and finally E-glass fibres.

Table 10 Quantitative rating of fibre types (Hooks & Siebels 1997, p. 31)

Criterion	**Weighting factor**	**Fibre type**		
Range of weighting factors	1-3	Carbon	Aramid	E-glass
Tensile strength	3	9	9	9
Compressive strength	2	6	0	4
Modulus of elasticity	3	9	6	3
Long-term behaviour	3	9	6	3
Fatigue behaviour	2	6	4	2
Bulk density	2	4	6	2
Alkaline resistance	2	6	4	0
Cost	3	6	6	9
Total Points		55	41	32
Ranking		1	2	3

Note: 0 = inadequate, 1 = adequate, 2 = good and 3 = very good

The price of reinforcing fibres varies substantially between the different types (Chlosta 2012). Glass fibres are generally considered comparatively inexpensive and are for that reason considered a valid option in civil engineering applications (Chlosta 2012). In Table 11 is a comparison of cost for different fibre types displayed. The costs of the reinforcing fibres are notably higher that the cost of conventional reinforcing steel generally lie in the range of 0.6 €/kg to 0.7 €/kg (Chlosta 2012). However it is not justified to compare the bulk prices of the different materials since composites have a higher strength to weight ratio and thus requires less material (Chlosta 2012). Figure 13 displays cost ratios for different fibre types.

Table 11 Comparison of cost for different reinforcement types (Chlosta 2012, p. 231)

Fibre type	Cost Euro/kg
E-glass	1.25-2.5
R-glass or S-glass	15-25
Carbon	10-45
Aramid	18-30
Boron	70-500

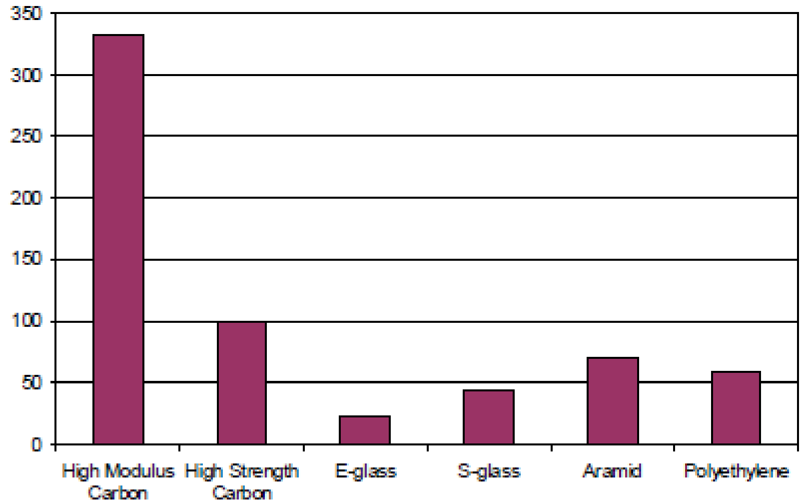


Figure 13 Cost ratio for different fibres (Cytec n.d, p.9)

2.2.2 Forms of Fibres

2.2.2.1 Rovings (Continuous filament rovings)

A roving is a unidirectional (1D) reinforcement of polymer composites, which means that almost all fibres are arranged in the same direction (Clarke 1996). Rovings made of fibre glass are produced by melt spinning of glass. If carbon fibres are used the unidirectional material is called tow (Clarke 1996). Rovings are so called sub-assemblies, in the form of spools, which are used to construct for example pultruded profiles (Chlosta 2012).

Rovings comes in many forms such as: smooth rovings, interlaced rovings and tangled rovings, see Figure 14. Rovings are strands of multifibres that are packaged on drums and used extensively in automated composite processes such as pultrusion and filament winding

(Clarke 1996). The diameter of the fibres is generally in the range of 10µm (Chlosta 2012). Binders and coupling agents are often integrated to diminish the degradation of the fibres during the following manufacturing steps (Clarke 1996). The fibre strength is reduced when rovings are used as woven rovings (Clarke 1996).

Figure 14 Various forms of rovings: a) smooth roving b) interlaced roving c) tangled roving (Potyrala 2011, p. 7)

Rovings are available in two types: direct rovings and assembled rovings (Chlosta 2012). The direct rovings consists of parallel filaments and the assemble rovings are spun. In Figure 15 is an E-glass spool of the types direct and assembled rovings displayed. As can be seen in Figure 15 the assembled roving is packed more loosely. The direct roving is more suited for high strength applications than assembled rovings since the strands are more closely packed and more parallel. Direct rovings are generally more used in the manufacturing processes pultrusion and continuous filament winding and assembled rovings in spray-ups, continuous filament mats and chopped strand mats (Chlosta 2012).

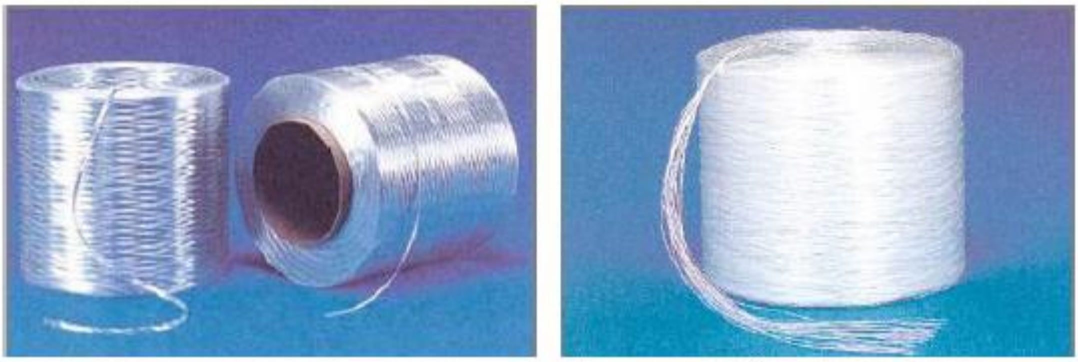


Figure 15 E-glass fibre spool, Left: Direct roving, Right: Assembled roving (Chlosta 2012, p. 29)

In Table 12 is the mechanical properties compared between the reinforcement products continuous roving, woven cloth and chopped strand mat. The conclusions that can be drawn from the table is that continuous roving is that the continuous roving provides the best mechanical properties which is due to its higher weight and fibre volume fraction. If comparing the tensile modulus of the E-glass fibres in Table 6 with the values of the chopped strand mat the magnitude is about 10 times as high. This indicates that the mechanical properties are influenced by both the fibre volume fraction and the fibre direction (Chlosta 2012).

Table 12 Mechanical properties of three different GFRP products (Chlosta 2012, p. 29)

Type	Unit	Woven cloth	Chopped strand mat	Continuous roving
Glass content	%	55	30	70
Specific gravity	-	1,7	1,4	1,9
Tensile strength	N/mm^2	300	100	800

Compressive strength	N/mm^2	250	150	350
Flexural strength	N/mm^2	400	150	1 000
Tensile modulus	N/mm^2	15 000	7 000	40 000
Impact strength	kJ/m^2	150	75	250
Coeff. of thermal expansion	10^{-6}/°C	12	30	10
Thermal conductivity	W/mK	0,28	0,2	0,29

2.2.2.2 Mats

Mats consist of discontinuous and random fibres see Figure 16 (Potyrala 2011). It is the least expensive planar reinforcement; however unidirectional rovings are even less expensive (Clarke 1996). Mats can be divided in two types: chopped strand mat (CSM) and continuous filament mat (CFM) (ZRMK et al. 2013). Mats are referred to as non-aligned materials since the fibres are orientated randomly (Clarke 1996).

Mats consist of chopped rovings that are assembled with a binder (Clarke 1996). The binder can either be soluble or insoluble in water (Clarke 1996). Binders that are insoluble in water should not be used for application where there is a risk of water immersion. This can result in loss of integrity of the FRP composite (Clarke 1996). Hence it is very important that the binder is compatible with the resin system (ZRMK et al. 2013).

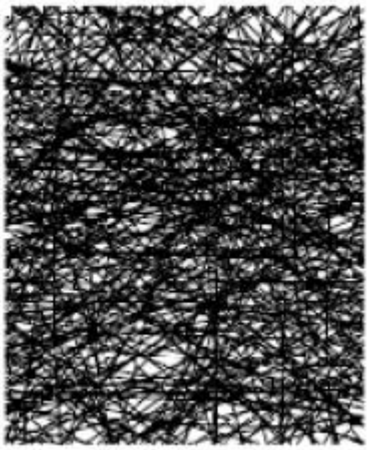


Figure 16 Mat (Potyrala 2011, p. 7)

2.2.2.2.1 Chopped Strand Mat (CSM)

Rovings are used to construct chopped strand mats (Chlosta 2012). It is a non-woven planar material where the fibres strands are chopped in short pieces approximately 25-50mm which are distributed evenly and orientated randomly on a conveyor belt (Clarke 1996; ZRMK et al. 2013; Chlosta 2012). The mat is kept together with a binder, for example polyvinyl or acetate, which has the purpose providing bond and achieving an easier handling (Clarke 1996). With CSM the effective fibre fraction is often not more than 10% to 25% in any in-plane direction depending on which manufacturing technique that is used (Clarke 1996). The chopped strand mat is mainly used in manufacturing processes such as hand lay-up and hot press moulding

(Chlosta 2012). Due to discontinued fibres the load transfer will depend more on the resin system (Clarke 1996). Widths of CSM up to 2m are available (Clarke 1996) and the typical weights ranges from 225-900g/m^2 (Chlosta 2012). The quality of the chopped strand mat is dependent on the parameters weight/m^2, strand length, type of binder and the strand fitness (Chlosta 2012). A typical glass fibre chopped strand mat can be seen in Figure 17.

Figure 17 Typical glass fibre chopped strand mat (Chlosta 2012, p. 30)

2.2.2.2.2 Continuous Filament Mat (CFM)

The production of continuous filament mat (CFM) are similar to CSM, however the fibres are continuous and randomly swirled which are locked together with a binder (Clarke 1996; ZRMK et al. 2013) and then compacted and rolled on a spool (Chlosta 2012). The continuous fibres in the CFM are locked together which provides some advantages over CSM (Clarke 1996). The quality of the continuous filament mat is dependent on the same factors as for CSM with the addition of mesh type (Chlosta 2012). CFM is mainly used in pultrusion process (Clarke 1996) as well as continuous production methods and hot press moulding (Chlosta 2012). A typical glass fibre continuous filament mat can be seen Figure 18.

Figure 18 Typical glass fibre continuous filament mat (Chlosta 2012, p. 30)

2.2.2.3 Woven Roving

Woven rovings (WRs) are made through warp and weft array of untwisted tows of fibres, and thus making it bidirectional and a heavy weave fabric (Clarke 1996). WRs are easy to handle and can be applied in large constructions (Clarke 1996). This is due to that the build-up can be performed for large areas in a short amount of time, however almost only for construction of ships (Clarke 1996). Since woven fabrics are made of continuous strands they have a greater stiffness and strength than random fibre reinforcements such as CSM (Clarke 1996). Figure 19 displayed a woven glass fibre roving.

Figure 19 Woven glass fibre roving (Chlosta 2012, p. 31)

In heavy weight reinforcement the fibre fraction for woven fabric can be reduced to about 40% due to crimp if there is lack of compaction and manufacturing technique (Clarke 1996). The effective volume fraction is generally about 20% in both warp and weft direction (Clarke 1996). For coarse textured WRs with a density of 400–600 g/m^2 there might be risk of incomplete resin impregnation with voids and inadequate adhesion and with reduced interlaminar shear strength as a consequence (Clarke 1996). This can however be prevented by implementing CSM in-between the woven roving layers (Clarke 1996).

2.2.2.4 Fabrics

Fabrics are very lightweight materials which in comparison with WRs are much finer per ply (Clarke 1996). There are many types of weaving pattern styles of fabrics such as plain, twill, satin and unidirectional and they are constructed by braiding warp and weft yarns, fibres or filaments (Clarke 1996). See Figure 20 for different weaving pattern styles. The factors that are decisive for the style are fabric count, warp yarn, fill yarn and weaves (Clarke 1996). The strength of the fabric is related to the fabric count and warp- and fill yarn (Clark 1996). The weave of the fabric is the factor decisive for the appearance as well as characteristics regarding handling (Clarke 1996). Volume fractions can be as much as 50% due to less crimp than WRs since they are lighter. Fibre fraction of 50% is achieved if the composite compaction is sufficiently good (Clarke 1996). If the weaving pattern is considered advantageous in terms of the manufacturing process or performance of the composite fabrics is a good option (Clarke 1996). During manufacture of glass fibre fabrics the thickness, weight and strength are in general quite precise which can be controlled throughout the process (Clarke 1996).

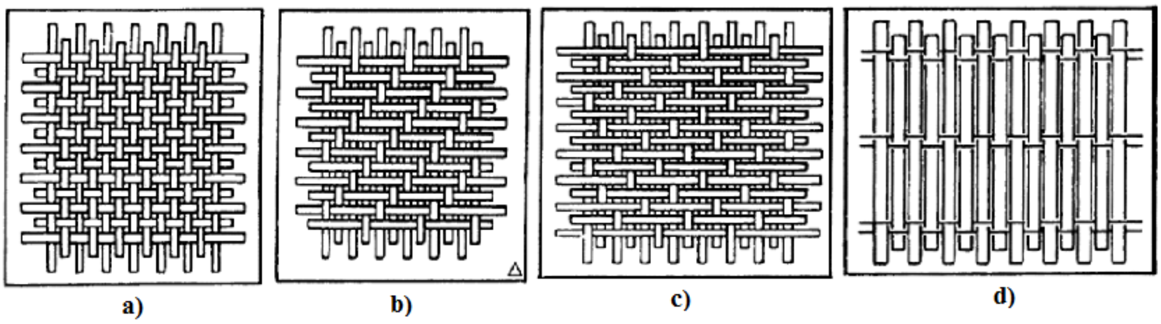


Figure 20 a) plain weave b) Twill weave (3 on 1) c) Satin weave d) unidirectional weave (Clarke 1996, p. 293)

The oldest weaving style is the plain weave (Clarke 1996). It has many advantages such as providing the most stability, porosity and minimum slippage (Clarke 1996). If the same amount of fibres is used in each direction, uniform strength is achieved in the fabric (Clarke 1996). Twill weave have better draping than plain weave (Clarke 1996). Furthermore twill weave can be conformed in complex shapes and have a more open weave than plain weave (Cytec n.d). Satin weave is smoother than plain weave and is easily adaptable to moulds (Clarke 1996). In addition high densities can be achieved by weaving (Clarke 1996). Another advantage is that satin weave fabrics show high strength in both directions (Clarke 1996). With the use of unidirectional weave maximum strength in one direction is achieved (Clarke 1996).

2.2.2.5 Non-Crimp Fabric

Non-crimp fabrics also referred to as multi axial fabrics are made by laying unidirectional fibres parallel to each other in a specific position and then stitched together with a light thread (Clarke 1996; Cytec n.d). These generate much aligned properties and high fibre fractions of more than 50% within plies (Clarke 1996). Difficulties with non-crimp fabric can arise during handle; however there arise more freedom during manufacture than for other fabric types since it is easy to achieve 45° plies (Clarke 1996). Non-crimp fabrics have the advantage of conforming readily to complex shapes and having a fast build-up of laminates (Cytec n.d). An advantage with non-crimp fabric is that it is very creep resistant (Clarke 1996). If the highest material properties are sought non-crimp fabric should be used. However there is a risk that crimp can lead to resin rich areas where the volume fraction of fibres is low. In addition areas with localised high shear and lowered mechanical properties can occur (Clarke 1996). In Figure 21 a schematic figure of non-crimp fabric is displayed.

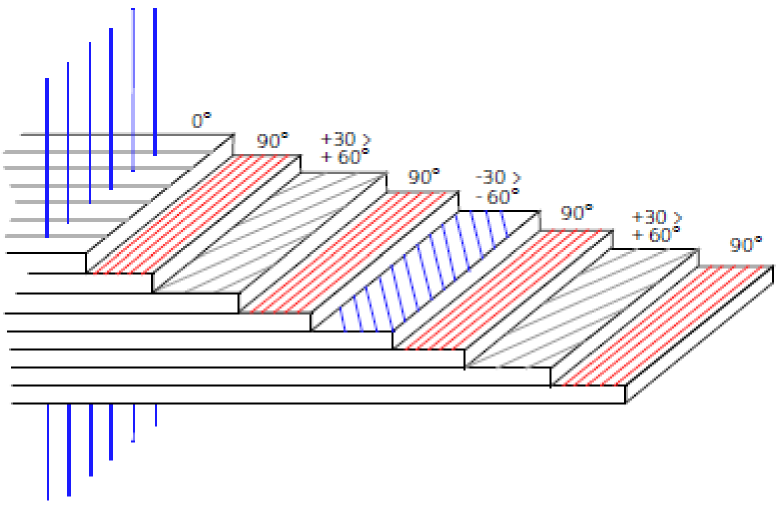


Figure 21 Schematic picture of multiaxial non crimp fabric (Cytec n.d, p. 11)

2.2.3 Surface Veils

Surface veils consist of thin and lightweight materials often swirled mats such as CFM which are made out of glass or synthetic fibre (Clarke 1996). C-glass fibres are commonly used due to that they have a good resistance towards corrosion (Clarke 1996). In Figure 22 a swirled mat of glass fibres is displayed.

Figure 22 Glass veil mat (Technical Fibre Products 2012)

If the appearance, i.e. smooth surface, and properties of the surface is of importance surface veils should be incorporated preferably with the pultrusion process (Clarke 1996). Another application for surface veils is for chemical environments, since they have a high corrosion resistance (Clarke 1996). In addition by combining surface veils with gel coats and top coats benefits with regard to support for the reinforcement and increased retention of the resin are gained (Clarke 1996).

Surface veils should not be considered for surfaces that are to be bonded together. If surface veil have been applied to a surface that should be bonded it is important that the whole layer is removed by grinding (Clarke 1996).

2.2.3.1 Three Dimensional Integrated Fibre Preforms

For particular design requests three dimensional integrated fibre preforms can be used. Here continuous fibres are tailored into a three-dimensional array through an automated weaving process (Clarke 1996). It is a possibility to mix fibres and shapes of members are for example box-, I-beams as well as sandwich elements (Clarke 1996). The members are commonly manufactured through continuous processes such as pultrusion and transfer moulding, where fibre arrangements can be chosen as ±45° for flanges and unidirectional for web (Clarke 1996). Since the fibres are continuous and will be locked into each other, strength will be provided where the fibres change direction (Clarke 1996). The choice of three dimensional integrated fibre preforms are most economical if large amounts of components of the same shape are produced (Clarke 1996).

2.2.4 Comparison Types of Reinforcement

In Table 13 is a comparison of cost for different reinforcing types displayed, where 1 is denoted the least expensive option and 10 the most expensive option.

Table 13 Comparison of cost for different reinforcing types, where 1=lowest cost and 10=highest cost (Chlosta 2012, p. 231)

Reinforcement type	Cost factor
Continuous strand	1.0-2.5
Cloth fabric	3.5-6.5
Woven roving fabric	2.0-3.5
Chopped strands	1.0-1.5
Reinforcing mats	1.5-2.5
Surfacing mats	5.0-6.0

2.3 Polymer Matrices

A matrix is composed of resins, fillers and additives (Potyrala 2011) as well as catalysts and in some cases accelerator, release agents, inhibitors and monomer etc. (Clarke 1996). One important characteristic with matrix is that the modulus of elasticity must be lower and the elongation larger than the fibre for the fibres to be able to carry the load (Potyrala 2011; Chlosta 2012). The matrix has many functions some of those are: (Potyrala 2011; Clarke 1996; Muniz & Bansal 2009; Hollaway 2010; Bisby 2006).

- Hold the fibres together and arranging them as intended
- Transfer load between fibres
- Separate fibres within composite
- Give stiffness and shape to the member
- Reduce or stop the crack propagation rate through letting fibres act independently
- Protect fibres from environmental impact such as chemical and mechanical
- Increase ductility and impact strength
- Shields from abrasion for notch sensitive fibres
- Provides shear, transverse tensile and compression properties

In addition the matrix of the FRP composite has a big influence of the in-plane shear and interlaminar load transfer (Muniz & Bansal 2009; Yquel 2012) as well as the temperature and electrical resistance (Yquel 2012). The tensile load bearing capacity for the matrix is however low (Muniz & Bansal 2009). The physical and in-service characteristics are the most important properties of the matrix (Hollaway 2010). The short term strength of the polymer is a function of the in-service properties, the bond and degree of cross-linking, density as well as the type of loading. The durability of the polymer is the single most important factor regarding the long-term stability of the polymer. The stiffness of the polymer is dependent on the degree of cross-linking. However the stiffness of the FRP composite is mainly dependant on the fibres and the stiffness of the polymer is due to that not critical (Hollaway 2010).

2.3.1 Resins

Resin is the largest compound of the matrix (Potyrala 2011). Properties that are strived for when it comes to resins are strength, stiffness toughness and durability (Clarke 1996; ZRMK et al. 2013). Parameters that should be considered when choosing polymer resin is the intended application, the service temperature, the environment, the manufacturing process, the cure condition and the intended properties (Clarke 1996; ZRMK et al. 2013). The factors that separate the resins are the curing, hardening, strength and the interface between resin and fibre (Chlosta 2012). In terms of service temperature it is important to note that if the service temperature is close to the resins second order glass transition temperature (T_g) it will cause loss of stiffness and creep (Clarke 1996). All resins types available are sensitive to exposure of UV radiation and a measure to overcome this is adding additives (Potyrala 2011).

There are two main classes of polymers which are inorganic and organic which can be seen in Table 14 (Muniz & Bansal 2009). An advantage of inorganic polymers in comparison with organic polymer are that they have better fire properties, since the majority of the inorganic, or synthetic, polymers are prepared from hydrocarbons whom in general burn readily. Inorganic polymers are for that reason not a valid option in housing (Muniz & Bansal 2009).

Table 14 Matrices classification of polymers (Muniz & Bansal 2009)

Class	Type	Examples
Inorganics	Cement, geopolymers, plasters, ceramic matrices, metallic matrices	
Organics	Thermoset polymers	Epoxy, vinyl ester, polyester, phenolic, cyanate esters, bismaleimides, polyimides, polyetherimide
	Thermoplastic polymers	PVC, ABS, SAN, PS, PE, PP, PC, PMMA, POM, PBT, PEI, PET, PA, PEEK

All organic polymers will be subjected to moisture ingress which will change the mechanical, chemical and thermo physical properties (Hollaway 2010). A measure to decrease the diffusion is to reduce the permeability of the polymer which is performed with a lower degree of cross-linking and through full cure. Additives can also be incorporated to decrease the diffusion as well as adding epoxy-layered silicate nano-composites whom unfortunately are expensive (Hollaway 2010).

The organic polymers can be subcategorized into two types of polymer matrix: thermoplastic and thermosetting polymers and they are categorized by the manufacturing process and their properties (Potyrala 2011; Clarke 1996; Cytec n.d). The term that separates a thermoplastic polymer from a thermosetting polymer is the response towards temperature (Muniz & Bansal 2009). The thermoset resins are the most common type used in application and in 1997 the market share in Europe was approximately 70% (Chlosta 2012). However the use thermoplastic is increasing and stood in 1999 for 42% of the FRP market in Europe (Chlosta 2012). In Table 15 a comparison between thermoplastic and thermoset resins is displayed.

Table 15 Comparison between thermoplastic and thermoset resins (KAW 2005)

Thermoplastics	Thermosets
Heat and pressure softens the polymer, hence easy to repair	Decomposes with heat
Shelf life is indefinite	Shelf life is definite
High strains to failure	Low strains to failure
Easy to handle, not tacky	Tacky
Reprocessing is possible	Reprocessing not possible
Cure cycles are short	Cure cycles are long
Excellent resistance towards solvents	Reasonable resistance towards solvents
Higher fabrication temperatures and viscosities required	Lower fabrication temperatures

It is essential to create a cure condition that generates full cure of the polymer in order to get the optimal mechanical properties of the resins, prevent creep, limiting heat softening amongst other parameters (Clarke 1996; ZRMK et al. 2013). In addition it is important that the manufacturing of the polymer is correct to get the intended in-service functions (Hollaway 2010). By thoroughly blending the components before forming full cure of the composite is possible (Clarke 1996). However full curing is problematic if the composite section is thick since the heat from the curing due to the exothermic reaction will be uneven which ultimately can cause damage of the composite (Clarke 1996; ZRMK et al. 2013). This can be prevented by building up a thick section out of thinner sections, however then the adhesion between the laminate plies is of importance (Clarke 1996).

2.3.1.1 Thermoplastic Polymers

If comparing thermoplastic polymers with thermosetting polymers they have better ductile behaviour and are tougher but are not as stiff and have lower strength (Potyrala 2011). In addition they have the advantage of being thermally stable and having a higher resistance towards environmental agents such as UV radiation (Muniz & Bansal 2009). Thermoplastic polymers are versatile and can through heating and cooling easily be reshaped (Potyrala 2011; Muniz & Bansal 2009) without losing any properties (Muniz & Bansal 2009). For thermoplastic polymers there is no cross-linking of molecules resulting in it being very flexible and deformable (Potyrala 2011) since the bond is weak and of the van der Waals type (KAW 2005). In addition they provide a light-weight alternative in comparison with the conventional building materials (Muniz & Bansal 2009). However many positive characteristics with thermoplastic polymers there are some setbacks such as it having reduced creep resistance at elevated temperatures and that they are more sensitive towards solvents compared to thermosetting polymers (Potyrala 2011). However, the two largest problems associated with thermoplastic polymers are the T_g and the long-term behaviour (Muniz &

Bansal 2009). The problems related to the T_g can be avoided in design by choosing polymers with T_g higher than 40°C in order to prevent softening of the polymer (Muniz & Bansal 2009).

The most commonly used thermoplastic polymers in civil engineering application today are: nylon, polyetheretherketine (PEEK), polypropylene (PP) and polyphenylene sulfide (PPS) (Potyrala 2011). In Table 16 typical mechanical properties of the most common thermoplastic resins are presented.

Table 16 Mechanical properties of the main thermoplastic resins (Muniz & Bansal 2009, p. 11)

Property	PES	PEEK	PP	PS	ABS	SAN	PET	PBT	PMMA	PA	PC
Tensile strength (MPa)	90	93.8	25-38	19-55	35-48	55.6-72	45-160	50-170	41	82.7	69
Young's Modulus (GPa)	2.7	3.5	1.4-1.9	2.4-3.35	1.75-2.5	3.585-3.8	2.3-10.3	2.3	2.3	2.83	2.3

Thermoplastic polymers can be divided into two groups which are high-performance thermoplastics and conventional thermoplastic (or commodities thermoplastic) polymers (Muniz & Bansal 2009). See Table 17 and Table 18 for properties of the two types of thermoplastic polymers. The conventional thermoplastic polymers have low T_g's and can be recycles and the main application are fibres, isolation and cans etc. (Muniz & Bansal 2009). The high-performance polymers are mainly used in composites and have a T_g higher than 100°C (Muniz & Bansal 2009). Due to the high cost of the high-performance thermoplastic polymers the use in civil engineering application is not justified presently (Muniz & Bansal 2009). In addition there is no experience of thermoplastic polymers for long-life application (Muniz & Bansal 2009). Presently appropriate applications for thermoplastic polymers are for example secondary structural components, light rails in lorries, improving appearance of facades of building, formwork for concrete casting and acoustic and safety barriers (Muniz & Bansal 2009). A suitable solution for acoustic and safety barriers is to combine both thermoplastic and thermoset polymer in order to take advantage of the high resistance towards UV radiation of the thermoplastic polymer and the higher strength and stiffness of the thermoset polymer (Muniz & Bansal 2009).

Table 17 Conventional thermoplastic polymers (Muniz & Bansal 2009, p. 23)

Matrix	Morphology	T_g (°C)	Process temp. (°C)
PBT	SC	56	190
PA-6	SC	48	220
PA-12	SC	52	190
PP	SC	-20	190

Table 18 High-performance thermoplastic polymers (Muniz & Bansal 2009, p. 24)

Matrix	Morphology	Tg (°C)	Process temp. (°C)
PEEK	SC	149	390
PEI	A	217	330
PPS	SC	89	325
PEEK	SC	156	340

2.3.1.2 Thermoset Polymers

In civil engineering applications thermosetting polymers are the most commonly used (Potyrala 2011). When thermosetting polymers are manufactured liquid or semi-solid precursors are used. These are left to harden through a sequence of chemical processes which is called polycondensation, polymerization or curing (Potyrala 2011). Thereafter they are converted into a hard solid thus creating a three-dimensional network of polymer chains (Potyrala 2011). The polymerisation can be divided into two classes which are addition and condensation polymerisation (Hollaway 2010). In addition there are two systems which are the cold and hot cured system which have the purpose of polymerise the thermosetting polymer (Hollaway 2010). Indicative properties for the most common thermoset resin are displayed in Table 19.

Table 19 Indicative properties of thermoset resins (Clarke 1996)

Property	Unit	Range of values
Specific gravity	-	1.08-1.25
Tensile strength	N/mm^2	50-85
Tensile modulus	kN/mm^2	2.2-3.7
Flexural strength	N/mm^2	80-130
Flexural modulus	kN/mm^2	2.9-4.2
Hardness Barcol 939/1	-	40-45
Elongation at break	%	1.2-6.5
Water absorption by weight	%	1-2
Glass transition temperature	°C	50-160

The most commonly used thermosetting polymers used in resins in civil engineering applications are: polyester, epoxy, vinyl ester and phenolic, however urethane methacrylate also occurs in applications (Potyrala 2011; Clarke 1996; Muniz & Bansal 2009). In Table 20 the mechanical properties for the thermoset resins epoxy, polyester and vinyl ester are presented.

Table 20 Mechanical properties of the main thermoset resins (Muniz & Bansal 2009, p. 10)

Property	Unit	Epoxy	Polyester	Vinyl ester
Tensile strength	MPa	80	65	75
Modulus of elasticity	GPa	3.25	2.75	3

Table 21 contains a comparison between the common thermoset resins epoxy, polyester, vinyl ester and polyurethane displayed.

Table 21 Advantages and disadvantages for epoxy, polyester, vinyl ester and polyurethane polymers (Yquel 2012, p. 5; Zhou & Lesko 2006, p. 6-7)

	Advantages	Disadvantages
Epoxy	high mechanical properties, high water resistance, temperature resistance (up to 140°C dry and 220°C wet), chemical resistance, low cure shrinkage, long working times, high strength, relatively low cost	more expensive than vinyl ester (£3-15/kg), critical mixing, corrosive handling, short pot life, exothermic reaction
Polyester	Ease of processing, pot life, cure cycles, easy to use, lowest cost (£1-2/kg)	Temperature resistance, chemical resistance, high cure shrinkage, moderate mechanical properties, high styrene emissions in open mould, limited working times
Vinyl ester	Ease of processing, pot life, cure cycles, very high environmental and chemical resistance, higher mechanical properties than polyester	high cure shrinkage, post cure generally required, higher cost than polyester (£2-4/kg), high styrene content
Polyurethane	low cure shrinkage, excellent flexibility even at low temperatures, moderate cost	cure cycles, temperature resistance, moisture sensitive, poor resistance at elevated temperatures, short pot life

The two graphs in Figure 23 illustrate a comparison of strength and stiffness between the common thermoset resins polyester, vinyl ester and epoxy.

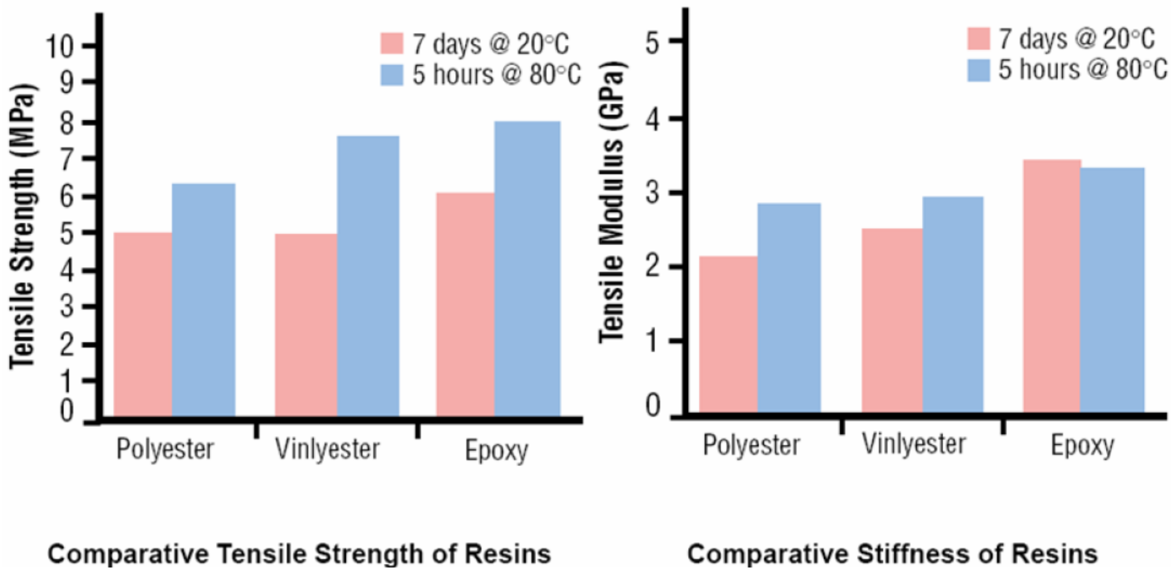


Figure 23 Comparison of tensile strength and tensile modulus for different thermoset resins (Zhou & Lesko 2006, p.9)

Unlike the thermoplastic polymers the thermoset polymers are not able to be remoulded or reshaped after curing (Potyrala 2011; Hollaway 2010). When thermosetting polymers reach a specific temperature, known as the T_g, the mechanical properties will change irreversible and the polymer will go from a being rigid to flexible (Muniz & Bansal 2009). The mechanical properties that are affected are among other the modulus of elasticity which in turn lowers the tensile, shear and compressive strength of the polymer (Muniz & Bansal 2009). In addition parameters regarding colour and water resistance are impaired (Muniz & Bansal 2009). In addition if the cold cured system is used it is important to assure that the environmental temperature in which the composite is subjected to is at least 20°C less than the Tg (Hollaway 2010).

The thermoset polymers are also very brittle in their nature compared to the thermoplastic polymer (Potyrala 2011; Hollaway 2010) which has advantageous in terms of creep and relaxation (Muniz & Bansal 2009) but disadvantages in terms of a limited tolerance to damage (Hollaway 2010). In addition thermoset resins are less prone to physical aging than thermoplastic resins (Muniz & Bansal 2009). The advantages with choosing a thermoset resin is that it is more rigid and have a higher thermal and dimensional stability as well as better electrical, chemical and solvent resistance (Potyrala 2011; Hollaway 2010). Thermosets used in high performance application should in addition have a high mechanical and compressive strength as well as stiffness (Hollaway 2010). By combining a thermoset resin with fibre reinforcement the outcome will be a lighter material than if for example a metallic material would have been used, however the mechanical properties are not compromised (Muniz & Bansal 2009). In addition since thermosetting polymers generally have a low viscosity this generates a higher level of impregnation of the composite and consequently a lower void ratio (Clarke 1996). However, if choosing a polyester- or vinyl ester resin without adding additives the risk of heavy fire is prominent (Clarke 1996). Another disadvantage with thermoset polymers is that unlike thermoplastic polymers they are not recyclable (Muniz & Bansal 2009).

2.3.1.2.1 Polyester Resins

Due to that the polyester gives the FRP composite many advantages with regard to the overall properties it is one of the most used matrix today (Potyrala 2011). Examples of advantages are that they are economical and have a flexible formula which enables either slow or fast change of the viscosity of the fluid (Clarke 1996) in addition they can achieved translucent (KAW 2005). Polyester resins with incorporated reinforcement are in general light-weight, have high strength and with a high resistance to weathering and chemical attacks (Clarke 1996). Another advantage is that polyester resins provide possibilities of producing large and complex mouldings and that production of small scale products are cost-effective (Clarke 1996). Polyester resins also have the convenience of being able to cure at either room- or at elevated temperatures (Clarke 1996). However higher degree of cure and better stability to environmental factors of the composite is achieved if the resin is cured at elevated temperatures (Clarke 1996). The factors that are decisive for the final properties of the composite such as mechanical factors and resistance towards environmental factors are the rate of change of viscosity and the degree of cure (Clarke 1996). A disadvantage with polyester resins is that they have high mould shrinkage during curing (Clarke 1996) which can be up to 8% (KAW 2005). In addition they have the disadvantages of being brittle and having service temperatures below 77°C (KAW 2005).

The choice of starting monomer from the unsaturated polyester backbone leads to different properties such as increased heat resistance, decreased shrinkage during cure, resistance to weathering and UV radiation etc. (Clarke 1996). However generally what is gained with adjusting the backbone material is lost in other properties, especially the mechanical properties (Clarke 1996). If adding fire retardants to polyester some of the advantages will be a reduction in flammability and less generation of smoke, however disadvantages will include slightly diminished mechanical properties, less durability of wetting and unhealthy smoke emissions (Clarke 1996).

The main applications for polyester resins in terms of civil engineering applications are structures with moderate requirements for mechanical and thermal properties (Cytec n.d). A polyester resin worth mentioning is the chlorendic polyester resins. It is made from HET acid and due to the presence of chlorine it has good resistance against fire (Clarke 1996; ZRMK et al. 2013). However compared to isophtalic resins it has lower strength and toughness (Clarke 1996). See Table 22 for properties of typical polyester resins. Pigmented polyester resins are speciality polyester where gel and top coats are incorporated (Clarke 1996). The general applications for these are surface coating of glass-reinforced laminated mouldings (Clarke 1996).

There are two subgroups of unsaturated polyester which are: ortopolyester, isopolyester (Potyrala 2011).

Table 22 Properties of typical polyester resins (Clarke 1996)

Property	Unit	Ortophtalic polyester (G 105E)	High-grade ortophtalic polyester (G 300)	Chemical resistant isophtalic polyester (K 530)	Elevated temp. Isophtalic polyester (S 599)	Fire retardant HET-acid based polyester (F 892)	Fire retardant brominated polyester (F 820)
Density	g/cm^3	1.1	1.1	1.1	1.1	1.3	1.3
Water absorption	mg (24h)	19	24	18	28	-	23 ISO 62
HDT[1]	°C	66	95	93	125	62	60 ISO 75 Method A
Viscosity at 23°C[2]	Ns/mm^2	180	250	800	1100	500	400 Brookfield
Tensile strength	N/mm^2	55	70	65	55	50	45 ISO 527
Tensile modulus	kN/mm^2	3.6	3.3	4.1	3.7	3.4	3.6 ISO 527
Flexural strength	N/mm^2	90	110	125	100	75	80 ISO 178
Flexural modulus	kN/mm^2	4.1	3.8	3.7	3.7	3.2	3.8 ISO 178
Elongation at break	%	2.0	3.5	2.5	1.5	1.7	1.4 ISO 527

Note: [1] Heat distortion temperature, [2] Liquid resin

2.3.1.2.1.1 Ortopolyester resins

Resins based on orthophthalic acid should be used for general applications where there are less demanding requirements of the FRP composite (Clarke 1996). Due to that they are the most inexpensive resin option they are very popular in applications (Clarke 1996). Characteristics of ortopolyester resins are that they have good mechanical properties and chemical resistance and a reasonable service temperature capability (Clarke 1996; ZRMK et al. 2013).

Ortopolyester resins are mainly used in open mould manufacturing processes such as hand and spray lay-up moulding (Clarke 1996). Since open moulds are used it is of importance to use a resin with a low content of styrene, referred to as reduced styrene resins (Clarke 1996). The range of styrene in a reduced styrene resin is generally less than 35% of the weight

(MnTAP 2009). The styrene emissions can be decreased in the range of 20% to 50% if the styrene content is reduced from 40% to 35% (MnTAP 2009). Styrene is in general incorporated to the resin to decrease the viscosity and to compensate evaporation during application (Clarke 1996).

2.3.1.2.1.2 Isopolyester Resins

Isopolyester resins have a larger impact resistance, offer larger flexibility and have a better resistance to temperatures than what ortopolyester have (Potyrala 2011). In addition it has an increased resistance against corrosion (Potyrala 2011; Clarke 1996). In addition isophtalic acid (IPA) based resins also show good water, heat and chemical resistance (Clarke 1996; ZRMK et al. 2013). However they are more expensive than ortophthalic resins (Clarke 1996). Isopolyester resins should not continuously be subjected to environments with pH exceeding 10.5, which can generate degradation of the resin (Reichhold 2009)

2.3.1.2.2 Vinyl Ester Resins

Vinyl esters are based on epoxy resins but derived from backbone of polyester such as acrylate of methacrylate (Clarke 1996). They have the highest corrosion resistance when compared to both orto- and isopolyester resins (Potyrala 2011) and should be considered for high-performance applications (ZRMK et al. 2013). Vinyl ester lies in the middle between polyester and epoxy resins in terms of cost and overall performance (Cytec n.d). Another advantages regarding vinyl ester compared to orto- and isopolyester resins are that it has an better ability to elongate, it offers higher resistance against impact and provides better fatigue properties for the composite (Potyrala 2011). In addition the failure strain for vinyl ester can be as much as the double of orto- and Isophtalic polyesters (Clarke 1996).

Polyester, urethane or epoxide is backbones that vinyl ester resins can be derived from (Clarke 1996). The latter is the most commercially used (Clarke 1996). By deriving the vinyl ester resin from bisphenol-A (BPA) epoxies favourable properties such as good chemical resistance (Clarke 1996; ZRMK et al. 2013) and a failure elongation of 6% during manufacturing either by pultrusion or filament winding (Clarke 1996). The resistance to alkaline is in general good for BPA derived vinyl ester resins (Reichhold 2009) and they show exceptional resistance against acids, bases and solvents (Clarke 1996; ZRMK et al. 2013). In addition it has higher toughness and maintains strength and stiffness better than isopolyester resins at elevated temperatures (Clarke 1996; ZRMK et al. 2013). Vinyl esters derived from BPA have superior resistance against alkaline, which have been proven through many cases stories (Reichhold 2009).This type of polyester is however much more expensive compared to the other polyester and are used in high-performance applications (Clarke 1996). In addition BPA derived vinyl esters have a large styrene content which is added to modify the viscosity of the resin (Clarke 1996). Styrene is an air pollutant that is very harmful (McAlvin 2011).

Vinyl ester derived from novolac epoxy is another vinyl ester worth mentioning. There are many advantages regarding this type of vinyl ester such as better Life cycle assessment (LCA) than for metals, good resistance towards solvents and high capability in terms of temperature (Clarke 1996; ZRMK et al. 2013). The alkaline resistances of these are adequate however they are very sensitive towards strong bases in combination with elevated temperatures (Reichhold 2009). The consequence is that phenolate salt are generated which consequently lead to destruction of the laminate (Reichhold 2009). See Table 23 for comparison between BPA vinyl ester and Novolac vinyl ester.

Table 23 Properties of typical vinyl ester resins (Clarke 1996)

Property	Unit	BPA Vinyl ester	Novolac Vinyl ester

Specific gravity	-	1.12	1.16
Tensile strength	N/mm^2	82	68
Tensile modulus	kN/mm^2	3.5	3.5
Elongation at break	%	6	3-4
Flexural strength	N/mm^2	131	125
HDT	°C	120	150

Vinyl ester compared to polyester in terms of curing mechanism is relatively similar with the main difference being a more sensitive curing temperature and window of initiator (Clarke 1996). This generally leads to a more problems regarding the manufacturing (Clarke 1996). However the shrinkage and the peak exotherm temperature during curing is less for vinyl ester than for polyester resins (Clarke 1996). In addition the toughness and T_g is larger for vinyl ester than for polyester (Clarke 1996).

The manufacturing techniques associated with vinyl ester are filament winding, pultrusion, resin injection, vacuum moulding and hand lay up (Clarke 1996).

2.3.1.2.3 Urethane methacrylate

Urethane methacrylate have the similar fire properties as polyester and vinyl ester, however it has better smoke and toxicity performance (Clarke 1996). Similarly with polyester resins urethane methacrylate has high mould shrinkage (Clarke 1996).

2.3.1.2.4 Epoxy Resins

Epoxy is one of the most used polymers and a large extent is related to aerospace applications (KAW 2005). The reason why epoxy is commonly chosen is due to its high strength, low viscosity, low amount of volatiles during cure and low shrinkage (KAW 2005). Furthermore they are very versatile since they can be produced with many manufacturing techniques and in over 20 different forms (KAW 2005; Cytec n.d). Epoxy resins provide mechanical properties better than the other polymers (Clarke 1996; ZRMK et al. 2013; KAW 2005). In addition they have good environmental resistance and a high toughness (Cytec n.d). By comparing epoxies to other resins it offers the best resistance against thermal influences and provides better electrical properties (Potyrala 2011). The performance under fire is similar to that of polyester resins (Clarke 1996), however epoxy resins provide better water resistance and shear strength than that of polyester resins (Clarke 1996; Muniz & Bansal 2009; ZRMK et al. 2013). Epoxy resins also show less shrinkage during curing than vinyl ester, methacrylates and phenolic resins (Clarke 1996; ZRMK et al. 2013), which contributes to lower internal stresses (Muniz & Bansal 2009). Nevertheless the cost of epoxy resins in relation to polyester resins are about 2-3 times higher for standard laminates and about 10-15 for high-performance materials (Clarke 1996; ZRMK et al. 2013; KAW 2005). Another disadvantage of some epoxy resins is that they require surface protection due to their inadequate resistance against UV radiation (Clarke 1996). In addition they are in general difficult to produce (KAW 2005).

Epoxy resins should be chosen over polyester resins for applications where requirements regarding shear strength, mechanical properties at elevated temperatures and durability have to be met (Clarke 1996; ZRMK et al. 2013). Regarding elevated temperatures during curing, epoxy resins reach its optimal properties if subjected to post curing temperatures of 60°C to 150°C (Clarke 1996). However since almost all epoxy resins need high curing temperature it indicates that for large structural members the mechanical properties may not be satisfactory (Clarke 1996). If a liquid epoxy resin is used the curing is fast and curing temperatures then ranges between 5°C to 150°C, depending on curing agent (Muniz & Bansal 2009). In applications epoxy resins are most commonly used together with carbon-reinforced profiles, which provide a composite with high fatigue and mechanical properties (Potyrala 2011) as well as a more rigid composite than any other combination of fibres and resins (Muniz & Bansal 2009). The composite consisting of epoxy resin and glass fibres generates the composite with highest shear strength (Muniz & Bansal 2009). Epoxy resins have a good adherence with other materials such as fibres and fillers and are compatible in many manufacturing techniques (Clarke 1996; Muniz & Bansal 2009; KAW 2005) and a common application is for composite laminates and sealings (Muniz & Bansal 2009).

The manufacturing processes most commonly used for epoxy resins are pultrusion, filament winding, resin transfer moulding, compression moulding and prepreg manufacturing (Clarke 1996). A number of different curing agents such as different types of amines can be incorporated in the epoxy resin to achieve desired properties. If epoxy resins are cured above the service temperature the composite will gain more temperature stability (Clarke 1996). In Table 24 properties for epoxy resins cured at different temperatures can be seen.

Table 24 Typical properties of epoxy cast resins (Clarke 1996)

Property	**Unit**	**DGEBA-APTA amine cured at 20°C**	**DGEBA-MDA amine cured at 120°C**	**DGEBF-rubber modified epoxy MDA/MPDA cured at 120°C**
Specific gravity	-	1.2	1.2	1.2
Tensile strength	N/mm^2	62	90	125
Tensile modulus	kN/mm^2	3.2	3.0	4.1
Elongation at break	%	2	8	5
Shear strength	N/mm^2	61	52	84
HDT	°C	62	121	110

2.3.1.2.5 Phenolic Resins

Phenolic resins have the benefits of being inexpensive and having a high mechanical strength (KAW 2005). However compared to epoxies the phenolic provide poor mechanical properties (Cytec n.d). They can in general be regarded as non-combustible or material intrinsically fire-resistant (Clarke 1996; Muniz & Bansal 2009). The application of phenolic resins are when there exist requirements for high fire- and temperature resistance, low smoke emission and little flame spread (Potyrala 2011; Clarke 1996; Muniz & Bansal 2009; ZRMK et al. 2013; Cytec n.d). In comparison, phenolic resins emit about 10% of what isophtalic resins do (Clarke 1996). In addition if comparing phenolic resins with polyester and epoxy resins they have the advantage of not needing to apply any additives to enhance the fire performance (Muniz & Bansal 2009). The additives that need to be applied to epoxy and polyester resins are disadvantageous both in terms of cost and the increase in use of pollutant agents (Muniz & Bansal 2009). Since phenolic resins perform well during fire and has a high heat distortion temperature (HDT), as can be seen in Table 25, it has become more increasingly used (Clarke 1996). Another advantage with phenolic resins is they have lower shrinkage when compared to polyester resins (Clarke 1996). Furthermore they have outstanding adhesive qualities and heat and dimensional stability (Clarke 1996).Phenolic resins have in general a high void content which is disadvantageous (KAW 2005) and are difficult to process (Cytec n.d).

Table 25 Typical properties of phenolic cast resin (Clarke 1996)

Property	Unit	Resole-acid cured
Specific gravity	-	1.24
Tensile strength	N/mm^2	24-40
Tensile modulus	kN/mm^2	1.5-2.5
Elongation at break	%	1.8
Flexural strength	N/mm^2	60-80
HDT	°C	250

Phenolic resins were developed for the pultrusion process in order to seize the good fire properties it comprises (Clarke 1996). Phenolic resins have the ability to cure at room temperature, however in order to get dimensionally stable materials an elevated temperature exceeding 80°C is required. This implies that phenolic resins only are applicable to manufacturing processes and size of elements permitting a high curing temperature, as was the case for epoxy resins. The manufacturing techniques associated with phenolic resins are hand lay-up, pultrusion and filament winding. A problem that can arise during production is corrosion in the moulding tool which can be prevented by avoiding acid based catalyst. In addition, when phenolic resins cure large amounts of water is produced as a by-product from a condensation mechanism as well as micro voiding in the matrix. The micro voiding however, has small influence of the properties of the composite, however in combination with moisture may result in absorption of water that is more than three times that of isopolyester resins. In addition the combination of high water content and high temperatures can cause delamination of the structure. Another disadvantage of phenolic resins is that if they are subjected to thermal shock the risk of cracking is large (Clarke 1996).

2.3.1.2.6 Modified Acrylic Resins (Modar)

Modified acrylic resins have a similar curing process and mould shrinkage properties as polyester, but differentiate in having lower initial viscosity and faster curing reaction (Clarke 1996; ZRMK et al. 2013). Due to that the curing is fast and in combination with an odour of the monomer the chosen manufacturing process is often either pultrusion or resin transfer moulding (Clarke 1996). However even though the curing is fast the ultimate mechanical performance is not affected by the phenomenon (Clarke 1996). An advantage with modified acrylic resins is that it has good flammability (Clarke 1996; ZRMK et al. 2013). This is due to the low viscosity, and hence low styrene content, which enables incorporation of the filler alumina hydrate which has good fire properties (Clarke 1996). However, in comparison with phenolic resins they have more limited fire properties. In comparison with other resins the practice of modified acrylic resins is more limited (Clarke 1996).

2.3.1.3 Other forms

2.3.1.3.1 Prepregs

Prepregs are a ready-made tape consisting of fibre reinforced resins that are pre-impregnated, but cured after application (Clarke 1996; KAW 2005; Cytec n.d). The tape comes in the standard widths ranging from 76 to 1270mm (KAW 2005). The manufacturing scheme of prepregs can be seen in Figure 24 where a row of fibres is resins impregnated when passing through the resin bath (KAW 2005). The resin can either be a thermoset or a thermoplastic (KAW 2005) and the reinforcement can either consist of unidirectional or fabric (Cytec n.d). In order to advance the curing reaction the resin-impregnated fibres are heated (KAW 2005). The temperature is in the range of 70°C to 150°C and depending on the resin system the prepreg can also be subjected to a consolidating pressure (Clarke 1996). Subsequently the prepregs are wound over a take-up roll (KAW 2005). In order to avoid the prepregs from sticking to each other during storage a release film added to the take-up roll (KAW 2005)

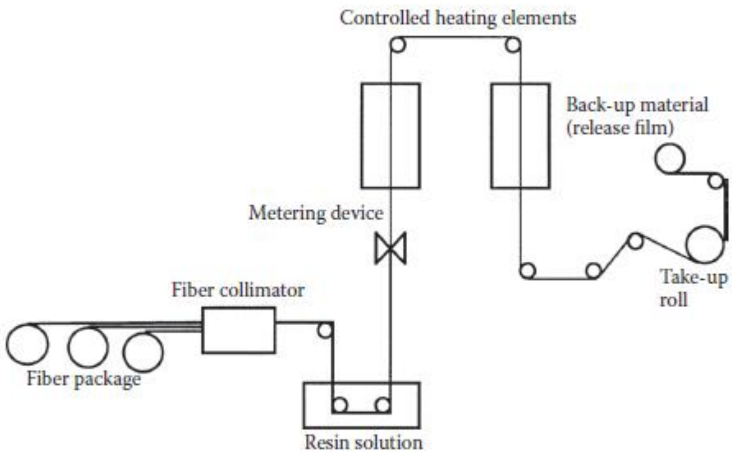


Figure 24 Manufacturing scheme of prepregs (KAW 2005)

Prepregs are beneficial since they provide the fabricator full control during manufacture (Cytec n.d). In addition they provide the benefit of a controlled fibre volume fraction which is, as for non-crimp fabric, in the range of 50% (Clarke 1996; Cytec n.d). Some other advantages with prepregs are that they have a low void content, high mechanical properties and superior composite performance (Clarke 1996). A disadvantage regarding prepregs is that they need both pressure facilities for consolidation and elevated temperature to cure and that this determines the final mechanical properties and environmental resistance (Clarke 1996). For prepregs consisting of a thermoset resin there is a need for storage in freezing units since the shelf life is short (Clarke 1996; KAW 2005). Prepregs made of thermoplastic resins can be stored at room temperature (KAW 2005).

The resins that are most commonly for high-performance application are epoxy and phenolic since these have proven most cost effective (Clarke 1996).

2.3.1.3.2 Gel Coats

Gel coats and top coats are non-structural and there are many purposes of their application, some of these are: to filter UV radiation, improve weathering, increase chemical resistance, provide colour, improve erosion, add electrical insulation and a barrier against moisture etc. (Clarke 1996). In addition the gel coat provides extra thickness of the composite as well as providing an attractive surface finish. There are two components incorporated in the gel coat to achieve the desirable characteristics which are pigments and additives. Both components are in general applied by brush but spraying also exists. If the spraying process is used the styrene content has to be increased for a decreased viscosity (Clarke 1996).

Pigments are incorporated in the gel coat to provide colour and to improve the resistance of UV radiation (Clarke 1996). The disadvantages of adding pigments are that the viscosity is changed and in some cases also the cure characteristics. It is in general problematic to get the desired colour of the composite since it is difficult to get an even distribution of the pigments during manufacture. Finally, since many of the previous pigments contained heavy metals which today have been prohibited there is now a problem to find the right pigment (Clarke 1996).

There are a large number of additives available presently and the purpose of these is to make the handling of the composite easier (Clarke 1996). Examples of additives are thixotropic agents, bentonites and surfactants. The surfactants are especially important and examples of these are air release, wetting and levelling additives and additives that prevent pigments from separating. The thixotropic additive is incorporated to strengthen the vertical mould surfaces since no reinforcement is added. When choosing an additive it is very important that they fit the chosen pigment (Clarke 1996).

Gel coats and top finishing flow coats increase the overall durability of the composite, for that reason it is important to incorporate it in sequences in the whole composite system (Clarke 1996). If a composite which is subjected to an alkaline environment has deficiencies such as lack of compatibility between gel coat and underlying materials and with incorporated low quality materials there is a risk of blistering and loss of adhesion. When the gel coat is curing during the build-up process it is important that it is not cured beyond its “green” state. In addition to achieve the highest adhesion it is important to apply the flow coat if the gel coat surface is in the “green state”. In general it is more difficult to get a uniform surface for top coats than for gel coats (Clarke 1996).

2.3.1.3.3 Green Composites

Previously the research regarding resins have been focused on to get composites stronger, faster manufacture, weigh less, getting fewer defects and reducing the cost (McAlvin 2011). Today however manufacturers have to take green technologies in consideration, which includes resins that are styrene-free and derived from biologically recycled or renewable materials. Research about alternatives to the petrochemical based resins are motivated due to that crude oil are finite and are getting more expensive (McAlvin 2011).

The resins that have been discussed until now, such as vinyl ester and polyester, are extracted from petrochemicals and have a high concentration of the harmful air pollutant styrene (McAlvin 2011). An alternative is to use so called “green composites” which are extracted from renewable or recycled materials and contains no hazardous air pollutions (non-HAP). These types of composites have had problems previously to meet the performance requirements. Today however there are resins extracted from recycled and biologically renewable resources which meet the requirements. There are also ecologically friendly composites available that have are free from styrene and have a low content of volatile organic compound (VOC) (McAlvin 2011).

In order to get a valid alternative to the petrochemical based resins it is important that properties such as viscosity, gel time, wet-out, peak exothermic temperature and catalysed stability are compatible to the existing manufacturing processes (McAlvin 2011). In addition the physical properties should be consistent with the petrochemical based resins, in terms of for example mechanical properties and chemical resistance. Today resins free from styrene and with a low HAP content of less than 2% have been produced with the conventional manufacturing techniques which can be seen in Table 26. Styrene-free resins are becoming more increasingly used due to regional requirements and have the benefits of reducing emissions and odour (McAlvin 2011).

Table 26 Mechanical properties for resin free from styrene (McAlvin 2011, p. 6)

Property	Unit	Test Method	Filled styrene-free ISO	Filled styrene-free VE	UV Curable styrene-free VE
Tensile strength	N/mm^2	ASTM D 638	8.7	8.0	8.8
Tensile modulus	kN/mm^2	ASTM D 638	0.67	0.73	0.47
Tensile elongation	%	ASTM D 638	1.7	1.9	2.5
Flexural strength	N/mm^2	ASTM D 790	10.8	12.60	15.3
Flexural modulus	kN/mm^2	ASTM D 790	0.660	0.710	0.510
HDT	°C	ASTM D 648	113	117	105
Renewable/recycled content	%	By weight	16	0	0

Previously soybean oil, glycerine, propanediol etc. was used for unsaturated polyester resin production which resulted in acceptable liquid properties but however lower mechanical properties such as specific modulus and HDT as well as corrosion resistance than for conventional resins (McAlvin 2011).

Some of the commercial bio-based chemicals used today to prepare unsaturated polyester resins are hydroxy, carboxylic acid and anhydride functional materials (McAlvin 2011). Bio-based Propylene Glycol (PG) is a recent building block used for producing unsaturated polyester resins, and is derived from the renewable resources corn and plant oils. Recycled PG is also being increasingly used on the market. PG's have the advantages of having a high resistance towards corrosion and mechanical properties. Both recycled and renewable PG's can be used to produce ISO-PG resins. The ISO-PG resins are of interest since they have equal properties as to conventional petrochemical based resins. Another new building block used for preparing unsaturated polyester resins is the Polyethylene Terephthalate (PET) which is extracted from recycled feedstock. It has the advantages of having high strength, good elongation, high heat resistance and an average resistance against corrosion (McAlvin 2011).

For solid surface applications the most traditional type is isophtalic acid and neopentyl glycol (ISO-NPG) resins, but it has more increasingly been substituted for a resin system consisting of 20% renewable material which have physical properties within allowable ranges (McAlvin 2011). See Table 27 for comparison between the two different types of unsaturated polyester resins.

Table 27 Comparison between conventional ISO-PNG unsaturated polyester resin and renewable material derive resin used for solid surface application (McAlvin 2011, p. 3)

Property	Unit	Test Method	ISO-NPG	Renewable
Tensile strength	N/mm2	ASTM D 638	12.5	11.3
Tensile modulus	kN/mm2	ASTM D 638	0.456	0.580
Tensile elongation	%	ASTM D 638	3.7	2.4
Flexural strength	N/mm2	ASTM D 790	20	20.8
Flexural modulus	kN/mm2	ASTM D 790	0.590	0.630
HDT	°C	ASTM D 648	78	85

As can be seen in Table 27 the tensile strength is similar for the renewable-derived resin and the ISO-PNG resin, however the ISO-PNG has a larger elongation and lower HDT (McAlvin 2011).

For bonding application a resin consisting of both renewable and recycled materials are available. The resin is a thixotropic polyester with a content of 39% consisting of renewable and recycled materials. In comparison with the conventional petrochemical based resin it has similar mechanical properties (McAlvin 2011). See Table 28 for comparison between the conventional and renewable-derived resin.

Table 28 Comparison of properties between petrochemical-derived and renewable-derived acrylic bonding resin (McAlvin 2011, p. 8)

Property	Unit	Test Method	Conventional petrochemical derived acrylic bonding UPR	Renewable/recycled -derived acrylic bonding UPR
Tensile strength	N/mm2	ASTM D 638	8.80	8.80
Tensile modulus	kN/mm2	ASTM D 638	0.480	0.480
Tensile elongation	%	ASTM D 638	2.7	2.4
Flexural strength	N/mm2	ASTM D 790	13.3	13.3
Flexural modulus	kN/mm2	ASTM D 790	0.510	0.490
HDT	°C	ASTM D 648	50	54
Tensile strength of acrylic-UPR sandwich	N/mm	ASTM C 297	1.20	1.40

construction	2			
Percent styrene	%	By weight	38	38
Gel time	min	25°C, 100g, 1.25% DDM-9	24	19
Gel to peak time	min	As above	18	15
Peak exotherm	°C	As above	121	129
Total renewable/recycled content	%	By weight	0	39

A resin with good fire properties is achieved if renewable and recycled material is combined with alumina trihydrate (ATH) (McAlvin 2011). Through tests with regard to surface burning of laminates where the resin was incorporated with ATH, results indicate a class 2 (McAlvin 2011).

Examples of styrene-free and non-HAP diluents for laminating resin applications are vinyl toluene, tertiary butyl styrene, and paramethyl styrene (McAlvin 2011). They have similar properties in comparison with the styrene based composites, but at a higher cost. However, an advantage with the styrene-free laminating resins is that they are more environmentally friendly. There are resins based on high boiling methacrylates and unsaturated polyester that has a minimum content of VOC and insignificant level of emissions. However the mechanical properties of the composite are reduced as well as the HDT in comparison with the conventional styrene-based resins (McAlvin 2011). A comparison between the conventional styrene-based resin and the styrene-free laminating resin can be seen in Table 29.

Table 29 Comparison properties for conventional styrene-based resin and the styrene-free laminating resin (McAlvin 2011, p. 3)

Property	Unit	Test Method	Conventional styrene-based UPR	Styrene-free GP Laminating resin
Tensile strength	N/mm^2	ASTM D 638	9.0	11.0
Tensile modulus	kN/mm^2	ASTM D 638	0.570	0.490
Tensile elongation	%	ASTM D 638	2.0	3.5
Flexural strength	N/mm^2	ASTM D 790	14.0	16.3
Flexural modulus	kN/mm^2	ASTM D 790	0.590	0.500
HDT	°C	ASTM D 648	95	87

As can be seen in Table 29 the HDT is lower for the styrene-free resin than for the conventional styrene-derived resin but is however still in an acceptable range (McAlvin 2011).

2.3.2 Comparison of Resins

The thermoset resins isopolyester, epoxy and vinyl ester can be regarded as very combustible, which indicates that large amounts of flammable volatiles will leak out when they thermally decompose (Gibson, Mathys & Mouritz 2006). In general phenolic resins provide better resistance against flames, and have lesser leakage of volatiles (Gibson, Mathys & Mouritz 2006). A similarity between epoxy, vinyl ester and polyester resins are that they all are cross-linked (Hollaway 2010). Figure 25 illustrates comparisons in smoke emission, maximum strength, service temperature and cost for some common resin types.

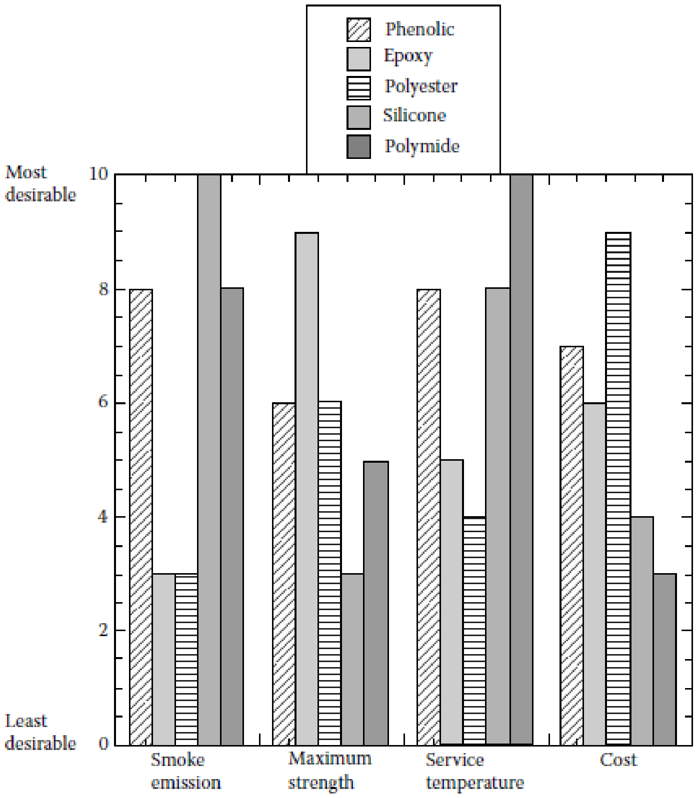


Figure 25 Comparison of performance of common polymer matrix composites (KAW 2005)

Cost regarding development of resin systems and raw materials are the main reasons to the high costs of polymer matrices today (Chlosta 2012). A comparison in cost between different thermoset polymers is available in Table 30.

Table 30 Comparison of density and price for different resin types (Bank 2006)

Resin type	Density [g/m^3]	Price [SEK/kg]
Epoxy (Bisphenol-A)	1.05	17.8
Epoxy (Novalac)	1.05	32.7
Vinyl ester	1.05-1.10	19.3-26.0
Phenolic	1.5-2.0	9.7
Polyester	1.15-1.25	9.8-16.3

Table 31 shows a detailed comparison between six common resin types.

Table 31 Comparison resins (Chlosta 2013)

Resin type	Characteristics	Limitations
Polyester	• Able to cure at room temperature and at elevated temperature • Very good properties of the composite • Good chemical and electrical properties • Variety of resins available, easy to use	• Emit styrene • Flammable • Shrinks during curing • Cannot be B-staged
Phenolic	• Very good thermal and fire properties • Good electrical properties • Can be B-staged	• Resistance against alkali • Limitation in colour
Vinyl ester	• Good toughness and fatigue resistance • Very good resistance against chemicals • Excellent properties of the composite	• Emit styrene • Flammable • Shrinks during curing • Cannot be B-staged
Epoxy	• Excellent properties of the composite • Very good chemical and electrical properties • Good thermal properties • Low shrinkage during curing • Can be B-staged (prepreg)	• Cure cycles are long • Best properties obtained for cure at elevated temperatures
Polyurethane	• Good properties of the composite • good resistance against abrasion • very good resistance against chemicals • very high toughness (impact)	• Require agents • Cannot be B-staged • Colour limitations • Anhydrous curing
Silicone	• Very good thermal and electrical properties • excellent resistance against chemicals, good fire properties • non-toxic • resistant against hydrolysis and oxidation	• Cure cycles are long • Can only be cured at elevated temperatures • Lack of adhesion

2.3.3 Fillers

Fillers are non-structural and inorganic particulates (Clarke 1996). The function of the filler is to reduce the use of reinforcement and matrix materials thus reducing the cost by increasing the utilization through an improved filling of the form (Potyrala 2011). By the implementation of fillers the cost for the final product is lowered (Potyrala 2011; Clarke 1996). Other characteristics with the incorporation of fillers are reduced shrinkage, reduce peak exotherm during cure due to generation of water, increase local hardness and abrasion, opaqueness, UV-stabilisation, colour and reducing flammability i.e. a less combustible material (Clarke 1996). In addition by adding fillers the compressive strength and modulus can be increased as well as smoother surface finish (Clarke 1996).

However some disadvantages with fillers are that they reduce the durability and the long term structural properties of the composite (Clarke 1996). For example can the incorporation of fillers result in an increased viscosity, reduced wetting as well as increased void in the composite. It has been shown that composites not containing fillers manage better when exposed to environmental condition than composites that do (Clarke 1996).

The most common fillers are calcium carbonate, kaolinite and aluminium oxide whom all are inorganic materials (Potyrala 2011).

2.3.4 Additives

Additives are used to improve the properties of the composite matrix and thus resulting in an increase of the performance (Potyrala 2011). Additives can be organized into two groups: process-related additives and function related additives. Independent of the additive chosen it will have an impact on the corrosion resistance as well as mechanical and fire resistance of the profile (Potyrala 2011).

2.3.4.1 Process-Related Additives

Process-related additives have a beneficial influence on the manufacturing process as well as appearance and properties of a structural element (Potyrala 2011). An example of a process related additive is the low-profile additive.

2.3.4.1.1 Low-Profile Additives

Low-profile additives are used in the pultrusion process, described in the chapter: 4.6 Pultrusion, and are used to avoid excessive shrinkage when the profiles are curing (Potyrala 2011). There are many benefits by using low-profile additives such as that it prevents cracks to form, increase resistance to corrosion and provide better fatigue properties. Low-profile additives also influence the geometric tolerances of the profile by making it more exact and decreases internal stresses (Potyrala 2011). In addition the use of low-profile additives conveys smoother surface and higher dimensional stability of the composite (Clarke 1996).

Low-profile additives consist in general of thermoplastics and are common in the hot moulding processes manufacturing processes SMC and DMC (Clarke 1996).

2.3.4.2 Function-Related Additives

The function-related additives are implemented to improve the properties of the final product. Examples of function-related additives are pigments and fire retardants (Potyrala 2011).

2.3.4.2.1 Pigments

Pigments are added to get a preferred colour and comprise approximately 1% by weight of the composite (Clarke 1996). They can either be incorporated in the gel coat or in the resin. Pigments based on metallic salt can decrease the adhesion in the fibre-matrix bonding as well as affecting the rate of cure. However by implementing pigments will increase the blocking of UV radiation and consequently also weathering properties (Clarke 1996).

2.3.4.2.2 Flame Retardants

Flame retardant additives have the purpose of reducing and delay flame spread of the surface and have self-extinguishing properties (Potyrala 2011; Clarke 1996). However by incorporating flame retardants also reduces the weathering resistance and mechanical properties as well as colour properties of the composite (Clarke 1996). Another disadvantage with flame retardants is that they are in general very toxic and increase the generation of smoke (Clarke 1996).

Examples of flame retardants are aluminium tri-hydrate (ATH) and halogens. Advantages with ATH are that has both lowers the smoke and toxicity levels but also releases water at flame temperature (Clarke 1996).

By incorporating either ATH additives or halogen additives have beneficial effects on the polyester resins (Clarke 1996). The halogen additives work best when incorporated in vinyl esters. Even with the incorporations of ATH and halogen additives in vinyl ester and polyester there will be smoke emissions due to the high styrene content. By incorporating ATH additives in a Modar resin the smoke emission will be lower than for polyester resins, since they have lower styrene content (Clarke 1996).

2.4 FRP Composites

Factors that determine the physical and in-service properties of the FRP composite are among other the physical and in-service properties of the fibre and polymer, the bond between fibre and resin, the volume fractions of the fibre and resin and the manufacturing technique (Hollaway 2010).

The typical tensile mechanical properties of the FRP composite consisting of glass fibres and vinyl ester polymer can be seen in Table 32.

Table 32 Typical tensile mechanical properties of glass fibre/vinyl-ester polymer (compression moulding – randomly orientated fibres) (Hollaway 2010, p. 2441)

Fibre/matrix ratio (%)	Specific weight (-)	Flexural Strength (Mpa)	Flexural modulus (Gpa)	Tensile strength (Mpa)	Tensile modulus (Gpa)
67	1.84 - 1.90	483	17.9	269	19.3
65	1.75	406	15.1	214	15.8
50	1.8	332	15.3	166	15.8

A FRP composite consisting of carbon fibres and epoxy resin is the most rigid composite. The composite with the highest shear strength consist of glass fibres and epoxy resin (Muniz & Bansal 2009). Composites consisting of a vinyl ester or epoxy polymer emit less smoke if aramid fibres are used for glass fibres (Gibson, Mathys & Mouritz 2006).

2.5 FRP Composites (compatibility issues between fibres and matrix)

2.5.1 Fibre-Matrix Bonding

The governing parameters regarding the mechanical properties of the bond between fibre and polymer are both the compatibility between matrix and fibre, called the "interface", in addition with the loading direction and angle between fibres (Potyrala 2011; Hollaway 2010). The same parameters also govern the stiffness and strength of the matrix (Potyrala 2011). The interface region is affected by many parameters such as the coating composition and the arrangement of for example surface glass fibres (Hollaway 2010). The fibre/matrix interface is important since it determines the FRP's physical, mechanical and durability characteristics (Bisby 2006). The characteristic of the bond between the fibres and the matrix is of importance since it controls the load transfer in the structure (Bisby 2006). If the fibres are arranged in a general direction and then loaded in this direction, the highest values of strength and stiffness will be obtained (Potyrala 2011). Fibre types to use if the loading direction is changed are woven and non-woven fabrics (multi-layered) since they show a quasiisotropic behaviour. If unidirectional laminates would have been used instead of multi-layered the stiffness and strength would have been reduced (Potyrala 2011).

The fibres of the composite are the decisive parameter regarding the linear-elastic deformation behaviour (Potyrala 2011). The failure strain of the fibres should be less than for the matrix in order to avoid microcracks before the elongation limit is reached (Potyrala 2011). A high elongation is beneficial in terms of toughness and less tendency to crack (McAlvin 2011). Little stiffness of the matrix is needed to prevent buckling under compression (Potyrala 2011).

It is of great importance that the adhesion between the surface coating and the resin is sufficient. This is important for the fibres to able to carry the stresses. However the adhesion should not be so strong that the composite acts in a brittle manner due to prevention of cracks (Clarke 1996).

Other requisites for a good matrix-fibre bonding is the resin needs to fully penetrate and wet the fibres and needs to have a high enough viscosity to not dry out before curing. In addition the curing temperature must be less than the environment in which the composite will be subjected to or else the performance will be reduced (Clarke 1996).

The interaction between the matrix and the fibre has a large influence on the structures failure mode (Potyrala 2011).

2.6 Cores

Cores have two applications; either they can be used as load bearing elements (structural cores) or as forms for shaping FRP sections (Clarke 1996). The structural cores are available as foams, honeycombs or solids (e.g. balsa-wood) which are used in different types of sandwich structures. See Table 33 for a qualitative comparison between the different core materials. The sandwich is constructed by attaching two thin skins made of a structural material to a thick and light-weight core. The purpose of sandwich constructions is to increase the efficiency of the structure (Clarke 1996).

Table 33 Qualitative comparison of core materials (Clarke 1996, p. 302)

Form	Material	Advantages	Limitations

Solid	Balsa-wood	• Easy to shape • Robust	• Affected by moisture • variable
Foamed	PVC	• Temperature limitations • Controlled density • Can be foamed in situ • Service temperature to 200°C	• Poor fire performance
	Polymethacrylimides		
	Polymethoenylimide		
	Polyurethane		
	Melamine		
Honeycomb	Pure Al sheets	• High strength • low weight	• Can corrode next to carbon reinforced plastic
	Nomex®	• Good strength-to-weight ratio • Good fatigue resistance	• More difficult to shape • Expensive
	Ti alloy sheets	• high resistance towards temperature	• Cost • weight

Cores can be made out of metals, wood, plastic and others (Clarke 1996). In terms of metals the materials used for core manufacture are for example steel, aluminium and titanium used for hexagonal honeycomb. The hexagonal honeycombs provide maximum shear strength but are very expensive. In terms of cores made of wood, chipboard, plywood and strawboard etc. are common. For plastic cores the most common types are honeycomb, cross-linked PVC foam, expanded polystyrene etc. In addition cores can be constructed from glass fibres, mineral-wool resins, paper or cardboard honeycombs etc. (Clarke 1996).

When constructing core materials the following properties are essential to fulfil: low density, stable dimensionally and thermally, resistance against fatigue, high shear modulus and shear strength, easy to shape, high moisture resistance etc. (Clarke 1996).

2.7 Foam

The foams either consist of open or closed cell materials that are constructed from plastics such as ABS, epoxies, phenolics, cellulose acetate, polycarbonate, polypropylene, polyurethanes, polyimides and cross-linked PVC (Clarke 1996). Cross-linked PVC cores are considered very important in practice due to its advantageous properties such as good resistance against styrene, high strength and stiffness to weight ratio, good strength against impact, high resistance against fatigue, non-biodegradable etc. (Core Composites 2014). In Table 34 properties of different PVC foam cores are displayed.

Table 34 Properties of PVC foam cores (Clarke 1996, p. 303)

Property	**Unit**	**Test method**	**H30**	**H45**	**H60**	**H80**	**H100**	**H130**	**H160**	**H200**	**H250**
Density	kg/m^3	ASTM D	36	46	60	80	100	130	160	200	250

		1622									
Compressive strength[1]	N/mm^2	ASTM D 1622	0.3	0.6	0.8	1.2	1.7	2.5	3.4	4.4	5.8
Compressive modulus[1]	N/mm^2	ASTM D 1622 procedure b	20	40	60	85	125	175	230	310	400
Tensile strength[1]	N/mm^2	ASTM D 1623	0.9	1.3	1.6	2.2	3.1	4.2	5.1	6.4	8.8
Tensile modulus[1]	N/mm^2	ASTM D 1623	28	42	56	80	105	140	170	230	300
Tensile strength[2]	N/mm^2	ISO 1926	0.8	1.2	1.5	2.0	2.4	3.0	3.9	4.8	6.4
Shear strength[2]	N/mm^2	ASTM C 273	0.35	0.5	0.7	1.0	1.4	2.0	2.6	3.3	4.5
Shear modulus[2]	N/mm^2	ASTM C 273	13	18	22	31	40	52	66	85	108
Note: [1] perpendicular to the plane [2] parallel to the plane											

The foams most generally used in civil engineering applications are polyurethanes, rigid polyvinyls and polymethacrylimides (PMI) (Clarke 1996). In Table 35 properties of rigid PMI foam cores are displayed.

Table 35 Properties of rigid PMI foam cores (Clarke 1996, p. 304)

Properties	Units	51S	71S	110S	200S
Gross density	kg/m^3	52	75	110	205
Compressive strength	N/mm^2	0.75	1.53	2.97	7.66
Compressive modulus	N/mm^2	45	73	130	388
Compression	%	9	8	5	11
Tensile strength	N/mm^2	1.12	1.97	3.27	8.48
Tensile modulus	N/mm^2	52	91	157	352
Elongation at break	%	3.8	4.1	3.6	4.1
Shear strength	N/mm^2	0.70	1.27	2.28	5.47

Shear modulus	N/mm^2	22	34	58	138
Dimensional stability under heat	°C	190	190	190	200

Foams can be used in sandwich panels where they are manufactured either in-situ or from slab stock (Clarke 1996). One disadvantages regarding foams manufactured in-situ is that it is more problematic to get uniform properties. High density foams can be used very efficiently in sandwich constructions with thinner skins. Advantages with high density foams are that they provide good compression and shear properties to the foam.

The mechanical properties of foams are non-linear and depend on the density. The densities of foams are in the range of $5kg/m^3$. Foams can be constructed as both graded density foams and integral sandwich foams. The integral sandwich foam consists of a cellular core with solid surfaces (Clarke 1996).

2.7.1 Reinforced Foams

If foams are reinforced with for example glass fibres with a fibre content of approximately 50% the mechanical and physical properties of the foam is improved with a magnitude of 400 to 500% for thermosets (Clarke 1996). If a thermoplastic polymer is used the magnitude of improvement of the properties will be lower than for thermoset polymers. The degree of improvement is dependent of quantity, direction and type of fibre. However if fibres are added to the foam it is harder to control and ensure the properties (Clarke 1996).

2.7.2 Structural Foam

Structural foam is a component consisting of a cellular core and a solid surface i.e. with graded densities (Clarke 1996). An advantage with the built in sandwich construction is better structural properties. Due to the sandwich construction they have a high strength and stiffness to weight ratio and can advantageously be used as structural components. In addition the costs of structural foams are relatively low. Structural foams can be manufactured with two processes; one under high pressure and the other under low pressure. However the end product is similar: a cellular core surrounded by a dense skin (Clarke 1996). They can have a finish surface consisting of skins, see Figure 26 for examples of different FRP skin series.

Figure 26 Different FRP skin series (Polycore technology Co., Ltd n.d)

2.7.3 Other Foams

Other types of foams are for example syntactic foams which have high compressive strength (Clarke 1996). In general these types of foams are very lightweight and a common application is to fill cavities and moulds where the rigid foams are unpractical. It is possible to tailor the finished product with suitable formulations (Clarke 1996).

2.8 Honeycomb

The application where honeycomb cores are to be considered is when a light-weight structure is required (Clarke 1996). Honeycomb cores can be constructed from a variety of materials such as aluminium and aramid where both bring various advantages. Advantages with honeycombs are that they in general have high shear and compression strength (Clarke 1996). A typical honeycomb is displayed in Figure 27.

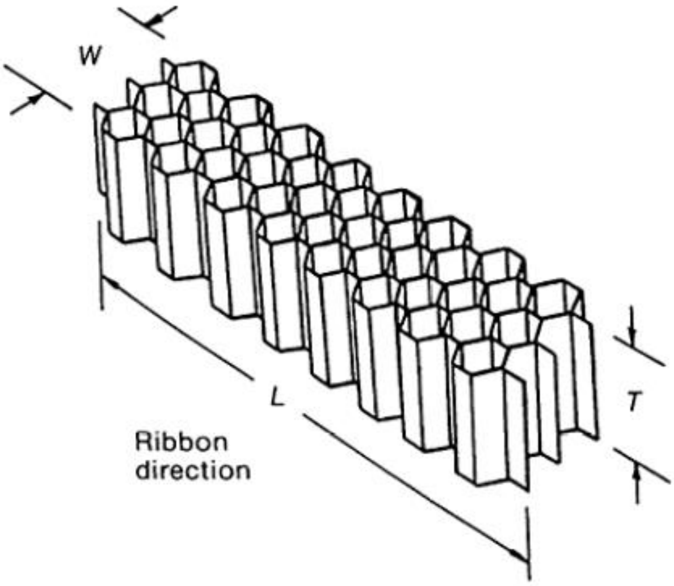


Figure 27 A typical honeycomb (Clarke 1996, p. 306)

The manufacture of honeycombs are consists of impregnating resin sheet materials such as paper glass fabric or metal foil and the bonding them at certain interval, and finally expanding the honeycomb to the final shape which is most often a hexagon (Clarke 1996). Other shapes of honeycomb are for example over expanded and flex-core. An advantage with the over expanded honeycomb is that it has better drapability and are a better choice in case of curved elements (Clarke 1996). See Figure 28 for the different types of honeycombs.

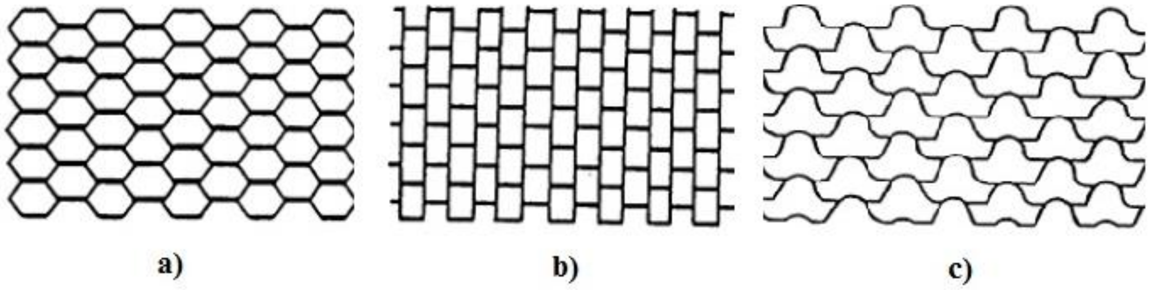


Figure 28 a) Hexagon honeycomb b) Over expanded honeycomb c) Flex-core honeycomb (Clarke 1996, p. 308)

Honeycombs are divided into two groups: metallic and non-metallic (Clarke 1996). A metallic honeycomb generally consist of aluminium, titanium, corrosion resistant steel and alloys based on nickel. The non-metallic honeycombs are generally made of fibre glass, Kraft paper and Nomex (Clarke 1996).

Corrosion problems that can occur if using aluminium honeycombs in combination with carbon fibres can be avoided by adding a glass fibre layer in-between. A common aluminium honeycomb is the 5052 H39 alloy which has a coating that prevents corrosion (Clarke 1996).

Nomex is manufactured by dipping aramid fibres in most commonly phenolic liquid but also polyester and polyamide and by doing so forming a paper. This type of honeycomb has in general high toughness, strength and corrosion resistance and this is due to the combination of aramid fibres and phenolic resin. The thickness of the paper in combination with cell geometry and size are factors that determine the properties of the aramid honeycomb. In contrast to the aluminium honeycomb there is no problem with corrosion since aramid is non-metallic, in addition aramid honeycomb are more resilient against impact (Clarke 1996).

2.9 Solids

Application of solids in sandwich elements is justified if the solid is lightweight. The use of solids, most commonly wood, in cores is of general application in for example partitions and doors (Clarke 1996).

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3 Properties of FRP Composites

As shown in the previous chapter there are many different types of resin and reinforcement available. Additionally other materials such as additives and fillers can be incorporated resulting in a vast variety of FRP composites with different properties such as strength and stiffness (Chlosta 2012). Strength of FRP composites varies from 50MPa to about 2000MPa while the stiffness could change in a range from 10GPa to 400GPa (Chlosta 2012). The factors that mainly influence the final properties of the FRP composite are the fibre volume fraction, the orientation of the fibres, the properties of the constituent materials and the fibre/matrix bond (Potyrala 2011; Clarke 1996). The general characteristics of FRP composites are:

- ability to form complex shapes
- low density
- anisotropy
- relatively good mechanical properties
- the physical and mechanical properties are dependent on the composition of the constituent materials
- Good resistance to corrosion and oxidation

FRP composites are generally regarded as a homogenous, anisotropic and linear elastic material in design which is the most common assumptions (Chlosta 2012). The anisotropy, i.e. different properties in different directions, of FRP composites is both related to strength and stiffness properties, but also in terms of temperature expansion, swelling, electric conductivity and heat transfer (Chlosta 2012).

3.1 Thermal Properties

3.1.1 Thermal expansion coefficient

The coefficient of thermal expansion (CTE) varies to a large extent between different FRP composites and in different directions (Bisby 2006). GFRP in the longitudinal direction and concrete have similar values of CTE. AFRP and CFRP however have CTE's that varies from conventional building materials in the order of one magnitude (Bisby 2006; Hollaway 2010). The CTE's in the transversal direction of the FRP composite generally is much higher compared to concrete, which can result in splitting of the concrete cover (Bisby 2006). A comparison of CTE for GFRP, steel and concrete is displayed in Table 36.

Table 36 Thermal expansion coefficients for FRP, concrete and steel (Murphy 2013)

Material	GFRP	Concrete	Steel
Fibre direction [10^{-6}/°C]	17.9	14.5	10-13
Transverse direction [10^{-6}/°C]	18.4		

Composites whit incorporated aramid or carbon fibres can have a CTE which is near-to-zero or negative as a result of the low negative CTE's of the two fibre types (Clarke 1996). The resulting CTE of the FRP composite depends on various factors such as the matrix and fibre type, the fibre volume fraction, the geometry of the reinforcement and the type and amount of incorporated fillers (Clarke 1996). In Table 37 is the relation between fibre volume fraction V_f and CTE displayed.

Table 37 The relation between coefficient of thermal expansion and fibre volume fraction (Clarke 1996)

	Unidirectional 0°	Unidirectional 90°	Bidirectional fibre	Mat + roving pultrusion
Fibre volume fraction V_f [%]	65	65	65	37
Coefficient of thermal expansion [10^{-6}/°C]	8.6	14.1	9.8	11

3.2 Physical Properties

3.2.1 Density

The density of the FRP composite ranges from 0.9g/cm^3 to 2.3g/cm^3, however generally lie in the range of 1.2 g/cm^3 and 1.8 g/cm^3 (Potyrala 2011). This can be compared to the density of steel which is about 7.87 g/cm^3 (Muniz & Bansal 2009). A comparison of the density ranges of wood, FRP composites, concrete, aluminium, titanium and steel can be seen in Figure 29. The low densities related to FRP composites enables higher values of the specific modulus (stiffness-to-weight ratio) and specific strength (strength-to-weight ratio) compared to metals (Muniz & Bansal 2009). General values of density for carbon-, aramid- and glass fibres can be seen in Table 38. The general values of resins lie in the range between 1.3 g/cm^3 and 1.8 g/cm^3 (Muniz & Bansal 2009).

Table 38 Typical values of density for carbon-, glass- and aramid fibres (Muniz & Bansal 2009)

Material	Density [g/cm^3]
Carbon	1.7-1.9
Glass	2.4-2.6
Aramid	1.4

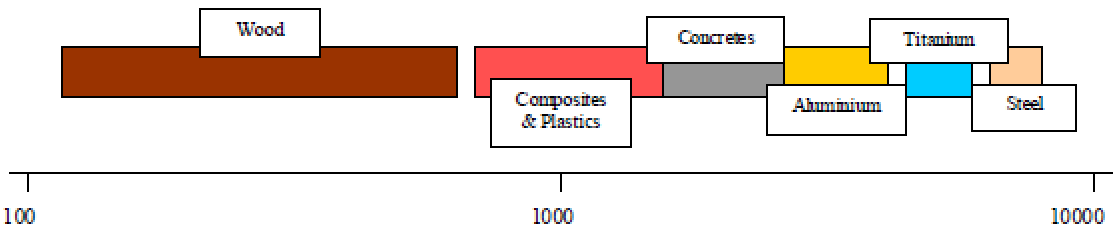


Figure 29 Comparison of density for different construction materials (Cytec n.d)

The density of the FRP composite is determined by the following equation (Potyrala 2011; Muniz & Bansal 2009):

$$\rho_c = \rho_m \times V_m + \rho_f \times V_f$$

Where:

$\rho_c$is the density of the composite, ρ_m is the matrix density ρ_f is the fibre density,

V_m is the volume fraction of the matrix material and V_f is the volume fraction of the fibre material

3.3 Mechanical Properties

The factors influencing the mechanical properties of the composite is mainly the matrix and fibre type, the orientation of the fibres and the relative quantities of the constituents (Clarke 1996). The quality of the interface between the fibre and the matrix has furthermore a major impact on the mechanical properties of the FRP composite (Hollaway 2010). The post curing procedure and curing system also influences the final properties of the FRP composite (Clarke 1996). Important mechanical properties of FRP composites include ultimate tensile strength, ultimate compressive strength, uniaxial compressive strength, stiffness and creep (Hollaway 2010).

As can be seen in Figure 2 there are three categories of fibre orientation including: unidirectional, bidirectional and multidirectional (random). A composite with fibres arranged mainly unidirectional achieves high strength and stiffness in the longitudinal direction, however poor properties in the transverse direction in terms of modulus of elasticity and strength (Clarke 1996). By arranging the fibres in a bidirectional manner with equal amount of fibres in each direction will generate equal properties of strength and stiffness in both directions which are lower than for the unidirectional case (Clarke 1996). In practice the laminates generally are constructed through a variety of fibre orientations (Muniz & Bansal 2009). As can be seen in Table 39 the orientation and the fibre volume fraction have an impact on the product properties such as tensile strength and stiffness (Clarke 1996).

Table 39 The influence of orientation of the fibres and fibre volume fraction on the product (Clarke 1996)

Fibre type	Reinforcement directionality factor	Typical volume fraction Vf	Product
Unidirectional	1	65%	0.65
Bidirectional non-crimp	0.6	50%	0.3
Bidirectional woven	0.5	40%	0.2
Random in plane	0.375	20%	0.075

It can be concluded from the table that the difference in properties, such as tensile strength and stiffness, differs about 50% between unidirectional and bidirectional non-crimp and with three-eighths between unidirectional and random fibres (Clarke 1996; Muniz & Bansal 2009). Hence the orientation of the fibres has larger influence of the properties than the type of fibres used (Clarke 1996). The rigidity of a composite is related to the orientation of the fibres, and if the composite is loaded in the same direction as the main direction of the fibres the highest rigidity of the composite is achieved (Muniz & Bansal 2009). Table 40 presents a comparison of the mechanical properties of GFRP composites with three different fibre compositions incorporated.

Table 40 Mechanical properties for three types of GFRP products (Chlosta 2012, p. 29)

Property	Unit	Continuous roving's	Woven cloth	Chopped strand mat
Fibre volume fraction	%	70	55	30
Specific gravity	-	1.9	1.7	1.4
Tensile strength	MPa	800	300	100
Compressive strength	MPa	350	250	150
Flexural strength	MPa	1 000	400	150
Flexural modulus	MPa	40 000	15 000	7 000
Impact strength	kJ/m^2	250	150	75
Coefficient of thermal expansion	$10^{-6}/°C$	10	12	30
Thermal conductivity	W/m K	0.29	0.28	0.2

The general, strength of a composite is mainly influenced by the following factors: (1) fibre- and matrix type, (2) orientation of fibres, (3) fibre volume fraction, (4) curing rate and (5) quality control (QC) during manufacture (O'Connor 2009). The compressive- and tensile strength of FRP composites is mainly determined by the properties of the fibre, such as orientation and fibre volume fraction, since they, to a large extent, carry the axial load (Potyrala 2011; Muniz & Bansal 2009). Fibres generally have excellent performance in terms of tensile loads, and poor performance in terms of flexure or pressure (Chlosta 2012). The most rigid FRP composite available is the combination of carbon fibres and epoxy resin (Muniz & Bansal 2009). The composite offering the best shear strength properties is the combination of glass fibres and epoxy resin (Muniz & Bansal 2009).

3.3.1 Tensile Strength

The difference in tensile strength of a FRP composite in the longitudinal and transversal direction is mainly in the range of 30 to 40 which can be seen in Table 41 (Muniz & Bansal 2009). This is due to that stiffness in the transversal direction is much lower, see Table 47, which can result in failure of the composite without signs of fibre breakage (Muniz & Bansal 2009). The fibre breakage can furthermore causes displacements (Potyrala 2011). These displacements are resisted by the matrix through shear stress taking place on the fibres lateral surface (Potyrala 2011).The strength in the transverse direction is mainly determined by the resin (Muniz & Bansal 2009; Hollaway 2010).

Table 41 Tensile strength of single direction FRP composites (Muniz & Bansal 2009)

Material	Longitudinal tensile strength [MPa]	Transversal tensile strength [MPa]

Carbon/Epoxy	1148	52
Glass/Vinyl ester	610	49
Aramid/Epoxy	1400	12

The tensile strength in the longitudinal direction of a FRP composite can be calculated with the following formula (Muniz & Bansal 2009):

$$TS_c = TS_f \times V_f + TS_m \times V_m$$

Where:

TS_c is the ultimate tensile strength of the composite, TS_f is the ultimate tensile strength of the fibres, TS_m is the ultimate tensile strength of the resin, V_f is the volume percentage of fibres and V_m is the volume percentage of the resin

A unidirectional GFRP composite with a fibre volume fraction of 65% generally achieves a tensile strength and tensile modulus of 700MPa respectively 40GPa (Clarke 1996). This can be compared with the corresponding AFRP which have a general tensile strength of 1400MPa. As mentioned previously AFRP has low compressive strength which generally lie in the range of 230MPa which is about one-sixth of the tensile strength. The low compressive strength influences the flexural strength which is about 300MPa for AFRP. The properties tensile modulus and tensile strength in the longitudinal direction for the aramid type Toray T300 generally lie in the range of 125-135GPa and 1700-1800MPa (Clarke 1996).

In Table 42 presents a detailed comparison of tensile strength of different FRP laminates in relation to the orientation of the fibres. The letter (s) written outside the brackets indicates that the layers are repeated symmetrically (Muniz & Bansal 2009). The general procedure in laminate design is to arrange the fibres in the order 0°, +45°, -45° and 90° so called quasi-isotropic composites (Muniz & Bansal 2009). This arrangement however generates laminates with lower strength-properties than unidirectional laminates (Muniz & Bansal 2009).

Table 42 Influence of fibre orientation for FRP laminates in terms of tensile strength (Muniz & Potyrala 2009)

Type of FRP composite and orientation	Direction 0°		Direction 90°	
	Modulus of elasticity [GPa]	Breaking tension [MPa]	Modulus of elasticity [GPa]	Breaking tension [MPa]
High strength carbon/epoxy				
$[0_4]$	100-140	1020-2080	2-7	35-70
$[0_1 90_1]s$	55-76	700-1020	55-75	700-1020
$[45_1 45_1]s$	14-28	180-280	14-28	180-280
E glass/epoxy				
$[0_4]$	20-40	520-1400	2-7	35-70

$[0_1 90_1]s$	14-34	520-1020	14-35	520-1020
$[45_1 45_1]s$	14-21	180-280	14-20	180-280
		High strength aramid/epoxy		
$[0_4]$	46-68	700-1720	2-7	35-70
$[0_1 90_1]s$	28-34	280-550	28-35	280-550
$[45_1 45_1]s$	7-14	140-210	7-14	140-210

It can be concluded that the tensile strength of FRP composites varies considerably depending on the fibre type and orientation. As can be seen in Figure 30 the tensile strength of GFRP is generally lower than that of steel. However by incorporating boron and carbon fibres instead, composites with similar or higher tensile strength than steel are achieved. It can furthermore be noted that the FRP composites generally used in civil engineering applications have considerably higher tensile strength than both concrete and timber which is displayed in Figure 30. Typical values of tensile strength of steel can be seen in Table 43.

Table 43 Tensile strength of different steel grades (Domone & Illston 2010)

Grade	Tensile strength [MPa]
S235	360-415
S275	410-560
S355	470-630
S450	550-720

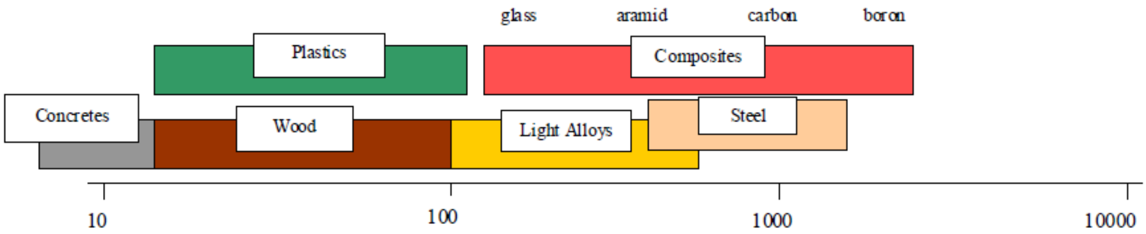


Figure 30 Comparison of tensile strength for different construction materials (Cytec n.d)

3.3.2 Compression Strength

As can be seen in Table 44 the compressive strength in the transverse direction is larger than for the tensile strength, seen in Table 41 (Muniz & Bansal 2009). The compressive strength of the composite is mainly influenced by the modulus of elasticity and strength of the matrix, the misalignment of the fibres and the bond of the fibre/matrix interface (Hollaway 2010).

Table 44 Compressive strength of single direction FRP composites (Muniz & Bansal 2009)

Material	Longitudinal compression strength [MPa]	Transversal compression strength [MPa]
Carbon/Epoxy	600	206
Glass/Vinyl ester	215	49
Aramid/Epoxy	230	53

If the FRP composite is subjected to compression, there is a risk of compressive buckling at low levels of stress (Potyrala 2011). This risk is however limited by the matrix which stabilises the fibres (Potyrala 2011). Resins have in general higher compressive strength than tensile strength by a factor of 1.5 to 4 times (Muniz & Bansal 2009; Hollaway 2010). The difference is generally related to the defects in the material which influence the tensile performance to a larger extent than the compressive performance (Hollaway 2010). The fibres contribute mainly to the tensile strength of the FRP composite in the transversal direction (Muniz & Bansal 2009). From Table 44 it can be further concluded that the composite has higher compressive strength in the longitudinal direction than in the transversal direction. It can be noted that the difference in tensile- and compressive strength for AFRP is significant. This is mainly due to that aramid is composed of small fibres which results in a low compressive strength in the longitudinal direction (Muniz & Bansal 2009).

3.3.3 Shear Strength

Typical values of shear strength for different types of FRP composites are displayed in Table 45. It can be seen from the table that the shear strength of unidirectional FRP laminates are relatively low. This is due to that the fibres cannot resist the strain resulting from the maximum shear direction (Muniz & Bansal 2009).

Table 45 Shear strength of unidirectional FRP composites (Muniz & Bansal 2009)

Material	Shear strength [MPa]
Carbon/Epoxy	93
Glass/Vinyl ester	16
Aramid/Epoxy	34

By arranging the fibres in the direction ±45° in relation to the applied load, the shear strength will be significantly improved (Muniz & Bansal 2009). The maximum shear strength of the composite is achieved if all fibres are orientated ±45°. This will however result in a low tensile strength. In order to design for shear strength, however not sacrificing the tensile strength, some layers should be orientated ±45° (Muniz & Bansal 2009).

3.3.3.1 Shear Modulus

Similar to the shear strength, the shear modulus is also largely influenced by the orientation of the fibres (Muniz & Bansal 2009). The maximum value of the shear modulus is achieved when the fibre orientation is 45° and the minimum for angles of 0° and 90° (Muniz & Bansal 2009). Typical values of shear modulus for different FRP unidirectional laminates can be seen in Table 46. The corresponding value for steel is 80GPa, hence it can be concluded that the shear modulus for FRP composites are relatively low (Domone & Illston 2010).

Table 46 Typical values for shear modulus for unidirectional FRP composites (Potyrala 2011; Clarke 1996)

Composite (fibre/resin)	Shear modulus G [GPa]
Carbon/epoxy	7.17
glass/polyester	5.44
aramid/epoxy	2.28

3.3.4 Permeability

Measures that can be used to improve the permeability properties of FRP composites include apply a thin gel-coal to the surface of the GFRP that works as a moisture barrier or by incorporating coupling agents to the fibres during manufacture. Resins with low permeability generally have a high degree of cross-linking and/or a high density (Hollaway 2010).

3.3.5 Young's Modulus

The modulus of elasticity is referred to as a materials ability to resist deformation for a given area (Clarke 1996). The factors that mainly influence the modulus of elasticity of the FRP composite are the fibre type and their orientation (Potyrala 2011; Clarke 1996). Table 47 shows the modulus of elasticity for typical FRP composites. The relation between modulus of elasticity and fibre orientation can be seen in Figure 32.

Table 47 Typical values of modulus of elasticity for unidirectional FRP composites (Potyrala 2011; Clarke 1996)

Composite (fibre/resin)	E (longitudinal) [GPa]	E (transversal) [GPa]
Carbon/epoxy	181.00	10.30
glass/polyester	54.10	14.05
aramid/epoxy	75.86	5.45

It can be seen from the table that composites consisting of carbon fibres and epoxy display the highest stiffness (Potyrala 2011). However for applications where the composite will be subjected to loads in both the longitudinal- and the transversal direction the composites consisting of glass fibres and polyester resin will perform better. Aramid fibres generate high longitudinal stiffness, but have poor stiffness in the transversal direction (Potyrala 2011). A comparison of the range of modulus of elasticity for FRP composite and conventional materials is displayed in Figure 31.

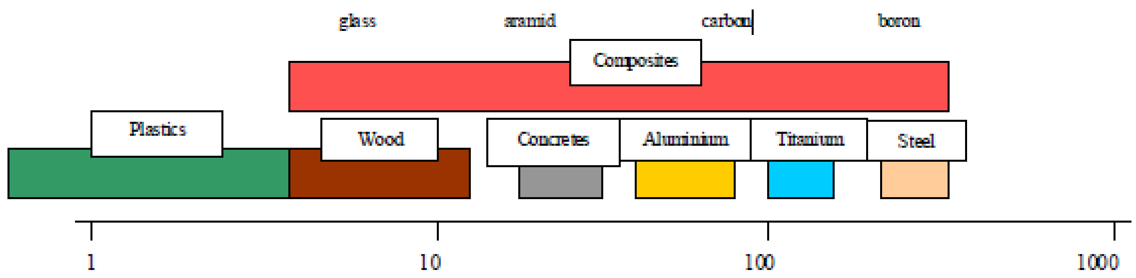


Figure 31 Comparison of the modulus of elasticity for different construction materials (Cytec n.d)

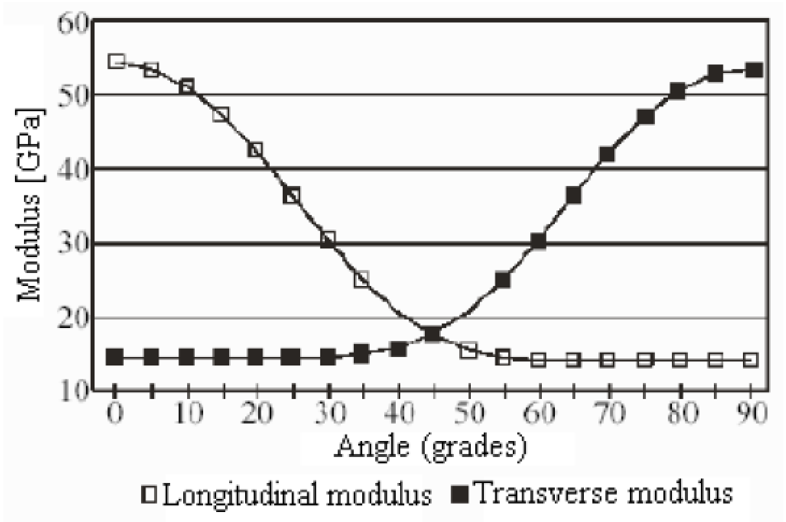


Figure 32 The relation between modulus of elasticity in both directions and the indication of angle of the fibres (Potyrala 2011)

As can be seen in Figure 32 the maximum value of the modulus of elasticity in the longitudinal direction is achieved when the fibre inclination is equal to 0°. The corresponding maximum value in the transversal direction is achieved when the inclination is 90° (Potyrala 2011).

The fibre volume fraction of the fibres also has an influence of the modulus of elasticity which can be seen in Figure 33 (Muniz & Bansal 2009). A higher fibre volume fraction generally results in a higher modulus of elasticity.

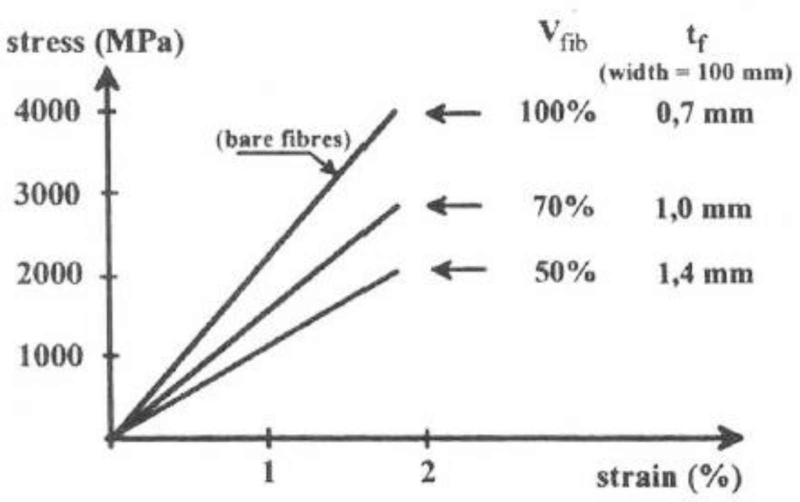


Figure 33 Stress-strain relation for different fibre volume fractions (Muniz & Bansal 2009)

The modulus of elasticity of a composite is calculated as follows in the longitudinal- and transversal direction (Potyrala 2011; Muniz & Bansal 2009):

$$E_L = E_f \times V_f + E_m \times V_m$$

$$E_T = \frac{E_f \times E_m}{E_f \times V_f + E_m \times V_m}$$

Where:

E_L is the modulus of elasticity in the longitudinal direction, E_T is the modulus of elasticity in the transverse direction, E_f is the modulus of elasticity of the fibres, E_m is the modulus of elasticity of the matrix, V_f is the volume fraction of fibres, V_m is the volume fraction of matrix

Since the modulus of elasticity also depends on the construction process it is not recommended in design to only rely on the calculations described above since they are approximations (Clarke 1996).

3.3.6 Poisson's Ratio

The Poisson's ratio is mainly influenced by the fibre orientation (Potyrala 2011; Muniz & Bansal 2009). The relation between the Poisson's ratio and the fibre orientation can be seen in Figure 34.

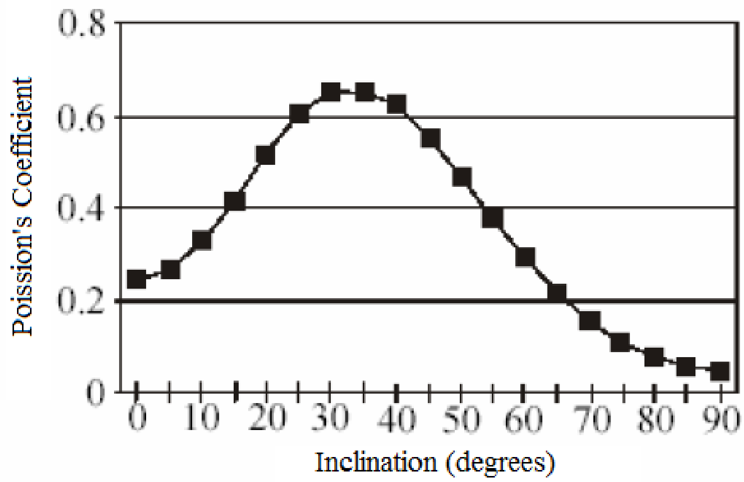


Figure 34 The relation between the Poisson's ratio and the orientation of the fibres for a glass/polyester composite (Muniz & Bansal 2009)

The values of Poisson's ratio for different FRP composites are displayed inTable 48. The values in the table are achieved with a fibre inclination of 0°. The values in Table 48 are similar to Poisson's ratios of metals which generally lie in the range of 0.3 (Potyrala 2011; Domone & Illston 2010). For fibre inclinations approaching 90° lower values of the Poisson's ratio are achieved, generally in the range of 0.002 to 0.005 (Muniz & Bansal 2009). Large values of the Poisson's ratio are achieved when the inclination of the fibres in relation to the load are in-between 30° and 40° (Muniz & Bansal 2009).

Table 48 Typical values of the Poisson's ratio for unidirectional FRP composites (Potyrala 2011; Clarke 1996)

Composite (fibre/resin)	Poisson's ratio ν [-]
Carbon/epoxy	0.3

glass/polyester	0.25
aramid/epoxy	0.34

In design the Poisson's ratio can be calculated as follows (Potyrala 2011):

$$\nu = \nu_f \times V_f + \nu_m \times V_m$$

Where:

ν is the composites Poisson's ratio, ν_f is the Poisson's ratio of the fibres, V_f is the volume fraction of fibres, ν_m is the Poisson's ratio of the matrix and V_m is the volume fraction of the matrix

3.3.7 Ductility

For FRP composites the breaking strength is generally the same as the ultimate limit strength since they are brittle and do not yield (Potyrala 2011). The stress-strain relation for the fibres, matrix and composite can be seen in Figure 35.

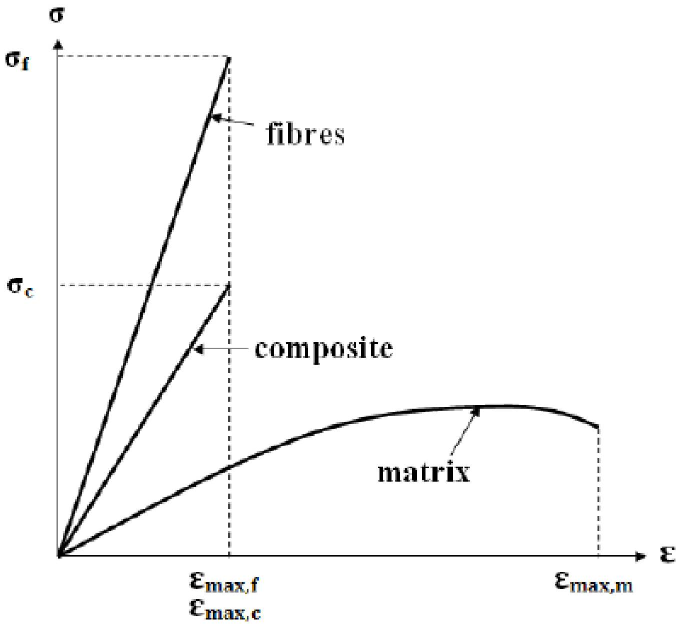


Figure 35 The stress-strain relationship for FRP composites (Potyrala 2011, p. 11)

A comparison of different FRP reinforcing fibres as well as steel is displayed in Figure 36, where HM-aramid stands for high modulus aramid fibre, SM-carbon for standard modulus carbon fibre, HT-carbon for high tenacity carbon fibre and HM-carbon for high modulus carbon fibre (Chlosta 2012).

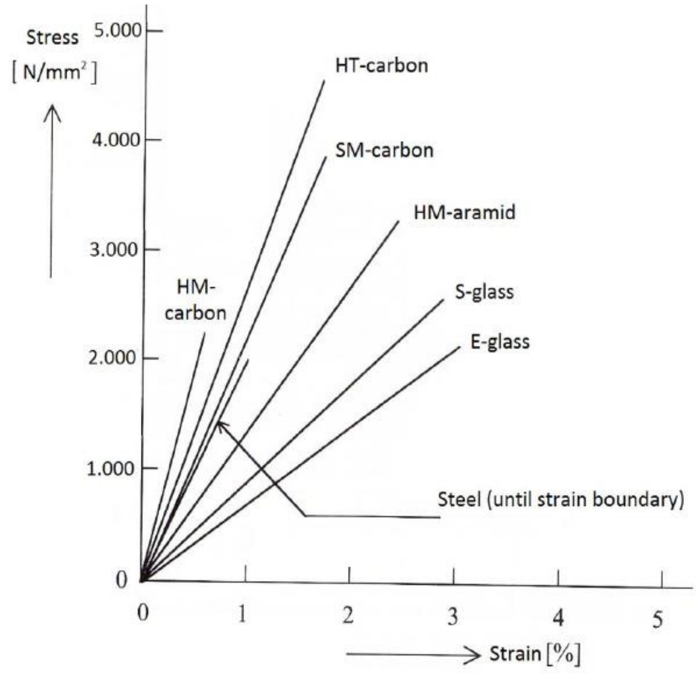


Figure 36 Stress-strain relationship for different reinforcement material, including steel (Chlosta 2012, p. 73)

FRP composites are generally regarded as linear-elastic until failure, if analysed in one direction, and has no plastic region or yield point (Clarke 1996; Potyrala 2011). However, the yield point for FRP composites is generally defined as the point where there is a deviation from the linear stress-strain relationship (Potyrala 2011). Reasons for non-linearity are for example buckling in compression of fibres, cracks in the resin, debonding of fibres and viscoelastic deformation of fibres and/or matrix (Potyrala 2011). When comparing GFRP and AFRP composites with metals they are regarded as having relatively low modulus of elasticity's and additionally low values of strain to failure (Clarke 1996). Furthermore the area under the stress-strain curve is larger for metals than for FRP composites. This knowledge is of special concern when it comes to design of joints (Clarke 1996).

Ductile materials such as steel exhibit a redistribution of stresses that is favourable since it provides energy dissipation in terms of seismic impact, increased structural safety and large inelastic or plastic deformations prior to failure which gives a warning of structural failure (Potyrala 2011). Since FRP composites acts in a brittle manner it can arise problems for the designer. One measure to avoid brittle failure in bridge application is to bond the GFRP deck to steel girders which generates progressive and slow failure with large deformations (Potyrala 2011).

3.4 Durability

Infrastructure applications are often exposed to harsh environments such as moisture and/or water, thermal cycles, etc. and for this reason it is important to know both the short- and long-term behaviour of composites with regard to environmental parameters. FRP composites are well known their good durability properties (Muniz & Bansal 2009). Long history of FRPs in marine and aerospace applications proves the durability and long-term performance of these materials. Research is however needed to establish a better understanding of the characteristics of FRP composites over a longer span of time in structural applications. The definition of the durability of a member or a structure is commonly described as "its ability to resist cracking, oxidation, chemical degradation, delamination, wear, and/or the effects of foreign object damage for a specified period of time, under the appropriate load conditions, under specified environmental conditions" (Hastak, Halpin & Hong 2004; Hollaway 2010; Bisby 2006). Figure 37 displays the factors generally regarded in terms of durability.

Degradation is of importance since the more extensive the degradation is over time of a structure, the more will the load carrying capacity decrease (Hollaway 2010). The durability over a longer time for the composite is dependent on the resin, fibre, fibre/matrix interface characteristics, the environment, loading type and the manufacturing process (Hollaway 2010; Bisby 2006). The environmental factors that influence the durability of the FRP composite are mainly moisture, temperature, chemical substances, UV and ozone (Muniz & Bansal 2009) as well as creep, fatigue and fire (Chlosta 2012). If fibres are subjected to the combined actions of stress and environment it can result in stress corrosion attack (Clarke 1996). The main failure mode, if the fibres are not subjected to an aggressive environment and stresses, is degradation of the matrix and interface due to chemical effects (Clarke 1996).

The in-service properties and the mechanical properties of the FRP composite are highly dependent of the matrix material and ultimately influence the durability of the composite (Hollaway 2010). The degradation of the polymer matrix is generally a consequence of physical and chemical changes (Muniz & Bansal 2009). The mechanical properties of the composite are primarily affected by the interface between the fibre and the matrix and the properties of the fibre (Hollaway 2010). The problems that can arise to the fibre/matrix interface are generally loss of adhesion or peeling (Muniz & Bansal 2009). Other mechanisms that influence the durability of the composite are strength of the fibres and the reduction of the modulus of elasticity (Muniz & Bansal 2009).

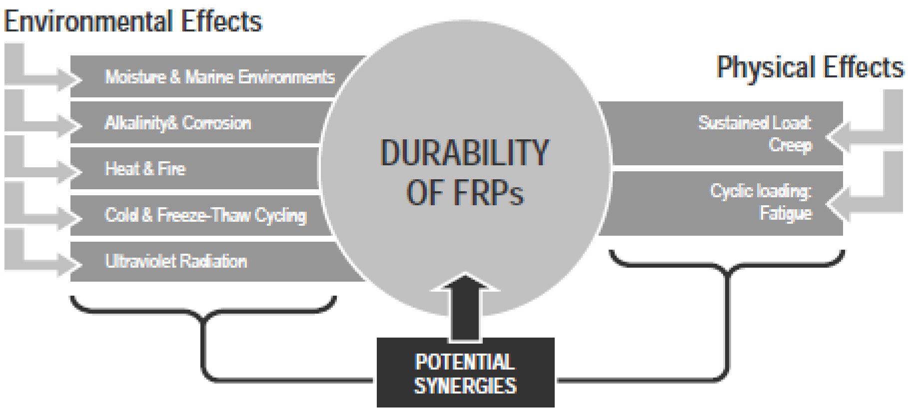


Figure 37 Potential harmful effects for FRP materials in civil engineering applications (Bisby 2006)

Test performed on FRP rods and fibres have shown that carbon rods in general have good durability (Hollaway 2010). For example by subjecting carbon rods to an alkaline environment the ultimate capacity was only decreased with 4% (Chlosta 2012). Aramid rods however have shown less durability when subjected to UV radiation, acidic environment and static fatigue (Hollaway 2010). Glass fibres have good durability in terms of freeze thaw environments but decreased durability when subjected to alkaline environments. The conclusion from the tests was that for applications where FRP is used as internal reinforcement the tensile load should be limited depending on the duration. The test methods related to durability of a specific material are the field test (also called "long-term testing in the natural environment") and accelerated test (Hollaway 2010). Vinyl ester is commonly used as reinforcement in concrete structures thus providing superior durability characteristics (Bisby 2006). Epoxy is the general choice for external strengthening application since it has very good adhesive properties to the underlying concrete. Due to that strength and stiffness is mainly provided by the fibres is it of importance that they are protected, through the polymer matrix, from environmental degradation (Bisby 2006).

A disadvantage with FRP materials is that the information in terms of durability is limited which is due to that is a relatively new material (Bisby 2006). The information is also to a large extent gathered from other application such as the aerospace industry where the durability cannot be assumed to be the same. Another disadvantage regarding FRP is that there is a lack of accepted testing methods and insufficient correlation of the existing methods. However a large extent of the anecdotal evidence indicates that FRP composites used in civil engineering applications can achieve exceptional longevity (Bisby 2006).

3.4.1 Environmental Effects

FRP composites have the benefit of being insusceptible to electrochemical corrosion (Bisby 2006). This makes them ideal in applications such as concrete reinforcement and in strengthening of structural members situated in moist or marine environments. However, if the FRP composite is used improperly in harmful environment it can have a damaging effect. Environments that are potentially harmful to the FRP composite are moisture, alkaline, freeze-thaw temperatures and UV-radiation (Bisby 2006).

3.4.1.1 Fibre and Resin Durability under Aging

The change of the matrix properties is the one of the main aspects that has to be considered with regard to durability of FRP composites (Muniz & Bansal 2009). The process of slow change in the molecular structure that the polymer undergoes is known as aging and is mainly associated with temperature and moisture. The mechanical characteristics of the FRP composite can change if subjected to temperatures that are lower than the T_g. This is because the material does not reach the instantaneous thermodynamic equilibrium but instead develops a free volume equilibrium. The change in mechanical properties is reversible by heating the polymer, but should however not be applied in civil engineering applications where it is crucial that the polymer is not subjected to temperatures above the T_g (Muniz & Bansal 2009).

Physical aging can furthermore cause the polymer to be brittle and more rigid which ultimately can influence the response of the matrix is shear (Muniz & Bansal 2009). It has been proven that thermoplastic resins are more severely affected by physical aging than thermoset resins. However since the load transfer mainly occurs through the fibre and the fibres are not significantly affected by physical aging, the influence of aging of the matrix is not crucial (Muniz & Bansal 2009).

3.4.1.2 Effects of Moisture and Marine Environments

One of the main problems regarding FRP composites is the ingress of moisture and contact with alkaline environments (Hollaway 2010). All of the organic polymer matrices absorb moisture through absorption and diffusion, to a smaller or larger extent, if exposed to humid air and water (Muniz & Bansal 2009; Chlosta 2012; Bisby 2006; Clarke 1996). The moisture absorption can influence the thermo-physical, mechanical and chemical properties of the composite in a reversible or irreversible manner (Chlosta 2012; Bisby 2006). The absorption of moisture will result in softening (plasticisation) of the matrix (Bisby 2006). This is due to the fact that the weak van der Wahl bonds are interrupted which may cause a reduction in strength, strain at failure, toughness and modulus of elasticity of the polymer matrix as well as a reduction in T_g (Bisby 2006; Clarke 1996). This reduction can ultimately result in changes in properties like shear, bond strength, stiffness and flexural strength of the matrix (Bisby 2006). A variation of moisture content from dry condition to 1.5% can result in a reduction in flexural strength of 50% and a moisture content of 4% can result in a reduction of the T_g of 75% for GFRP (Clarke 1996).

The characteristics of the absorption is influenced by the polymer matrix, composition and quality of the laminate, thickness, curing conditions, manufacturing process, ambient temperature as well as fibre/matrix interface (Chlosta 2012; Bisby 2006). For most polymers the rate of absorption of moisture generally declines with time (Bisby 2006). This is also the case for the reduction of strength and stiffness which can be seen in Figure 38 (Bisby 2006). The process of the moisture absorbed by the composite consists of an increase with time until it reaches the saturation point which can be seen in Figure 39 (Muniz & Bansal 2009). The time elapsed to reach the saturation point is influenced by the thickness of the composite and the ambient temperature. The process is reversible, however when the composite is dried out the initial characteristics are not always fully recovered. For calculations of water absorption of FRP composites Fick's rule can be applied. When calculating the moisture absorption, the considered parameters are generally: void content, resin type, fibre type, orientation of fibre, temperature, stress level, thermal gradient and microcracks (Muniz & Bansal 2009).

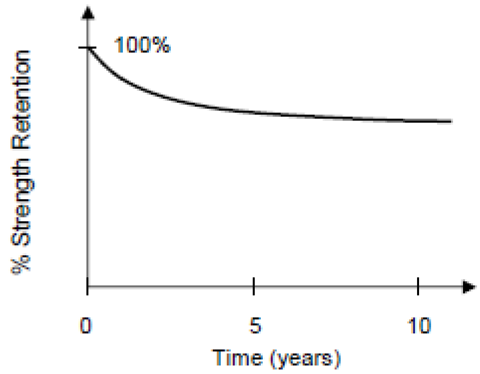


Figure 38 Reduction in strength of a FRP composite due to absorption of moisture (Bisby 2006, p. 7)

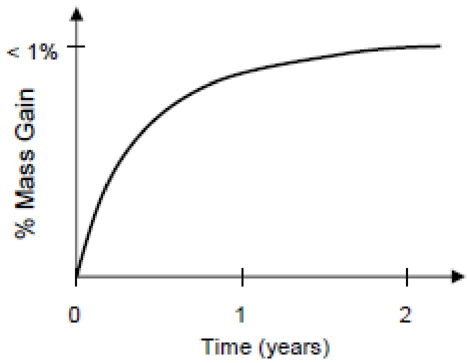


Figure 39 Typical moisture absorption of FRP composite (Bisby 2006, p. 7)

It is mainly the matrix that is influenced by the moisture uptake but also the fibre/matrix interface and in some cases also the fibres (Chlosta 2012). Vinyl ester and epoxy resin are considered to be the best respectively the second best option for civil engineering applications (Bisby 2006). Research has furthermore shown that polyester resins perform very poorly and are hence not recommended for civil engineering applications (Bisby 2006). The sensitivity of FRP composites towards moisture ingress generally depends on how sensitive the matrix is (Hollaway 2010). The sensitivity is measured by the ratio in tensile strength between the fibres and the polymer matrix. CFRP barely absorb water and has a high strength. GFRP however have a low strength, compared to CFRP, which indicates a high level of absorption (Hollaway 2010). Aramid fibres need to be protected by an appropriate resin system since they absorb water (Chlosta 2012; Bisby 2006). The absorption experienced by the aramid fibres can lead to swelling and fibrillation as well as reduced properties on terms of shear, compression and bond strength (Bisby 2006).

Synergies where the interaction between moisture, sustained loading and elevated temperatures are known to exist and result in increased moisture absorption (Bisby 2006). In addition temperature also influences the moisture absorption and drying of FRP composites (Muniz & Bansal 2009). The factors that the temperature has an impact on are the quantity of water absorbed and the absorption rate (Muniz & Bansal 2009).

It can be concluded that the larger absorption of moisture, the larger is the losses in properties (Clarke 1996). In addition by choosing an appropriate resin system which has exceptional resistance towards influences of moisture the disadvantages regarding moisture absorption can be limited (Clarke 1996). Another measure to prevent moisture absorption is to apply a gel coat to achieve resin rich areas in order to decrease the movement of moisture into the composite and consequently the fibre surface (Chlosta 2012; Bisby 2006). A requirement of the gel coat is that it is sufficiently ductile to prevent cracks to form (Chlosta 2012). Cracks in the gel coat can result in matrix cracking or fibre/matrix debonding which are irreversible and are formed when the polymer swells due to moisture absorption (Bisby 2006). The swelling and the small initial stiffening of the matrix can ultimately result in softening and plasticisation of the FRP composite (Clarke 1996). The chemical compatibility between the solvent and matrix is the main factor determining to what degree the matrix swell (Clarke 1996). The chemical compatibility and the environment in which the resin is exposed are the main factors determining the choice of the resin (Clarke 1996). There is a lack of knowledge in design however recommendations regarding conservative design values of guaranteed strength for FRP composites are 25% for GFRP, 30% for AFRP and 40% for CFRP (Chlosta 2012).

3.4.1.3 Effects of Alkalinity and Corrosion

3.4.1.3.1 Alkalinity

The action where a structure is affected by a liquid is called chemical attack (Clarke 1996). There are many sources of alkaline media that FRP composites can come in contact with such as chemicals, soil and concrete etc. (Chlosta 2012). One of the main problems is related to the interaction of concrete pore water and FRP reinforcement bars, especially glass fibres, which results in degradation (Chlosta 2012; Bisby 2006). Glass fibres are commonly used in applications such as chemical plants due to their inherent resistance to both acidic and alkaline environments (Clarke 1996). Despite the high resistance, glass fibres show some susceptibility towards alkalis and acids, since they contain silica, which can result in degradation respectively cracking of the fibres (Clarke 1996; Hollaway 2010; Chlosta 2012; Bisby 2006). Glass fibres are furthermore, generally, not susceptible to organic solvents and only moderately attacked by water (Clarke 1996). A disadvantage with glass fibres is that they generally are susceptible to chemical attack due to their high ratio of surface area to weight (Hollaway 2010). In addition since glass fibres absorb moisture it can result in microcracks and surface defects which ultimately can lead to a reduction in tensile strength of the fibres (Hollaway 2010). In order to protect the fibres an adequately ductile and thick resin layers should be applied (Chlosta 2012; Bisby 2006). It is also very important that the composite is fully cured before it is subjected to the environment since under-cure can increase the susceptibility of moisture uptake in the composite (Chlosta 2012). Other parameters affecting the FRP composites susceptibility to alkaline effects are the temperature and the applied stress (Bisby 2006). Increased stresses generally increase the risk of migration of alkalis which can lead to microcracks and elevated temperatures can cause an increase of the sorption rates (Bisby 2006).

If GFRP is incorporated in concrete, it can pose many disadvantageous situations such embrittlement of the fibre if the alkaline solution penetrates the FRP in combination with surface growth of hydration products on the fibres (Bisby 2006). This embrittlement can result in damage to the fibre/matrix interface and that the tensile properties of the FRP composite are reduced which ultimately causes a reduction of the properties in both the longitudinal and the transverse directions. The choice of glass fibre type has however an impact of the alkali resistance of the FRP composite. AR-glass is for example a better alternative than E-glass in applications subjected to alkali environments, they are however more expensive. On the other hand if the E-glass fibres are adequately protected by the resin, AR-glass fibres are not required. Another phenomenon that GFRP composites can be subjected to is creep rupture. Creep rupture can occur if the FRP composite is subjected to a combination of both alkaline solution and elevated temperatures (Bisby 2006). For more information about creep rupture see chapter: 3.4.3.1.1.1 Creep Rupture.

Some field surveys of civil engineering applications have shown that the impact of alkaline is minimal on glass fibres (Hollaway 2010). However an example of a test that consisted of subjecting E-glass fibres to a combination of different levels of sustained loading, alkalinities, temperatures and pH's demonstrated a decrease in tensile strength ranging from 0% to 75% and a decrease in stiffness ranging from 0% to 20% (Bisby 2006). There have been few tests of durability with regard to alkaline environments conducted on carbon and aramid fibres (Bisby 2006). Carbon fibres have the advantage of not being able to absorb liquids and are thus resistant to ingress of moisture such as alkaline (Hollaway 2010). Test subjected to carbon fibres have however shown a decrease in strength and stiffness ranging from 0% to 20% when subjected to alkaline environments (Bisby 2006). Aramid fibres have shown some degradation in terms of reduced tensile strength when subjected to an alkaline environment (Hollaway 2010). Tests performed on aramid fibres consisting of subjecting the fibres to the combined effects of alkaline environment, elevated temperatures and with or without tensile stress showed decrease in strength ranging from 10% to 50% and a decrease in stiffness of 0% to 20% (Bisby 2006).

Research has furthermore demonstrated that vinyl ester is the best polymer resin choice in terms of applications subjected to alkaline environments (Bisby 2006). Advantages of vinyl ester when subjected to an alkaline environment are that they have a large resistance to microcracks and in addition resistance to chemical solutions such as acids. As was the case for applications in moist environments polyester should not be used in alkaline applications such as reinforcing bars in concrete (Bisby 2006).

The commonly used resins are generally not affected by dilute mineral acids, concentrated sulphuric acids and nitric acids however can cause oxidation of the matrix (Clarke 1996). The consequences of alkalis are generally severe which result in softening of the matrix. If the application of the FRP composite takes place in an environment with concentrated alkalis orthophthalic polyesters are not suitable. Isophtalic polyester generally show better performance if exposed to organic solvents than polyesters based on Bisphenol-A, which suffers if attacked by solvents such as toluene. Lastly it can be noted that fibre reinforced polyester composites have the benefits of high strength, low weight and a high resistance to both chemical attack and weathering (Clarke 1996).

3.4.1.3.2 Corrosion

The corrosion resistance that FRP composites inhibit, which is superior to that of the conventional building materials steel and concrete, is one of the major benefits of the FRP composites (Chlosta 2012). Of this reason, FRP composites are generally deemed to be more durable than steel and concrete. Carbon fibers are generally regarded as the most durable fibers, which is mostly due to their corrosion resistance (Chlosta 2012). The characteristics of the thermoset polymers, that determine their resistance towards chemical attack, are the bond in their monomer and the chemical composition (Hollaway 2010). The degradation of the polymer matrix is generally divided into either chemical or physical corrosion. The chemical corrosion generally occurs when the polymer is situated in an environment that the bonds in the polymers are broken due to chemical reactions. The breakage of the bonds can lead to softening, embrittlement, charring, discolouring, delamination and blistering of the matrix. The process is generally non-reversible but can be avoided by correct curing of the composite. The physical corrosion involves mechanisms, except for chemical reactions, that alter the properties of the thermoset composite when exposed to the environment (Hollaway 2010).

Thermoset resins generally exhibit poor resistance towards concentrated sulphuric and nitric acids (Hollaway 2010). In addition the thermosetting resins molecular bonds degrade when exposed to aqueous solutions through hydrolysis. A measure to avoid intrusion of liquids is to choose a resin with a low permeability, since small particles and gases will not permeate through it. Resins with low permeability generally have a high degree of cross-linking and/or a high density (Hollaway 2010).

A disadvantage regarding glass fibres is that if they are subjected to strongly acidic environments, with pH well below 7, they are very susceptible to chemical corrosion (Hollaway 2010). They are furthermore also susceptible to alkaline environments where the pH is much higher than 7 where the fibres are degraded through a combination of mechanisms such as hydrolysis, leaching, pitting and hydroxylation. Glass fibres are additionally susceptible to attack of chlorine ions where the surface dissolves (Hollaway 2010).

3.4.1.3.2.1 Galvanic Corrosion

One of the main advantages of using FRP composites in civil engineering is that they are insusceptible to electrochemical corrosion (Bisby 2006). However if using CFRP in combination with steel and/or aluminium, galvanic corrosion can occur and thus contribute to an increase in corrosion. Galvanic corrosion is the process when two metals have electrical contact and the least noble metal is sacrificed and corrodes. Steel and aluminium components should not be direct contact with CFRP since this can cause galvanic corrosion as carbon is considered a non-metallic conductor. This can be prevented by plastic spacers between the metallic component and the CFRP. In strengthening application when CFRP sheets are applied to metallic structures a thin glass fibre sheet can be placed between the components (Bisby 2006).

3.4.1.4 Cold Temperatures and Freeze-Thaw Cycling

The influence of temperature can be divided in short- and long term effects (Hollaway 2010). The short term effects refer to the physical alterations which are reversible if the temperature returns to its original state (Hollaway 2010). The long term effects, however, are referred as to the irreversible alteration in the chemical composition, called aging (Clarke 1996). The properties of the polymer matrix that is influenced by temperature are: the glass transition temperature, the melting point (T_m), the coefficient of thermal expansion, the coefficient of thermal conductivity and UV radiation (Hollaway 2010).

Damage due to cold temperatures and freeze-thaw cycles is relevant in cold climates and should then be considered if FRP composites are used (Bisby 2006). The freeze-thaw cycles change the material properties mainly in terms of micro cracking of the matrix, hardening of matrix and degradation of bond between fibre and matrix (Chlosta 2012). The consequence of the freeze-thaw phenomenon is due to the combination of residual stresses from the stiffening of the matrix due to cold temperatures and the differences in CTE of the fibre and matrix

(Bisby 2006). The CTE for the polymer generally is in the range of 50×10^{-6}/°C to 110×10^{-6}/°C which is much greater than for the fibres (Chlosta 2012; Bisby 2006). Small variations within the service temperature range can cause a small amount of micro cracking in the matrix due to different CTEs of the matrix and the fibre (Bisby 2006). These micro cracks can result in further damage in combination with moisture absorption and other mechanical effects. The residual stresses incorporated in the FRP composite can furthermore lead to micro cracking of the matrix and degradation of the fibre/matrix bond. Freeze-thaw cycles can subsequently lead to that the micro cracks grow and finally form transversal cracks in the matrix (Bisby 2006). These cracks can in some cases lead to debonding of the fibre/matrix bond and ultimately result in delamination failure (Chlosta 2012; Bisby 2006). Consequences for the FRP composite of the fibre/matrix debonding include changes in dimensional stability, strength, stiffness, fatigue resistance, moisture absorption and resistance to alkaline solutions (Bisby 2006).

The part of the composite mainly affected by cold temperatures and freeze-thaw cycles is the fibre/matrix interface (Bisby 2006). A test consisting of cyclically loading a FRP composite at a temperature of -55°C demonstrated a decrease in stiffness of about 11.5% and a strength reduction ranging from 10% to 27% (Chlosta 2012). In addition matrix hardening and micro cracking as well as fibre/matrix debonding was confirmed with an acoustic emission test (Chlosta 2012). Exposing FRP composites to temperatures in the range of -10°C to -40°C often results in a reduction of the tensile strength in the direction of the fibre (Bisby 2006). The transverse tensile strength however can increase as a result hardening of the matrix (Bisby 2006).

Repeated freeze-thaw cycles commonly results in a large quantity of matrix cracks that are very severe, decreased tensile strength and increased brittleness of the matrix (Bisby 2006). The effect of repeated freeze-thaw cycles have however shown a small impact on the mechanical properties of the FRP composite and is for that reason of slight concern in terms of civil engineering applications (Bisby 2006; Clarke 1996). The combined effects of freeze-thaw cycles and alkaline environments such as marine environments and de-icing salt can however be very damaging for FRP composites since the salt crystals expand within the FRP composite (Bisby 2006).

Currently there is very little information available regarding the behaviour of FRPs in civil engineering applications exposed to cold temperatures, there are however a large amount of information from the aerospace industry (Bisby 2006).

3.4.1.5 High Temperatures and Fire

A rigid polymer subjected to a temperature above the T_g will generally turn into a viscous liquid, possessing neither strength nor stiffness (Hollaway 2010). A difference between thermoplastic and thermosetting polymers is that the former incorporates a melting point T_m which causes difficulties in predicting the T_g. Above the T_m the thermoplastic resin loses the crystalline structure and below the T_g it regains the structure again (Hollaway 2010).

FRP composites have been used for outdoor civil engineering application such as bridges for several decades (Bisby 2006). The use in building applications are however scarce which are mainly due to that FRP composites are deemed to perform poorly in terms of elevated temperatures such as fire (Bisby 2006). However it is difficult to make a generalisation of how FRP composites will respond in case of fire since there are so many different types of composites and production methods available (Bisby 2006).

3.4.1.5.1 High Temperatures

It is generally known that the temperature influences the mechanical properties of the FRP composite and the general relation is that the deterioration increases with increasing temperature (Bisby 2006). When the temperature exceeds the glass transition temperature T_g of the composite the matrix will go to a rubbery state from a glass-like state which will result in a decrease in modulus of elasticity as a consequence of the reduced bond between the polymer chains (Bisby 2006). The general range of T_g for resins can be seen in Table 49 and it can be noted that the type of resin has a large influence on the T_g (Clarke 1996). The T_g varies slightly between literature, which is due to that different testing procedures have been used to establish the glass transition temperature Hollaway 2010). The methods that are allowed are the "Dynamical Mechanical Thermal Analysis" (DMTA) (ISO/CD standard 6721-11 (2001)) and the "Differential Scanning Calorimetry" (DSC) (ISO 11357-1) (Hollaway 2010).

Table 49 Typical mechanical properties of resins (Clarke 1996)

Property	Unit	Range of values
Specific gravity	-	1.08-1.25
Tensile strength	N/mm^2	50-80
Tensile modulus	kN/mm^2	2.2-3.7
Flexural strength	N/mm^2	80-130
Flexural modulus	kN/mm^2	2.9-4.2
Hardness Barcol 939/1	-	40-45
Elongation at break	%	1.2-6.5
Water absorption by weight	%	1-2
Glass transition temperature	°C	50-160

The reduction in bond strength due to elevated temperatures will furthermore result in decreased stiffness and shear- and longitudinal strength of the matrix (Bisby 2006). Figure 40 shows the mechanical and bond properties plotted against temperature. It displays a reduction in strength with increasing temperature. In many structural applications, FRP composites have shown degradation as their T_g has been exceeded. Strength reductions up to 80% in the fibre direction have been reported for GFRP members subjected to a temperature of 300°C (Bisby 2006). Therefore, care should be taken if the FRP composite is subjected to high temperatures, such as radiation from the sun, which can result in softening and ultimately failure of the resin (Chlosta 2012). Design guidelines regarding the upper boundary temperature should be followed to avoid this type of failure. The upper boundary temperature is generally defined as the point where the flexural strength is half of the original value (Chlosta 2012). Another design requirement that has been established is that a FRP composite should not be subjected to an environment where the temperature is 20°C higher than the T_g (Hollaway 2010). Furthermore, in application where FRP reinforcing bars are incorporated in concrete there is a risk of decreased bond if the temperature exceeds the T_g (Bisby 2006).

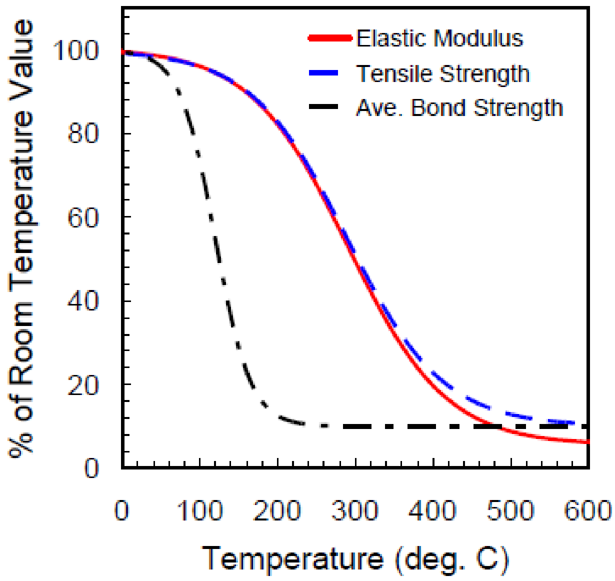


Figure 40 Typical deterioration of mechanical and bond properties of GFRP bars (Bisby 2006, p. 10)

3.4.1.5.2 Fire

3.4.1.5.2.1 Definition of Fire

There are typically three zones that can be distinguished in a fire consisting of: solid flame region, the intermittent flame region and the thermal plume region (Chlosta 2012). In the solid flame region the major part of the exothermic reactions of the flammable vapours occurs and a large amount of heat is produced. The temperatures mainly ranges from 800°C to 900°C for solid fuels and are for gases in the range of 1150°C to 1250°C. The boundary between the solid flame region and the intermittent flame region is not well-defined, however for the intermittent flame region the temperatures are lower and lie generally in the range of 300°C to 600°C. In the thermal plume region there are no visible flames and the temperatures decreases with the depth of the structure. The zone consists mainly of vapour, soot particles and gases (Chlosta 2012).

Factors influencing the initiation and growth of fire are mainly related to the type and size of fuel, the fuel load, the velocity of the wind, the oxygen content of the flame and if the structure is placed in an open or closed space (Chlosta 2012). The growth is mainly dependant on the fuel and only to a little extent of the combustible FRP material (Chlosta 2012). FRP composites are also a source of fuel since they consist of organic compound, i.e. thermosetting/thermoplastic resin and/or aramid fibres (Bisby 2006; Gibson, Mathys & Mouritz 2006; Chlosta 2012). The composite materials can increase the flame spread and cause an increase in temperature (Chlosta 2012). Performance in terms of fire is regarded as the main safety concern for FRP composites used in civil engineering applications (Gibson, Mathys & Mouritz 2006; Hollaway 2010; Chlosta 2012). Figure 41 displays a bridge fire in Germany.

Figure 41 A bridge fire in Germany (Chlosta 2012, p. 135)

In a fire five stages can generally be distinguished which can be seen in Figure 42. These stages are ignition, growth, flashover, fully developed fire and decay (Chlosta 2012; Hollaway 2010). When FRP composites are subjected to high heat fluxes they ignite with the consequence of additional release of heat which ultimately can result in additional growth of the fire (Gibson, Mathys & Mouritz 2006). The temperature continuous to grow and when the fire exceeds the level of 350°C to 500°C the parts of the composite exposed to the fire will ignite (Chlosta 2012). The next stage is the flashover where the fire is fully developed and all combustible parts of the composite ignites. The flashover generally takes place at a temperature of approximately 600°C. The highest values of the heat release rate are taken place in the stage where the fire is fully developed. The temperatures of this stage generally lies in the range of 900°C to 1000°C but can be as high as 1200°C. The final stage of a fire is decay and occurs when all combustible material has been consumed or by the means of fire suppression systems like sprinklers. At this stage the temperature drops substantially (Chlosta 2012).

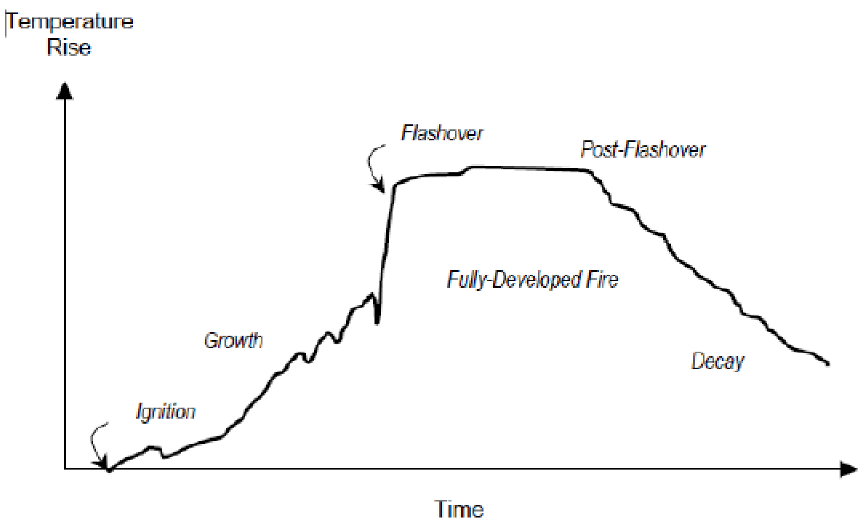


Figure 42 The typical five stages of a fire (Chlosta 2012, p. 136)

3.4.1.5.2.1.1 Fundamental Requirements

The fundamental requirements of FRP composites, which should be considered in terms of fire, are: choice of resin, application, effects of the composite in terms of fire, consequences in case of failure both in terms of stiffness and effect on parts not affected by the fire (Clarke 1996). In case of organic resins the inherent flammability should be considered. Some of the direct effects of fire include heat generation, toxic and noxious fumes, smoke emission and flammability (Clarke 1996). In case of civil engineering applications, such as bridges, they are required to be structurally safe even though subjected to fire in case of for example a car- or lorry-explosion (Chlosta 2012).

3.4.1.5.2.2 Fire Performance of FRP Composites

The fire performance of FRP composites varies considerably and ranges from non-combustible to highly flammable (Clarke 1996). FRP composite applications generally consist of fillers and glass fibres both of which are non-combustible. Resins and additives however are combustible and burn if exposed to fire, with the exception of phenolic resins (Clarke 1996). The fibres are furthermore less susceptible to high temperatures than the polymer matrix, resulting in the polymer matrix being the decisive factor for the degree of degradation of the mechanical properties (Bisby 2006; Hollaway 2010). Other influencing parameters of the fire performance of FRP composites are presence of fire retardant additives, type and quantity of filler as well as type and arrangement of the reinforcement (Clarke 1996).

It can be concluded that the main source of flammable volatiles is the resin, however, organic reinforcement such as aramid also contribute to the volatiles (Gibson, Mathys & Mouritz 2006). The resins mainly used in civil engineering applications consist of thermosetting materials (Clarke 1996). Resins consisting of polyester and vinyl ester result in poor fire performance and burn readily under fire if fire retardant additives are excluded (Clarke 1996). In Table 50, a comparison of reduction in flexural strength for different polyester resins is presented. From the table it is clear that polyester resins, derived from bisphenol, are the most durable, as mentioned before.

Table 50 Reduction in strength of different polyester resins due to influence of temperature (Clarke 1996)

Polyester resin type	**% of retention of 20°C flexural strength**		
	75°C	130°C	160°C
Isophtalic			
General purpose	-	32	-
Flame resistant	-	32	-
Heat resistant	85	45	18
Heat and flame resistant	-	44	18
Bisphenol			
Heat, flame and chemical resistant	95	57	33
Orthopthalic			

General purpose - high reactivity	73	19	12

Urethane methacrylate performs similarly to fire as polyester and vinyl ester, they have however better toxicity and smoke properties (Clarke 1996). In addition a larger amount of fillers can be incorporated in the FRP composite which ultimately leads to better fire performance. Fire retardant polyesters that reduce the flammability and smoke emissions are available however they contain chemical substances such as bromide, phosphorus, chlorine or antimony which leads to decreased mechanical properties and durability in wet environments as well as unhealthy flames. Epoxy resins have furthermore a fire performance similar to that of polyester. Phenolic resins can generally be regarded as non-combustible and consequently have the best performance under fire. Novolac is a phenolic resin that is both infusible and insoluble. Nonetheless phenolic resins show poor resistance towards thermal shock which can cause cracking (Clarke 1996).

The fire retardant additives provide advantages in terms of ignition and surface spread-of-flames. They are however considered toxic and contribute additionally to the smoke generation. In addition they will contribute to lower mechanical properties, poor weathering resistance and in some cases fading of the pigments (Clarke 1996).

The type and quantity of fillers has an impact on the fire performance related to that more inert fillers in the composite generates better performance since there is less combustible material to be burnt. Another advantage with incorporating fillers is that water is generated when some composites come in contact with fire which reduces the development of heat. In general FRP composites incorporate large amounts of fillers and incombustible fibres, such as glass, which contributes to better a fire performance (Clarke 1996).

By incorporating non-combustible fibres such as glass and carbon, the fire performance of the composite will be improved, since there is less material to be burnt (Bisby 2006; Clarke 1996). Carbon fibres start to show a decrease in strength and stiffness at temperatures above 1000°C. The corresponding values for aramid and glass fibres are 300°C respectively 600°C at which both fibre types show reductions in strength of approximately 20% to 60%. Another advantage with non-combustible fibres are that they will work as an insulating layer (self-extinguishing) in case of fire when the outmost layer of the composite has been combusted (Bisby 2006). The orientation of the fibres has furthermore an impact of the performance under fire where unidirectional and bidirectional orientations of the fibre provide better fire performance than random fibres since a higher fibre volume fraction can be achieved (Clarke 1996). It can furthermore be noted that chopped fibres generate more mechanical damage than continuous fibres and subsequently provide shorter integrity of the structure (Clarke 1996).

3.4.1.5.2.3 Performance Criteria of FRP Composites

The criteria most commonly considered in terms of fire performance are: ease of ignition, surface spread-of-flame, penetration and propagation of fire, fuel contribution and limiting oxygen index (Clarke 1996).

Factors regarding the structural performance generally considered in fire design of FRP composites can be divided in fire resistance and fire reaction (Chlosta 2012). The fire resistance includes the parameters: burn-through resistance, structural and mechanical integrity and heat insulation (Chlosta 2012). Fire reaction includes the parameters: heat release rate, surface spread of flame (flame spread rate), time-to-ignition, limiting oxygen index and gas toxicity and smoke density (Chlosta 2012; Clarke 1996; Gibson, Mathys & Mouritz 2006). The factors related to safety namely are smoke emission and toxic and noxious fume emissions which should also be considered (Clarke 1996). It can be concluded that lower values of both parameters smoke density and gas toxicity results in decreased health threats posed to humans as well as better behaviour of the materials when subjected to fire (Chlosta 2012). The properties yield of toxic gases such as carbon monoxide and density of the smoke are of importance since they are indicators of the survivability of the FRP composite (Gibson, Mathys & Mouritz 2006). The amount of smoke yielded is lowered with the formation of char. Char can be formed for FRP composites incorporating a phenolic matrix and/or aramid fibres (Gibson, Mathys & Mouritz 2006).

It can be noted that even though a composite incorporates good fire reaction properties its fire resistance properties is not necessarily good and vice versa (Chlosta 2012). Phenolic resins is an example of this where its fire reaction properties regarding the parameters heat release rate, time-to-ignition, smoke generation and spread of flame are better compared to unsaturated polyester. In terms of fire resistance properties such as keeping structural and mechanical integrity phenolic resins perform worse than unsaturated polyester (Chlosta 2012).

To guarantee the performance of FRP composites in terms of fire there are some specifications which vary between different countries (Clarke 1996). Examples of these are *BS476 Part 7 Class 1* which is related to surface spread-of-flame, *BS476 Part 6 Class 0* related to propagation of fire and *BS476 Part 3 Class AA* related to both surface spread-of-flame and fire penetration. The test method *BS476 Part 3* is mainly used for testing the flame spread of roofing materials. In general it can be concluded that phenolic resins are difficult to process but have the ability to achieve the requirements without adding fire retardant additives. Compared with urethane methacrylate, polyester and vinyl ester resins have difficulties to achieve the required levels of performance. The test method *BS 476: Part 6* is used to measure the ease of ignition and rates of temperature rise of materials specified with an index I. Test regarding surface spread-of-flame of materials are specified with the standards *BSF 476: Part 7* which requires special instruments. The spread-of-flame resistance of a material can through this test be divided in four different classes: *Class 1* (165mm), *Class 2* (less than 215mm for first 1½min and less than 455mm for 10min), *Class 3* (less than 265mm for first 1½min and less than 710mm for 10min) and *Class 4* (larger spread-of-flame than *Class 3*). The test method *ASTM E48-76* is used to measure the smoke generation and the burning rate for tunnels (Clarke 1996).

There are also performance criteria related to fire resistance of building elements such as beams, columns and ties through the standards *ASTM E119*, *ISO 834* and *BS476 Part 20*. The tests are conducted by subjecting the members to high temperatures and loading. The time is measure of which the member is able to resist the load, and deflection in case of flexural members, and used as an indication of the member's fire resistance (Clarke 1996).

3.4.1.5.2.3.1 Fire Reaction

3.4.1.5.2.3.1.1 Heat Release Rate

The heat release rate (HRR) is considered the most important factor in terms of controlling the fire hazard (Gibson, Mathys & Mouritz 2006; Chlosta 2012). This because it influences the fire spread, yield of carbon monoxide gas, mass loss rate and smoke generation (Gibson, Mathys & Mouritz 2006; Chlosta 2012). The HRR gives an indication of how much thermal energy is generated by a material subjected to a constant heat flux per square meter (Chlosta 2012). The total loss of mass is lower for composites incorporating non-combustible fibres since only the polymer matrix is degraded, as supposed to using combustible fibres that also degrade (Gibson, Mathys & Mouritz 2006). A higher HRR generally results in a higher mass loss due to larger generation of volatiles and pyrolysis. The rate of mass loss and the HRR are furthermore influenced by the decomposition reaction rate. The process when polymers and organic fibres decompose is endothermic, meaning that heat is absorbed during the reaction, which can result in a reduction of the HRR. The net HRR is the difference between the heat generated when the composite decomposes and the heat absorbed due to the exothermic reaction (Gibson, Mathys & Mouritz 2006).

The HRR is considerably lower for phenolic resins than for vinyl ester, epoxy and polyester resins (Gibson, Mathys & Mouritz 2006). The heat release rate for a composite consisting of vinyl ester resin and glass fibres can be seen in Figure 43 were also the peak heat release rate (PHRR) can be seen. The PHRR occurs when both the matrix and fibres decompose. Composites generally ignite prior to reaching the PHRR (Gibson, Mathys & Mouritz 2006). As can be seen in the right graph of Figure 43 high-performance resins generally incorporate lower HRR at higher heat fluxes (Chlosta 2012).

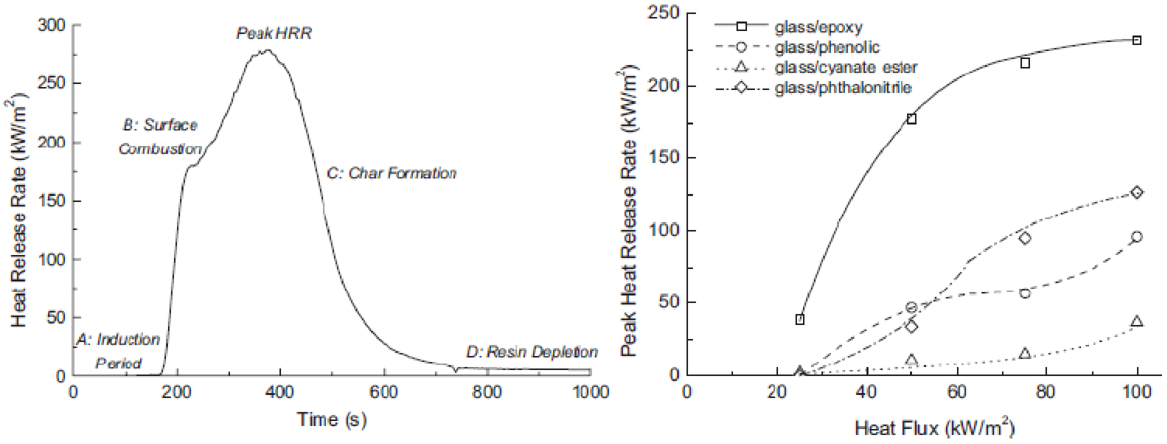


Figure 43 Left: Heat release rate for composite consisting of vinyl ester resin and glass fibres subjected to a heat flux of 50kW/m^2 Right: Comparison of HRR's for different composites (Chlosta 2012)

The HRR is influenced by the fibre volume fraction and the thickness of the laminate (Chlosta 2012). The HRR drops from 1050kW/m^2 to 300m^2 by increasing the fibre volume fraction from 0% to 60% for a glass fibre reinforced polyester resin (Chlosta 2012). The HRR generally decreased for the investigated resins if the lamina thickness is increased (Chlosta 2012). For phenolic resins however the lamina thickness shows insignificant impact on the HRR which can be seen in Figure 44 (Chlosta 2012).

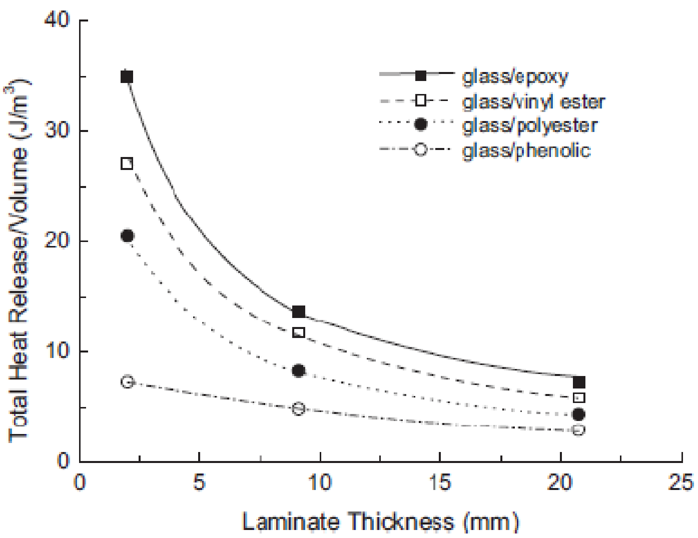


Figure 44 Lamina thickness influencing the HRR (Chlosta 2012, p. 153)

3.4.1.5.2.3.1.2 Time-to-Ignition

Time to ignition is considered the second most important property regarding the fire performance of FRP composites since most composites will ignite in a short period of time after being exposed to fire (Gibson, Mathys & Mouritz 2006; Chlosta 2012). Time-to-ignition is defined as the time it takes for the composite to develop a flaming combustion when subjected to a heat flux from a fire, thus the parameter measures the flammability resistance of materials (Gibson, Mathys & Mouritz 2006; Chlosta 2012). Generally long times-to-ignition are desirable (Chlosta 2012). In Figure 45 the time-to-ignition values for different thermoset and thermoplastic resins are displayed. Ignition takes place early in the process of combustion and is considered as an instantaneous occurrence (Gibson, Mathys & Mouritz 2006). The ignition is influenced by the decomposition rate, the heat flux, the oxygen available and the choice of matrix and reinforcement (Gibson, Mathys & Mouritz 2006; Chlosta 2012).

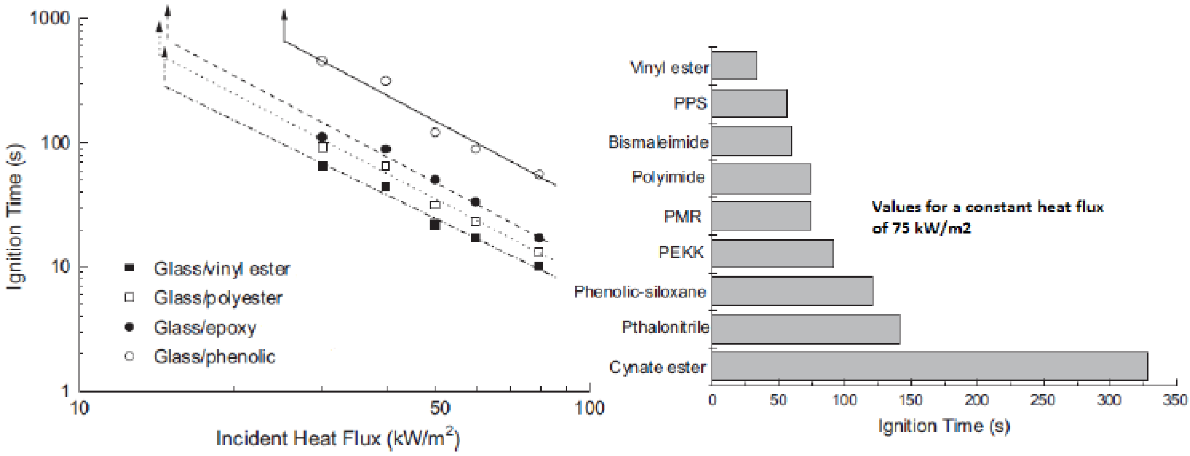


Figure 45 Left: Time-to-ignition for thermoset resins, Right: Time-to-ignition for thermoplastic resins (Chlosta 2012, p. 154)

The thickness of the laminate influences the time-to-ignition as well as the type of reinforcement chosen which can be seen in Figure 46.

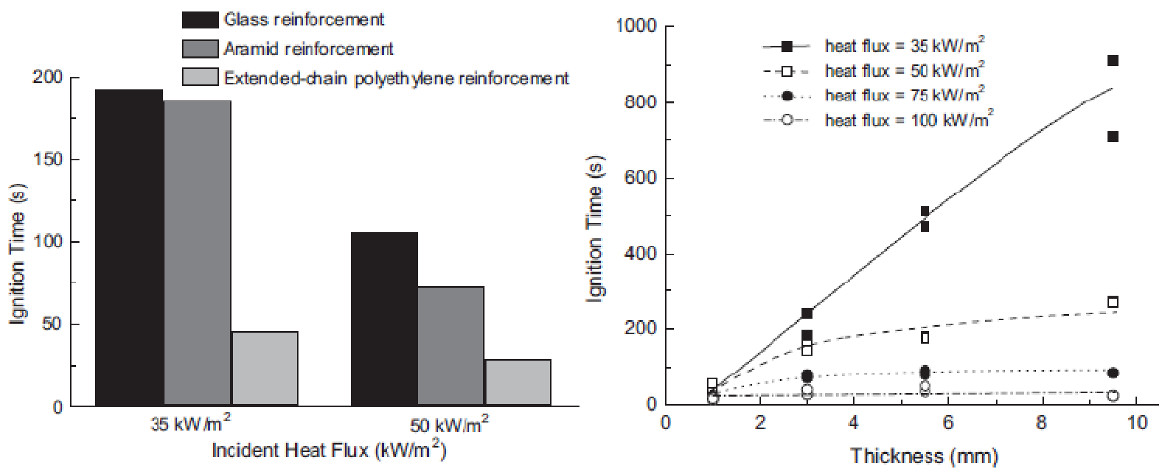


Figure 46 Left: Influence of different reinforcement types on the ignition time, Right: Time-to-ignition for different lamina thicknesses (Chlosta 2012 p. 154)

3.4.1.5.2.3.1.3 Surface Spread of Flame

The surface spread of flame describes how fast the flame front travels over the surface of the material (Chlosta 2012). In general low rates are desirable for the flame spread rate. Surface spread of flame poses a safety concerns since the majority of the available composites are highly flammable, which increases the difficulty of extinguishing the fire. Laminates consisting of glass/polyester and glass/epoxy are examples of FRP composites that are very flammable. Laminate consisting of the combination glass/phenolic however exhibits a high resistance against spread of flame and can be regarded as self-extinguishing. Subsequently composites consisting of phenolic resins can be regarded in civil engineering applications where the requirements regarding fire are high. Furthermore it can be noted that by incorporating organic fibres such as aramid the speed of flame is higher than when using non-combustible fibres such as carbon and glass. The PHRR has a large influence of the speed of the flame spread which can be seen in the right graph of Figure 47. It can generally be concluded that composites having high HRR also high flame spread indexes. The flame spread index is used to estimate the downward flame spread rate, and a higher value indicates a higher flame spread rate. The right graph of Figure 47 displays the flame spread distance over time. Since phenolic resins are regarded as self-extinguishing no spread of flame occurs (Chlosta 2012).

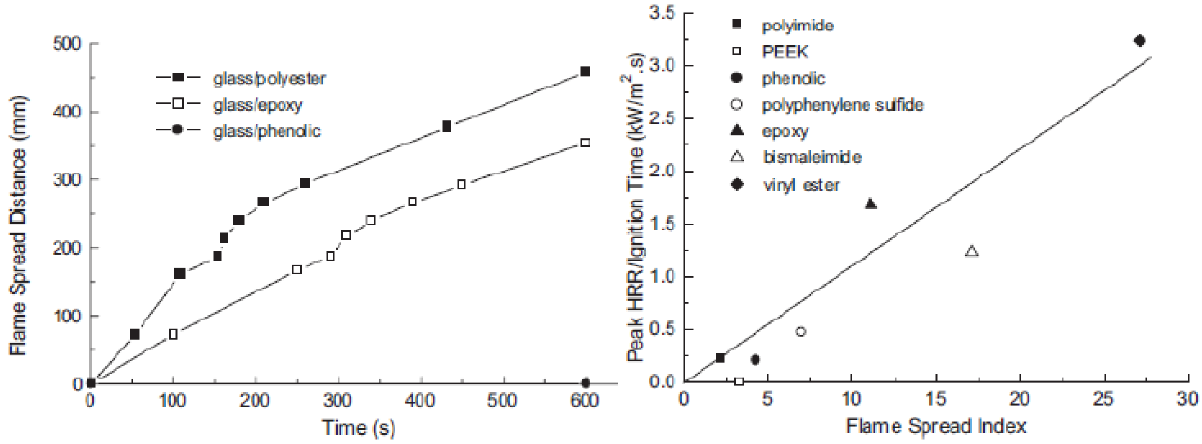


Figure 47 Left: Distance of flame spread varying with time, Right: Relation between the flame spread index and PHRR (Chlosta 2012, p. 155)

3.4.1.5.2.3.1.4 Limiting Oxygen Index

The limiting oxygen index (LOI) is referred to the minimum content of oxygen required to sustain a flaming combustion of a material (Chlosta 2012). In civil engineering applications where there are high requirements for fire performance on, materials with high LOI are preferred. This is because they act as self-extinguishing when the oxygen content is too low to sustain the fire (Chlosta 2012). Typical values of LOI for thermosetting and thermoplastic resins are displayed in the right graph of Figure 48.

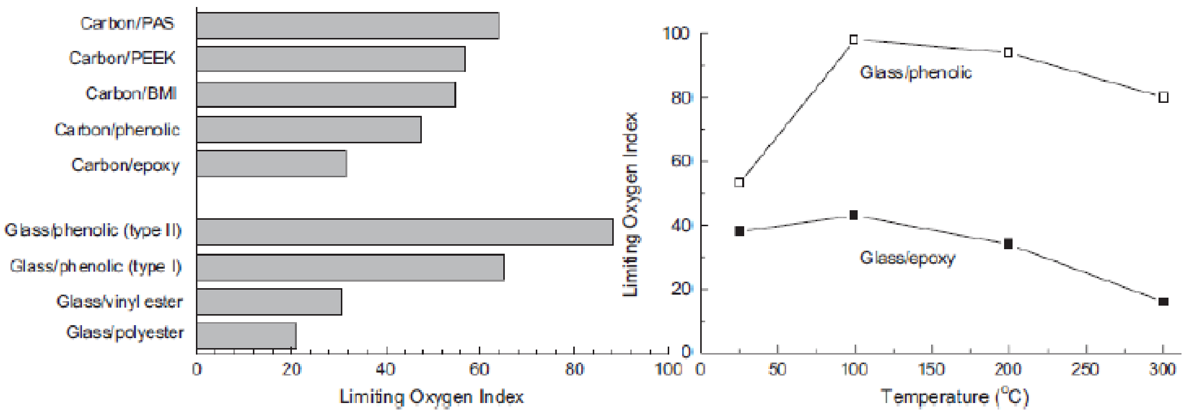
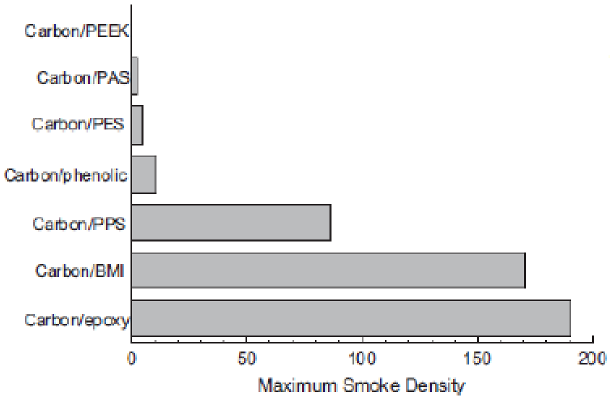


Figure 48 Left: Values of LOI for thermoplastic and thermosetting resins, Right: Variation in LOI with temperature (Chlosta 2012, p. 156)

The LOI of composites varies with its ability to form char in case of fire (Chlosta 2012). It can be noted that the LOI should be used for characterisation of how flammable a certain material is, however not for establishing the fire resistance of the same material. This is mainly because there are some uncertainties and no clear correlation to the other fire reaction properties such as the HRR (Chlosta 2012).

3.4.1.5.2.3.1.5 Smoke Density and Gas Toxicity

The most important parameters in terms of probability of human survival are the smoke density and gas toxicity (Chlosta 2012). The thick and toxic smoke produced during fire is generally more fatal to humans than the heat and flames. The density of the smoke is related to the concentration of particles, such as fibres and soot, within the fire plume (Chlosta 2012). The density of the smoke determines the visibility and will consequently affect people and fire-fighters (Chlosta 2012; Gibson, Mathys & Mouritz 2006; Hollaway 2010). This is a reason why FRP is not frequently chosen for civil engineering applications (Chlosta 2012). The soot particles are mainly in the range of 2mm and are produced when the organic compound of the composite is thermally decomposing (Gibson, Mathys & Mouritz 2006). The generation of smoke is generally measured as how much of the flammable volatiles that are converted into smoke in case of combustion of a material, and is called the Specific Extinction Area (SEA) (Chlosta 2012). Phenolic resins produce a less dense smoke compared to polyester, vinyl ester and epoxy resins which can be seen in the left graph of Figure 49. From the graph it can be concluded that some of the thermoplastic resins such as PEEK and PAS has lower density than phenolic resins and the composite carbon/epoxy have a very high smoke density. A comparison of the SEA for glass/vinyl ester and glass/phenolic is furthermore is shown in the right graph in Figure 49. It can be noted that the ability to form thick and continuous layers of char as well as a higher fibre volume fraction of the composite will result in less smoke generation (Chlosta 2012).



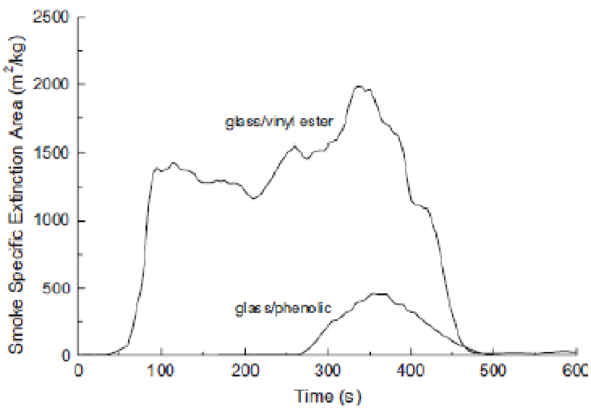


Figure 49 Left: Smoke densities for thermoplastic and thermosetting resins, Right: Comparison between vinyl ester and phenolic resins regarding SEA (Chlosta 2012, p. 157)

The toxicity of the gas is the largest health risk posed to people in case of fires and is related to the concentration of lethal gases of the smoke plume (Chlosta 2012). The most dangerous substance generated in fires is carbon monoxide (CO). If people are exposed to a concentration of 1500ppm of CO during one hour the outcome can be lethal, the corresponding concentration for carbon dioxide (CO_2) is 50000ppm. In case of civil engineering applications that are not enclosed, such as bridges, the problem regarding toxicity is less problematic. The levels of CO are furthermore largely influenced by the HRR. This indicates that by choosing polymers having low HRR the levels of the hazardous CO can be minimized (Chlosta 2012). The correlation between emissions of CO and the HRR can be seen in Figure 50.

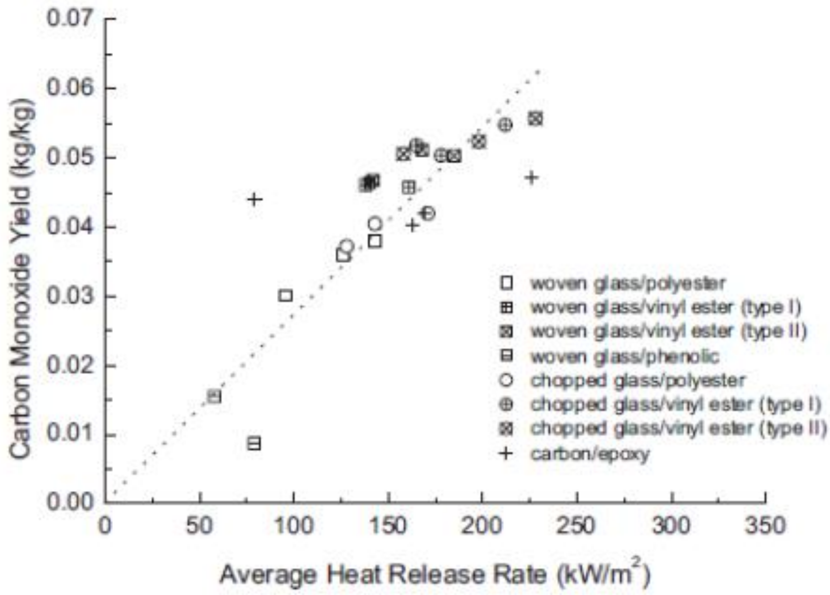


Figure 50 Relation between CO emissions and HRR for different types of FRP composites (Chlosta 2012, p. 158)

Since the emissions of CO and CO_2 generally are larger than the other substances, they are often used as an indication of the toxicity of the smoke emitted. Other substances that are of importance in terms of FRP composites are hydrochloride (HCL) and hydrogen cyanide (HCN) which are both toxic and corrosive (Chlosta 2012). In Table 51 and Table 52 are content of toxic substances for different FRP composites respectively limiting values of toxic gases displayed.

Table 51 Content of toxic gases emitted by different FRP composites (Chlosta 2012)

Composite	CO [ppm]	CO_2 [ppm]	HCN [ppm]	HCL [ppm]
Glass/ vinyl ester	230	0.3	not detected	not detected
Glass/epoxy	283	1.5	5	not detected
Glass/phenolic	300	1.0	1	1
Glass/PPS	70	0.5	2	0.5

Table 52 Limiting values of exposure to toxic gases (Chlosta 2012, p. 158)

Toxic Gas Species	Chemical	Exposure Limit [ppm]
Carbon Monoxide	CO	1.500
Carbon Dioxide	CO_2	50.000
Hydrogen Cyanide	HCN	50
Hydrogen Chloride	HCL	30

Sulfure Dioxide	SO_2	30
Nitrogen Oxides	NO_x	30

3.4.1.5.2.3.2 Fire Resistance

Fire resistance is mainly important in the later stages of the fire generally after post flashover, see Figure 42. The ability of the material to keep the structural and mechanical integrity in case of high temperatures, such as fire, is the most important parameter related to fire resistance (Chlosta 2012). Mechanical properties considered are generally stiffness, strength and resistance towards creep during and after fire. Heat insulation refers to the materials ability and rate to conduct heat in case of a fire and is related to the coefficient of thermal conductivity (Chlosta 2012). In general all polymers have low thermal conductivity coefficients which results in good insulation properties, see Table 40 for typical values of the thermal conductivity coefficient (Hollaway 2010). As can be seen in Figure 51, FRP composites provide better heat insulation than metal materials such as steel (Chlosta 2012). Furthermore higher resistance towards pyrolysis can be achieved since FRP composites can be tailored (Chlosta 2012). By altering the matrix composition, properties such as heat release rate, ignition time, toxicity of gas and generation of smoke can be improved (Chlosta 2012). In addition, by incorporating certain types of additives further alterations can be made in terms of flame spread, ignition and smoke generation (Bisby 2006). A disadvantage is, however, that the additives generally lead to lowered mechanical properties which are undesirable in structural applications (Bisby 2006).

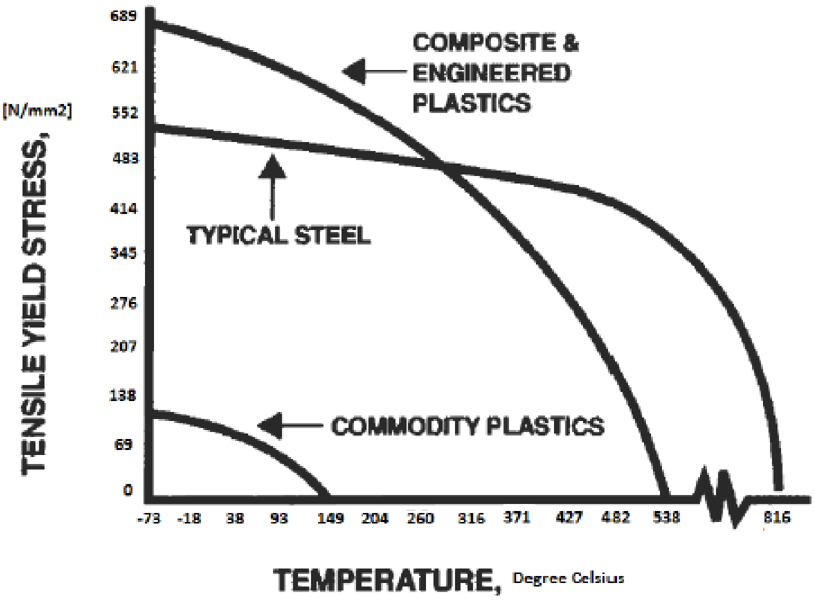


Figure 51 Comparison of tensile stress vs. temperature for steel and FRP (Chlosta 2012, p. 143)

The material's ability to resist burn-through is also an important parameter in fire resistance (Chlosta 2012). Resistance to burn-through can be defined as the ease of the flame to penetrate the material so that flames emerge on the opposite side of the material. FRP composites generally provide better burn-through resistance than metals such as aluminium alloys. A parameter commonly used to measure the resistance of the material for the fire to penetrate is the "back-face temperature build-up". The build-up process to reach the back-face temperature can be seen in the left graph of Figure 52 for the FRP composites glass/vinyl ester and glass/phenolic. The back-face temperature build-up consists of measuring the time it takes for the back-face to reach a temperature of 160°C. A comparison time to reach the back-face temperature for different FRP composites depending on lamina thickness can be seen in the right graph in Figure 52. It can be concluded that a thicker lamina results in a longer time to reach the back-face temperature (Chlosta 2012).

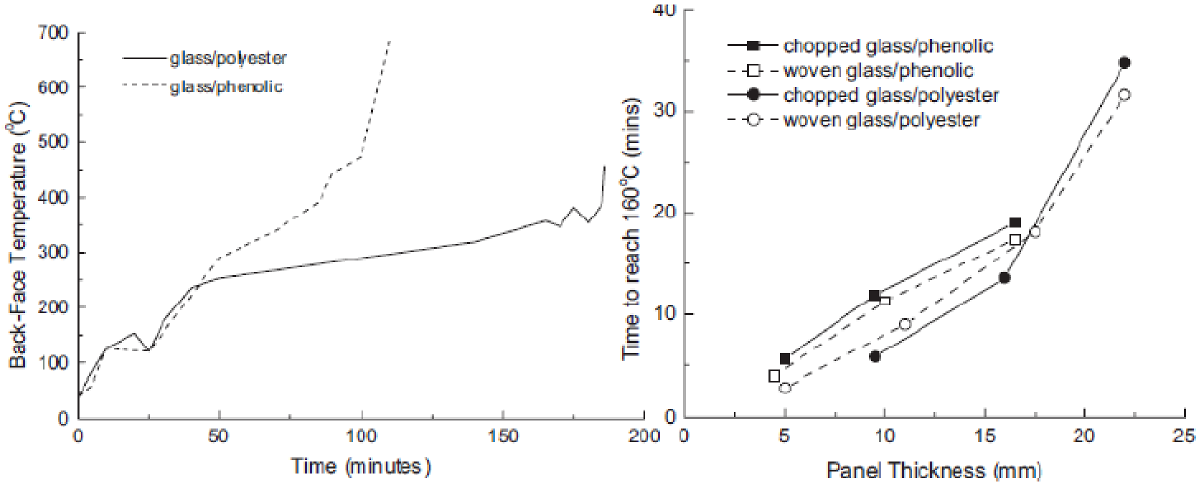


Figure 52 Left: Build-up of back-face temperature for different FRP composites, Right: Comparison between different FRP composites of the time to reach the back-face temperature (Chlosta 2012, p. 159)

3.4.1.5.2.4 Consequences of Fire on FRP composites

FRP composites subjected to temperatures in the range of 100°C and 200°C can experience creep, distortion and softening of the composite which can result in buckling and ultimately collapse of the load bearing structure (Hollaway 2010; Chlosta 2012). Therefore, fire is a safety concern since a collapse can result in injuries and death (Chlosta 2012). Furthermore when the composite is subjected to higher temperatures in the range of 250°C to 400°C the organic matrix and fibres will experience decomposition and yielding of volatiles, heat, char, soot and smoke (Hollaway 2010; Chlosta 2012; Bisby 2006; Gibson, Mathys & Mouritz 2006). In general the change in properties with regard to increasing temperature is reversible and does not have to be considered until the point where the matrix starts to decompose (Chlosta 2012). The decomposition scheme is seen in Figure 53. The content of the volatile gases are mainly vapour, flammable and non-flammable substances. Example of flammable substances are carbon monoxide and methane and for non-flammable substances water and CO_2. The heat released through the combustion can result in an increased rate of decomposition and thus enable a self-sustaining process. When the matrix is decomposing, due to high temperature, the polymer chains will experience a combination of the mechanisms chain scission, chain stripping and chain-end scission. Furthermore the polymer chains will be subjected to two additional mechanisms that are thermally induced, namely condensation and cross-linking. All these mechanisms will lead to rupture of the bonds, where the effect induced by chain scission is the most severe. The organic components of the FRP composite will produce volatiles already at 10% of bond rupture during fire with consequences of drastically lowered mechanical properties (Chlosta 2012).

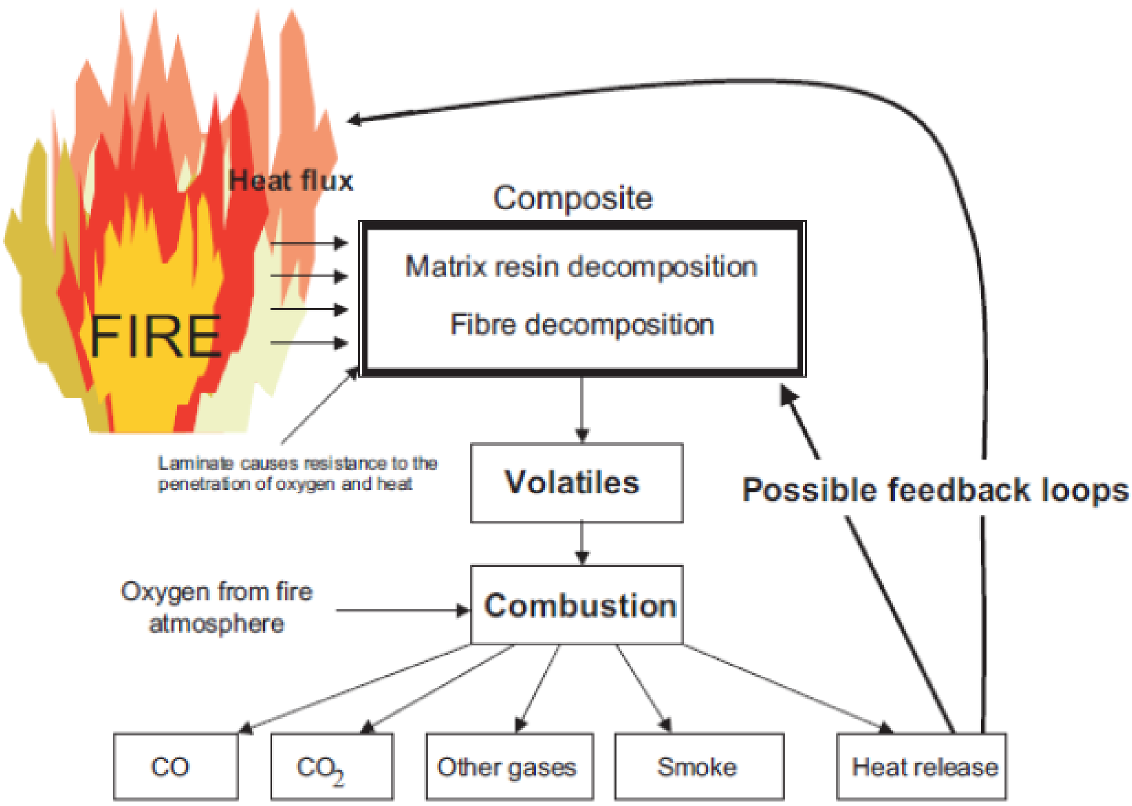


Figure 53 Decomposition of matrix when exposed to fire (Chlosta 2012, p. 146)

There are many available theoretical models that are derived from experimental testing and which describes, for example, the correlation between modulus of elasticity and temperature (Chlosta 2012). Examples of such models are the "Arrhenuis model", "Mahieux and Reifsneider model" and the "Kulkarni and Gibson model". General for these models are that the correlation between the modulus of elasticity and temperature is used to derive other reductions in mechanical properties. In Figure 54 the correlation between modulus of elasticity and temperature is displayed for different fibre directions and resin types. From Figure 54 it can be concluded that polyester experience a lower reduction in modulus of elasticity than vinyl ester (Chlosta 2012).

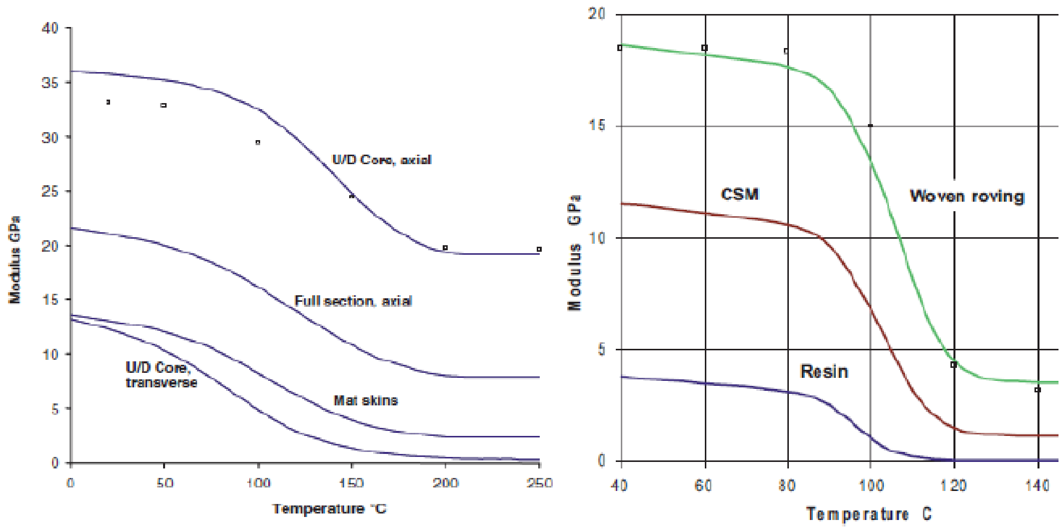


Figure 54 Left: Correlation between temperature and modulus of elasticity for UD glass/polyester pultruded profile with 60% fibre volume fraction and random swirl mat, Right: Correlation between temperature and modulus of elasticity for vinyl ester resin and different fabric types (Chlosta 2012, p. 160)

In Figure 55 the correlation between tensile and compressive strength with regard to elevated temperature is displayed. From the graphs it can be concluded that tensile strength decrease less rapidly compared to compressive strength when subjected to elevated temperatures (Chlosta 2012). The reason for the rapid decrease of compressive strength is because the shear properties of the resin are reduced which causes delamination failure (Chlosta 2012).

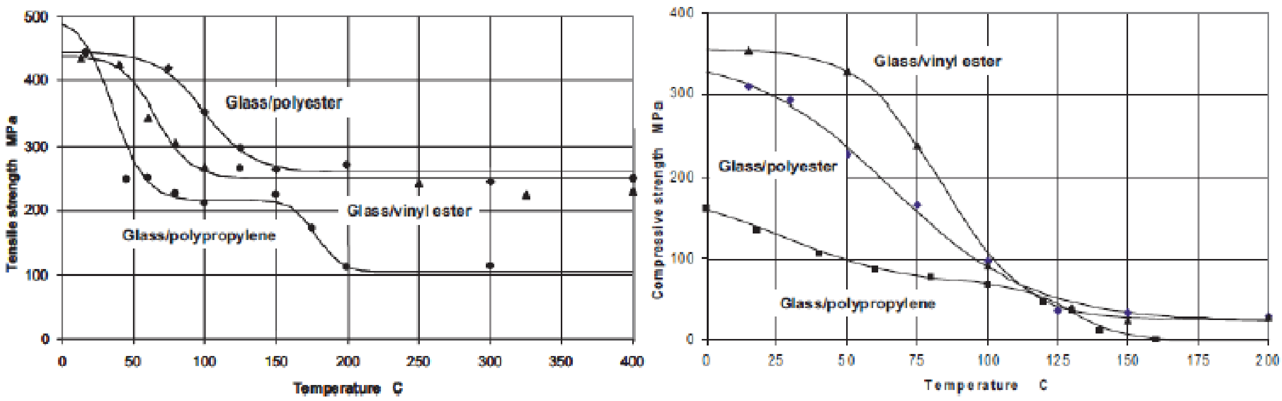


Figure 55 Left: Correlation between tensile strength and temperature for different resins, Right: Correlation between compressive strength and temperature for different resin types (Chlosta 2012, p. 161)

Tests results showing the correlation between tensile respectively compressive stresses to time-to-failure and subjected on GFRP composites consisting of the resin type's vinyl ester, polyester and propylene can be seen in Figure 56. The tests consisted of subjecting the GFRPs to a constant heat flux of 75kW/m^2 and subsequently increasing the stresses. From the graphs it can be concluded that depending on the type of resin it is possible to get a time-to-failure longer than 1000 sec for tensile stresses in the range of 50N/mm^2 to 200N/mm^2 (Chlosta 2012). In the case of compressive stresses, however, shorter time-to-failure is achieved where, depending on the GFRP, a times-to-failure of 100 sec is expected for stresses ranging from 0 N/mm^2 to 50 N/mm^2. The low compressive strength of the FRP composites when exposed to fire is mainly because the compressive properties is largely dependent on the properties of the matrix , and as had been previously mentioned, the matrix experiences severe degradation when exposed to high temperatures (Chlosta 2012).

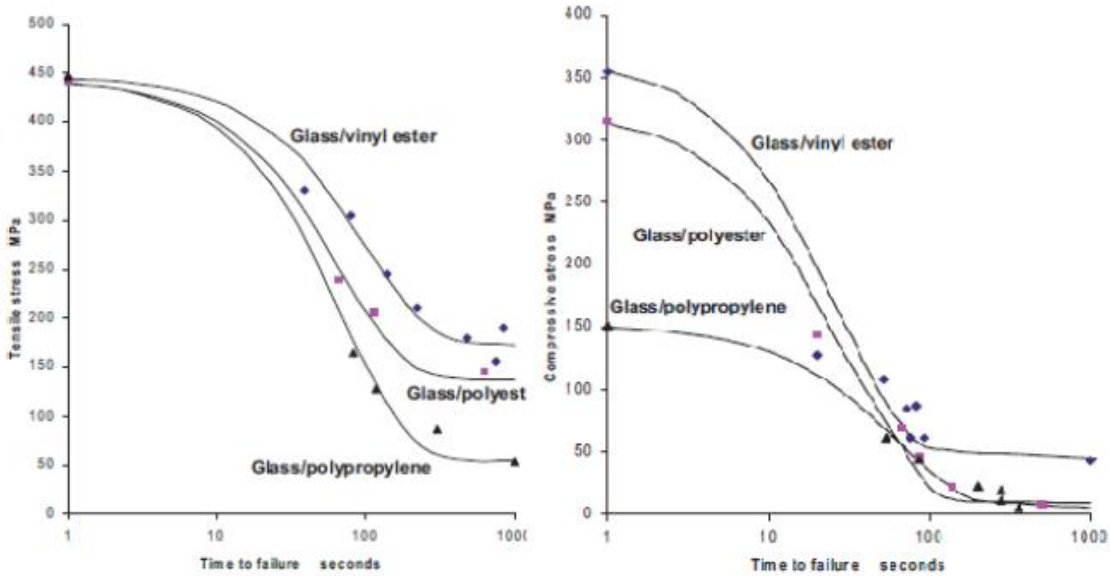


Figure 56 Left: Correlation between tensile stress and time to failure for different resins types, Right: Correlation between compressive stresses and time to failure for different resin types (Chlosta 2012, p. 162)

When normalizing the stresses, which can be seen in Figure 57, it can be concluded that phenolic resins (polypropylene) experience much shorter time-to-failure than both polyester and vinyl ester resins when subjected to tensile stresses even though they incorporates the lowest flammability (Chlosta 2012). In addition phenolic resins are more susceptible to the failure modes such as heat-induced delamination and matrix cracking in comparison with vinyl ester (Chlosta 2012).

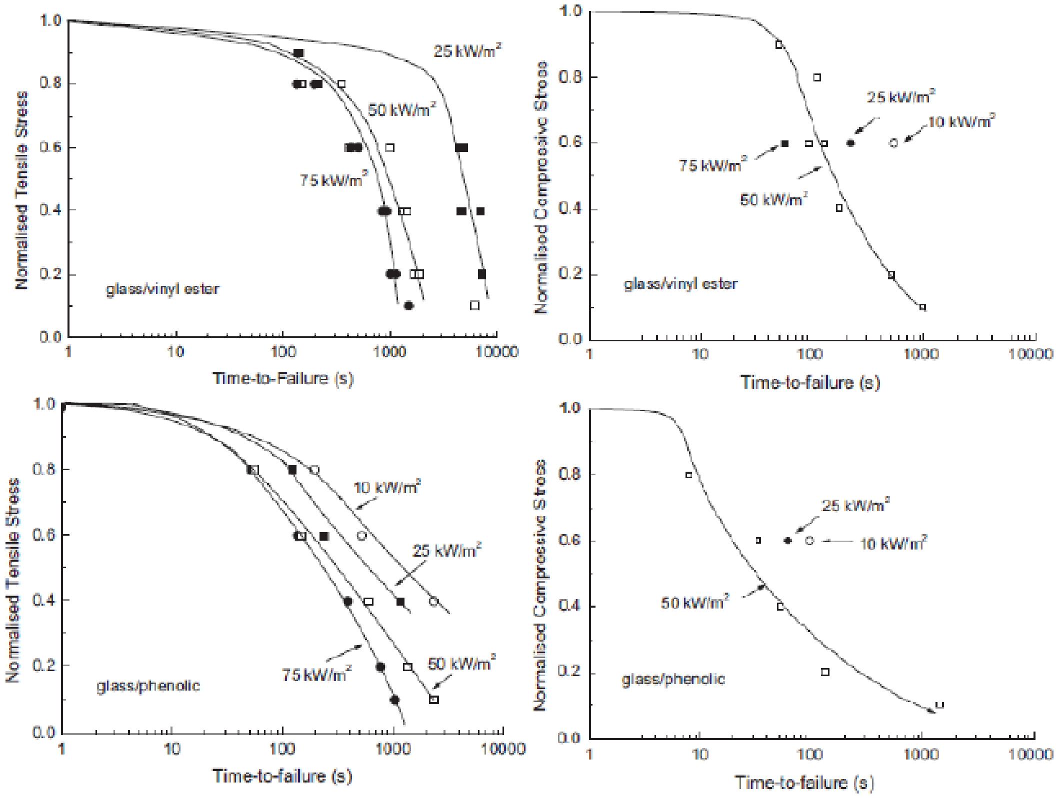


Figure 57 Left: Correlation between normalized tensile stresses and time-to-failure for different resins, Right: Correlation between normalized compressive stresses and time-to-failure for different resins (Chlosta 2012, p. 162)

3.4.1.5.2.4.1 Damages to FRP Composites due to Fire

There are mainly two mechanisms causing damage to FRP composites in case of a fire which are delamination (matrix cracking) and softening of organic fibres and matrix (Chlosta 2012). Delamination failure is the failure mechanism occurring between the plies and matrix cracking occurs within the plies. Both types of failure mechanisms generally occur at the region of the char zone, the char zone can be seen in Figure 61. The factors influencing the matrix cracking are mainly the build-up pressure from the formation of volatiles and vapour from the entrapped moisture. The adverse effects of delamination and matrix cracking on the fire performance of the composite mainly include the formation of non-bonding interfaces and increased release of volatiles due to the cracks. Furthermore delamination can cause plies to come off if the composite is located above a source of fire (Chlosta 2012).

A measure to avoid degradation of the fire performance in composites is to choose polymers that incorporate high char yield (Chlosta 2012). These type of polymers influence parameters such as heat release rate, time-to-ignition, generation of smoke and gases in an advantageous way. The higher percentage char yield a polymer generates the higher values of the limiting oxygen index are achieved which can be seen in Figure 58. Char has many benefits such as acting as a thermal insulation layer, limiting the access to oxygen and thus decreasing rate of combustion, increasing the structural integrity of the structure, shielding the decomposition zone from volatiles and therefore reducing spread of flames, delaying time-to-ignition and decreasing heat release rate. In order for the char to provide these improvements to the composite, the formation of char should form a continuous network and provide properties such as low thermal conductivity and gas transportation. Furthermore the adhesion between the char layer and the underlying composite must be strong (Chlosta 2012).

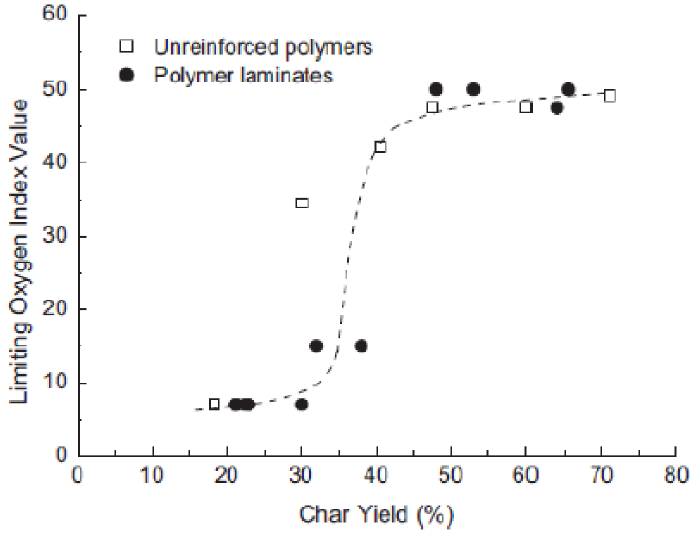


Figure 58 Relation limiting oxygen index and the char yield of polymer (Chlosta 2012 p. 147)

3.4.1.5.2.5 Post-Fire Properties of FRP Composites

The residual properties of FRP composites after the fire event are important to know after the fire is extinguished, the information on this area is however limited (Chlosta 2012).

In Figure 59 the results of a test, measuring the post-fire residual flexural strength for thermosetting and thermoplastic resins, are shown. The test consisted of subjecting the resins to a constant heat flux of 25kW/m^2 during a time period of 20 minutes (Chlosta 2012). A conclusion that can be drawn from the figure is that thermosetting resins generally suffer a larger degradation of flexural strength when subjected to fire than thermoplastic resins. It can be noted that epoxy resins lose all flexural strength in a short period of time, which is mainly due to the high flammability of the material. If epoxy resins are used in infrastructure applications this can pose a significant problem (Chlosta 2012).

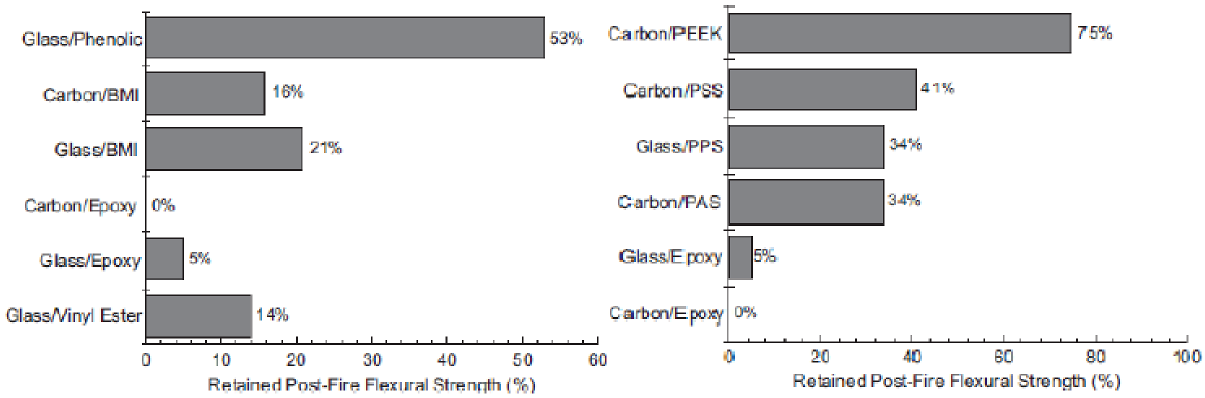


Figure 59 Residual flexural strength after fire for Left: thermoset resins and Right: Thermoplastic resins (Chlosta 2012, p. 163)

The correlation between the normalized post-fire flexural strength is plotted against heating time and heat flux in Figure 60. An important conclusion that can be drawn from the graphs is that even though phenolic resins have the best fire reaction properties, their residual post-fire flexural strength is similar to that of the vinyl ester resin in terms of both heating time and heat flux. Hence it can be concluded that although phenolic resins do not ignite, they still tend to lose a significant amount of strength when exposed to fire (Chlosta 2012).

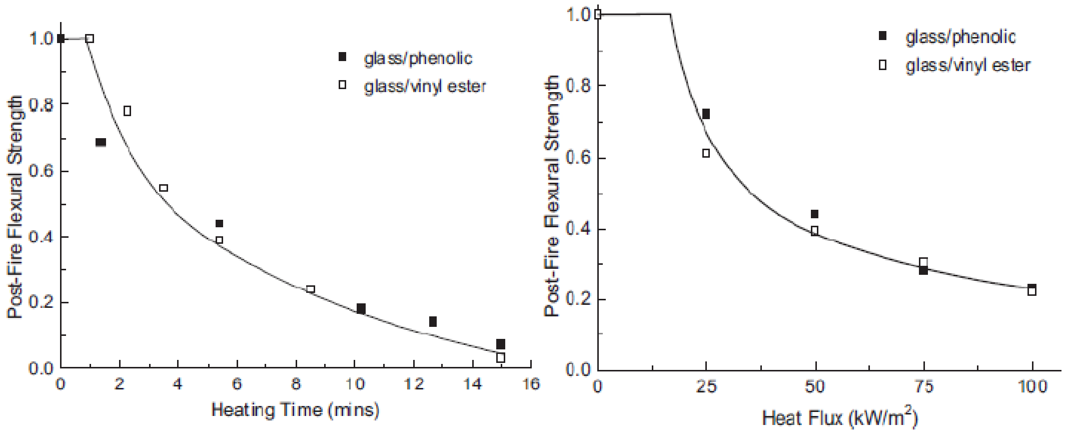


Figure 60 Left: Correlation between normalized post-fire flexural strength and heating time for phenolic and vinyl ester resin, Right: Correlation between normalized post-fire flexural strength and heat flux for phenolic and vinyl ester resin (Chlosta 2012, p.163)

3.4.1.5.2.5.1 *Determination of Post-Fire Mechanical Properties of FRP Composites*

There are currently no available standard procedures to determine the post-fire mechanical properties of FRP composites (Chlosta 2012). However, it has been established that the depth of the char layers is the main influencing factor of the mechanical properties. The "Two-layer model" conducted by Mouritz and Mathys is a method used to predict the post-fire mechanical properties, such as compression, tension and flexural strength of laminates subjected to one-side heating. The assumption made in the model, is that the zone of the composite that has been completely decomposed and subsequently tuned into char during fire has near-to-zero strength and stiffness, and thus cannot contribute significantly to the strength of the material. A generalisation made in the model is that the composite consists of two regions namely the char zone and the unaffected virgin region which can be seen in Figure 61. The thickness of the interface between the two regions is assumed to be insignificant and is thus ignored (Chlosta 2012).

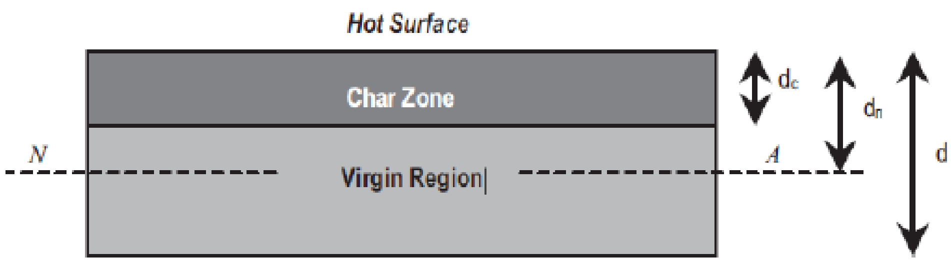


Figure 61 The two-layer model (Chlosta 2012, p. 164)

The residual elastic modulus post-fire can be calculated as follow for a unidirectional laminate (Chlosta 2012):

$$E_t = \left(\frac{d - d_c}{d}\right) E_{t(0)} + \left(\frac{d_c}{d}\right) E_{t(char)}$$

$$E_c = \left(\frac{d - d_c}{d}\right) E_{c(0)} + \left(\frac{d_c}{d}\right) E_{c(char)}$$

$$E_f = \frac{4E_{f(0)}}{d^3}\left[(d-d_n)^3 + (d_n - d_c)^3 + \frac{E_{f(char)}}{E_{f(0)}}(d_n^3 - (d_n - d_v)^3)\right]$$

$$d_n = \frac{d_c^2\left(E_{f(0)} - E_{f(char)}\right) - E_{f(0)}d^2}{2d_c\left(E_{f(0)} - E_{f(char)}\right) - 2E_{f(0)}d^2}$$

The $E_{t(0)}$, $E_{c(0)}$ and $E_{f(0)}$correspond to the original values of the tensile compressive and flexural modulus of elasticity's of the virgin region. The modulus of elasticity's of the char region is referred to as $E_{t(char)}$, $E_{c(char)}$ and $E_{f(char)}$ which for polyester resins generally lie in the range of 0GPa to 0.01GPa and for phenolic resins in the range of 0.27GPa. Thus the modulus of elasticity of the charred region is generally assumed to be zero (Chlosta 2012).

The equations for calculating the residual post-fire strength are as follows (Chlosta 2012):

$$\sigma_t = \left(\frac{d - d_c}{d}\right)\sigma_{t(0)} + \left(\frac{d_c}{d}\right)\sigma_{t(char)}$$

$$\sigma_c = \left(\frac{d - d_c}{d}\right)\sigma_{c(0)} + \left(\frac{d_c}{d}\right)\sigma_{c(char)}$$

$$P_f = \frac{8\sigma_{f(0)}b}{3L}\left[(d-d_n)^2 + \frac{(d_n - d_c)^3}{(d-d_n)} + \frac{E_{f(char)}}{E_{f(0)}}\frac{(d_n^3 - (d_n - d_v)^3)}{(d-d_n)}\right]$$

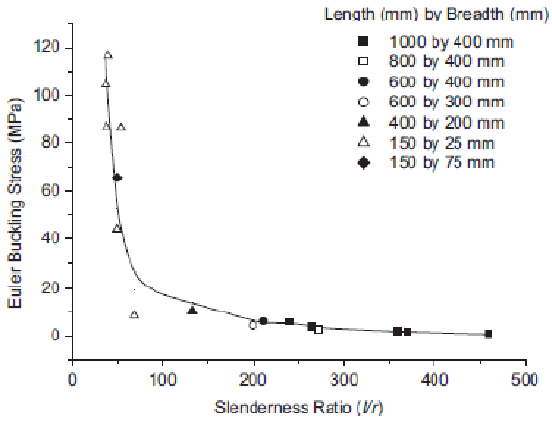
Here σ_t is referred to as the tensile strength, σ_c as the compressive strength and P_f as the flexural failure load (Chlosta 2012).

If assuming that the material is isotropic and behaves as an ideal column then the Euler buckling load P_c can be calculated. The Euler buckling load and the slenderness ratio can be calculated according to (Chlosta 2012):

$$P_c = \frac{C\pi^2 Eb(d - d_c)^3}{12L^2}$$

$$\left({}^1\!/_r\right) = \frac{1\sqrt{12}}{(d - d_c)}$$

The results from the equations have shown good conformance to experimental test results. The left graph in Figure 62 shows the correlation between the Euler buckling strength and slenderness ratio displayed for different laminates (Chlosta 2012). The right graph shows the reduction in post-fire strength with time.



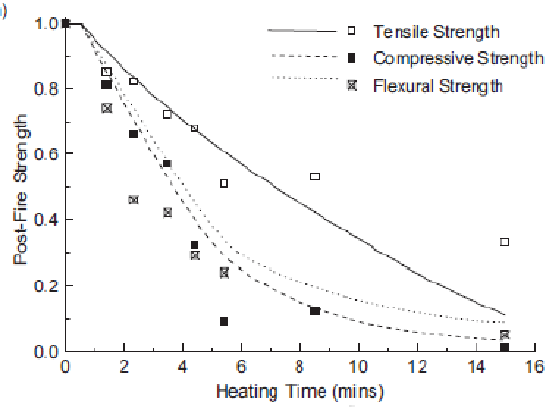


Figure 62 Left: Correlation between Euler buckling strength and slenderness ratio for different laminates, Right: Correlation between normalized post-fire strengths and heating time for glass/polyester composite subjected to a heat flux of 50kW/m^2 (Chlosta 2012, p. 165)

3.4.1.5.2.5.2 Improvements of Fire Properties and Fire Safety of FRP Composites

The objectives of fire safety design are mainly to protect people, the environment as well as the structure from the effects of fire. The environment should mainly be protected from pollutions such as spill of fuels and smoke emissions (Chlosta 2012).

At the present, there is little information and few codes and regulations regarding fire safety of bridges (Chlosta 2012). The design procedure generally consists of performance based design where a requirement is set, for example how long time a structure should withstand a fire without reduction in structural integrity. The safety period is generally determined and can be specified to for example 30min. The safety period depends generally on the cross section of the structure and wheatear it is open or closed. A closed cross section generally leads to worse heat dissipation and generally results in shorter safety periods of the structure. It is important to identify which hazards that can pose a threat to the structure and for bridges they could be spill and ignition of fuels, fire and/or explosion, exposure of fire to unprotected elements, initial damages and other severe damages to the bridge (Chlosta 2012).

As was mentioned earlier, the compressive strength is the most sensitive mechanical property with regard to heat (Chlosta 2012).Thermoset resins reach failure generally before 100 seconds have elapsed when exposed to a heat flux of 75kW/m^2. Since FRP composites generally show substantial degradation in mechanical properties it is of importance to protect the FRP elements from the influences of fire. In Figure 63 is a comparison between the post-fire flexural strength when applying different measures to the FRP composite consisting of glass fibres and vinyl ester resin. As can be distinguished in the graph the measures by adding a phenolic skin or an ablative mat increased the post-fire flexural strength with approximately 800% (Chlosta 2012).

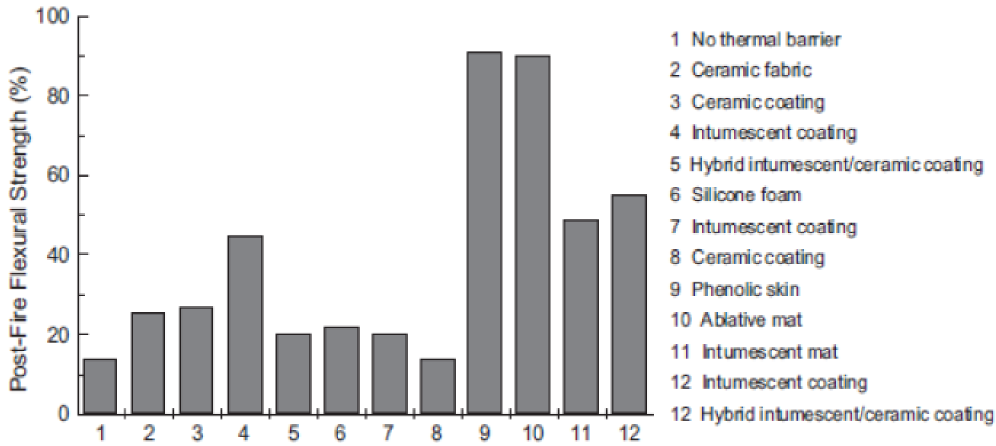


Figure 63 Comparison of post-fire flexural strength for different protective measures of a glass/vinyl ester composite exposed to a heat flux of 25kW/m^2 (Chlosta 2012, p. 166)

In fire design of FRP composite, measures to reduce the fire hazards of polymers can be divided in active and passive methods (Clarke 1996). The active methods include alarm systems and fire detection, fire suppress systems, constrains regarding use of materials that are combustible and flammable as well as conducting a fire escape plan (Clarke 1996). Sprinkler and foam system are additionally counted as means of active systems (Hollaway 2010). The passive method, which is the most common method, can be divided in the subgroups composite type and fire barrier type (Clarke 1996). Passive methods of protection, such as additives and coatings, are generally incorporated to a larger extent than active methods (Clarke 1996).

The composite type includes incorporation of additives or constituents that are non-combustible or low-hazardous into the gel coat (Clarke 1996; Hollaway 2010). There are many types of fire retardant additives available consisting of a range of different materials such as nanoclays, carbon tubes or the more traditional substances such as halogens and phosphor (Zoghi 2013). The disadvantages with additives are, as was mentioned previously, that they change the mechanical properties of the polymer and composite as well as decreasing the resistance towards weathering (Zoghi 2013; Bisby 2006). Hence, if incorporating flame retardant additives the structural integrity of the structure needs to be ensured (Clarke 1996). Adding flame retardant additives is the most common measure to increase the fire resistance of the polymer (Chlosta 2012). This has made the flame retardant additives the largest additive group which approximately comprise 27% of the market of plastic additives. In comparison, heat stabilisers, antioxidants, lubricants and UV stabilizers accounts for 15.6%, 7.6%, 6% and 5% respectively. The benefit of flame retardant additives is that they, for example, reduce the temperature by both acting as a heat sink and through endothermic decomposition of fillers, reduced HRR and a reduced amount of combustible materials. To achieve an FRP composite with improved fire properties, without sacrificing the mechanical properties and increasing the generation of smoke and toxicity of the gas, different types of flame retardant additives are usually combined (Chlosta 2012).

The fire barrier type consists of applying a surface coating or an intumescent surface coating that prolongs the time to reach the ignition temperature (Clarke 1996; Hollaway 2010). The general benefits of the surface coatings are retardation of flame, heat resistance and insulation (Clarke 1996). This is because the surface coating that consists of an organic material will char and produce a gas that foams the char which protects the composite (Hollaway 2010). An example of a coating is the nanofiber sheets which incorporates a bilayer structure where the outmost layer is thermally conductive and the underlying layer is thermally insulating which will turn into char during the propagation of heat (Zoghi 2013).

Another measure to protect bridges is by controlling the height both above and below the bridge. By limiting the height of the bridge and thus avoiding tanker to drive below the bridge and additionally increasing the over-passing height of the bridge will result in reducing the risks of under passing sources of fire (Chlosta 2012).

3.4.1.5.2.6 Design Considerations

Regarding the fundamental requirements there are two main objectives related to fire design (Clarke 1996). The first is to ensure safety and means of escape for the people located in close perimeter of the affected structure as well as people involved in the rescue service. The second objective is to ensure the integrity of the structure by means of detection measures, control and containment of the fire. It is generally very difficult to predict the behaviour of a structure when exposed to fire. Some of the influencing factors are the devised fire protection, the influences of mechanical properties due to high temperatures, the form, attachments and joints of the structure, the source of fire and the environment in which the structure is located (Clarke 1996).

The behaviour of joints that transfer forces between structural members is critical in design (Clarke 1996). In general an assessment of the joint has to be conducted, especially in case of metal connectors, after exposure to fire. In systems that are structurally indeterminate there can be redistribution of forces due to the impact of fire since the stiffness's of different parts can change as a result of the fire damage. Therefore, it is important to account the joints in consideration in terms of complete or partial yielding since the yielding has an influence on the structural action. Another factor that has to be considered in the design is the effects of fire on the thermal expansion on both affected and unaffected areas by the fire. In design, the effects of fire shall be considered for the properties: durability, mechanical properties and appearance of the FRP composite. If comparing the fire performance of FRP composites with timber, the main difference is that since FRP composites generally have thinner sections than timber, the specific area is generally larger. Since both materials have low thermal conductivity and char in case of fire, the larger specific area would result in less residual strength of the FRP composite compared to timber (Clarke 1996). The timber section is, however, more difficult to repair and get a finish surface exhibiting a high quality compared to corresponding FRP section (Clarke 1996; Cytec n.d). It is additionally very important to consider the CTE in the case where two different materials should be joined together (Hollaway 2010).

ISO standards associated to fire design of FRP composites can be seen in Table 53.

Table 53 ISO standards associated with fire design of plastics (Clarke 1996)

ISO standard	Plastics
ISO 181:1981	Determination of flammability characteristics of rigid plastics in the form of small specimens in contact with an incandescent rod
ISO 871:1980	Determination of temperature of evolution of flammable gases (decomposition temperature) from a small sample of pulverized material
ISO 1201:1982	Determination of flammability characteristics of plastics in the form of small specimens in contact with a small flame
ISO 4589:1984	Determination of flammability by oxygen index

3.4.1.5.2.7 Conclusion Fire

It can be concluded that FRP composites are suitable for many civil engineering applications however not in applications where there is high requirements on the fire performance of the structure (Bisby 2006; Hollaway 2010). In addition, prolonged exposure to high temperatures should be avoided due to synergy effects such as moisture and alkalinity (Bisby 2006). Further research is needed regarding the residual post-fire strength and allowed exposure temperatures (Bisby 2006).

3.4.1.6 Ultraviolet Radiation

All matrixes are susceptible to prolonged UV radiation with the consequence of discolour and hardening of the matrix to a varying degree (Muniz & Bansal 2009). This occurs if the UV radiation is strong and thus causes cleavage of the covalent bond in the polymer (Hollaway 2010). A measure to prevent this type of degradation of the matrix is to apply a UV-resistant coating, for example a gel coat (Muniz & Bansal 2009; Chlosta 2012) and incorporate UV stabilisers (Hollaway 2010). The coating works as a sacrificial layer and needs to be maintained constantly (Chlosta 2012). Other protective measures include UV resistant paint and UV resistance resins with incorporated nanoclays (Bisby 2006).

Since only the surface is influenced by the UV-radiation, generally the top few micrometres of the surface of the composite, the structural properties of thick composites will be less altered than for thin composites (Muniz & Bansal 2009; Chlosta 2012; Bisby 2006). The parts of the composite degraded by the UV radiations can act as stress risers and failure can occur at stress levels well below the strength of the virgin material (Chlosta 2012; Bisby 2006). The surface flaws can also result in an increase in effects of other mechanisms such as moisture absorption (Bisby 2006). It has recently been shown that the largest extent of the damage has been due to combination of UV radiation and moisture ingress (Chlosta 2012; Bisby 2006). Tests subjected to FRP composites with and without applied tensile stress with the combined effects of UV radiation and moisture absorption have shown decreased tensile strengths of 0% to 20% for CFRP, 0% to 30% for GFRP and 0% to 40% for AFRP (Bisby 2006). Hence new protective solutions have to be developed to account for the damages caused by the combined actions of moisture and UV radiation (Chlosta 2012). The combined effects of UV radiation and the factors such as thermal cycling, abrasion from moisture and elevated temperature have also shown an increase in deterioration of the FRP composites (Bisby 2006). Hence, it is generally difficult to separate effects solely from UV radiation (Bisby 2006).

UV radiation can, in addition, cause micro cracking of the matrix due to photo-oxidative reactions (Chlosta 2012; Muniz & Bansal 2009). The photo degradation causes breakage of the polymer chains as the bond dissociation energies are of the same wavelength as the UV light i.e. in the order of 290nm to 440nm (Chlosta 2012; Bisby 2006). Consequences of the photo-oxidative degradation are embrittlement of matrix, discolouration, oxidation of the surface and micro cracking of the matrix which can ultimately cause a reduction of the mechanical properties of the FRP composite (Bisby 2006). It can be concluded that in applications with finish surface requirements, extra care has to be taken for effects of sun rays (Muniz & Bansal 2009).

Regarding fibres, carbon and glass can be regarded as unaffected by exposure to UV radiation (Bisby 2006). Aramid fibres however are very sensitive towards degradation through UV radiation (Muniz & Bansal 2009; Bisby 2006). Results of an experimental work on exposing aramid fabric to UV radiation for five weeks showed a decrease in strength of 50% (Muniz & Bansal 2009).

3.4.2 Quantification of Environmental Effects

There are two approached available to quantify the effects of environmental factors (Chlosta 2012). The first approach was developed for the "Eurocomp Design code" and can be applied on GFRP. The factors regarded when determining the environmental reduction are the HDT of the polymer matrix and the operating temperature of the composite. In addition the approach distinguishes between short- and long-term loading (Chlosta 2012). The Eurocomp approach can be seen in Table 54.

Table 54 Environmental reduction factors for GFRP according to Eurocomp approach (Chlosta 2012)

Operating temperature [°C]	Heat distortion temperature (HDT) [°C]	Environmental reduction, short-term	Environmental reduction, long-term
25-50	55-80	0.83	0.33
	80-90	0.90	0.36
	> 90	1.00	0.40
0-25	55-80	0.90	0.37

	80-90	1.00	0.39
	> 90	1.00	0.40

Table 54 indicates that a lower operation temperature and a higher HDT cause a lower reduction due to environmental factors. The result can seem conservative if comparing them to the values for the second approach seen in Table 55.

The second approach was developed by the Swiss Federal Laboratories for Material Science and Technology (EMPA) and accounts for the environmental reduction factors for different epoxy based composites with carbon, glass and aramid reinforcements (Chlosta 2012). Furthermore, the second approach distinguishes between three exposure conditions which can be seen in Table 55.

Table 55 Environmental reduction factors for different FRP composites according to EMPA (Chlosta 2012)

Exposure condition	Fibre/Resin type	Environmental reduction
Interior exposure (in buildings etc.)	Carbon/Epoxy	0.95
	Glass/Epoxy	0.75
	Aramid/Epoxy	0.85
Exterior exposure (bridges, piers, parking garage etc.)	Carbon/Epoxy	0.85
	Glass/Epoxy	0.65
	Aramid/Epoxy	0.75
Aggressive environment (chemical plants)	Carbon/Epoxy	0.85
	Glass/Epoxy	0.50
	Aramid/Epoxy	0.70

Research has shown that CFRP shows less degradation compared to GFRP regarding alkaline, acidic and salt environments as well as UV radiation and fatigue (Chlosta 2012). This is also shown in the second approach as seen in Table 55. From the table, it is clear that the highest environmental reduction is related to glass fibres and the lowest reduction to carbon fibres, both with epoxy resin.

Concerning the polymer matrix it can be concluded that epoxy has an good overall resistance and can withstand deterioration to a large degree (Chlosta 2012). In addition the epoxy polymer has low water absorption in comparison with the other types of polymers (Chlosta 2012).

3.4.3 Physical Effects

3.4.3.1 Creep and Stress Relaxation

A requirement for structural components is that they need to withstand sustained loading to a certain degree without too much creep and/or relaxation (Bisby 2006).

3.4.3.1.1 Creep

Creep is referred to the increase in plastic strain under constant stress (Brush Wellman Inc. 2009; Clarke 1996; Bisby 2006; ZRMK et al. 2013; Chlosta 2012). The development of creep can be seen in Figure 64 and is generally divided in three phases which are the primary, secondary and tertiary (Clarke 1996). The primary and secondary phases mainly consist of delayed equalisation of the internal stresses. The tertiary phase consists of a progression of local failure mechanisms which eventually leads to a rupture. Whether the next phase would be reached depends on the applied load and the loading time (Clarke 1996).

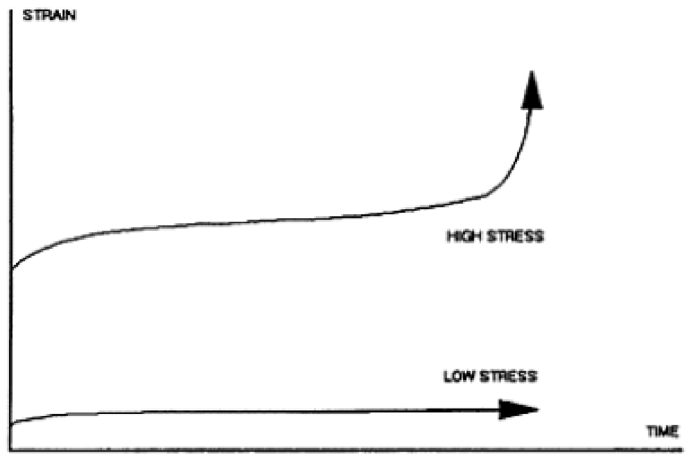


Figure 64 The creep behaviour of FRP composites subjected to high respective low loads (Clarke 1996, p. 253)

The creep behaviour is generally relatively good for FRP components but varies a lot depending on the manufacturing process and the constituent materials (Bisby 2006). The part of the composites most affected by creep is the resin (Muniz & Bansal 2009; Chlosta 2012). Resins subjected to sustained loading experience a high level of creep and/or relaxation (Bisby 2006). To avoid excessive creep of the FRP composite it is important that care is taken in the manufacturing process and during curing (Bisby 2006). In addition, it can be concluded that a ductile resin will experience more creep than a brittle resin (Muniz & Bansal 2009; Potyrala 2011). Thus there will most likely not be a problem with creep and relaxation for a heat hardened resin such as epoxy, however, problems could arise if choosing a ductile thermoplastic resin (Muniz & Bansal 2009). The fibres commonly used in civil engineering application such as aramid, carbon and glass generally experience near-to-zero creep rate (Bisby 2006; Muniz & Bansal 2009).

In design, creep is commonly described with an effective reduction in modulus factor that is time dependant (Clarke 1996; ZRMK et al. 2013; Chlosta 2012). The definition of the creep modulus is related to the additional strains exhibited by a material after a certain time has elapsed (ZRMK et al. 2013; Chlosta 2012). The creep modulus is both influenced by the properties of the constituent materials and the environment in which the composite is placed (Clarke 1996). The material factors include the type of resin, the degree of curing, the stability of the fibre/matrix bond, the fibre volume fraction, the reinforcement form (i.e. woven, non-woven etc.), fibre orientation in respect to load and the manufacturing process (Clarke 1996; Chlosta 2012; Muniz & Bansal 2009). The factors included in the environment are the ambient temperature, the loading type and stress levels, moisture content and aggressive chemicals (Clarke 1996; Chlosta 2012).

A low value of creep and consequently a high creep modulus is generally achieved if a resin with a high level of cross-linking is used (Clarke 1996; Chlosta 2012). This is because in this type of resins a high fibre volume fraction can be obtained creating a strong fibre/matrix bond which ultimately acts as a margin separating the resin temperature and the working temperature (Clarke 1996; Chlosta 2012). Furthermore it can be stated that the creep resistance of composites is related to the direction of the loading with regard to fibers. If the composite is loaded parallel to the fibers, minimum stresses in the matrix are obtained (Clarke 1996; Chlosta 2012). The load is related the greater load, the higher stress levels which ultimately results in a higher creep rates (Clarke 1996; Chlosta 2012). The temperature also influence the creep behaviour in a way that a higher HDT and T_g is advantageous and results in a higher creep modulus (Clarke 1996). It should be noted that some resins suffer from creep even at room temperature (Muniz & Bansal 2009). Resins susceptible to moisture and other solvents, such as polyester and vinyl ester, could have higher creep rates since the matrix usually softens from the degradation of the fibre/matrix bond (Clarke 1996).

3.4.3.1.1.1 Creep Rupture

Fibres used in FRP composites are generally unaffected by creep and have elastic behaviour (Clarke 1996). If the fibres incorporated in the FRP composite, by any mean, are attacked by a hazardous environment and in combination with high stresses creep rupture could occur(also called stress rupture and stress corrosion) (Clarke 1996; Bisby 2006). In acidic environments, this type of failure is considered to be the most common mode of failure (Clarke 1996). Creep rupture, in general, takes place in composites where stress raisers are available. Examples of stress raisers are cracks on the surface and barrier layers or as weld defects in thermoplastics (Clarke 1996). If the fibres come into contact with deleterious environmental factors through cracks or diffusion, the consequences could be the failure of the laminate at already low stresses, referred to as a premature failure (Clarke 1996; Chlosta 2012). In such a case, if a stress is applied to the laminate, it will result in continuous crack propagation until failure of laminate is reached (Clarke 1996; Chlosta 2012). The factors mainly influencing the creep rupture of an FRP composite are the stress level, matrix type, fibre type, time and environment (Clarke 1996).

Creep rupture is largely influenced by the fibre used, where the susceptibility alkali-induced degradation on strength is the main factor (Bisby 2006). Fibres susceptible to alkali-induced degradation generally exhibit a reduction in tensile strength (Bisby 2006).Carbon fibres are known to experience insignificant alkali-induced reduction in tensile strength and are considered the fibres the least susceptible to stress rupture (Bisby 2006; Chlosta 2012). In general they show no sign of stress corrosion until subjected to stress levels of 80% in compression and 95% in tension of the ultimate limit strength (Chlosta 2012). Aramid and glass fibres, however, experience higher levels of alkali-induced reduction in strength and are considered moderately (aramid fibres) respective most susceptible fibres (glass fibres) in terms of stress rupture (Bisby 2006; Chlosta 2012). Glass fibres are sensitive to the combination of physical and chemical impacts (Bisby 2006). Polyester resins generally have low permeability especially towards hydrochloric acid (Clarke 1996). This indicates that for creep rupture to occur the following parameters has to be fulfilled: significant stress, cracks and an aggressive environment (Clarke 1996). FRP composites having the highest resistance towards creep rupture are carbon reinforced epoxy and the lowest resistance belongs to glass fibre reinforced polyester (Chlosta 2012). Composites with aramid and vinyl ester show resistance to creep rupture in-between the other two composites (Chlosta 2012). Measures to improve the creep rupture resistance of the FRP composite are incorporation of fibres that are chemically resistant such as ECR-glass and by choosing a tough resin (Clarke 1996).

The time to rupture, or time to failure, is referred to as the endurance time (Bisby 2006). The endurance time is largely influenced by the quality of the resin and decreases as the ratio between the sustained stress-level and the ultimate strength of the FRP material increases (Bisby 2006). Other factors, mainly environmental, that influence the endurance time are UV radiation, alkalis, moisture, freeze-thaw cycles and elevated temperatures etc. (Bisby 2006).

Test results to determine the creep rupture strength after 50 years for FRP reinforcing bars which were performed in laboratories with room tempered air and varying sustained loading indicated values of 29-55%, 47-66% and 79-93% of the initial tensile strength for glass, aramid and carbon respectively (Bisby 2006). From the tests, it can be concluded that glass fibres suffer substantial loss of strength due to creep rupture (Clarke 1996). E-glass has furthermore shown to be susceptible to a range of acids including small concentrations of hydrochloric acid or sulphuric acid (Clarke 1996). The design requirement available for FRP materials in terms of creep rupture indicates the sustained stresses in GFRP should be limited to 20% to 30% of the ultimate strength (Chlosta 2012; Bisby 2006). The requirement can be regarded as relatively conservative and needs to be revised in the future (Bisby 2006).

The sources and consequences of creep rupture are complex and not completely understood at the present. However it is believed that synergy of different damaging mechanisms can contribute to creep rupture. Examples of factors that might contribute to the creep rupture are the environment, stress levels, fibre/matrix interface, cracking of matrix and fibres as well as creep rupture of fibres (Bisby 2006).

3.4.3.1.1.2 Design

In design when calculating the stiffness, a reduction of the modulus should be considered in order to account for creep (Clarke 1996). If a composite is loaded in the longitudinal direction, low levels of deformation is expected, loading transversally to the fibre direction however can lead to excessive deformation. In design, the creep modulus is generally considered for three fibre direction. These directions are unidirectional fibres (loaded in tension longitudinally respectively in shear) random mats loaded in-plane and orthotropic composites e.g. woven laminates (Clarke 1996). The fibre directions creep modulus versus time can be seen in Figure 65.

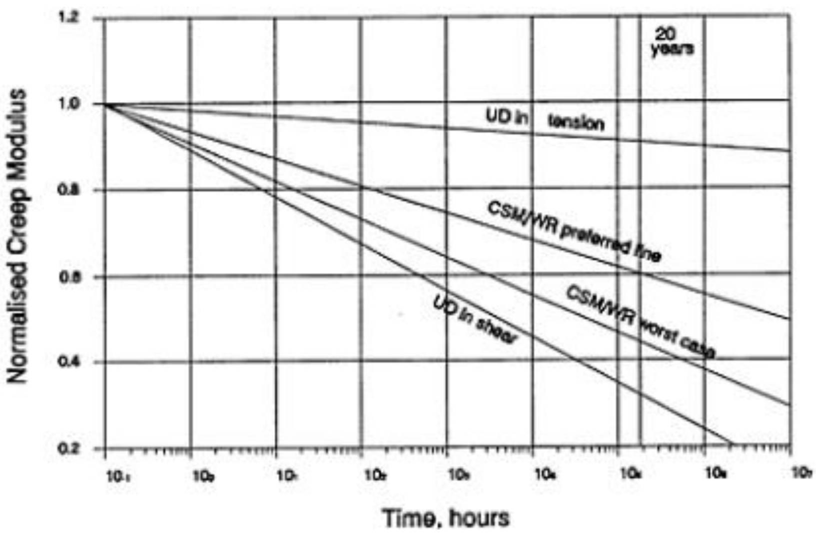


Figure 65 Relation creep modulus versus time for different types of fibre direction (Clarke 1996, p. 103)

Information regarding the creep behaviour of FRP composites subjected to compression is not available (Clarke 1996). In design the shear creep curve can be used for compression since composites subjected to compression show both compressive and shear deformations (Clarke 1996). If the stress is applied in tension to UD stiff fibres the composite will generally be highly resistant towards creep (Clarke 1996; Muniz & Bansal 2009; Chlosta 2012). Construction laminated consisting of bi-directional woven fabrics have inferior creep performance than compared to unidirectional fibres as can be seen in Figure 65 (Clarke 1996; Chlosta 2012). If crimp is present they act as local stress raisers which ultimately can lead to cracking (Clarke 1996; Chlosta 2012). It can be concluded that for critical application, unidirectional fibres are the preferred choice (Clarke 1996). The fabric least resistant to creep is those consisting of short, discontinuous and random fibres such as CSM (chopped strand mat) which is due to that the large amount of fibres give rise to stress raisers whit the consequence of high shear stress levels in the polymer matrix (Clarke 1996).

In addition to the reduction of the modulus of elasticity of the FRP composite subjected to creep, reduction in strength can also occur (Clarke 1996; ZRMK et al. 2013). This reduction can ultimately result in a rupture failure (Clarke 1996; ZRMK et al. 2013). A check of the chosen composites to ensure that the structure will not fail due to creep rupture can be made by checking Figure 66.

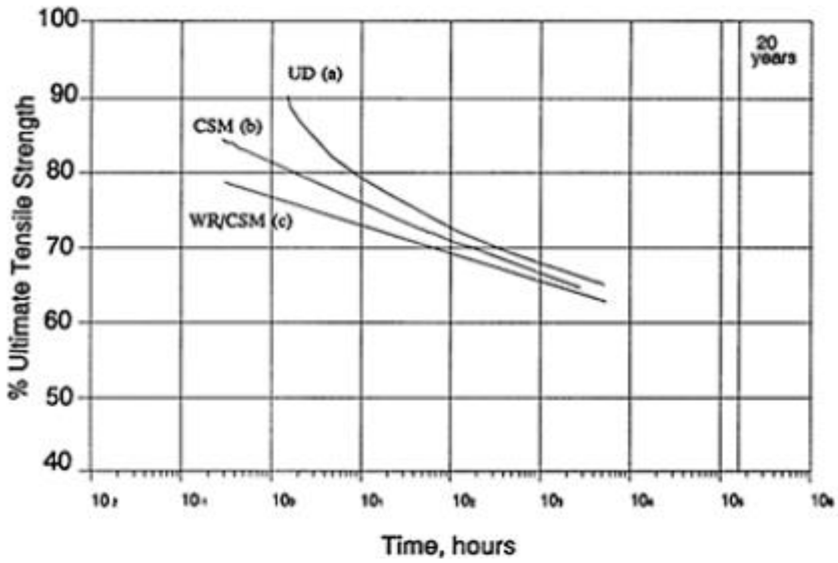


Figure 66 Creep rupture (tensile stress rupture) of a polyester composite subjected to air temperature (Clarke 1996, p. 105)

The available data regarding creep rupture in acidic environments are generally considered unreliable since there are many factors that influence the time to failure, such as the shape and the size of the composite (Clarke 1996). Identifying a maximum strain criterion of 0.2% is a conservative approach in design. In acidic environments, acid resistant glass fibres types such as ECR should be chosen. Brittle polymer matrix (i.e. thermoset polymers) generally performs rather poorly when subjected to creep rupture. This is because they act in a viscoelastic manner at ambient temperature. The viscoelastic behaviour of the thermosetting polymers generally recovers if the strain levels remain low when the stress is removed. Unreinforced thermoset polymer matrixes are generally susceptible to creep. In design the combined effects of creep rupture and chemical requirements of the polymer matrix should be considered (Clarke 1996).

It can be concluded that the long-term creep resistance of CFRP composites subjected to tensile stresses are generally very good (Clarke 1996). Furthermore, even though aramid fibres exhibit a high inherent tensile strength especially in the in unidirectional direction they display very high creep rates which are much higher than for composites with incorporated glass and carbon fibres (Clarke 1996; Chlosta 2012). In design of FRP composites aimed for civil engineering application creep is generally not considered since the creep characteristics of the common fibre types carbon, glass and aramid are negligible (Clarke 1996; Hollaway 2010).

3.4.3.1.1.2.1 CUR96

According to the Dutch recommendations, the creep is accounted by creep conversion factor γ_{CK} which can be calculated from (Chlosta 2012):

$$\gamma_{CK} = t^n$$

Where t is the load duration expressed in hours

$$n = 0.01\ for\ unidirectional - ply$$

$$n = 0.04\ for\ woven\ fabric - ply$$

$$n = 0.1\ for\ mat - ply$$

It is worth noting that the creep conversion factor can only be calculated for the ply in the longitudinal direction (Chlosta 2012).

3.4.3.1.2 Relaxation

Relaxation is referred to as the "reduction in stress in a material or structural component with time at a constant level of strain" (Bisby 2006; Brush Wellman Inc. 2009). A prerequisite for a material to be able to relax is that it first must be deformed (Muniz & Bansal 2009). The magnitude of how much a composite material relaxes is related to the fibre orientation, the initial applied tension, the fibre volume fraction and the ductility of the resin (Muniz & Bansal 2009).

The fibre orientation is of interest since higher alignment of the fibres in one direction will generate less creep and relaxation (Muniz & Bansal 2009). As for creep, a higher fibre volume fraction lowers the levels of relaxation in the material (Muniz & Bansal 2009). The relaxation of a composite material is higher for a ductile resin than for a brittle one, since the ductile resin will have a higher deformation (Muniz & Bansal 2009). A stronger fibre/matrix bond results in a tougher material and consequently a smaller risk of delamination (Muniz & Bansal 2009). The toughness of resins generally lie in the range of 200 J/m^2 to 8000 J/m^2 for composite materials. The corresponding value for A36 steel is 13 000 J/m^2 (Muniz & Bansal 2009).

3.4.3.2 Fatigue (Cyclic Loading)

Fatigue can be defined as the degradation of the mechanical properties of a material over time due to alternating stresses (Chlosta 2012). Many structures are exposed to cyclic loading that ultimately can cause failure of the structure at stress levels beyond the ultimate strength (Bisby 2006). Examples of cyclic loading are moving loads, thermal expansion, vibrations from wind etc. There is a lot of information regarding the response of FRP composites under fatigue loading from the aerospace industry. This information can however not be applied to FRP composites used in civil engineering application, resulting in lack of information of long-term fatigue data for civil engineering applications. The long-term performance with regard to fatigue is extrapolated from short-term performance laboratory data which causes uncertainties of the validity of the results. The existing data, however, indicates that the performance of FRP composites subjected to fatigue is generally better than steel (Bisby 2006; Chlosta 2012; Clarke 1996).

The fundamental requirement, in terms of fatigue, is that the structure should be properly designed and constructed so that the risk of failure, or damage so severe that repair is needed, caused by fatigue loading is insignificant (Clarke 1996; ZRMK et al. 2013). The small alternating stresses that are well below the ultimate static strength can result in fracture due to propagation of cracks (Chlosta 2012). The fatigue life process can be seen in Figure 67.

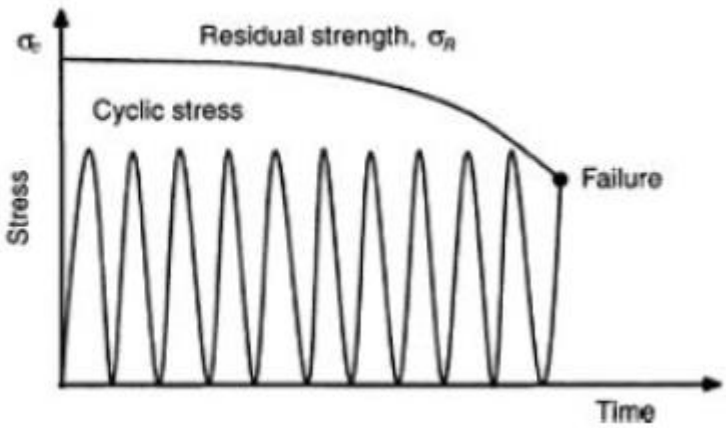


Figure 67 Fatigue life process (Chlosta 2012)

The requirements of the performance of FRP composites with regard to fatigue are related to the following factors (Clarke 1996):

- the required fatigue life of the member or structure
- the values of the shear and normal stresses in a stress cycle, where consideration should be taken to stress raisers arising from construction methods, geometric effects such as notches and from dynamic amplification factors
- the criteria regarding fatigue failure

The requirements of the performance of FRP composites with regard to fatigue are related to the following factors (Clarke 1996):

- the required fatigue life of the member or structure
- the values of the shear and normal stresses in a stress cycle, where consideration should be taken to stress raisers arising from construction methods, geometric effects such as notches and from dynamic amplification factors
- the criteria regarding fatigue failure

The best design procedure is to determine the fatigue strength of an FRP composite from the tests (Clarke 1996; ZRMK et al. 2013). The tested specimen should exhibit approximately the same composition of constituents, and be subjected to the same intended environmental- and loading conditions (Clarke 1996; ZRMK et al. 2013). If suitable test data is limited, the fatigue design in SLS should be verified according the limiting normal strain, which can be seen in Table 56, so that the risk of fibre debonding is limited in unidirectional, CSM and WR glass reinforcement laminates (Clarke 1996).

Table 56 Normal strain range and number of cycles N to fibre debonding (Clarke 1996)

Normal strain range [%]	Maximum strain [%]	Number of cycles N

0.30	0.20	10^3
0.23	0.15	10^4
0.17	0.13	10^5
0.10	0.07	10^6
0.03	0.02	10^7

In fatigue design, special care has to be taken for areas likely to experience stress concentrations (Clarke 1996). These areas are generally related to joints, connections and in points where there is a change in direction (Clarke 1996). Since these locations experience stresses higher than those in the plane sections of the composite they will seriously reduce the fatigue life of the member (Clarke 1996).

The main reason is that the fatigue performance of steel structures generally is determined by the connections; both welded and bolted (Chlosta 2012). These types of connections commonly include imperfections acting as stress raisers which ultimately will cause cracks reducing the residual life of the steel structure. For FRP composites, however, the factors determining the fatigue strength are related to the median stress level and the static strength of the composite. The fact that FRP composites, unlike metals, are inhomogeneous and generally contain a large amount of imperfections; the presence of notches does not influence the fatigue performance much. In comparison with steel, the propagation of small imperfections of FRP composites grow in a lower rate which is due to the fibres acts as crack-propagation-stoppers and thus dampens the effects. FRP composites generally exhibit lower residual stresses in comparison to steel (Chlosta 2012).

3.4.3.2.1 Influence of the Constituent Materials

The polymer matrix has the largest impact on the fatigue performance of FRP composites. The key characteristics of matrix are the toughness and the capacity to withstand cracking (Bisby 2006). A comparison between the fatigue life for phenolic, polyester, epoxy and silicone resins is displayed in Figure 68. From the figure, it can be concluded that phenolic resins performs best in terms of withstanding high amplitudes of stresses up to $N_f = 10^5$ (Chlosta 2012). Bridges generally exhibit a number of stress-cycles in the range of 10^7, and as can be seen in Figure 68 has the highest residual strength at this number of stress-cycles (Chlosta 2012).

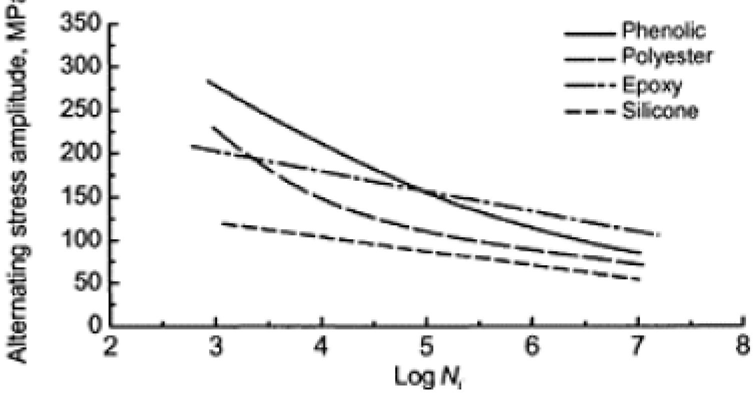


Figure 68 Relation between alternating stress amplitude and number of stress cycles (Chlosta 2012, p. 98)

The type of fibre, orientation of fibres and fibre volume fraction also influence the fatigue strength of FRP composites (Chlosta 2012). The fibres mainly used in FRP composites generally show low sensitivity to fatigue loading (Bisby 2006). Carbon fibres generate FRP composites that are deemed to have the best performance in terms of fatigue if compared to the fibres glass and aramid (Bisby 2006). CFRP with unidirectional fibres that are loaded in the fibre direction exhibits an excellent performance in terms of tension fatigue (Clarke 1996). If comparing unidirectional CFRP with the conventional building material steel, it can be concluded that it has better performance even at very high levels of stress (Clarke 1996; Chlosta 2012). This phenomenon is also applicable for quasi-isotropic CFRP where the fatigue resistance in comparison to steel and aluminium is two to four times higher (Clarke 1996). A disadvantage with CFRP is that the fatigue resistance is reduced if the composite is subjected to compression or stresses in the transversal direction of the fibres (Clarke 1996). However if the fibre/matrix interface is degraded, then the fibres can experience reductions in fatigue strength, especially if moisture and elevated temperatures are present (Bisby 2006). Glass fibres generally show good fatigue performance and aramid fibres generally have a low degree of degradation in strength when subjected to fatigue (Bisby 2006). As glass fibres have a low modulus of elasticity, there is a risk of matrix failure as the composite has to work at a high strain (Clarke 1996). Moisture, acidic and alkaline solutions will furthermore decrease the fatigue strength of FRP composites with glass fibres since fibre/matrix interface is damaged due to the reduced strength and stiffness of the fibres (Bisby 2006). Aramid fibres are generally susceptible to elevated temperatures and moisture which causes degradation of the long-term fatigue performance (Bisby 2006). The aramid type Kevlar 49® has better resistance to tension fatigue in comparison with E- and S-glass fibre composites (Clarke 1996). However, Kevlar 49® fibres show poor fatigue resistance if subjected to flexure fatigue, which is more apparent at low stresses (Clarke 1996).

In terms of fibre orientation, the best fatigue performance of the FRP composites is achieved through unidirectional fibres where the load is applied in the direction of the fibres, the resistance is somewhat lowered for bidirectional reinforcement such as woven roving's (Chlosta 2012). The best fatigue performance is generally achieved for composites incorporating a fibre volume fraction in the range of 65% to 70%. This is because the main source of degradation, as a consequence of fatigue loading, is related to matrix damage such as cracking and debonding. Hence a rigid matrix is desirable in order to get an FRP composite with high fatigue resistance and thus avoiding cracking of the matrix. The cracks in the matrix will furthermore cause absorption of water which ultimately can result in further degradation and reduced fatigue life as a consequence. The thermoplastic resin type PEEK has very high resistance towards moisture and has thus an outstanding fatigue resistance. An FRP composite consisting of a PEEK resin and carbon fibres is regarded as having exceptional fatigue properties since carbon fibres also are resistant to moisture. Lastly it can be noted that by using carbon fibres, the composite will be less dependent on the type of resin (Chlosta 2012).

Figure 69 shows the relation between peak stress and peak strain and number of cycles to failure (N_f) for different FRP composites (Chlosta 2012). The composites in the left graph are subjected to compression- and shear stresses, and in the right graph to repeated tensile loading.

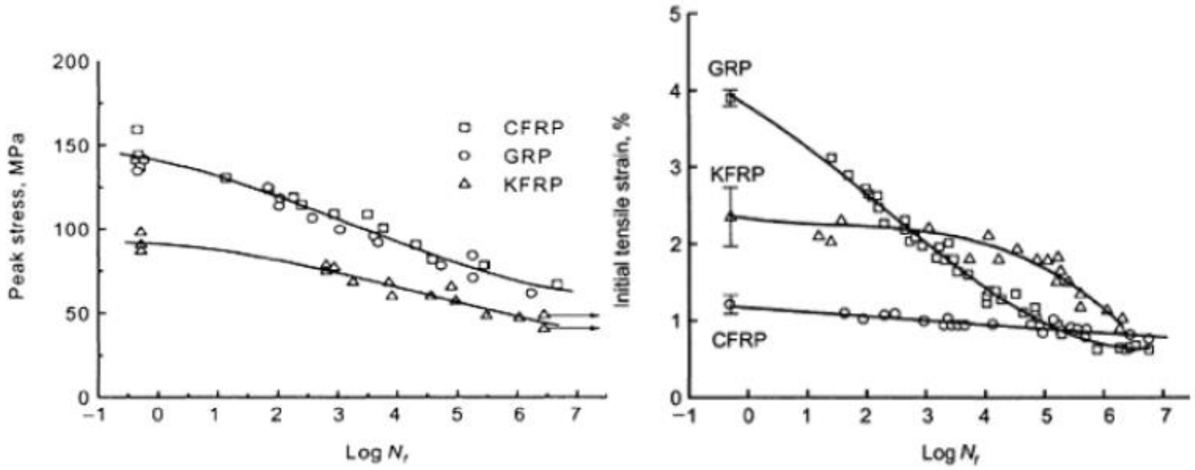


Figure 69 Left: Relation between peak stress and logarithmic values number of stress cycles for carbon-, aramid and glass reinforced epoxy with a Vf of 65% and load applied 45° to fibre direction Right: Relation between tensile strain and logarithmic values number of stress cycles for same composites (Chlosta 2012, p. 99)

It can be concluded from the curves in the left graph that composites consisting of aramid fibres (KFRP) is more severely affected by compression and shear stresses compared to composites with glass- and carbon fibres (Chlosta 2012). For CFRP and GFRP the main modes of failure consist of delamination and matrix cracking. Since AFRP exhibit an intrafibrillar weakness, it will behave differently from CFRP and GRP. The intrafibrillar weakness of KFRP can be seen in the right graph for $N_f = 5x10^3$ where there is a rapid increase of the inclination of the curve (Chlosta 2012).

Synergies exists where the combined effects of fatigue and other mechanisms such as high temperatures, moisture, corrosive fluids and humidity can decrease the fatigue resistance of the FRP composite (Bisby 2006). Further research and test are however needed to prove this claim. Other factors that can have synergetic effects on FRP composites in terms of fatigue are manufacturing techniques, presence of alkaline solutions, stress ratio and intensity etc. (Bisby 2006).

3.4.4 Conclusion Durability

It can be concluded that FRP composites in comparison with conventional building materials have a good behaviour in terms of durability and degrade less (Bisby 2006). However, since FRP is a relatively novel material is civil engineering applications there is little knowledge about the long-term behaviour. Further research is needed in order to get a holistic picture of the performance of FRP composites in terms of durability. The most critical knowledge gaps today are related to moisture, alkalinity, fire, fatigue and synergies. Even though there are some knowledge gaps, it can be concluded that FRP composites pose a highly durable alternative to the conventional materials such as steel, concrete and timber. The durability of the FRP composites mainly depends on the ability of the polymer matrix to protect fibres and fibre/matrix bond. It can also be concluded that new and more durable alternatives will be developed through further research. It can furthermore be concluded that the there is a lack of information about the effect of synergies for FRP composites. Lastly it can be concluded that it is important that the designer takes long-term durability and structural performance requirements into account when choosing an FRP composite composition for design (Bisby 2006).

3.5 Sustainability

The factors that should be considered when it comes to sustainability are society, economics and environment which can be seen in Figure 70 (Chlosta 2012).

Figure 70 A sustainability chart comprising social-, economic- and environmental factors (Chlosta 2012, p. 218)

The general approach used to estimate sustainability is the "Life Cycle Assessment" (LCA) analysis and is sometimes referred to as "Cradle-to-grave" (Chlosta 2012). The approach generally considers parameters such as the included raw materials, the manufacturing technique, transportation impact, in-service use, demolition and disposal. Specific factors considered in the LCA approach are mainly: amount of greenhouse gases, total energy consumption, production of smog, amount of discharge of nutrients to water, use of minerals and fossil fuels, depletion of the ozone layer and toxicity to humans and environment (Chlosta 2012).

Since FRP composites generally have much higher strength to weight ratio compared to conventional building materials they pose a big advantage in terms of sustainability as they enable for embedded energy savings (Chlosta 2012). Comparisons between FRP composites and timber have shown a 50% higher environmental footprint. If comparing FRP composites to steel and aluminium alloys, FRP composites have a lower environmental footprint. If however recycled materials are incorporated into the steel and aluminium, the environmental footprint is similar to that of FRP composites. By reducing the content of styrene and increasing the fibre volume fraction of the FRP composite, a more sustainable composite is achieved. This poses a significant advantage in terms of sustainability for bridge applications since they require high strength to weight ratios which could be obtained by a higher fibre volume fraction (Chlosta 2012).

Table 57 presents a comparison between the total amounts of embodied energy for steel with 25% recycled material, aluminium with 50% recycled material and virgin GFRP composite. As can be seen from the table, the composite alternative contains the 2 to 3 times less embodied energy compared to the two conventional building materials (Chlosta 2012). The major part of the embodied energy for the GFRP is used during the manufacture. For steel the largest part of the used energy is consumed during installation and maintenance with regard to for example corrosion resistance. Aluminium requires a large amount of energy for extraction of raw materials and consumes negligible energy during installation and maintenance. It can be observed that FRP poses advantages in terms of further processing, maintenance and installation (Chlosta 2012).

Table 57 Comparison between steel, aluminium and GFRP composite in terms of total embodied energy (Chlosta 2012, p. 220)

Property	Unit	Steel	Aluminum	GFRP
Primary raw materials		25% recycled	50% recycled	glass & resin mix
Energy raw materials	MJ/kg	26	101	70-74
Secondary operations		Hot/Cold/Section roll	Extrusion or other	Composite manufacture
Energy secondary operations	MJ/kg	4-6	40-50	4-6
Field installation		Blast and paint		
Energy field installation	MJ/kg	30-35	0	0
Maintenance and use phase		Blast and paint		
Energy maintenance and use phase	MJ/kg	30-35	0	0
Total	MJ/kg	90-106	141-151	74-80
Total compared to a composite	MJ/kg	270-318	169-181	74-80
Element of 1.9 kg weight		at 3.5 kg	at 1.2 kg	at 1.0 kg

3.5.1 Recyclability of Composites

Thermoplastic resins are more beneficial than thermosetting polymers in terms of recyclability since they can be re-melted (Chlosta 2012). Mechanical recycling of FRP composites are generally difficult since they consist of fibres and resin which is energy consuming to separate. If both the resin and matrix would consist of the same material the recycling would be optimal. An example of this is a composite consisting of polypropylene resin with incorporated melt-spun isotactic polypropylene fibres, however this composite is not currently applicable for structural large-scale parts. Thermoplastic polymers pose a big advantage in terms of recyclability but more research is required regarding their applicability for structural parts (Chlosta 2012).

3.6 Resistance towards different sources of Impact

3.6.1 Explosion/Blast

3.6.1.1 The Fundamental Requirements for Explosion/Blast

The fundamental requirements in terms of explosion/blast that should be considered in design are (Clarke 1996):

- The intended application of the FRP composite
- The choice of FRP composites. Thermoset resins act in a brittle way and failure will occur when the elastic limit have been reached
- Evaluating the consequences in the case of that the structure or parts of the structure not directly connected are subjected to explosion/blast, such as failure, deformation, losses in strength and stiffness etc.

The general design requirement of a structure consisting of FRP composites is that it should tolerate the over-pressure generated for a specified period of time in case of an explosion/blast (Clarke 1996). The client and designer commonly agree upon the allowable damage to a certain degree, but in general the structure should keep enough structural integrity that people can evacuate the structure in a safe and controlled way. In design the blast load is generally considered in a combination with the imposed and dead loads. If consideration is taken in terms of dynamic response, ductility, energy absorption and stiffness of the structure the blast load can be modelled as a static load subjected to the structure for a specified period of time (Clarke 1996).

3.6.1.2 Design Methods

When an FRP composite is subjected to explosion/blast, it can handle elastic distortion and permanent damage to a certain degree, namely the elastic limit (Clarke 1996). When this limit is reached, due to lack of ductility in the stress-strain curve, the consequence is the failure of the laminate through tearing or direct ruptures. The failure will mainly occur at stress raisers or in areas of the structure where the laminate is prevented to move i.e. joints or connections (Clarke 1996).

Proper design of joints is important when considering the effects of explosion/blast since a flexible dynamic response of the structure is vital (Clarke 1996). Examples of design considerations for joints are to allow deformations in the flexible parts of the system, to limit the stresses and/or strains in the joints, avoiding progressive collapse by allowing for quasi-ductile action of local components and finally enable movements at mechanical joints and allow the accompanying deformations (Clarke 1996).

Furthermore, since the assumed deflections and loss of stiffness can be underestimated in design in case of explosion/blast, it is important to take second order effects into consideration when designing for ultimate limit state (Clarke 1996).

3.6.2 Impact

3.6.2.1 General Information

Glass fibres in comparison with the other fibre types show good resistance towards impact due to the high strain to failure, as was seen in Figure 6 (Clarke 1996). Aramid fibres also incorporate a high resistance towards impact especially for ballistic impact. AFRP generally have a higher resistance towards impact than GFRP due to the comparatively low weight, however are more expensive. Carbon fibres can only tolerate low levels of impact since they have low strain to failure of approximately 1.5% and elastic behaviour to failure. By incorporating aramid and/or glass fibres to the CFRP better impact resistance is achieved (Clarke 1996).

3.6.2.2 Criteria and Requirements

The fundamental considerations of FRP composites generally include considerations regarding (Clarke 1996):

- The application of the FRP composite
- The environment in which the FRP composite is placed
- How the impact is applied on the composite, i.e. singular impact, repeated impact or a combination
- The characteristics of the projectile, i.e. a light projectile with high velocity or heavy projectile with low velocity, and the consequences of the impact from the projectile such as loss of strength and stiffness of composite and fixings, deformation and perforation of the FRP composite
- The effects of FRP composite not directly influenced by the impact load
- The generally brittle behaviour of FRP composites, where failure occurs soon after linear stress-strain point is reached
- If the FRP composite is subjected to an impact, delamination failure can occur in the plane perpendicular to the direction of the load

The design of structures consisting of FRP composites should include the event of impact loads that are realistic in-service and be able to withstand that kind of load (Clarke 1996). In general the client and the designer agree upon the extent of the allowable damage and additionally choose failure criteria. The failure criteria can be divided in ULS and SLS. The failure modes related to ULS are progressive collapse, collapse of an element, perforation resulting in full penetration and delamination. Failure modes related to SLS are limits regarding strain, penetration and deformations such as shear, flexure and direct loads, spalling and scabbing (Clarke 1996).

As for the case with explosion/blast, impact loads should be considered in combination with dead load design (Clarke 1996).

3.6.2.3 Design Methods

When predicting the performance of a FRP composite in terms of impact loading, the impact design should be verified with test performed on products, so called product impact tests, and not result from standard tests. The factors mainly included in the product impact test are (Clarke 1996):

- Temperature
- Stress raisers (holes, notches etc.)
- Velocity, size and mass of projectile
- The hardness between the projectile and the target
- The geometry of the target

3.6.3 Resistance to Weathering

The factors generally included in the weathering effects that influence the properties of the composite are: sunlight, temperature, dust, moisture, acid rain etc. (Clarke 1996).

The mechanisms that severely degrade the composite are for example embrittlement due to sunlight, leach of chemical constituents from resin and finally degradation through erosion by wind and dust. Measures to avoid weathering are for example to use UV stabilisers in the matrix, to choose resins that are suited for the environment and to use fibres such as C-glass or ECR-glass in the surface that are resistant against chemicals (Clarke 1996).

3.6.4 Blistering

Blistering can occur due to long time exposure to water for laminates with glass fibres, gel coat and the resin types epoxy, polyester or vinyl ester (Clarke 1996). Consequently FRP applications such as swimming pools and boat hulls are especially vulnerable. The mechanism of blistering consists of a slow penetration of water molecules into the resin voids leading to a hydrolytically unstable resin system. The resin can be damaged since salts can be formed. The gel coat can cause a build-up of pressure, since it acts as a semi permeable layer, which can ultimately cause blisters (Clarke 1996).

Measures to avoid this phenomenon are by a careful selection in terms of manufacturing techniques, raw materials and service environment (Clarke 1996). Furthermore, in order to prevent blistering it is of importance that resins and gel coats such as isophtalic polyester are chosen which include a good resistance towards water. In addition, it is more beneficial to use emulsion bound chopped strand mat instead of powder bound chopped strand mat for the reinforcement in the laminate surface. Another measure is to complement the gel coat with a surface tissue, however it is important that the tissue is thoroughly wetted and has a sufficient ratio between glass fibres and resin. A final measure is to strive for an environment both on site and during manufacture that are dry, clean and free from dust (Clarke 1996).

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4 Various Production Techniques

There are several production techniques available for manufacturing FRP composites. The relevant techniques in civil engineering are hand lay-up, spray lay-up, filament winding, resin transfer moulding and pultrusion (Potyrala 2011). The manufacturing process which has been used mostly is pultrusion followed by hand lay-up and vacuum assisted resin transfer moulding (VARTM) method (Hastak, Halpin & Hong 2004). Specifically in bridge engineering applications bridge-decks has mainly been manufactured using hand lay-up, VARTM and pultrusion methods which can be seen in Table 58 (O'Connor & Triandafilou 2009). The market share of different manufacturing techniques is illustrated in Figure 71.

Table 58 Manufacturing methods with respective number of built bridges (O'Connor & Triandafilou 2009, p. 7)

Used manufacturing method	Number of bridges
Pultrusion	56
VARTM	37
Hand lay-up	18
Other	10
Total	121

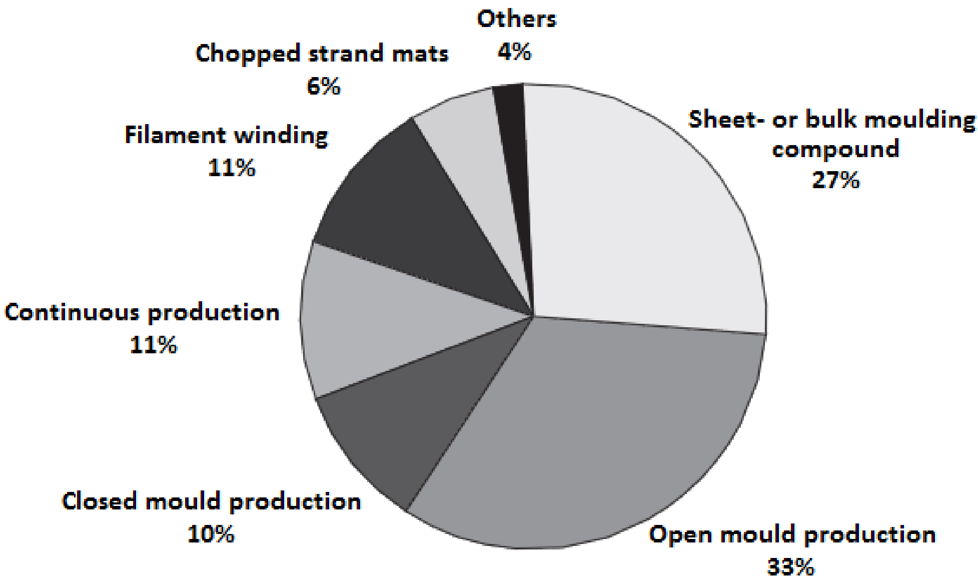

Figure 71 Market share of different manufacturing techniques (Chlosta 2012, p. 12)

The manufacturing processes that have been mostly denoted in codes and guidelines are the hand lay-up, pultrusion and resin transfer moulding process, which can be seen in Table 59 (Clarke 1996). The common denominators of these three processes are sensible and are able to produce profiles for civil engineering applications (Clarke 1996).

Table 59 Manufacturing processes for composites (Clarke 1996, p. 260-261)

Type	Process	Specific to code
Open lay-up	Hand lay-up	yes
	Spray lay-up	no
Intermediate	Moulding	no
	RTM/resin injection	yes
	Autoclave/vacuum bag	no
Compression moulding	Hot press moulding	no
Continuous	Pultrusion	yes
Winding processes	Filament winding	no

The manufacturing processes are basically divided to open moulding and closed moulding, but another classification is also manual, semi-automated methods and fully automated methods. The processes that are included in the open moulding techniques are (Hastak, Halpin & Hong 2004; Clarke 1996):

- hand lay-up
- spray-up and
- filament winding

Common applications of the open moulding processes are boat hulls, bridge-decks, bathtubs and other large uncomplicated shapes (Hastak, Halpin & Hong 2004). The closed moulding techniques include the processes (Hastak, Halpin & Hong 2004; Clarke 1996):

- resin transfer moulding (RTM)
- resin infusion moulding (RIM)
- injection moulding and pultrusion

The closed moulding processes are better than the open moulding processes in terms of less emissions and higher fibre-resin ratio (Hastak, Halpin & Hong 2004). In addition it provides finished surface appearances on both sides of the composite and better quality of the laminate. The limitations of the closed moulding processes are in comparison with the open moulding processes are that they, in general, are more expensive; hence applications are restricted to higher quality products (Hastak, Halpin & Hong 2004).

The manual and semi-automated methods include (Potyrala 2011):

- the hand lay-up
- spray-up and
- resin infusion moulding processes

The fully automated methods include (Potyrala 2011; Hollaway 2010; Hastak, Halpin & Hong 2004):

- pultrusion
- filament winding and
- resin transfer moulding
- injection moulding

The fully automated processes are more advantageous compared to the manual processes in terms of higher degree of control during production as well as compaction and curing (Hollaway 2010). In addition they have higher in-service properties, strength and stiffness leading to a higher robustness against aggressive environments than the manual processes (Hollaway 2010). In Table 60 comparison of production processes in terms of mechanical properties are displayed.

Table 60 Typical mechanical properties of GFRP manufactured with different production methods (Hollaway 2010, p. 2441)

Manufacture method	Tensile strength [MPa]	Tensile modulus [GPa]	Flexural strength [MPa]	Flexural Modulus [GPa]
Hand lay-up	62-344	4-31	110-550	6-28
Spray-up	35-124	6-12	83-190	5-9
RTM	138-193	3-10	207-310	8-15
Filament winding	550-1380	30-50	690-1725	34-48
Pultrusion	275-1240	21-41	517-14.448	21-41

4.1 Hand lay-up

The hand lay-up (also called wet lay-up) process was the first available manufacturing technique (Potyrala 2011; Clarke 1996). The process mainly involves a mould where first a highly soluble liquid resin is applied and then reinforcement is placed (Potyrala 2011). The reinforcement commonly consists of knitted rovings or chopped strand mats, where the former alternative provides better properties (Clarke 1996). To impregnate the fibre and to a remove entrapped air a metallic laminate roller called a squeegee is used (Potyrala 2011; Hastak, Halpin & Hong 2004; Clarke 1996). This procedure is repeated until the desired thickness of the composite is achieved (Potyrala 2011; Clarke 1996). Finally the laminate is cured and since the hand layup process is a cold moulding process a catalyst, often a peroxide, have to be applied (Clarke 1996). In Figure 72 the hand lay-up process is illustrated.

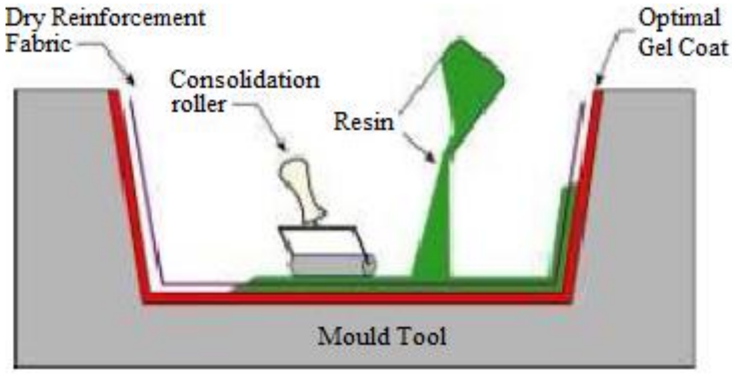

Figure 72 The hand lay-up process (Potyrala 2011, p. 22)

An advantage with the hand lay-up process is that by using many moulds a large quantity of products can be manufactured (Hastak, Halpin & Hong 2004). However since the process is very labour-intensive, the rate of production is in the order of 3kg/hour, production on a large scale is not suitable (Clarke 1996; Hurtado et al. 2012). The hand lay-up process provides many advantages such as being inexpensive and the ability to produce large and complex shapes (Clarke 1996; Yquel 2012). In addition the process is easy to teach (Yquel 2012). The sizes of the hand lay-up moulds ranges from 0.5m^2 to 300 m^2,hence applicable for bridges, however the general size of the moulds are approximately 3m^2 (Clarke 1996). Since the process is inexpensive, small manufacturing sequences ranging from 1 to 500 components can be justified. The inexpensive laminates are achieved due to that the curing of the laminate is simple and conducted at atmospheric pressure. This however causes a lower fibre fraction which ultimately leads to lower mechanical properties of the laminate. This implies that hand lay-up laminates will be thicker than laminates produced with processes offering higher fibre fractions. The cost of the extra material is however balanced with the lower cost of the process (Clarke 1996). The disadvantages of the hand lay-up process are the lack of consistency in quality and health and environmental risks due to emissions of styrene (Potyrala 2011). Finally, a profile produced with the hand lay-up process will only have one finished surface (Clarke 1996).

Application of hand lay-up method is desirable when rather high manufacturing defects are acceptable and complex shapes and geometries are required (Clarke 1996).

4.2 Spray-up

The spray-up and hand lay-up processes are very similar (Potyrala 2011; Hastak, Halpin & Hong 2004). However some of the differences are that the spray-up process is less time consuming and expensive (Potyrala 2011; Clarke 1996). A limitation, however, is that woven or knitted fabrics cannot be used (Clarke 1996). In practice, the spray-up and hand lay-up processes are often combined in order to reduce labour (Hastak, Halpin & Hong 2004).

The spray-up process consists of the catalysed and accelerated resin and the chopped reinforcement being applied with a spray gun to the mould (Potyrala 2011; Clarke 1996). The laminate is thereafter rolled with a squeegee and let to cure and subsequently cut into the desired size (Clarke 1996). The chopped fibres commonly consist of continuous special glass fibre rovings that are chopped into ranges of 10 to 40 mm (Potyrala 2011). The ortopolyester and isopolyester resins are commonly used in the spray-up process since they are highly reactive (Clarke 1996). Figure 73 illustrates the spray-up process.

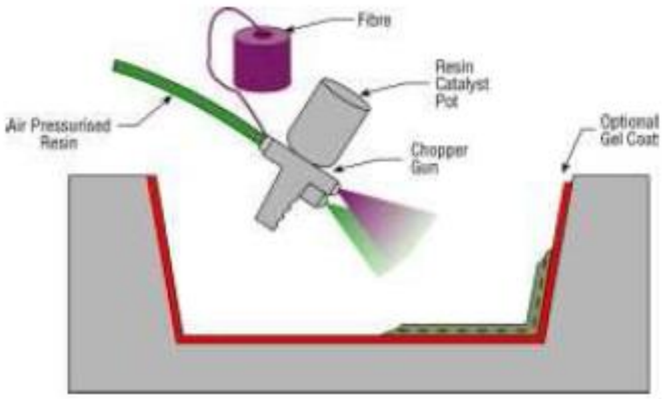

Figure 73 Spray-up process

There are two types of spray-up systems available which are twin-pot and catalyst injection system (Clarke 1996). The twin-pot machines have two pots, one pressurised for the catalysed resin and the other for the accelerated resin. The two pots are subsequently feeding the spray gun, and the two streams meet 300mm from the surface of the mould. Advantages with the twin-pot method are that it is easy to use and that premature gelation cannot take place since the two resin streams meet outside the spray gun. Disadvantages, however, are that the pots need to be continuously refilled which consumes a lot of time and consequently make it inappropriate for larger mouldings. The catalyst injection method only has one pot consisting of pre-accelerated resin. The catalyst is constantly incorporated into the pre-accelerated resin into the gun (Clarke 1996).

The spray-up process is most commonly manoeuvred by hand but can be operated with a robot (Clarke 1996). The fibre-resin volume ratio is commonly 1-2.5. The rate of which glass fibres can be applied is generally 20kg laminate per hour, which can be translated to a laminate with a thickness of 3mm and a surface area of $5m^2$. The size of the mould should be larger than $2m^2$ to be able to ensure control during manufacture, however the most common size of moulds are in the range of $10m^2$ (Clarke 1996).

The spray-up method if often limited to manufacturing non-structural parts since it is not possible to produce high strength composite components using this technique, hence not applicable for bride structures (Potyrala 2011). The disadvantages of spray-up method include controlling the fibre volume fraction and high dependency of the properties on operator skills (Potyrala 2011).

4.3 Filament Winding

The filament winding process consists of winding thermoset resin impregnated continuous fibres, commonly fibreglass rovings, in a predetermined angle around a rotating mandrel (Potyrala 2011; Clarke 1996). This process is shown in Figure 74. The most commonly used fibres are glass fibre rovings, carbon fibres and aramid fibres as yarns or rovings and for the matrix it is mainly epoxy but also polyester and vinyl ester are used (Potyrala 2011; Hastak, Halpin & Hong 2004; Clarke 1996). The rolls of fibre rovings, which can be seen in Figure 74, are easy to replace which facilitates for an easy manufacture (Yquel 2012). To increase to corrosion resistance of GFRP, thermoplastic veils can be added to the mould surface (Clarke 1996). The curing condition for the filament winding process is to put the composite in an oven at 60°C for 8 hours (Potyrala 2011). Prepregs or separated fibres together with resin can be used in the filament winding process (Clarke 1996). If the constituents are added separately, i.e. a non-prepreg system, then the composite can be cold cured (Clarke 1996).

Pipes and tubular structures such as composite pipes, electrical conduits and composite tanks are the main profiles produced from the filament winding process (Potyrala 2011; Hastak, Halpin & Hong 2004; Clarke 1996). The typical size of a tube manufactured with the filament winding process is 300mm in diameter with a length of 2m, however cylinders of 12m in diameter and with a length of 38m have been manufactured (Clarke 1996).

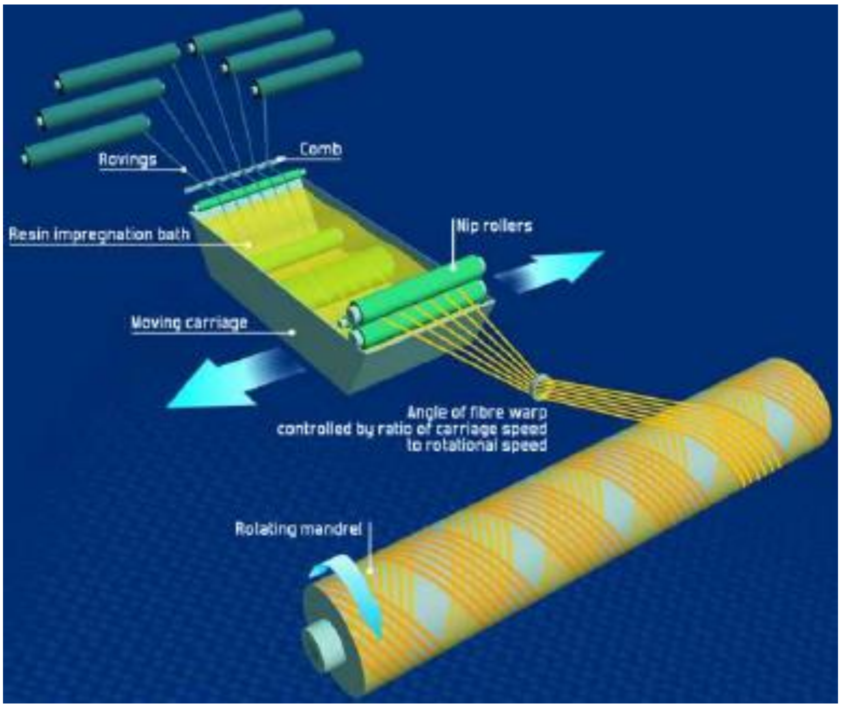

Figure 74 The filament winding process (Yquel 2012, p. 12)

Advantages with the filament winding process are that both the process and the materials are inexpensive (Potyrala 2011). In addition the process has a high level of control over fibre content and generates composites with exceptional properties (Clarke 1996; Yquel 2012). Very high quality laminates can be achieved using this method (Yquel 2012). However the disadvantages are that an only a low volume fraction can be achieved and the design is limited to closed and tubular structures (Potyrala 2011). In addition the filament winding process has a time consuming production and expensive machines (Jäger & Kluth 2013; Hastak, Halpin & Hong 2004; Clarke 1996). A production cycle generally takes 4 hours for the filament winding process but ranges from 1 to 24 hours (Clarke 1996). In addition high fibre impregnation is required in order to get sufficient properties (Yquel 2012).

4.4 Resin Transfer Moulding (RTM)

There are many varieties of RTM which generated different mechanical properties, depending on how the resin is added to the mould cavity (Potyrala 2011). An example of a RTM process is the vacuum assisted resin transfer moulding (VARTM) process, see Figure 75. The purpose of using vacuum is to increase the flow of the resin and reduce void formations (Hastak, Halpin & Hong 2004).

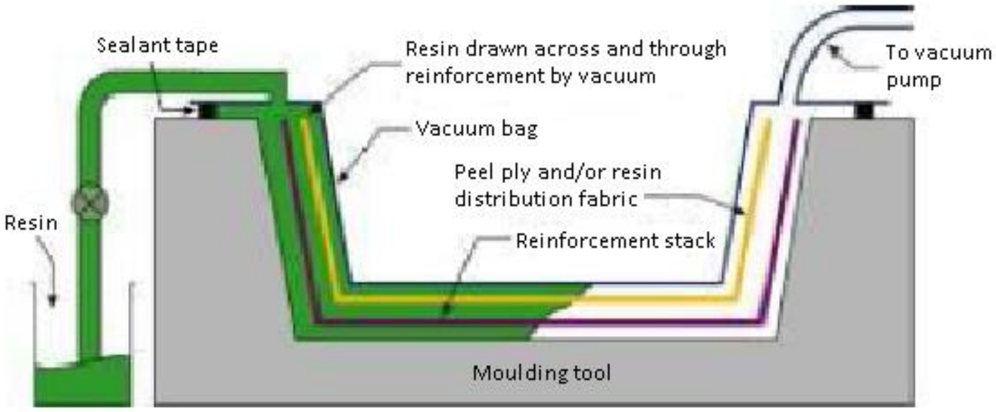

Figure 75 Vacuum assisted resin transfer moulding process (VARMT) (Potyrala 2011, p. 26)

The RTM process consists of stacking dry fabrics and binding them together with a binder (Potyrala 2011). A preferable option is that the reinforcement is pre-pressed to the mould shape (Potyrala 2011; Clarke 1996). The dry preformed fabric is placed in between a matched pair of moulds, which can be seen in Figure 76 (Potyrala 2011; Clarke 1996). The moulds are inexpensive and are generally made of FRP (Clarke 1996). The cavity is then injected with a pressurized, commonly 5bar, mixture consisting resin, catalyst, additives etc. in order to construct structural parts (Potyrala 2011). A pinch-off device is incorporated in the system and has the purpose of restricting the resin flow and ensuring that the cavity is filled by the means of a backpressure (Clarke 1996). The composite is let to cure after the fabric is completely wet out (Potyrala 2011; Hastak, Halpin & Hong 2004). In Figure 76 the resin transfer moulding process is displayed. The common resins used in the RTM process are low viscosity versions of polyester, phenolic and epoxy which all are highly reactive (Clark 1996; Yquel 2012). Since they are highly reactive, high temperature release agents are commonly incorporated (Clarke 1996). The most common reinforcement used in the RTM processes are CFM and CSM (Clarke 1996). An advantage with the RTM process is that autoclaving of the products is not required (Hastak, Halpin & Hong 2004). With the resin transfer moulding process the injection and cure are possible at both ambient and elevated temperatures (Potyrala 2011). Cold curing is most common (Clarke 1996), however the VARMT process is generally cured with heat (Hastak, Halpin & Hong 2004). Post-cure is often performed if the composite should be used in high temperature applications (Hastak, Halpin & Hong 2004).

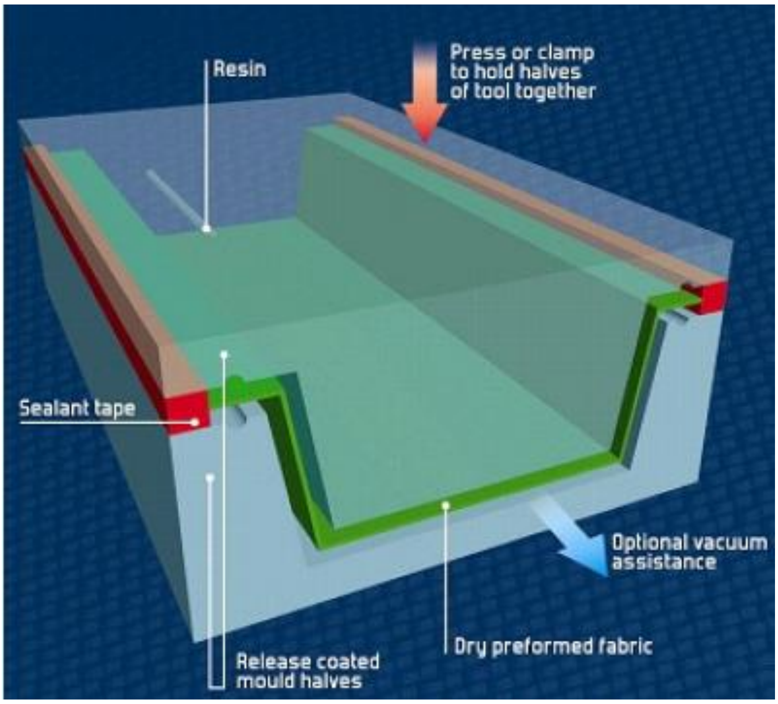

Figure 76 The resin transfer moulding process (Yquel 2012, p. 8)

An advantage with the resin transfer moulding process is that it is inexpensive (Hastak, Halpin & Hong 2004). In addition the emissions are less than for open mould processes (Hastak, Halpin & Hong 2004; Yquel 2012). The resin transfer moulding process is appropriate when a small to medium quantity of small to medium sized parts are required (Potyrala 2011; Yquel 2012). In the RTM process, it is possible to produce complex components, however at a medium speed of production (Jäger & Kluth 2013; Potyrala 2011; Hastak, Halpin & Hong 2004). The speed of production lies in the range of 15 to 30 minutes (Clarke 1996). If comparing the RTM process with open mould processes the speed of manufacturing parts are in the range of 5 to 20 times as high (Hastak, Halpin & Hong 2004). The RTM process is referred to as an intermediate process since it is neither a hand process nor a high volume process (Clarke 1996). This creates opportunities of producing cost effective structures at a smaller scale production (Potyrala 2011). The ability to economically manufacture small to medium quantities of components are related to that the equipment already is available (Clarke 1996). The size of the RTM moulds are commonly 0.5m^2 which are produced at rate of approximately 3 specimens/hour. However moulds of 10m^2 have been used. Quantities of 2000 specimens are required which is related to the rate of production and the investment cost of for example tooling and mixing and injection machine (Clarke 1996).

Another advantage is the ability to achieve high fibre volume fractions of up to 65% (Potyrala 2011). In addition, good surface qualities are achieved (Yquel 2012). A disadvantage with the resin transfer moulding process in comparison with the hand lay-up and spray-up method is higher cost and complexity of tooling and equipment (Potyrala 2011). Additionally, if comparing RTM with the pultrusion method the compliance of dimensional tolerances are lower (Potyrala 2011). The final mechanical properties of the composite can be compromised due to the fact that the resin must have a low viscosity when injected (Potyrala 2011).

4.5 Resin Infusion Moulding (RIM)

The resin infusion moulding process is regarded as a semi-automated process (Potyrala 2011). The process has many similarities with RTM and autoclave/vacuum bag moulding (Hastak, Halpin & Hong 2004). The process consists of stacking dry fabrics on a mould that is thereafter covered with a plastic bag and sealed against the steel mould (Hurtado et al. 2012). The plastic bag has two valves which are connected to a resin deposit respectively a vacuum pump (Hurtado et al. 2012). A vacuum is created in the bag resulting in the resin being sucked into the bag and consequently impregnating the dry fabric (Hurtado et al. 2012). It is of great importance that the fabrics are fully impregnated by the resin (Hurtado et al. 2012) and that the resin has a low viscosity such as epoxy (Yquel 2012). A disadvantage with the RIM process when manufacturing FRP bridge girders is problem with full impregnation, especially in case of thick laminates i.e. several centimetres (Hurtado et al. 2012). The resin infusion moulding process can be seen in Figure 77.

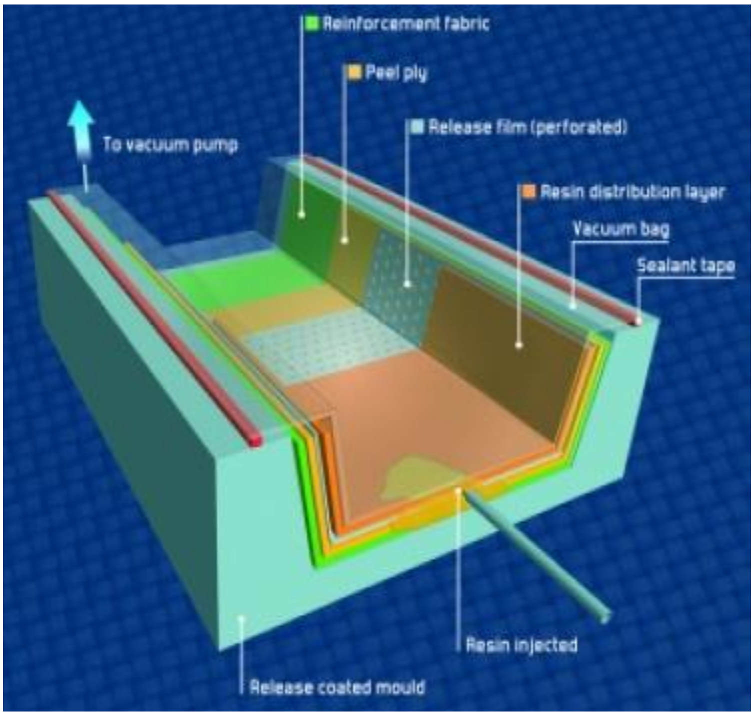

Figure 77 The infusion process (Yquel 2012, p. 10)

In production, both separated compounds and prepregs can be used in the RIM method, however there are many disadvantages with choosing prepregs such as higher cost and that they have to be stored in a fridge etc. (Hurtado et al. 2012).

Since RIM is a closed moulding process there are less emissions of styrene (Hastak, Halpin & Hong 2004; Yquel 2012). With the RIM process high performance laminates without bonding problems are produced (Hastak, Halpin & Hong 2004). The fibre-resin ratio for the RIM process is in the range of 70-30 and the product contains low amounts of void (Hastak, Halpin & Hong 2004; Yquel 2012). In addition the RIM method produces components with good surface qualities (Yquel 2012).

The main application is for retrofitting of steel, cast iron and concrete members where in general CFRP composites are used (Potyrala 2011). The process of retrofitting using RIM consist of that fibres are pre-formed in a mould off-site and then transported to the site. After that the member subjected to retrofitting is enveloped by a vacuum bagging system. An adhesive bond is thereafter achieved between the composite and the structure by injecting the resin in the preform (Potyrala 2011). Another common application is manufacture of large components such as boats hulls and sandwich structures (Hurtado et al. 2012; Yquel 2012). Figure 78 displays a pedestrian bridge manufactured with the RIM method.

Figure 78 The Canary Island footbridge manufactured by the resin infused method a) Transportation of FRP girders b) and c) two phase manufacture of FRP girders (Hurtado et al. 2012, p. 5)

4.6 Pultrusion

The pultrusion process is a highly automated process with the advantages of having a low investment cost and high speed of production (Jäger & Kluth 2013). Pultrusion is a continuous process where it is possible to get constant cross sections of both simple and complex forms (Potyrala 2011; Hastak, Halpin & Hong 2004; Clarke 1996). The continuous manner of the pultrusion process makes it very cost- and labour efficient (Clarke 1996).

In the pultrusion process, the continuous reinforcement, commonly rolls of fibreglass mat or fibreglass rovings, is continuously pulled through a guide in a predetermined pattern which is then impregnated with the resin and thereafter heated up, cured and finally cut into specified lengths (Potyrala 2011; Hastak, Halpin & Hong 2004; Clarke 1996). In Figure 79 the pultrusion process is shown. When the pultruded profiles leave the processing equipment the profile is fully cured and stable (Potyrala 2011). The resin is either applied with a dip tank or through injection (Clarke 1996). The former is more common, however the latter is cleaner. The resins commonly used in the pultrusion process are isopolyester and vinyl ester. Phenolic resins have exceptional fire properties and have been developed for the pultrusion process (Clarke 1996)

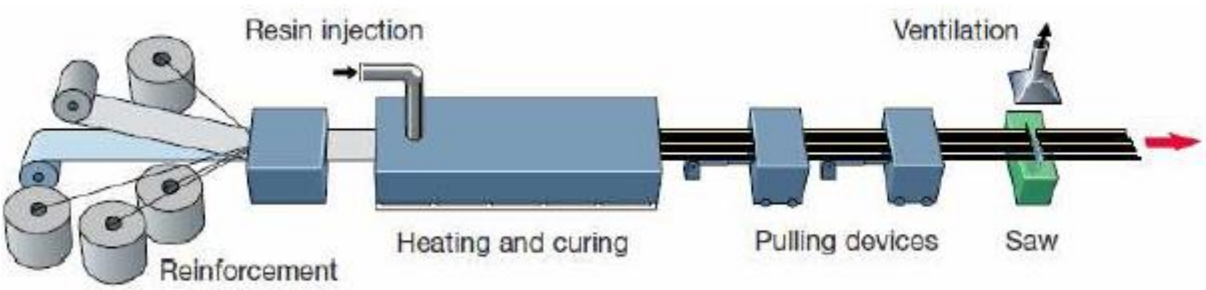

Figure 79 The pultrusion process (Potyrala 2011, p. 23)

An advantage with the pultrusion process is that visual inspection is possible during manufacture of profiles. Another advantage is that through the pultrusion process it is possible to accomplish very complex patterns of the reinforcement and in very detailed configurations (Potyrala 2011). This arrangement however requires technical resource, such as an engineered in-feed system, and experience (Clarke 1996). In order to get a profile with the highest quality, it is important that the fibre arrangement in relation to the cross section is correct (Potyrala 2011). The most critical parameters of the pultrusion process are the machine speed, the temperature of the die and reactivity of the resin (Clarke 1996). For the pultrusion process it is possible to alter the speed of the resin injection depending on the shape of the profile (Potyrala 2011). In addition, since the pultrusion process is fully enclosed the health and environmental risks are minimal since the styrene emissions are limited (Potyrala 2011). The process is highly optimized in terms of fibre use and since the colour of the profile is uniform there is not a need of repainting (Hastak, Halpin & Hong 2004)

If comparing the pultrusion process with other manufacturing techniques, it is the only process that can guarantee a satisfactory quality (Potyrala 2011). The pultrusion process achieves products that are comparable with the conventional materials steel and aluminium in terms of strength and weight (Hastak, Halpin & Hong 2004). The fibre fractions in pultruded profiles are high in the longitudinal direction which generates high mechanical properties (Clarke 1996). In the transversal direction the mechanical properties are lower (Clarke 1996). However by combining the common reinforcement types used in the pultrusion process, namely continuous filament mat and uni-directional rovings, the properties in the longitudinal and transversal direction can be optimised (Clarke 1996). The composite products produced with the pultrusion process can be formulated so to withstand conditions such as high chemical, fire and electrical environments (Hastak, Halpin & Hong 2004). With the pultrusion process it is possible to produce straight hollow sections (Clarke 1996), see Figure 80c for hollow sections.

Pultruded profiles are commonly used for all-composite applications and the profiles can be delivered either separately, partially or fully assembled to the site which can be seen in Figure 80 (Potyrala 2011). The application of pultruded profiles is extremely efficient if large quantities, in the range of at least 5000m, of beams or column sections are manufactured (Clarke 1996). However if standard sections are chosen, a small quantity of components can be produced to a reasonable cost. It is possible to produce a variety of shapes of the pultruded profiles ranging from a simple rod to a thin walled multi-cavity hollow box section (Clarke 1996).

Figure 80 Pultruded profiles as a) fully assembled b) partially assembled c) separate components (Potyrala 2011, p. 27)

The limitation in terms of shape of pultruded profiles is the size of the die (Clarke 1996). The size of the pultruded profiles ranges from a diameter of 3mm with a production speed of 180m/hour to 1m wide and 250mm deep section that can be produced at a speed of 12m/hour. The wall thicknesses of pultruded profiles range from 1mm to 50mm, however 2mm to 20mm are more common. A larger thickness of the wall can result in build-up stresses and cracking during curing. Consequently it is advisable to choose a pultruded profile with smaller wall thickness (Clarke 1996).

4.7 Continuous Compression Moulding (CCM)

The continuous compression moulding process (CCM) method can be regarded as a semi-continuous process (Mostostal Warszawa S.A. et al. 2012). In the CCM method the impregnation and solidification is performed in different parts of the machine (Mostostal Warszawa S.A. et al. 2012). The component will be impregnated and partially consolidated in the warm section and continued consolidation and solidifying in the cooling section (Mostostal Warszawa S.A. et al. 2012). In the continuous compression moulding process the heating and cooling rates are high due to separated cooling and heating zones (Jäger & Kluth 2013; Mostostal Warszawa S.A. et al. 2012).Glass and carbon fibres are the most common fibres (Jäger & Kluth 2013). In Figure 81 a scheme of the CCM process is displayed.

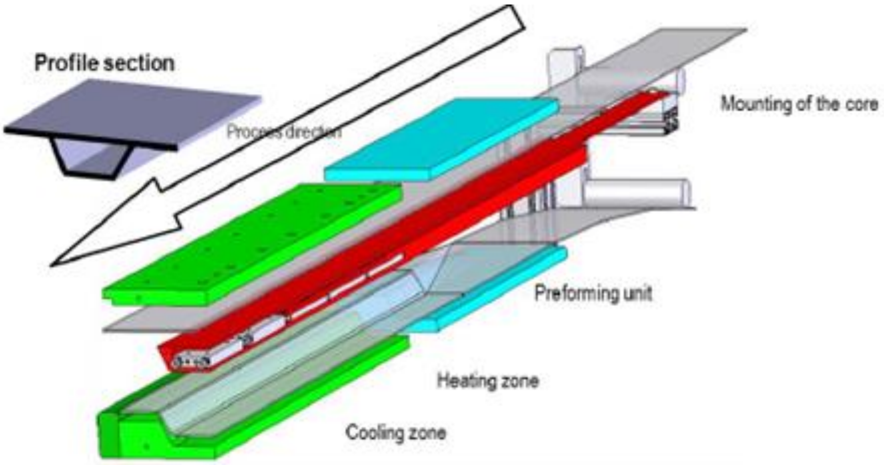

Figure 81 Scheme of continuous compression moulding (Mostostal Warszawa S.A. et al. 2012, p. 43)

4.8 Injection Moulding

Injection moulding was one of the earliest manufacturing processes and is considered the most closed system (Hastak, Halpin & Hong 2004). The process is fully automated and consists of injecting the melted plastic in a steel surrounded compound, thus forming the part (Hastak, Halpin & Hong 2004).

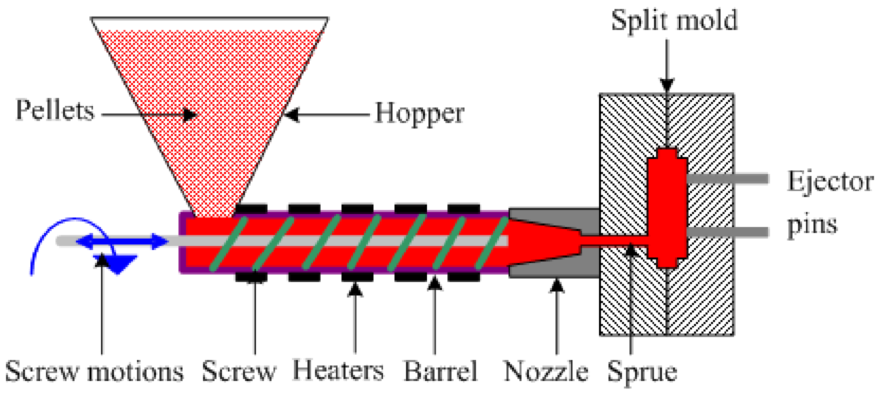

Figure 82 The polymer injection moulding process (SubsTech n.d)

4.9 Cold Press Moulding

The cold press moulding process is a moderately expensive and fast method which uses low pressure and temperature (Clarke 1996). The process consists of reinforcement being placed in the lower mould in as many layers as to reach the desired thickness. A catalyst and accelerator need to be incorporated to the resin since the system is cold cured. The mixing should be thorough and be applied on to the middle of the reinforcement. Subsequently a pressure of 5 bars is applied on the composite mix. A backpressure is created that enables flow of resin to all parts of the cavity. The cure time is relatively rapid and varies between 5 and 15 minutes which are due to the highly reactive resin mix. A highly reactive resin should be chosen such as epoxy or vinyl ester. The reinforcement commonly used in the cold press moulding process is continuous filament mat and needle mat made from glass fibres or woven roving and multi-axial fibres (Clarke 1996).

The size of the press used in the manufacture of the components will determine the size of the components (Clarke 1996). A common size of a component manufactured from the cold press moulding is in the range of $0.5m^2$. The economical quantity of produced component with the cold press moulding process is in the range of 100 to 5000 components. The general quantity of components is commonly in the range of 500 components (Clarke 1996).

4.10 Autoclave/Vacuum Bag Moulding

The process consists of resin pre-impregnated layers of fibres (prepreg) that are applied to the mould and then rolled (Clarke 1996). The air is thereafter removed by covering the lay-up with a rubber bag and subsequently pumping out the air with a vacuum pump. The next step is to put the mould in an autoclave. In the autoclave the resin is cured by subjecting the mould to high pressure of 10-20 bars and a temperature of 180°C. The resin could also be cured by placing it in an oven. The resin material mainly used is epoxy. The reinforcement used is prepregs consisting of glass, carbon and aramid fibres (Clarke 1996).

An advantage with the autoclave/vacuum bag moulding process is that it provides excellent properties (Clarke 1996). The process is beneficial in terms of clean handling and logistics (Yquel 2012). In addition the resin is well defined and fibres are generally thoroughly wetted out (Yquel 2012). However the process requires a large amount of labour and is time consuming (Clarke 1996). The sizes of the components are regulated by the size of the autoclave or oven available, but are generally in the size of $2m^2$ to $100m^2$. The autoclave/vacuum bag moulding process is not appropriate to production of large quantities of components, since the cycle time rate is slow ranging from 1 to 20 hours. The number of components is generally restricted to less than 500 where the typical quantity is approximately 50 components (Clarke 1996).

4.11 Hot Press Moulding

With the hot press moulding process large quantities of components can be produced (Clarke 1996). The hot press moulding process can be seen in Figure 83 and consists of placing thermoset polymer mix between two moulds that have been heated to 130°C to 170°C and then closing the moulds. The resin mix is let to cure for 2 to 3 minutes and subsequently the component is removed from the mould. The factors that influence the curing time are related to the type of resin, the level of curing agent and the components thickness. The reinforcement and resins can either be added to the mould separately or as prepregs. If resin and reinforcement are added separately then commonly sheet moulding compound (SMC), dough moulding compound (DMC) and bulk moulding compound (BMC) are used. They contain a polyester resin and fillers, catalyst, pigment, low-profile additives etc. If the compound is added as a prepreg then commonly an epoxy or polyester resin is used with glass or carbon fibres in the form of CSM or as CFM (Clarke 1996).

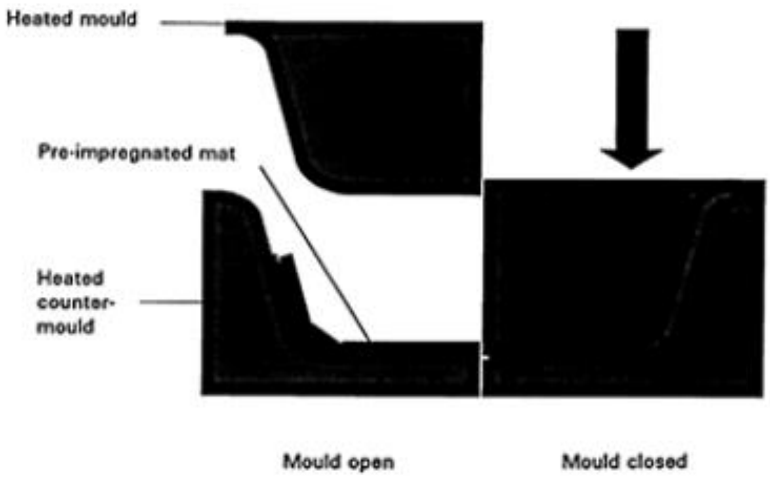

Figure 83 Hot press moulding (Clarke 1996, p. 271)

The sizes achievable with the hot press moulding method ranges from 0.5m^2 to 3m^2 (Clarke 1996). This indicated that the produced components are not applicable for vehicle bridge application. The tools and press are in general expensive leading to a high investment cost (Clarke 1996). Due to this produced quantities lower than 10 000 is not profitable (Clarke 1996).

4.12 Comparison Production Techniques

In Table 61 and Table 62 are the presented manufacturing techniques compared in terms of constituent materials, achievable fibre volume fraction, size range and cost etc.

Table 61 Summary of properties for FRP production methods

Manufacturing Process	Rate of production	Size of laminates [m^2]	Viable Quantity	Resin	Reinforcement
Hand lay-up	3 kg/h	0.5-300	1-500	Low viscosity mainly epoxy	Knitted rovings or chopped strand mats
Pultrusion	12-180 m/h	3mm diameter to 1mx250mm	> 5 000m	Isopolyester and vinyl ester also phenolic	Rolls of fibreglass mat or fibreglass rovings
Resin Transfer Moulding	3 Specimen/hour	0.5-10	Several hundreds to 2 000	Low viscosity mainly epoxy, also phenolic and polyester	CFM and CSM

Spray-up (Catalyst injection)	2.5 kg/min or 20 kg laminate/h	10 common but any size > 2 ok		Isopolyester and ortopolyester	Special glass fibre rovings (chopped)
Cold press moulding	Cycle: 5 to 15 minutes	0.5	Commonly 500 but 100-5 000 economical	Low viscosity/high reactive resins epoxy and vinyl ester	CFM and needle mat (both glass fibre) but also WRs and multi-axial (glass, carbon, etc.)
Autoclave/Vacuum bag Moulding	slow	2-100	Commonly 50, but < 500	Epoxy	Prepregs (glass, aramid and carbon)
Hot Press Moulding		0.5-3	10 000	Epoxy or polyester or prepreg	CSM or CSM (glass or carbon)
Filament Winding	Cycle: Commonly 4h but ranges from 1-24hours	Diameter: 300mm to 12m, Length: 2m to 38m		Mainly epoxy but also polyester, vinyl ester or prepregs	Glass fibre rovings, carbon fibres and aramid fibres as yarns or rovings
Resin Infusion Moulding				Very low viscosity: modified epoxy resin or prepreg	
Continuous Compression Moulding (CCM)					Glass and carbon fibres

Table 62 Comparison between different FRP manufacturing techniques (Chlosta 2012)

Type	V_f [%]	Size range [m^2]	Processing pressure [bar]	Processing temperature [C]	Detail tolerance [mm]	Relative production cost [-]
Open mould process						

Hand lay-up	13-50	0.25-2 000	ambient	ambient	1.0-5.0	High
Spray-up	13-21	2.0-100	ambient	ambient	1.0-3.0	Low
Filament winding	55-70	0.1-100	ambient	ambient	1.0-2.0	Moderate/low
Closed mould process						
VARTM	15-35	1.0-3.0	1.0-2.0	15-30	2.0-5.0	Moderate/hig h
Resin infusion moulding	10-15	0.25-5.0	1.0-2.0	20-50	1.0-2.0	Moderate
Injection moulding	510	0.01-1.0	750-1 500	140	0.1-5.0	Very low
Cold press moulding	15-25	0.25-5.0	2.0-5.0	20-50	0.25-1.0	Low
Hot press moulding	12-40	0.1-2.5	50-150	130-150	0.2-1.0	Very low
Autoclave/ Vacuum bag	35-70	0.25-5.0	1.0-10.0	20-140	0.5-1.0	Very high
Continuous process						
Pultrusion	30-65	up to 1m wide	varies	130-150	0.2-0.5	Low

A summary of the advantages and disadvantages of the different manufacturing techniques are displayed in Table 63.

Table 63 Advantages, disadvantages and applications for FRP production methods

Manufacturing Process	Advantages	Disadvantages	Applications
Hand lay-up	Easy to teach, Low investment cost, Inexpensive, Large and complex shapes, Small quantities justified	Manual process, Labour intensive, Open process (emissions of styrene), Hygienic working conditions required, Low production rate,	Low quantity of products, Complex and large shapes, Low intrinsic

		Large scale production not suitable, Lower fibre fraction and mechanical properties, Thicker laminates, Lack of consistency in quality, Only one finished surface	properties
Pultrusion	Closed process, Low investment cost, High speed of production, Larger scale production, Fast and economic impregnation and curing, High resin content, Wide range of profile geometries, Constant sections, High strength in fibre direction, Labour efficient, Visual inspection during production, Highly optimized system, No need of repainting, Only process that can guarantee satisfactory quality, Products comparable with steel and aluminium, High resistance to chemical, fire and electrical environment	Low strength in transverse direction, lLrge production area needed, Shrinkage must be low, Engineered in-feed system and experience required, Size of die limits size of elements, Thicker sections create build-up stresses and may crack	Decks, Beams, Columns, Straight hollow sections, Complex shapes such as thin walled multi-cavity hollow box section
Resin Transfer Moulding	Short cycle time, High quality, Closed process (low emissions of styrene), Autoclaving not required, Inexpensive moulds, Injection and cure possible at both ambient and elevated temperatures, Complex shapes, Cost effective structures at smaller scale, High fibre volume	Medium speed of production, Small to medium sized components, Small to medium quantities possible, Higher cost and complexity of tooling and equipment than hand lay-up, Lower adherence to dimensional tolerances than pultrusion process, Viscosity of resin need	Medium volume production available

	fractions 65%, Good surface qualities	to be low when injected	
Spray-up (Catalyst injection)	Less expensive and time consuming than hand lay-up	Manual process, Cannot produce high strength components, Problematic to control fibre volume fraction, Properties of composite highly dependent on operator	Non-structural parts
Cold press moulding	Moderately expensive, Fast, Low pressure and temperature, Small components	Accelerator and catalyst need to be incorporated due to cold cure	Small components
Autoclave/Vacuum bag Moulding	Excellent properties, Clean handling, Logistics	Time consuming, Labour intensive, Curing with autoclave, Not appropriate for production of large quantities, Low cycle time	High performance, Large components
Hot Press Moulding	Large quantities of components, Fast cure	high investment cost, small components	
Filament Winding	Inexpensive materials and process, Excellent properties, Process with high level of control, fibre placement repetitive, orientation of fibres in load direction easy and without joints, controlled fibre content, high quality of laminate achievable, exceptional properties	Low volume fraction, Only tubular shapes, Expensive machinery, Time consuming, Good fibre impregnation required	Tubular shapes, Demanding applications
Resin Infusion Moulding	Large elements, Good surface quality, Closed process (low emissions of styrene), Fast curing, High performance laminates, Contains low amounts of voids, High	Challenge with proper impregnation especially for thick laminates, Very important that the fabric is fully impregnated by the resin, Prepreg is more	Large elements such as boat hulls, sandwich structures and bridges also retrofitting

	fibre volume fraction 70%, Good surface qualities	expensive than separated compounds	
Prepreg	Well defined resin content, Clean handling, Excellent fibre wet-out, Logistics		Bridges, for example the PUMACOM bridge and M-111 bridge
Continuous Compression Moulding (CCM)	High heating and cooling rates		

4.13 Selection of Production Technique

The parameters that should be considered when choosing manufacturing technique are: (Potyrala 2011)

- number of elements that should be manufactured
- desired shapes and dimensions
- tensile strength requirements
- mechanical parameters such as Young's modulus
- thermal properties such as thermal expansion coefficient
- surface quality

4.14 Logistics and Assembly

With the Trans-IND project the aim is to develop "a cost-effective integrated construction process that will enable the maximum capability of industrialisation of composite components for transport infrastructures" (Mostostal Warszawa S.A. et al. 2012).

For the Trans-IND project one of the main focuses have been to improve the logistics and on-site assembly process in order to shorten installation times to limit traffic disturbances (Mostostal Warszawa S.A. et al. 2012). In Figure 85 are the different phases of the Trans-IND construction process displayed. The Trans-IND brings advantages such as a more cost effective construction process with a more efficient industrialization of infrastructure members such as beams, decks, joints etc. consisting of FRP (Mostostal Warszawa S.A. et al. 2012). In addition the system Design for Manufacture and Assembly (DFMA) has been incorporated in the Trans-IND projects which have led to a reduction in efforts regarding manufacture and assembly which have ultimately led to a decreased cost (Mostostal Warszawa S.A. et al. 2012).

New technologies that have been developed within the Trans-IND projects are: RFID systems used for tracking elements, adapted ICT's and intelligent positioning systems (Mostostal Warszawa S.A. et al. 2012). These new technologies have enabled just-in-time delivery and easier construction on space-limited sites (Mostostal Warszawa S.A. et al. 2012). The intelligent positioning system facilitates the positioning of large elements with precision (Mostostal Warszawa S.A. et al. 2012). This have led to a more rapid and safe positioning of the members (ZRMK et al. 2013). The scheme of the intelligent positioning system can be seen in Figure 84. In order for FRP to be able to compete with the conventional construction materials in civil engineering application the use of these new technologies is crucial (ZRMK et al. 2013).

Figure 84 Scheme of intelligent positioning system (Mostostal Warszawa S.A. et al. 2012, p. 34)

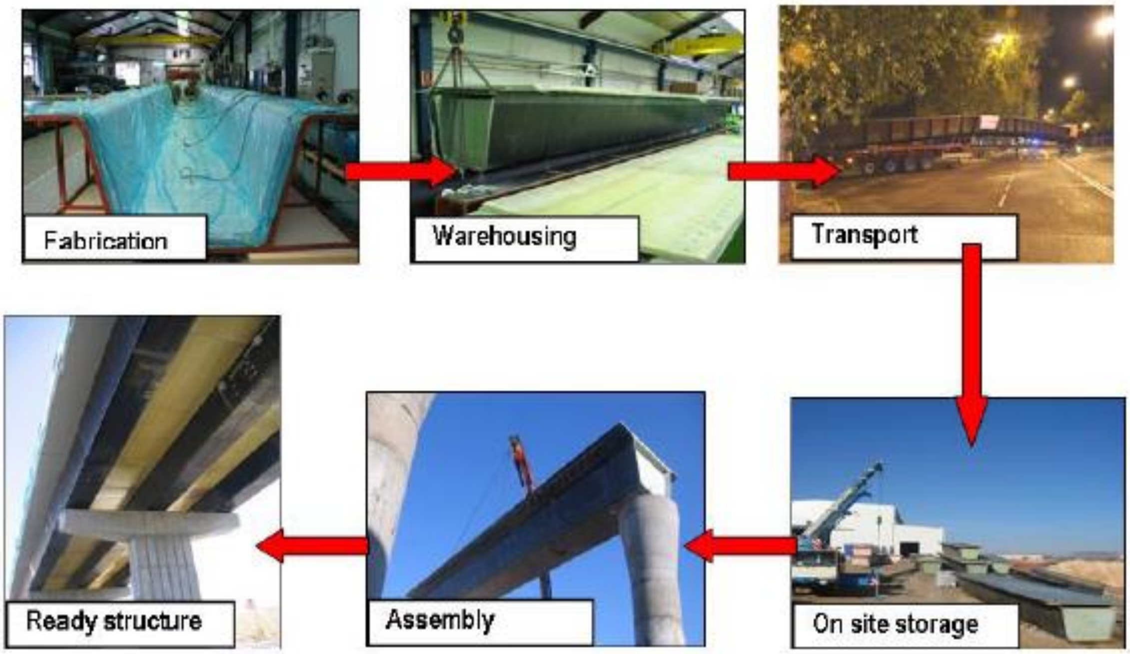

Figure 85 Main phases of the Trans-IND construction process (Mostostal Warszawa S.A. et al. 2012, p.57)

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5 Quality Assurance and Workmanship

The quality assurance (QA) and quality control (QC) are one of the more important issues during the manufacturing process (Zoghi 2013).The FRP composite material properties are very unique, during the design and manufacturing process many stages can be adjusted and controlled to produce the required quality of the material (Zoghi 2013).

The first step of QA begins with evaluating and characterizing the properties of the raw materials used for the production of composite components (Zoghi 2013). The second step includes equipment and tooling to ensure the fabrication process. During the manufacturing process the component can be tested with mechanical, vibroacoustic and thermal loading condition. The subcomponents are generally subjected to tensile, compressive and damage tolerance tests (Zoghi 2013). The last step of QA is to use a non-destructive testing (NDT) to evaluate the whole manufacturing process and the finish composite product (Zoghi 2013). Testing standards can be found in Appendix B.

5.1 Types of Production Defects and how they affect Properties

No additional information

5.2 Allowable Defects and Defect Size

No additional information

5.3 Non-destructive testing Techniques for Quality Control

The non-destructive testing is a wide group of inspection techniques to evaluate and observe the condition of the structural components and the structural performance (Meyer 2006). Along with the NDT techniques many forms of defect can be detect which could reduce the possible service disruptions or restrictions for extended periods of time (Karbhari, Kaiser, Navada, Ghosh & Lee 2005). A better balance between quality control and cost-effectiveness can be provided with NDT testing (NDT resource center 2012).

There exist several types of steps related to the NDT which are both performed during field test and in industries. These include the non-destructive testing (NDT), non-destructive evaluation (NDE) and non-destructive inspection (NDI) which can be seen in Figure 86 (Karbhari et al. 2005).

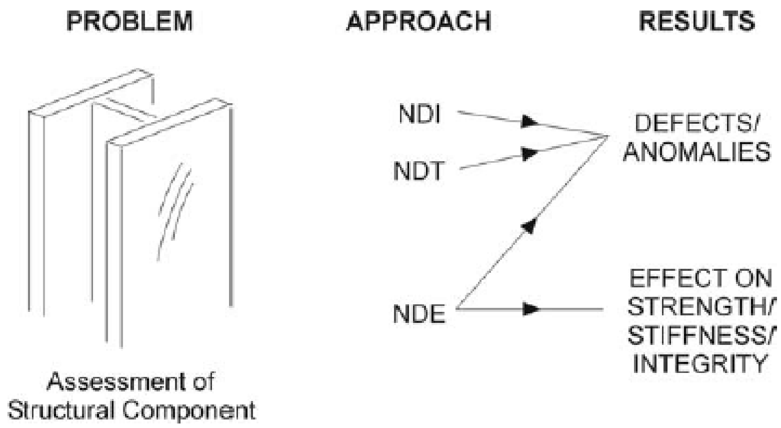

Figure 86 Categorization between non-destructive methods (Karbhari et al 2005)

The NDT and NDI Testing methods are used to detect the type, location and size of the defect (Karbhari et al.2005). A further step to define the effect of damage on structure condition is often accomplished in an evaluation process as well as NDE (Karbhari et al.2005). The method of NDE focus more on details and measurement of the defect size, shape and orientation, even material properties could be determined, such as fracture toughness, formability etc. (NDT resource center 2012).

Several NDT techniques are used for FRP composite material, which are:

- Visual / Optical Testing
- Tap Testing
- Thermography Testing
- Acoustic Emission
- Ultrasonic Testing
- Radiographic Testing
- Modal analysis
- Static load Test

5.3.1 Visual Testing

The Visual inspection testing is the commonly used method of testing included in NDT. The Visual testing (VT) is able to discover the defects of the surface only (Meyer 2006). These instruments of VT includes flashlight, marker, binoculars, inspection mirrors, magnifying glass, feeler gages, markers, a straight edge, measure tap and geologists pick (Meyer 2006). The defects generally include UV damage, deboning from the wearing surface, blistering and moisture effect (Zoghi 2013).

Another method to detect cracks or other defect with VT is by loading for example water on a dump truck which reveals cracks and undesirable vertical deck movement of the decks see Figure 87 (Meyer 2006). In general the VT inspection could be combined with sounding testing as well, which would create an extra dimension of the inspection process (Zoghi 2013).

Figure 87 Visual inspection with dump truck placed on deck (Meyer 2006)

5.3.2 Sound/Tap Testing

The sound testing is the second most used testing method for FRP bridge decks (Meyer 2006). The advantage of this testing is that it is inexpensive and effective in finding defect like delamination or deboning problems. The method generally uses a hammer tap, seen in Figure 88, or sound emitted by a coin to detect issues of the composite material. With a larger coin, the sound emitted is more capable to remark defection like voids or delamination (Meyer 2006).

The frequency can furthermore distinguish issues associated with void or delamination (Meyer 2006). A dull sound is generally identifies as an issues of delamination or void where the material has a lower stiffness (Zoghi 2013). A clear sharp ringing sound can be associated with that the bonded structure still is in good shape (Meyer 2006). Due to the geometry changes of the structure the sound frequency will vary (Meyer 2006).

Figure 88 Electronic tap-test (Meyer 2006)

An advantage of the coin test in comparison with the hammer test is that it is more effective for thick composites with large surface areas (Meyer 2006). The hammer test is however used more effectively in a noisy environment. The hammer test is furthermore more effective for FRP composite deck such as sandwich core deck with the exception for pultruded decks. This is related to that the pultruded decks come in a variety of dimensions and geometric shapes which can produce frequency changes and erroneous indication of the defect (Meyer 2006).

5.3.3 Thermal Testing

The thermal testing uses a heat source along with an ultraviolet camera to measure the temperature variation of the object (Meyer 2006). In general the heat is applied to the surface with natural sunlight or a pulsed light source. The variation of the surface or voids included in the material could interfere with the wave of radiate and the discontinuities of the composite can cause the gradient changes during the measurement of the camera (Meyer 2006). Figure 89 displays the thermal testing of FRP composites and Figure 90 the difference of thermal testing of a FRP composite and steel.

Figure 89 Thermography image of a bridge deck during heat source is applied (Meyer 2006)

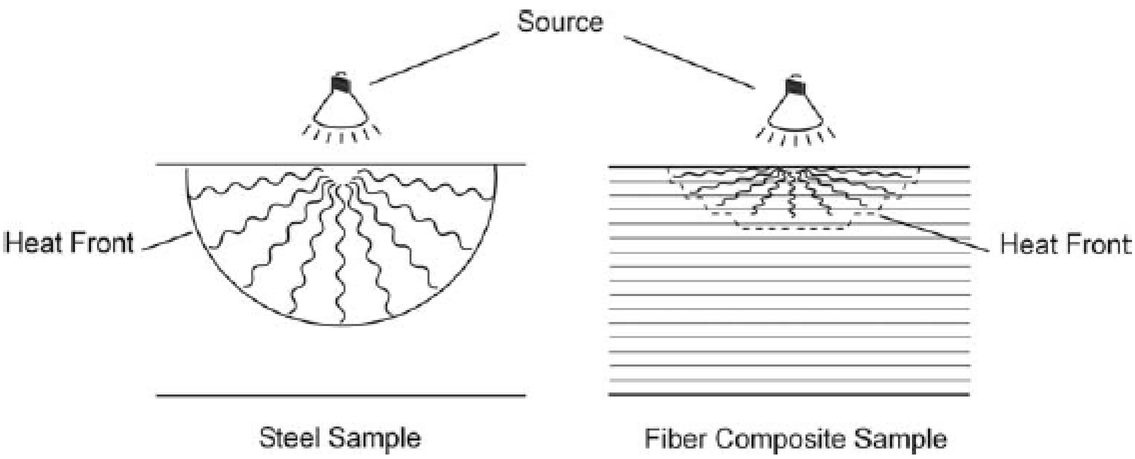

Figure 90 Comparison due to thermal conduction in steel and composite materials (Karbhari, Kaiser, Navada, Ghosh & Lee 2005)

Another method which can be used for thermal testing is the shearography. This method is a non-destructives testing to measure the first derivative of the out of plane displacement which is subjected by a thermal or mechanical load (UNIVPM, ITIA-CNR and D'APPOLONIA 2011). The Laser vibometry is also a promising NDT method which uses a laser. The energy requirements of this testing method are however very high and more suitable for the aeronautic or automotive industries using FRP composites (UNIVPM et al. 2011).

The advantage of the thermal testing method is non-contacting system; the heating process to the material is done by remote control (Meyer 2006). Complex shapes are additionally easier to test with the non-contacting testing method (UNIVPM et al. 2011). The thermography testing is furthermore effective to detect problems such as voids, delamination, deboning surface and impact damage (Meyer 2006). Figure 91 illustrates a void found in a sandwich deck with thermal testing. The disadvantage is however the cost of the thermography system which can be up to 200.000 US dollar for high definition of the image process system (Meyer 2006).

Figure 91 Void found in the face sheet of sandwich deck (Meyer 2006)

5.3.4 Acoustic Emission Testing

The Acoustic Emission (AE) testing is a method which can monitor the precise location and assessment of the damage for complex structures (UNIVPM 2011; Meyer 2006). The AE testing includes stress wave which are generated on the material which is subsequently recorded by one or several sensor or transducers (UNIVPM et al. 2011; Meyer 2006). The acoustic sound rate will usually produce around 20 KHz to 1 MHz of the test element (Meyer 2006). The typical defects in the material could be fibre breakage, delamination composite material, crack initiation and growth (UNIVPM et al. 2011; Meyer 2006). The AE testing method cannot however determine the size of the defect or the configuration (Meyer 2006; Zoghi 2013). The AE inspection may be not the optimum choice for structural members subjected to fatigue loading (UNIVPM et al. 2011). Figure 92 illustrates the acoustic emission test.

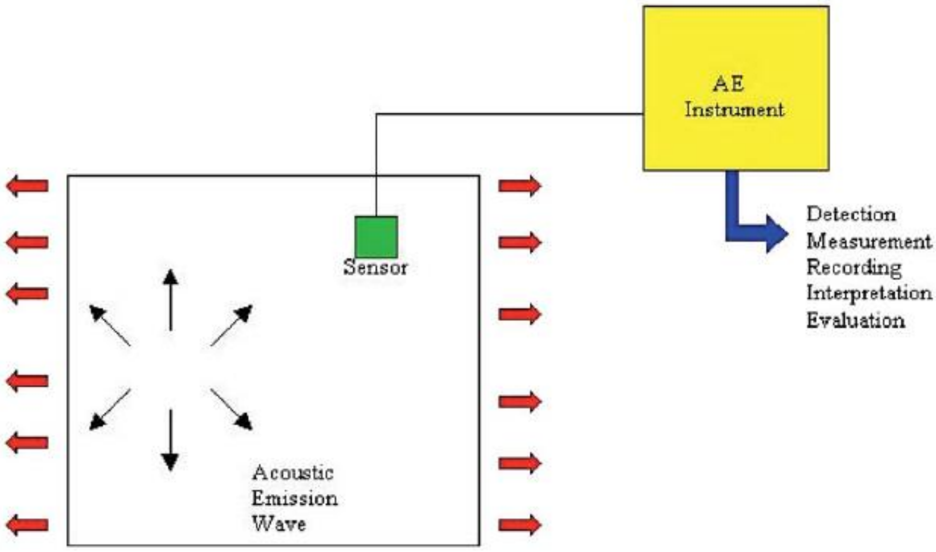

Figure 92 The sensor is arrayed on the structure member and connected to detection measurement (Meyer 2006)

5.3.5 Ultrasonic Testing

The ultrasonic testing (UT) method has a great potential to inspect different types of materials by using different configuration and frequencies (UNIVPM et al. 2011). For the UT method a couplant is applied to the area of the structural member subjected to inspection subsequently the area is scanned with a transducer which is attached to a UT machine. The transducer contains a type of crystal which is called piezoelectric which transmits the high-frequency sound to the sample and returns the signals to a form of "A" or "C" scan (Meyer 2006). The "A" scan can be displayed on an oscilloscope display and gives an amplitude data of the time from the flight and reflection (Meyer 2006). The "C" scan is scanning equipment and gives a plan view of the defect (Meyer 2006) which can be seen in Figure 93. In general UT uses high-frequency sound in the range between 20 KHz to 25MHz (Meyer 2006). Typical defect can be found from UT method are delamination, debonding, broken fibres, moisture effect, impact damage etc. (Meyer 2006; Zoghi 2013).

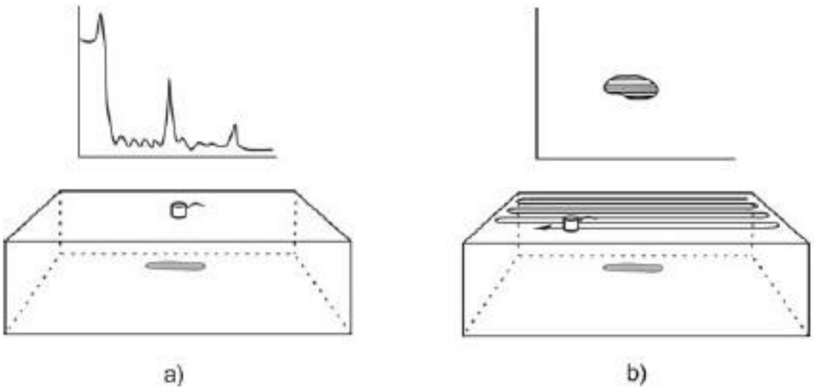

Figure 93 a) idealized from A-scanner delamination, b) C-scanner delamination (Karbhari et al. 2005)

Compared to the previous testing methods, the UT method requires a higher level of expertise to carry out the data properly (Meyer 2006). The UT method is not suitable to inspect the top of FRP bridge deck due to the uneven surface which contains aggregate and will ultimately not carry out any good results. It is more appropriate to start with inspections such as visual inspection, tap test or AE, then the UT method can be used to retrieve the size and location of the defect. However is more suitable to use on the bottom and the sides of FRP bridge deck (Meyer 2006). Several configurations are used today for inspections which are air-coupled ultrasonic, contact ultrasonic and laser ultrasonic.

5.3.5.1 Air-Coupled ultrasonic

Figure 94 is showing three different types of air-coupled ultrasonic testing where the left is the transmission mode along with two sensors for top and bottom, in the middle is Pulse Echo mode and to the right is the Pitch & Catch mode with double sensors on the top (UNIVPM et al. 2011).

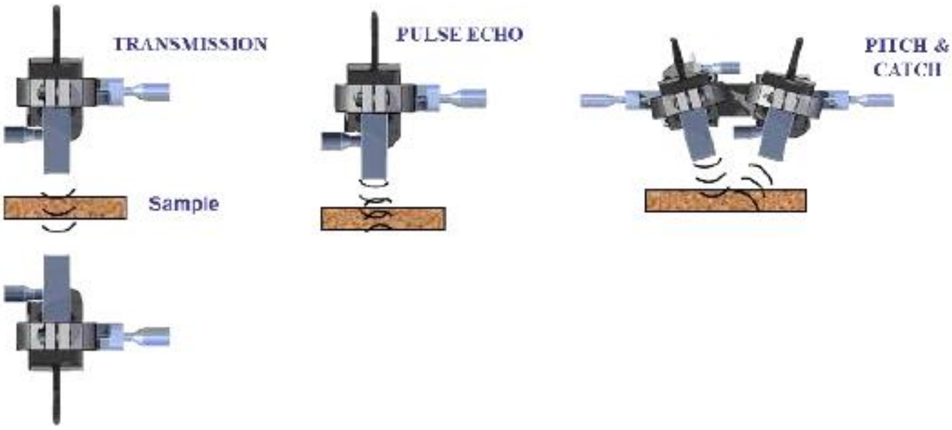

Figure 94 Air-coupled ultrasonic configurations (UNIVPM et al. 2011)

The air-coupled ultrasonic test is well suited for inspection of complex structural elements. They are in addition flexible and simple which enables for an easy inspection process (UNIVPM et al. 2011). By using robotic manipulators the method is even more precise in alignment and position. The Pitch & Catch mode is the one of the most used air-coupled method for thin panel structures or honeycomb sandwich elements. The method is more appropriate for thin panel structures since investigation has shown that thicker sandwich panels have high attenuation which gives lower accuracy of the frequency. The transmission mode is the most feasible for non-contact and is well suited at the production site. Figure 95 displays the transmission and pitch & catch modes from a C-scan, where it is clear that the defects can be identified more clearly with the transmission mode. A disadvantage of the air-coupled method is that large amplitude losses between the solid and the gas (air) can be produced for thick sandwich components (UNIVPM et al. 2011).

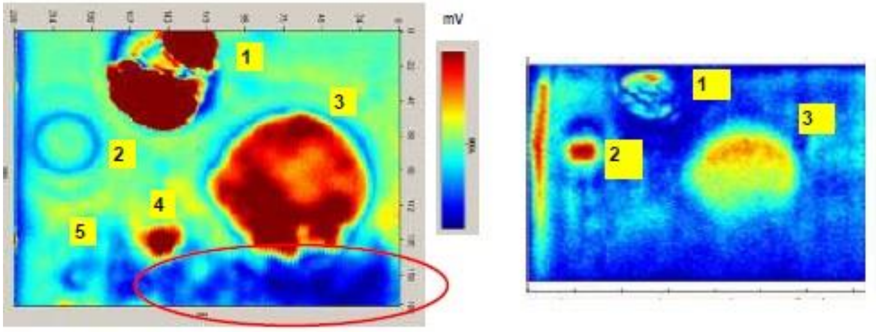

Figure 95 Air-coupled ultrasound, Left: C-scan for transmission mode, Right: C-scan for pitch & catch (UNIVPM et al. 2011)

Figure 96 demonstrated two panels with different thicknesses with dry fibres in the surface. A C-scan demonstrates that the transmission mode simulates the defects very well and can be considered a promising technique which gives an optimal resolution.

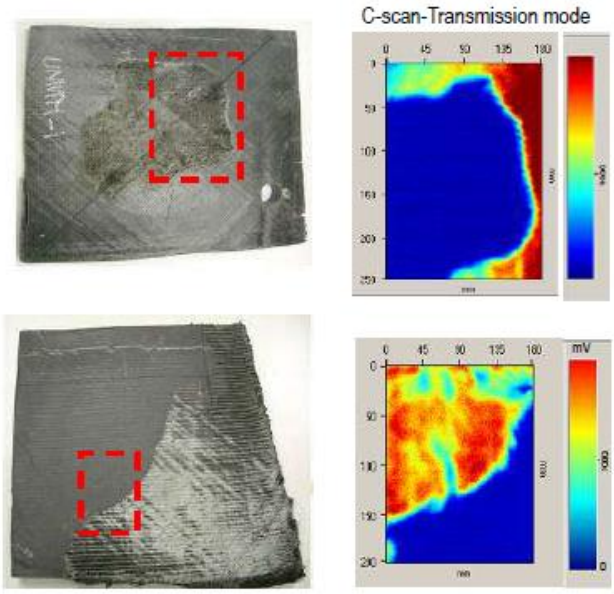

Figure 96 Transmission mode of an air-coupled ultrasound subjected to a CFRP laminate panel (UNIVPM et al. 2011)

An advantage with the non-contact technique is that it is easy to adjust the configuration of the modes depending on how the structural element looks like, see Figure 97.

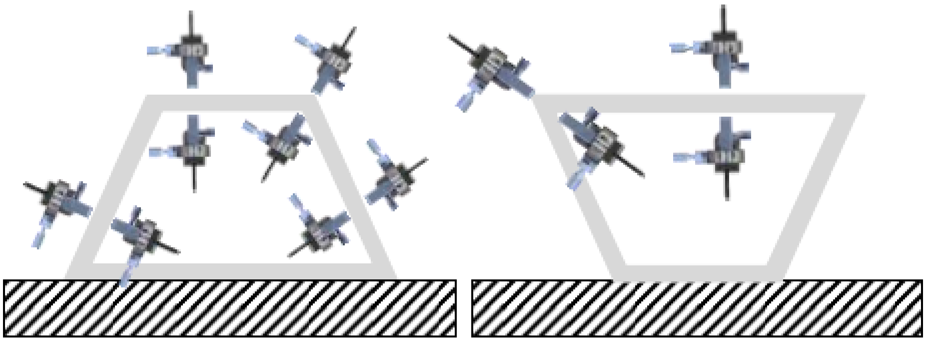

Figure 97 Close-shaped beam inspection with non-contact sensors (UNIVPM et al. 2011)

5.3.5.2 Contact Ultrasonic

The contact ultrasonic method is similar the air-coupled ultrasonic method; the only difference is having liquid, gel coupling in between the transducers. This type of method is appropriate for accurate inspection of high thickness elements (UNIVPM et al. 2011). Lower frequency is usually applied in on high thickness elements (>6-8mm at 50 kHz). Small defects on complex structures could be challenging to detect. It is necessary to find the appropriate set-up frequency between the penetration and resolution. The contact ultrasonic method is appropriate for CFRP, GFRP and sandwich structure (UNIVPM et al 2011).

The advantages with the contact ultrasonic inspection are that it is quick and the results are reliable for structural components with large areas and curved shapes (UNIVPM et al. 2011). The disadvantage is that for large structural component it is challenging to recognize the particular shape of the sensor and hard to move on an unsmooth surface. In general the contact ultrasonic method could be used for the medium frequency (400-500 kHz) to control bigger structural component in a water tank. However that will not be a suitable due to the size of the structure (e.g. bridge beams) and will be expensive and complex (UNIVPM et al. 2011).

5.3.5.3 Laser-Based Ultrasound Method

Laser-based ultrasound is also one of the ultrasonic testing methods. The technique is combination of optics and ultrasonic in order to identify, locate and control the defect size of the material (Meyer 2006). The laser-based ultrasound involves a pulsed laser which produces ultrasonic waves into the material. The second laser which is coupled to an optical interferometer identifies these waves (Meyer 2006). Figure 98 and Figure 99 illustrates laser-based ultrasound method

Figure 98 Left: C-Shape laser scan for external scanning; Right: Laser scanning system for internal inspection (UNIVPM et al. 2011)

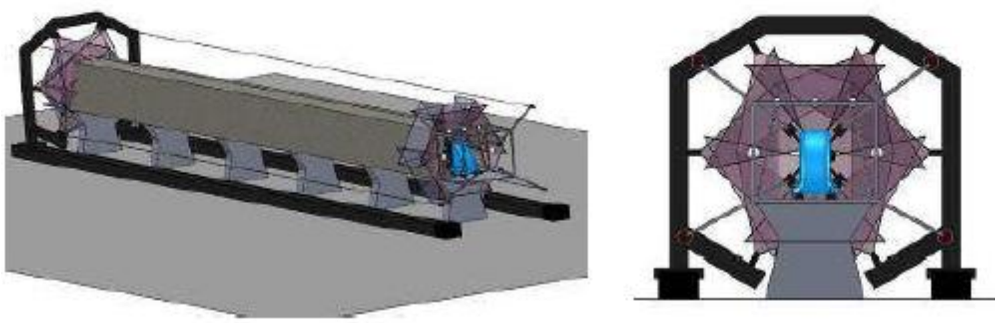

Figure 99 Laser scanning for both internal and external structural elements (UNIVPM et al. 2011)

The advantage of the laser-based ultrasound method is that it is a non-contact method which does not require couplings and is capable of inspecting large-scale field testing. The equipment of the laser-based ultrasonic testing method is however expensive and the basic equipment generally cost 10.000 US dollar (Meyer 2006).

5.3.6 Radiography Testing

Radiography inspection on the composite material mostly uses x-rays and neutron radiation to detect defects (Zoghi 2013). The defect can often be detected by the difference in absorption of radiation between composite parts; the comparisons accounts for the effect of the difference in the materials density. The unabsorbed radiation of a material can be detected by photographic film or a camera (Zoghi 2013). The radiography might not capture the volumetric characteristics as ultrasonic testing; however it can provide a higher resolution of the planar defects (Meyer 2006).

The reverse-geometry digital x-ray is another method of radiography which can be used (Meyer 2006). It will provide a lower level of x-ray imaging system, using the television-type instead of film sheet which is combining with computer-read digital data from a sensor unit. The x-ray method show similarities in the inspection process with the previous mention testing methods where one side being the source and the other side the receiver. Three-dimensional image can be done by the alignment of the x-ray source and the objects. Compared with the radiography inspection the digital x-ray method has a faster scanning process and is much safer (Meyer 2006).

The typical defects which can be discovered with radiography methods are broken fibres, voids, debonding (depending on the fibre orientation), impact damage, cracks and delamination to some extant (Meyer 2006). The radiography method is however a very expansive process and requires higher levels of skill when conducting tests and evaluation and the method might not be appropriate to use as periodic inspection for quality control (Zoghi 2013; Meyer 2006).

5.3.7 Modal Analysis

The vibrational (modal parameters) inspection method is a health control for the NDE method; that uses the changes in the dynamic response (i.e. natural frequency and modal characteristics) to evaluate and locate defects of the composite material (Zoghi 2013; Meyer 2006). The inspection process is often subjected equipment such as impact hammer and pulse excitation on the composite material (Zoghi 2013). The acceleration behaviour is recorded and converted into a natural frequency and mode shapes using vibrational analysis methodologies which enables for further investigation of the results which can be compared to the defect-free sample (Zoghi 2013). This type of method should only be used when other methods are incapable to locate the hidden defect and the global structural performance of the FRP deck (Meyer 2006). Figure 100 illustrates an example of a modal testing set-up.

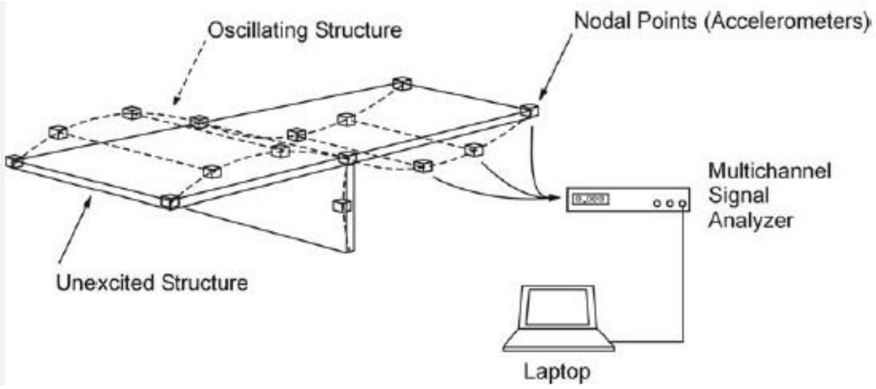

Figure 100 Modal testing for large-scale structural members (Karbhari et al. 2005)

There is also inspection to evaluate the stiffness changes in structure by identifying the damage location index (Meyer 2006). The result from the damage location index can be investigated in order to determine the potential damage of the structural member. The disadvantage of this method is that it requires the researcher to have a high level of experience and the experimental level to implement the inspection process is very high. The type of method is furthermore expansive but is however a viable option if the structure has undertaken changes in the stiffness (Meyer 2006).

5.3.8 Static Load Test

Static Load test is a non-destructive field performance evaluation test (Meyer 2006). This method includes sensors to record the live loading performance such as strain gages, accelerometers and displacement sensors. The placement of the sensor can vary depending on the selection of the load pattern. By using the load testing method the structural health can be verified for long-term conditions. The testing method is well-suited for FRP bridges before they are put in service. The static loading is generally tested at periodic intervals to control the bridge deck condition over time. The requirement for the method includes skill during the set-up and for evaluating recording data. The static load test should only use if no other technique could detect the hidden damages and the global structural behaviour over time (Meyer 2006).

The procedure of the static load test to verify the bridge performance and detect the potential damages is (Meyer 2006):

Timing – The load testing should be performed shortly after the bridge construction is completed and periodic testing for weather and environmental condition should additionally be implemented.

Test load – The loading method can be applied with heavy trucks where the deflection of the deck can be regarded, see Figure 101.

Figure 101 Heavy trucks placed on the PUMACOM Bridge - the static load test (Muniz & Bansal 2009)

Test configuration – by moving and stopping the trucks and predefining at least two symmetric lanes. Depends the span length of the bridge, the mid-span and quarter point length span is recommended.

Test procedure – by placing the heavy trucks on a specified location for a specified period of time (e.g. ½ h). Signs of damage under the load and the deflection data are subsequently collected by end of the time. The test procedure is repeated when the truck have moved to the next position.

Instrumentation and data collection – several positions at the bridge are recommended to carry out the collection of deflection data, such as quarter points and mid-span along the bridge and three transversely, see Figure 102. In general the measurement equipments that can be used are electronic displacement transducer, mechanical dial gages, hand ruler and taut string. The measurement of the deflection is appropriate to conduct at the end of each stop time and halv hour after the unloading.

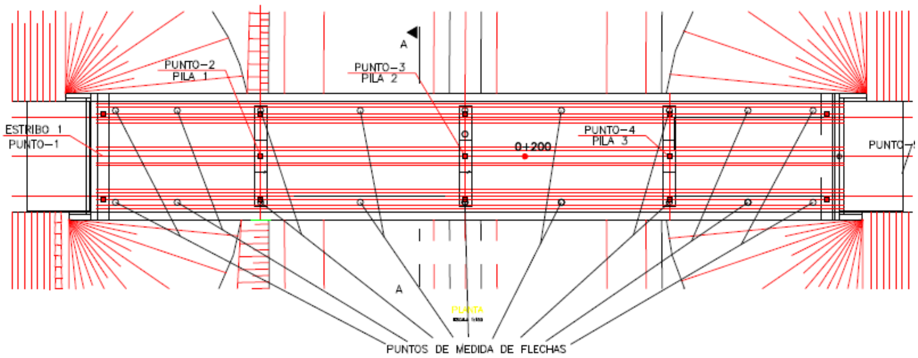

Figure 102 The PUMACOM bridge in Spain where the measurement points are marked with black circles (Muniz & Bansal 2009)

Criteria – There exists many criteria's and standards, for bridge deflections however the recommendations given by AASHTO can be followed. The deflection should recover ± 5% after unloading. The deflection will differ with time and the bridge required future inspection with visual inspection and static load tests.

5.4 Comparison of Non-Destructive Testing Methods

Table 64 includes a summation of the presented NDT testing methods with regard to advantages, disadvantages etc.

Table 64 Summation of NDT testing methods

Methods	Advantages	Disadvantages	Time required	Detected defects	Application
Visual test (Level I)	Combination with other test method more defects can be detected Fast and low cost	Can only detect defect on surface	2 – 4 hours	Blistering or deboning of wearing surface	Well suited for assessment of FRP decks
Sound/Tap test (Level II)	Fast and low cost Very little experience required	Not effective for all types of FRP decks Not able to determine the state of internal member. Not fit for thick pultrusion decks	2 – 4 hours	Delamination and deboning of composite materials	Thick composite and large area (coin test). Noisy environment and sandwich decks (Hammer test).
Thermography test (Level II/ III)	With non-contacting system it is easy to inspect complex structural shapes The heating process to the material is done by remote control	Expansive equipment Not effective for thick composite elements	0.5-1 hour for setup time, scanning is instantaneous	Void, delamination, deboning surface, impact damage.	Heating source applied on material along with measurement camera.

	Fast for evaluation, Include permanent record of defect (shearography)	Hard to detect internal defects for hollow core sections (shearography)	0.5-1 hour for setup time, fast scanning for local evaluation at each Location (shearography)		
Acoustic Emission test (Level II/ III)	Precise location of the damage and assessment possible for complex structures Fast High sensitivity can identify of flaws in early stage	Extra Fatigue loading creates during the inspection in cycle period Full characterization of defects cannot be identified	4-8 hours for setup, continuous sensing as load testing is applied.	Fibre breakage, delamination of composite material, crack initiation and growth	Acoustic range is between 2kHz to 1MHz
Ultrasonic test (Level II)	The flexibility and simplicity of the method eases the inspection process Can identify the defect's position by robotic manipulator and volumetric characteristics (Air-coupled) Quick and reliable for large areas and curved shapes of the	Require high level of expertise to carry out the data Expensive No suitable for on-site inspection only production site The acoustic impedance mismatch between the solids and gas (air) will produce amplitude loss (Air-	1-2 hours for each location 0.5-1 hour per localized defect for each defect. (Laser-based or non-contact)	Delamination, debonding, broken fibres, moisture effect, impact damage etc.	Evaluate the internal volumetric condition of the material Air-coupled more suitable on thicker panel composites and complex structures Contact ultrasonic is mostly use on curved shaped composite elements

	composite components (contact ultrasonic) Capable to inspect large-scale field testing, both for internal and external of the structure element (Laser scanning)	coupled) Unsuitable for bigger size (bridge beams) of the structural components Can reduce the lateral determination (contact ultrasonic)			
Radiography test (Level II)	Digital x-ray method can provide faster and safer scanning. Provides higher resolution of the planar defects, provide permanent 3-Dimensional digital of defects (Reverse-geometry digital x-ray)	Very expensive Require high level of skill for evaluation of conducted tests Can include unrelated emission from outside source	1-2 hours setup time for localized defect at each location 0.5-1 hour setup time for localized defect. Very slow process (Reverse-geometry digital x-ray)	Broken fibres, voids, debonding depending on the fibre orientation, impact damage, cracks and some extent of delamination	The method requires access to both sides of the structure, on one side with the radiation source and the other side with film/detector.
Vibration (modal) test (Level III/ IV)	Appropriate to test and locate the damage and the change of stiffness in structure members	Expensive Requires high level of experience to implement the inspection		Several FRP material can be detected, such as GFRP bridge deck, CFRP girders	Uses the change in the dynamic response (i.e. natural frequency and modal characteristics) to evaluate and locate the defects of the composite material

Load test (Level I)	Able to perform tests for hidden damage and global structural performance Able to identify if the bridge deck is experiencing large deflection due to stiffness loss in the structure	Require for high level of experience to implement the inspection Expensive Cannot isolate locality of damage	1 day for set-up and testing (from reference bridge)	Deflection and displacement at the deck	Placing heavy trucks as design loading on different position on the bridge and the sensor will record deflections.

Note:

- Level I – The testing method can only identify if damage has occurred.
- Level II – The testing method can identify if damage has occurred and determine the location of damage.
- Level III – The testing method can identify if damage has occurred, determine the location of damage and also evaluate the severity of the damage.
- Level IV – The testing method can both identify the and located the damage, and also evaluate the severity and the impact of the damage on the structure members.

Table 65 comprises comparisons between the different NDT testing methods for the ability of detecting different damage mechanisms.

Table 65 Summation of NDT technologies (Zoghi 2013; Meyer 2006)

Technique	**VT**	**Sound**	**Thermal**	**Radiography**	**Ultrasonic pulse-echo**	**Acoustic-ultrasonic**	**Laser-based ultrasound**	**Acoustic emission**
Moisture absorption	x							
UV damage	x							
Fibrillation, unravelling and broken fibres	x				x	x	x	
Fibre breakage								x
Loss of mechanical properties					x	x	x	
Delamination of composite from substrate		x	x	x	x	x	x	x
Debonding between composite layers		x	x	x	x	x	x	x
Bond strength							x	
Delamination in subsurface concrete		x	x	x	x	x		x
Foreign matter	x							
Impact damage	x	x						
Cracks	x		x	x				x
Core or internal elements		x	x	x	x			
External elements	x	x	x		x			

5.5 Testing Methods for Verifying Quality

Every type of fibre and resin has individual properties which lead to a large variety of resulting composites in comparison with conventional materials (Clarke 1996). Simple testing methods could estimate the properties of the composites based on the properties of the individual properties of the resin and fibres; nevertheless the results might be incorrect. In more complex laminate structures the accuracy of the estimation is lower. Testing is generally required for new combinations of resin and fibres. Testing of the material properties furthermore provides benefits to the designer since lower material partial safety factors can be utilized (Clarke 1996).

In the Eurocomp Design Code, tests are divided in two categories namely compliance testing and development testing (Clarke 1996). The compliance testing generally requires few samples which are tested regularly and is performed to check the manufacturing process of standard FRP composite components. The aim of the compliance testing is to provide a final product in accordance with the specification. In development testing many samples are tested at one single time with the intent of checking the properties of one single laminate, component or structure. The number of compliance test that are required to be carried out is specified in the Eurocomp Design Code. It is furthermore important that the compliance tests are carried out in each stage of the construction process to ensure confidence of the application. The test should be carried out with agreed standards such as ISO (International Standard Organisation) and approved laboratories (Clarke 1996).

FRP composites is, as have been mentioned earlier, a new construction material and there are no available standards set for global use. There exist ISO and other European National Standards that are equivalent and many of the standards have been subjected to revision and might become Euronorms in the future. The American standards called ASTM, which also are used for testing, does not conform with the ISO tests and should only be used when there does not exist a ISO standard (Clarke 1996).

In Appendix B a list of standard tests are demonstrated for different kinds of for FRP composite materials.

5.5.1 During Production

During the testing process the first step compliance tests are used to check the constituent materials i.e. resin, fibres, fillers etc. This is done in order to confirm that the material has the correct properties and is suitable for the specified production process (Clark 1996). Compliance tests are also performed in accordance with specification when the fibres are formed into woven mats, multi-axial fabrics etc. The specifications of the fabrics are mainly visual and geometric since the properties of the fibres already have been confirmed. With a specific application of woven or multi-axial fabric is produced, it should be also be aware of the location in the finished laminate, which is ease to identify the location in advance. The strength of the element is required to be testes if the manufacturer has given specification of the strength of the standard element. The characteristic strength is generally specified to the strength where no more than one in twenty results fails (Clarke 1996).

During the manufacturing process and of the finished product, visual checks are an important part of the compliance test. The visual checks are generally carried out in a decided rate to ensure that an consistent standard is maintained (Clarke 1996). The type of structure will furthermore influence which type of testing that is required. A lightly loaded element would for example not require an ultimate load test and it the deflection is critical the stiffness of the material has to be known (Clarke 1996).

Standards associated with the production process can be seen in Appendix B.

5.5.2 On-site

The type of structure and the construction process are two factors that are decisive of the amount of testing that has to be carried out on site (Clarke 1996). When the units arrive at the construction site it is recommended to check the critical dimensions before the units are joined together. The importance of the connections further influences the accuracy of the holes and fixings (Clarke 1996).

During the construction process is quite important that construction components are delivered with a certificate of conformity stating the dimension within specified tolerance (Clark 1996). Since many adjustments can be done on-site, the critical joints are between the connection and components, any adjustments at the connection can affect the long term strength or behaviour of whole structure. Furthermore, the component should always check after the unit is arrived on-site and before the installation as well. The connections should preferably be made under factory conditions (Clarke 1996).

5.5.3 Completed Structure

The complete structure should generally be tested for a number of situations, for example when the design assumptions and the actual structure don't confirm (Clarke 1996). Another reason is when the workmanship or the material is doubted or if the structure has been repaired after being subjected to overload or fire. A final reason could be if the designer has refrained from the Eurocomp Design Code due to uneconomic results. The main contractor of the construction project has the obligation to provide a detailed agenda with consideration of types of maintenance and controls that should be needed in the future. There should also include details of information about the appropriate repairs due to the structural damages. Disadvantages with tests of the complete structure are the high cost and complexity and should be avoided for simple structures (Clarke 1996).

5.6 References

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6 Existing FRP Bridges

This chapter presents several FRP bridge examples as case studies where the focus has been on all-composite bridges and their performance.

6.1 Bridge Examples

6.1.1 Tech 21 FRP Bridge

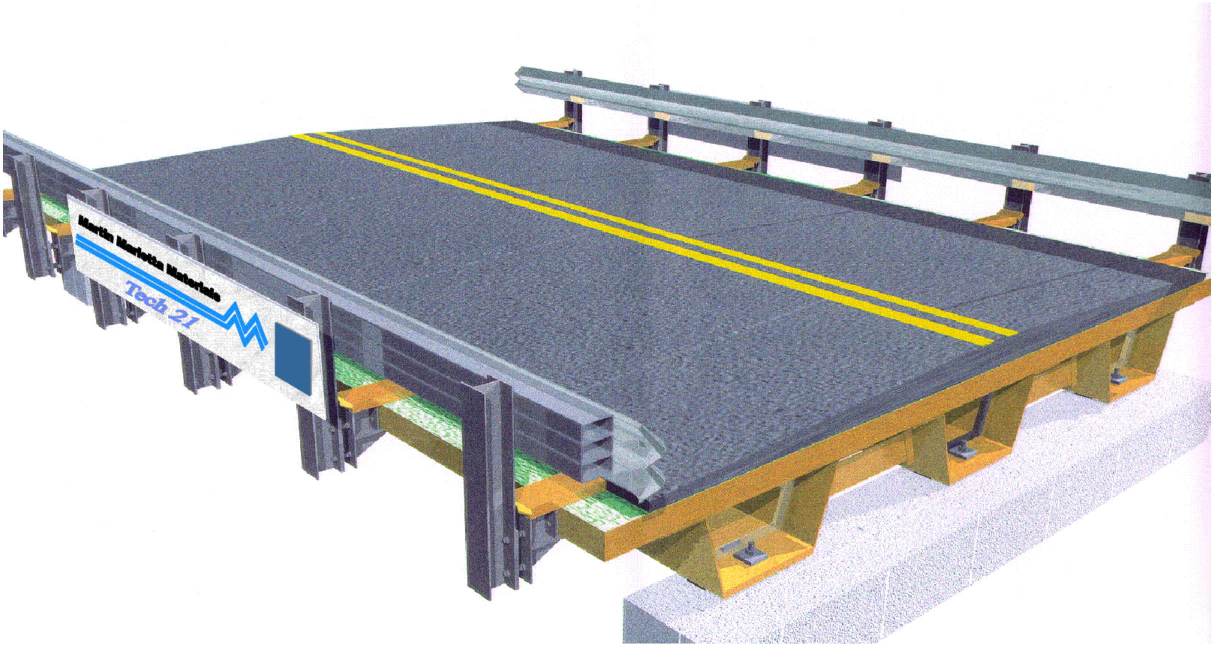

Figure 103 Overview of Tech 21 Bridge (BCEO 2001)

The construction of FRP bridges is widespread throughout the United States. Tech 21 FRP bridge was constructed in 1997 and was the first all-composite vehicular bridge in the state of Ohio and the third all-composite bridge in the US (Black 2003; Farhey 2005). Due to light weight of the structure, compared to its concrete counterpart, the structure was installed in just 6 weeks (Foster, Richards & Bogner 2000). Further benefits with the shorter construction time was a lower overall project cost and less traffic disruption compared to a similar concrete bridge (Foster, Richards & Bogner 2000).

The Tech 21 Bridge was constructed as a two-lane single span bridge with two concrete abutments to support the beam elements (Foster, Richards & Bogner 2000). The span of the bridge was 10 m and the width 7.3 m. As an all-composite bridge, the supporting beams and bridge deck consisted of FRP composite materials, in this case of GFRP (Black 2003). Figure 104 illustrates the cross-section of the girders which were designed as an open box section.

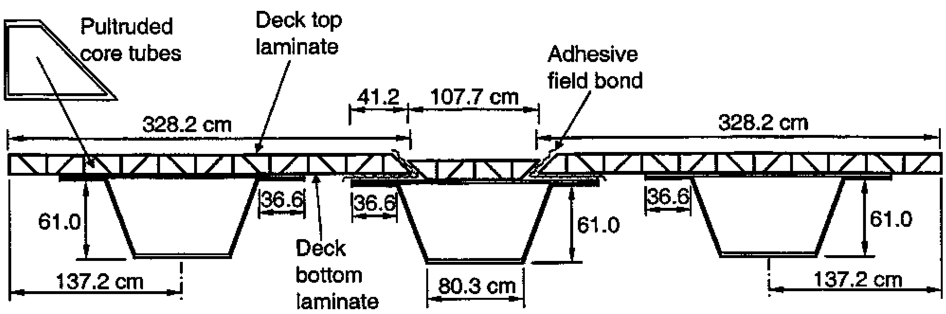

Figure 104 Bridge cross-section of the Tech 21 Bridge (Foster, Richards & Bogner 2000).

The middle beam was installed in the centre of the abutment and fixed with mechanical bolted connections to the concrete abutment which can be seen in Figure 105. The two edge beams were thereafter bonded to the deck and jointed to the middle beam (Farhey 2005). The connection between the two beams that supports the bridge deck was joined with adhesive bonding (Foster, Richards & Bogner 2000). The deck was made of pultruded sandwich panels which were adhesively bonded to the trapezoidal shaped beams (Foster, Richards & Bogner 2000). This installation technique is generally considered as easy and quick (Foster, Richards & Bogner 2000).

Figure 105 Installation of the middle beam (BCEO 1998)

The adhesive used for joining the top flange of the girder and the bridge deck consisted of vinyl ester (Farhey 2005). To accomplish the connection between the decks, an epoxy adhesive was used. The surfaces were subsequently protected from UV radiation with a coating. The entire installation process was finished in three hours (Farhey 2005). The installation of the girders and joining of the decks can be seen in Figure 106 and Figure 107.

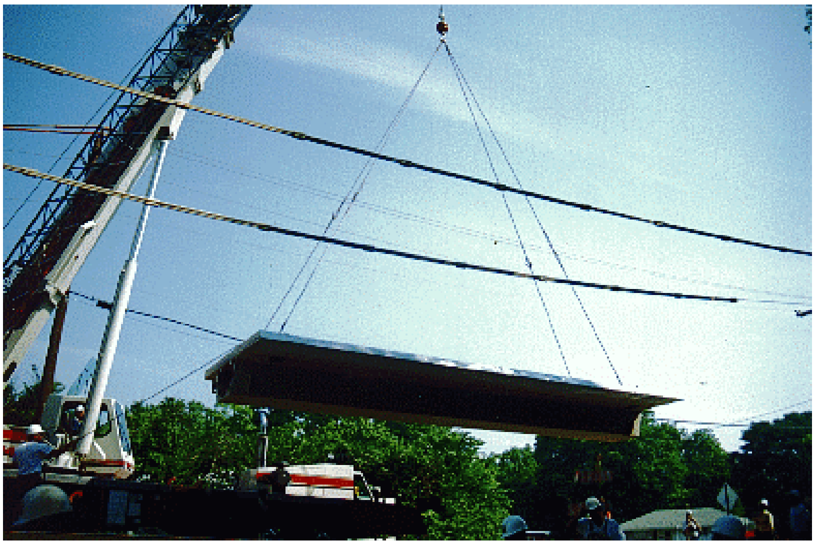

Figure 106 Beam element hoisted in place by crane (BCEO 1998)

Figure 107 Constructor sets the bridge in place (BCEO 1998)

During the construction, sensors and measurement equipment were installed on the structural elements in order to collect data for further projects (Foster, Richards & Bogner 2000). An AASHTO HS-20 live load test, which was introduced in chapter: 5.3.8 Static Load Test, was performed on the structure (Foster, Richards & Bogner 2000). It was established that the bridge fulfilled the serviceability limit state requirements. There was however some minor problems with transverse cracking due to thermal expansion which were fixed on-site (Meyer 2006).

Table 66 Information of Tech 21 Bridge

Information of Tech 21 Bridge

Year	1997
Length (m)	10
Width (m)	7.3
Loads	AASHTO HS-20
Type	Two-lane bridge
Materials	All composite bridge, the deck and the underlying support beams made of composite, GFRP Wearing surface thickness of asphalt layer vary between 6.4 to 12.7 cm
Manufacturing technique	Deck: pultrusion Beams: hand lay-up
Installation & Joints	Replacement of a one-lane concrete deck, Installation in 6 weeks

Monitoring	4 years monitoring
Condition of the bridge	Stable structural response, no degradation, sufficient strength and fulfilled serviceability limit design requirements Minor problems of transverse cracking of the asphalt due to thermal expansion have been observed on the contact face of the bridge
Comments	

6.1.2 West Mill Bridge

Figure 108 Overview of West Mill Bridge (Canning 2012)

The original West Mill Bridge was built in the 19th century and consisted of a highway bridge over the River Cole in Oxfordshire, United Kingdom. The original size of the bridge was a length of 7.5 m and a width of 3.5 m consisting of a reinforced concrete deck supported on cast-iron beams and brick abutments (Zoghi 2013).

In 2002 the West Mille Bridge was reconstructed and became the first all-composite FRP bridge in Europe. The span of the new bridge was 10 m with a width of 7 m which included footpaths on each side of the lanes (Täljsten 2007; Zoghi 2013). Since the size of the new bridge was increased compared to the old bridge, the abutments required to be replaced and this was accomplished with reinforced concrete (Zoghi 2013). The new West Mill Bridge can be seen in Figure 109 and consists of a GFRP pultruded deck supported on four rectangular GFRP beams (Täljsten 2007). The beams are additionally coated with a thin layer of CFRP at the flanges to increase the strength of the beam (Täljsten 2007). After the new bridge was built, test was performed during a period of eight years to study and monitor the possible changes of the structural integrity of the bridge (Canning 2012).

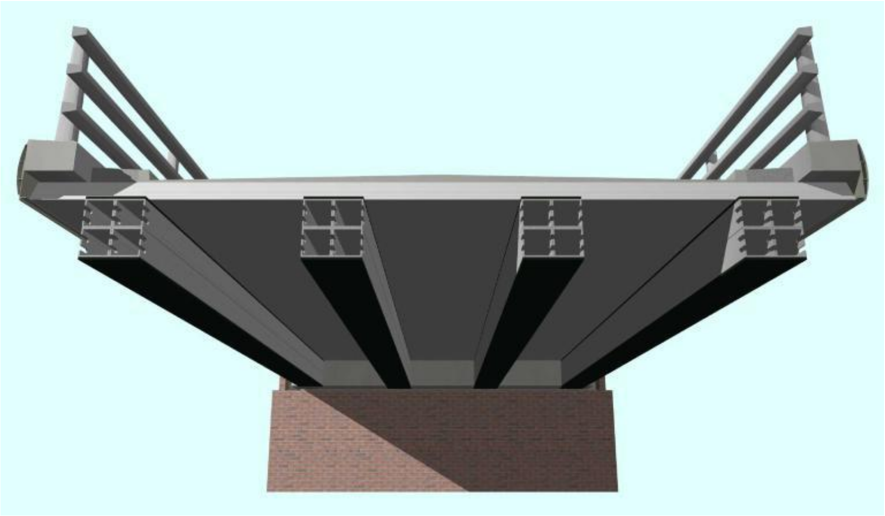

Figure 109 View of the cross-section of the West Mill Bridge (Canning 2012)

The beams are manufactured by assembling four rectangular longitudinal sections and bonding them together using an epoxy adhesive which can be seen in Figure 110 (Täljsten 2007).

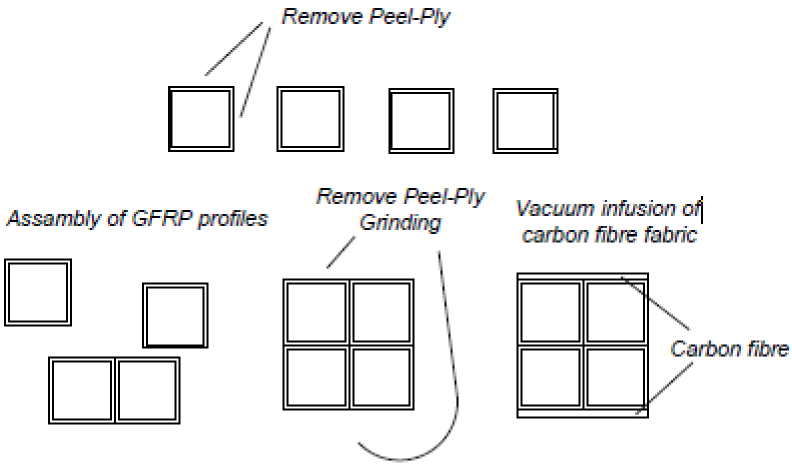

Figure 110 Manufacture process of the beam used for the West Mill Bridge (Täljsten 2007)

The edge of the beams were constructed using polymer concrete which was connected to the beams using steel bolts which can be seen in Figure 111 .

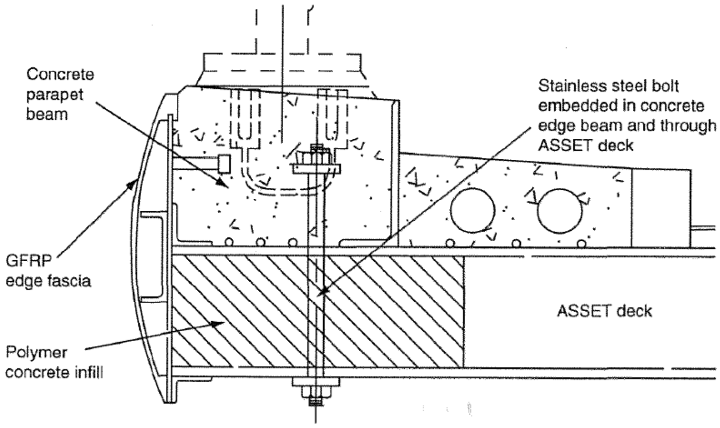

Figure 111 Connection details of the West Mill Bridge

Both the beams and the ASSET deck panels were produced in factories, transported to the site and subsequently bonded together (Täljsten 2007). After the ASSET decks had been bonded together on-site tests and checks were carried out on the worksite for parameters such as cleanliness, temperature and relative humidity (Zoghi 2013). Checks related to the environment of the worksite were also conducted in order to ensure a sufficient workmanship when joining the ASSET decks (Zoghi 2013).

The assembly consists of casting the supporting GFRP beams into the concrete membranes; thereafter the beams are ready for application of the adhesive and arrangement of the sub-deck (Täljsten 2007). A disadvantage of the adhesive bonding process is a relatively long curing time of the adhesive where each deck panel had to wait for 12 hours for the adhesive to harden before the next deck element could be installed (Täljsten 2007). The weight of the West Mill Bridge was approximately 12 tons and in comparison with a counterpart reinforced concrete bridge with a weight of 40 tons the West Mill bridge had a weight about one-third that of the concrete bridge (Zoghi 2013). The assembly and installation of the West Mill Bridge can be seen in Figure 112.

Figure 112 Manufacture process of the deck (Täljsten 2007)

A series of load tests were performed on the West Mill Bridge during a period of 8 years. The first test was performed after the construction, the second one three years after the construction and the last test was done eight years after the construction (Canning 2007). The load tests was carried out by passing a military tank over the bridge in order to control the static deflections, the dynamic performance and the creep behaviour (Canning 2007). The result of the tests generally showed many positive results, such as: the beams and deck had reasonable performance, the adhesive bond between the structural components performed and the bolted connection between the concrete parapet beam and FRP deck proved sufficient behaviour of the medium term durability. The only defect found was cracking of the polymer concrete, in particular, at the edge beam (Canning 2007).

Table 67 Information of West Mill Bridge

Information of West Mill Bridge	
Year	In 2002, the bridge replaced the deteriorated existing bridge which dated from 1870's.
Length (m)	10
Width (m)	7
Load & design	Finite element method
Type	All-composite bridge, two-lane traffic bridge, simply supported
Materials	Four rectangular longitudinal polymer composite main girders consisting of GFRP stiffened with thin layer of CFRP on flanges and an ASSET composite bridge deck manufactured from GFRP.
Manufacturing technique	Pultrusion deck Main beam consists of four rectangular GFRP profiles bonded together adhesive. Thin layers of CFRP on top and bottom flanges of beams.
Installation & Joints	The deck modules were bonded to the composite girders with epoxy adhesive and then lifted in place with a crane.
Monitoring	Structural monitoring instruments such as electrical resistance strain gauges and fibre optic sensors were installed during the deck fabrication process. Field monitoring after 10 years
Condition	Today, after 10 years of service, the bridge is performing well structurally. The adhesive bond between the different components has sufficient durability medium-term and provides a high degree of composite action between the deck and the girders. One problem observed during visual inspection, was cracking of the polymer concrete at particular in the corners of the FRP deck and in addition organic growth.

6.1.3 Asturias Road Bridge

Figure 113 Overview of Asturias road bridge (Acciona 2014)

The Asturias Road Bridge, also referred to as the PUMACOM Bridge, is located over a four-lane highway leading to the Asturias Airport in the north of Spain (Bansal, Monsalve Cano, Bladimir, Muñoz & Paulotto 2010). This was the first FRP composite highway bridge in Europe and was installed in 2004 (Muniz & Bansal 2009). The overall length of the highway bridge is 46 m and consists of three longitudinal CFRP beams with trapezoidal cross-section, which can be seen in Figure 114 (Bansal et al. 2010). The bridge has four spans with a maximum of 13 m and the girders are supported on concrete columns (Bansal et al. 2010).

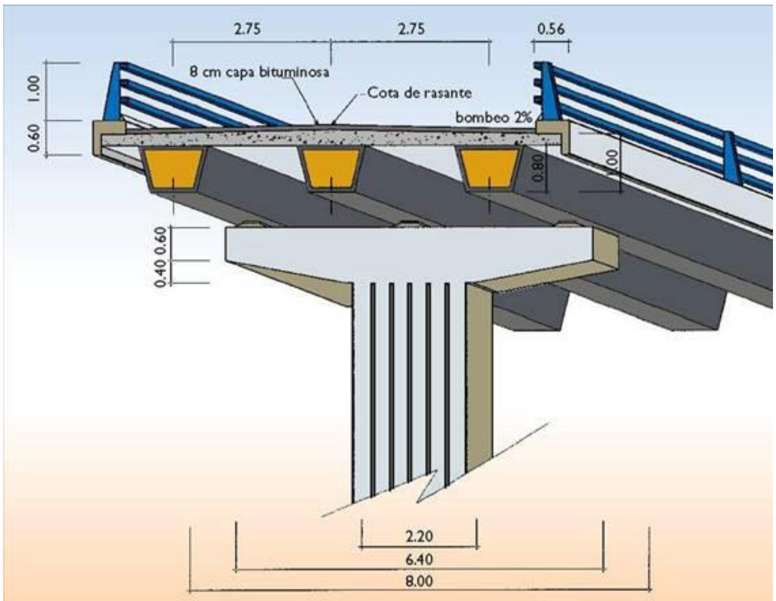

Figure 114 General cross-section of the Highway Bridge (Muniz & Bansal 2009)

Unlike the two previous bridge examples, the Asturias Bridge is not all-composite where the deck and supporting columns are manufactured from reinforced concrete (Bansal et al. 2010). The girders were manufactured using carbon sandwich structure which weighed only 0.1 ton/m and the total weight for each girder was approximately 46 kN (Muniz & Bansal 2009; Areiza Hurtado, Bansal, Paulotto & Primi 2012). The 46 m trapezoidal cross-section girders were manufactured by wrapping carbon fibre prepreg around the beam with a stay in place polyurethane mould (Areiza Hurtado et al. 2012).

The beams were manufactured in Madrid and transported to Asturias's bridge site and due to the lightweight composite beams, transportation of the beams was easily carried out (Bansal et al. 2010; Muniz & Bansal 2009). To ease the transportation the beams were divided in two shorter elements and jointed subsequently joined together at the worksite by using adhesive step joints (Bansal et al. 2010; Areiza Hurtado et al. 2012). The adhesive step joints was arranged alongside two beam elements and thereafter the elements was wrapped with pre-impregnated carbon fabric which joined the elements by using the vacuum bag system (Bansal et al. 2010).

Due to the lightweight composite beams the formwork for concrete casting did not need any support (Muniz & Bansal 2009) and the 46 m long beams just needed a half day to be lifted in place (Bansal et al. 2010). Figure 115 displays the installation of the Asturias Bridge.

Figure 115 Using crane to install the girders of the Asturias Bridge (Areiza Hurtado 2012)

Figure 101 shows the bridge during a static load test in which trucks were positioned on the bridge in order to check the bridge in serviceability limit state (Muniz & Bansal 2009). The deflection measurement was done at the mid-span of each beam and at every support which considered being critical sections which can be seen in Figure 102 (Muniz & Bansal 2009).

The dynamic testing conducted on the Asturias Bridge included the Rilem test and the impact hammer test (Muniz & Bansal 2009). The Rilem test analyses the performance of the bridge under the event of a high level of energy input when trucks are passing over a hump-obstacle which will deliver an impulse to the deck (Muniz & Bansal 2009). The impact hammer test also involves a high level of energy input, however the measurement was only carried out at one point where the hammer was applied (Muniz & Bansal 2009). The damping behaviour of the bridge was recorded and the data was collected from the testing to be used in the future analyses (Muniz, & Bansal 2009).

Table 68 Information of Asturias Bridge

Information of Asturias Bridge	
Year	2004
Length (m)	46
Width (m)	8
Loads	Each girder weigh 46kN
Type	four-span bridge, max span is 13 m
Materials	Concrete deck and columns CFRP beams (trapezoidal cross-section)
Manufacturing technique	The beams were transported to the work site and joined by adhesive step joints. By wrapping them with pre-impregnated carbon fabric which was finally consolidated using the vacuum bag system.
Installation & Joints	Carbon fibre beams on three intermediate supports, connected to the reinforced concrete deck through alkali-resistant glass fibre shear connectors. The beams were manufactured in two parts and transported to the work site where they were joined by means of adhesive step joints.
Monitoring	Using a crane, it took only half a day to place the three 46 m long beams on their supports. This was possible thanks to the minimal weight of the beams at 1 kN/m.
Condition	

6.1.4 M 111 Bridge

Figure 116 Overview of M 111 Bridge (Burgos Muniz 2012)

The M111 Bridge is located in Madrid alongside the M111 highway and was completed in 2008 (Areiza Hurtado 2012). The bridge has three spans which are 10 m, 14 m and 10 m and the deck is supported on two concrete columns which can be seen in Figure 116 (Areiza Hurtado 2012). The shape of the cross section of the girders was selected to be open, which enabled the hand lay-up production technique. The girders consists of a mixture of both carbon and glass fibre prepregs which is cheaper than a fully carbon fibre prepreg materials (Areiza Hurtado 2012). The manufacturing process of the FRP girders can be seen in Figure 117, Figure 118 and Figure 119. For further information of the hand lay-up manufacturing process, see chapter: 4.1 Hand lay-up.

Figure 117 Manufacture process for open cross-section beam – impregnation (Burgos Muniz 2012)

a) b)

Figure 118 Manufacturing process a) Lamination (Burgos Muniz 2012) b) Vacuum bag preparation (Burgos Muniz 2012)

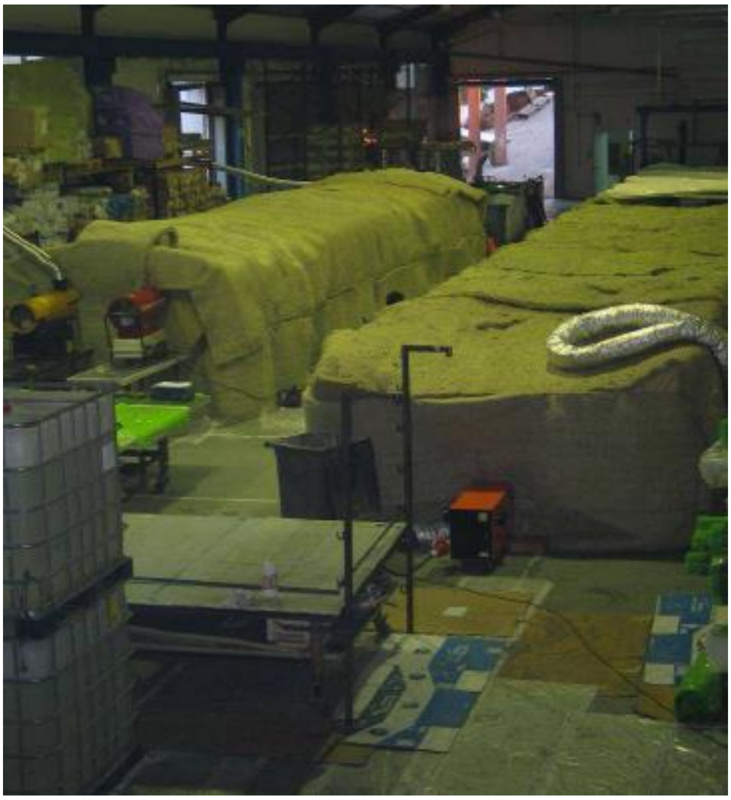

Figure 119 Manufacture process – curing (Burgos Muniz 2012)

The beam spanning over the largest span, i.e. 14 m, has a weight of only 21kN and was consequently easy to transport to the site and install (Areiza Hurtado 2012). Figure 120 displays the installation of one beam. To cast concrete deck on open shape cross-section; glass fibre stay-in-place formworks were used both in order to accelerate the construction process and to reduce the weight of the deck (Areiza Hurtado 2012). The formwork had a weight of approximately 0.35kN and only required two workers to be installed (Areiza Hurtado 2012)

Figure 120 One of the beams lifted in place by crane truck (Burgos Muniz 2012)

Some problems occurred during the manufacturing process of the FRP girders. An exothermic chemical reaction, due to heat from the material thickness, during the curing process caused problem which was solved by the resin supplier with development of a lower exothermic resin (Areiza Hurtado 2012).

The M111 Bridge has undergone many tests and measurements before installation on-site. A 3D optical stereoscopic measurement technique was used during testing which provided the possibility of studying the behaviour of the FRP girders in detail (Capéran, Poljansek, Gutierrez, Paluotto & Primi 2011). Figure 121 displays the 3D optical measurement of the M111 Bridge girders.

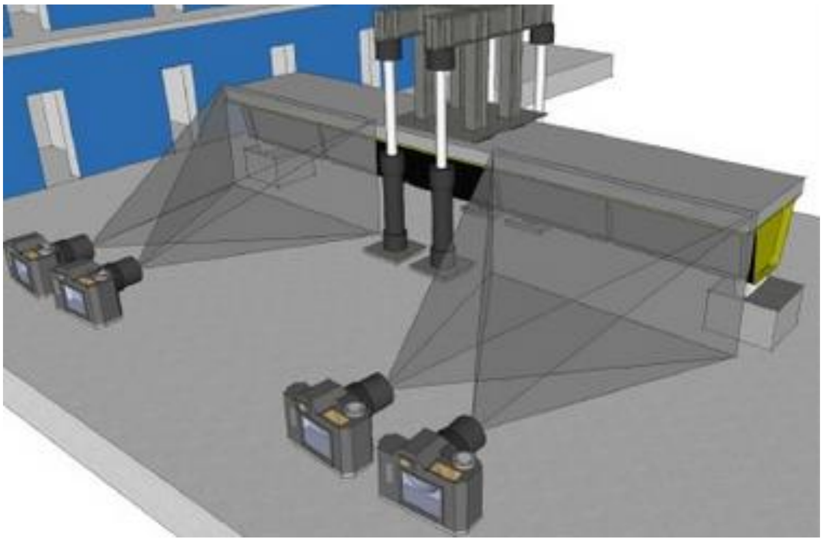

Figure 121 3D optical measurement set up (Poljansek, Caperan, Gutierrez, Paluotto & Navarro Lera 2011).

Figure 122 presents the test set-up during the test retrieving information regarding the ULS, displacement and shear behaviour of the M111 Bridge (Poljansek et al. 2011). During the measurement in ULS, a linear elastic response was observed, which can be seen in Figure 123. At a load of 2657kN, failure took place with a displacement of nearly 79 mm (Capéran et al. 2011). Shear buckling and tensile failure on the bottom side of the beam at the mid span were also reported in the results which took place at a load corresponding to approximately 1.76 times the ULS load (Capéran et al. 2011). Figure 124 displays the shear buckling failure and fracture failure of the beam.

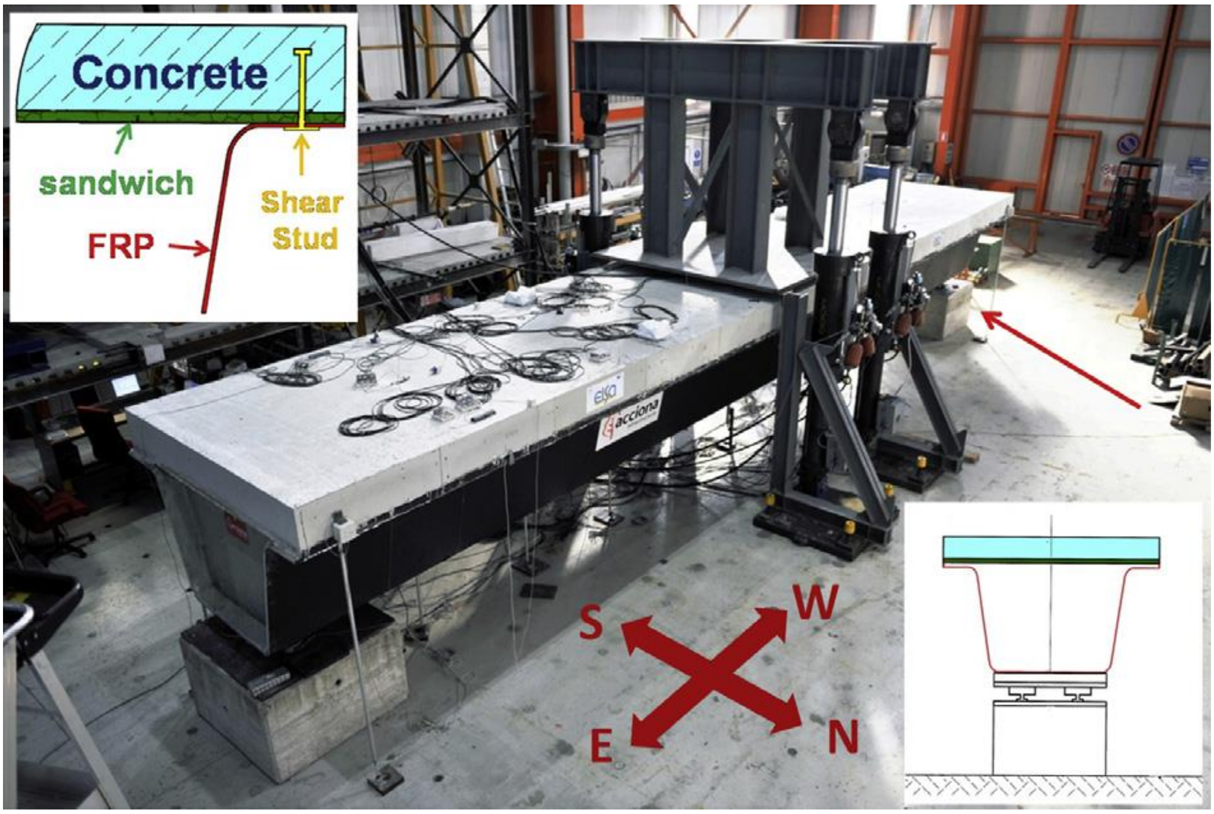

Figure 122 The detail layer of the beam's cross-section and the loading set up (Capéran et al. 2011)

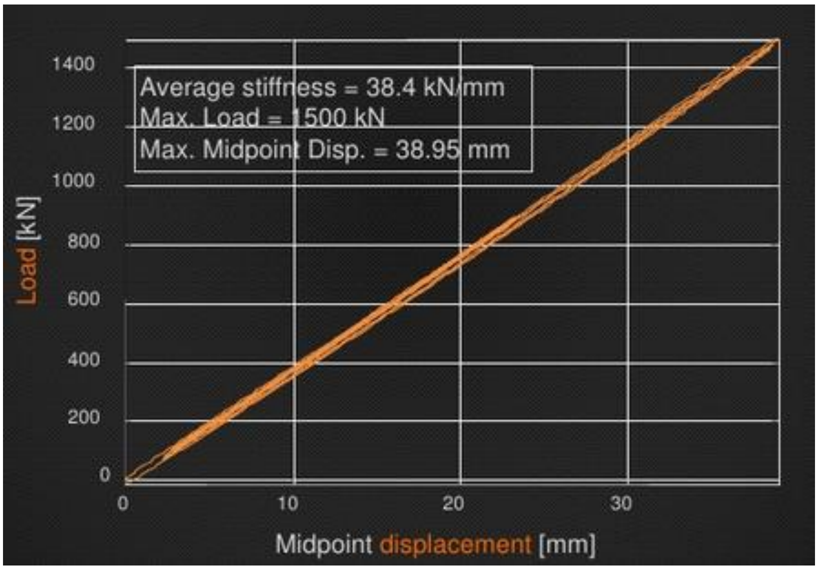

Figure 123 Responding data of load testing of ULS (Capéran et al. 2011)

Figure 124 Left: Shear buckling has occurred on the web, Right: The failure mode has also occurred fracture failure at the bottom of the beam (Capéran et al. 2011)

Table 69 Information of M111 Bridge

Information of M111 Bridge	
Year	2007
Length (m)	34
Width (m)	20.4
Loads	14m beam weighted 21kN GFRP formwork had a weight of 0.35kN/m
Type	Made of three simply supported girders (10, 14 and 10 m) supported on two concrete column each.
Materials	Concrete deck with GFRP formwork, concrete columns Hybrid carbon–glass fibre girders
Manufacturing technique	Hand lay-up manufacturing technique for the girders
Installation & Joints	The girders were lifted by a truck crane and the lightweight formwork of the deck can be installed by hand by two workers. The deck was subsequently cast in the form Shear studs between the concrete deck and the FRP girders was used.

Monitoring
Condition

6.1.5 Oosterwolde Heavy Traffic Lift Bridge

Figure 125 Overview of the Oosterwolde heavy traffic lift bridge (Fibre core Europe 2010; Chlosta 2012)

Another interesting all-composite bridge is the Oosterwolde Bridge which was built in Oosterwolde in the Netherlands in 2010 and can be seen in Figure 125. This bridge was the first vehicular FRP composite lift bridge in the world and won an innovation award in the environment category of the Industrievereinigung Verstärkte Kunststoffe (AVK) (Imtech 2010). The bridge consists of two spans of 3.3 m and 8.42 m with a width of 11.2 m to 12.5 m (Provincie Friesland 2010). The bridge was designed to allow for 60 tons of traffic which allows for passing of heavy trucks, which can be seen in Figure 126 (Chlosta 2012).

Figure 126 The lift bridge withstands load from heavy trucks (Fibre core Europe 2010)

The lifting mechanism uses a hydraulic jack which is mounted on the pylons hence the cables are not carrying any load and are only used as aesthetic elements (Chlosta 2012). The beams of the Oosterwolde Bridge are simply supported the bridge edges and the middle support is supported on the pylon (Chlosta 2012). The height of the pylon is 10.5m and the waterway to the boat traffic is 7 m. The static load was also performed several times by the civil engineering department of Delft University of technology (Chlosta 2012).

Figure 127 Detail of the lifting mechanism (Provincie Friesland 2010)

Table 70 Information of Oosterwolde Bridge

Information of Oosterwolde Bridge	
Year	2010
Length (m)	11.72 (3.3+8.42)
Width (m)	11.2-12.5
Loads	The weight of the bridge is 65tons
Type	Lift bridge with two lanes

Materials	All-composite (GFRP)
Manufacturing technique	Vacuum bag, pressure bag, hand lay-up
Installation & Joints	-
Monitoring	-
Condition	The lift bridge is built for 60 tons traffic
Comments	

6.2 Lessons Learned

Since the application of FRP materials for construction of new bridges is rather young and no specific standards are dedicated for construction of FRP road bridges, further research is needed to tackle the problems and answer questions regarding uncertainties involved in these structures.

The FRP bridge construction is considered a relatively new area and the first FRP composite bridge was constructed in the 1980s. The little experience in construction of FRP composite bridges, especially all-composite bridges, limits the extent of knowledge about these structures, more specifically when it comes to long-term performance, fire performance and degradation mechanisms. It is believed that the lack of knowledge and experience regarding installation, logistics, production techniques and material are the main reasons for the high initial cost of these bridges (Mara 2014). Thus, it is necessary to obtain good knowledge on long-term performance to judge these bridges better in LCC analyses.

At the present, the areas of concern with regard to FRP bridges are mainly associated with:

- Wearing surface
- Connections
- Degradation due to environmental effects
- Fire resistance

Information regarding wearing surface, connections and degradation due to environmental effects will be treated here, for information related to fire resistance of FRP composites see chapter: 3.4.1.5.2 Fire.

6.2.1 Wearing Surface

In general, the most common surface wearing materials used on FRP bridges decks are polymer concrete or asphalt (O'Connor & Triandafilou 2009). The polymer concrete wearing surface can reduce problems associated with skid, ultraviolet effects and abrasion (O'Connor & Triandafilou 2009; Meyer 2006). However the deboning of the polymer concrete is the main issues for the FRP bridge decks and thus asphalt is usually preferred on lightweight FRP decks (Mara 2014). Illustrations of wearing surface debonding can be seen in Figure 128.

Figure 128 Wearing surface as deboning problem (O'Connor & Triandafilou 2009)

The main causes of damage in the wearing surface are associated with:

- Poor adhesion between the wear surface and FRP deck
- Thermal expansion
- Concentrated wheel loads that causes excessive strains and cracking of the wearing surface as a consequence

A requirement of the wearing surfaces is that it has to have a sufficient level of ductility to resist the strains developed due to local deflections of the FRP deck and temperature changes (O'Connor & Triandafilou 2010; Mara 2014). Figure 129 shows an example in which the wearing surface have cracked between two FRP panels. This problem could be avoided by using silicon in between the FRP panels which contributes to a better flexibility performance (O'Conner & Triandafilou 2010).

Figure 129 Cracking between FRP composite panels (O'Connor & Triandafilou 2010)

Figure 130 shows an example of cracks in the wearing surface as a consequence of thermal loads (O'Connor & Triandafilou 2010).

Figure 130 Wearing surface debonding due to thermal loads (O'Connor & Triandafilou 2010)

For movable bridges problems have occurred at the bond between the FRP deck and wearing surfaced due to that the uplifting mechanisms impose extra stress in terms of gravity load (O'Connor & Triandafilou 2010). An example of a movable bridge is the Lewis and Clark Bascule Bridge was built in 1924 (Bottenberg 2010). The bridge was rehabilitated between the years 2000 and 2002 where the old deck was replaced with a FRP composite deck with an adhesively joined asphalt concrete wearing surface. During the installation of the bridge the asphalt concrete wearing surface started to crack and finally slid off, which can be seen in Figure 131. In this case the bridge was left open for 5 hours and a lesson learned is that a FRP deck with an adhesively bonded wearing surface should not be in its upright position for a longer period of time. It can also be established that asphalt concrete is not suitable for moving bridges. The asphalt concrete wearing surface was for the Lewis and Clarke Bascular Bridge replaced with an epoxy polymer concrete. The epoxy polymer concrete wearing surface have also shown cracking problems since it behaves in a brittle way for temperatures above 38°C and it has been established that the wearing surface is required to be replaced in the future (Bottenberg 2010).

Figure 131 Wearing surface failure of the Lewis and Clark Bridge (Bottenberg 2010)

6.2.2 Connections

The connections of FRP composite bridges have significant influence on the overall performance of the bridge (Meyer 2006). The connection of FRP decks at panel- and system level are among the most important and more information of these connections can be found in chapter: 8.8.5 Connections.

One example of failure that has occurred for tongue and groove connections is cracking and spalling of the wearing surface above the connection (Mara 2014). Case studies have furthermore demonstrated problems associated with separation of the deck and the haunch support for shear stud connections. The source of the impact causing separation is mainly associated with impact damage of vehicles (Mara 2014). The effects of vehicle impact loading is relative high which mean more cracking around the impact point can be developed over time (Meyer 2006). The problem associated with separation due to vehicle impact is important in terms of the durability and fatigue performance of the FRP composite materials (Mara 2014). Measures to avoid separation of the surface material, the durability and design of the FRP material should be tested and tried for improvement of the performance (Mara 2014; O'Connor & Triandafilou 2009).

Another problem associated with shear stud connections of FRP composite materials is failure of the surface surrounding the shear stud, which can be seen in Figure 132. In order to avoid this problem ductile wearing surface materials should be used as well as stronger and more flexible attachment materials in the FRP deck panel (Bottenberg 2010).

Figure 132 Failure of grout around the shear stud connection in study case of "Old Youngs Bay bridge" (Bottenberg 2010)

Another issue is the connection between the railing and the FRP deck which is further presented in chapter: 8.8.5.6 Guard Rail Connection.

6.2.3 Degradation of FRP members

6.2.3.1 Thermal effect

The thermal behaviour of FRP material is slightly different compared with conventional material such as concrete and steel; see more information in chapter: 3.1 Thermal Properties. The designer should for that reason be aware of differences in thermal effects and parameters such as different direction of the fibres, coefficients of thermal expansion etcetera of the structural members (Meyer 2006).

In addition, the temperature changes increases rapidly between the days and nights during the spring and autumn, the issues of micro-cracking would likely occur during this time of year (Meyer 2006; O'Connor & Triandafilou 2010). The micro-cracking damage is reduced with the stiffness of the material and increase the permeability to the fibre interface (Meyer 2006). The temperatures on different parts of the bridge is generally not constant and is generally much higher on the top of the deck is than on the bottom surface of the deck (O'Connor & Triandafilou 2010). Analysis has furthermore shown that the stresses from the variation in temperatures of different surfaces might be even higher than those generated from mechanical loading, such as traffic (O'Connor & Triandafilou 2010).

In general, the thermal effects are usually limited, to the wear surface when the bonding to the FRP deck could not handle the tensile and shear stress (Mara 2014). However the thermal damage effect might not be the biggest effect to the bridge but the issues should not be avoided during the design process.

6.2.3.2 Ultraviolet Radiation

Effects of UV radiation on FRP composite materials have been well documented from earlier research and field testing (Meyer 2006). The largest extent of the radiation-related damage from solar radiation consists of damages such as change in pigment and hardening of the matrix. A measure to avoid the effect from UV exposure is by applying a coating, or similar treatment, on the FRP surface for protection (Meyer 2006).

6.2.3.3 Chemical

FRP is generally resistant towards chemical corrosion, glass fibres are however susceptible to alkaline solution due to their high ratio of surface area to weight (Hollaway 2010). In addition since glass fibres absorb moisture it can result in microcracks and surface defects which ultimately can lead to a reduction in tensile strength of the fibres (Hollaway 2010). In order to protect the fibres an adequately ductile and thick resin layers should be applied (Chlosta 2012; Bisby 2006). It is furthermore very important that the composite is fully cured before it is subjected to the environment since under-cure can increase the susceptibility of moisture of the composite (Chlosta 2012).

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7 Comparison of FRP and Traditional Constructional Materials

FRP materials offer a number of advantages over conventional building materials. The conventional materials that are scrutinized in this chapter are mainly reinforced concrete and steel but also aluminium, titanium and timber are concerned to some extent. There is a variety of FRP composites available on the market, incorporating unique properties (Chlosta 2012). This generally makes FRP composites more complex compared to traditional materials (Chlosta 2012).

Experience from projects have shown that FRP composite bridges can provide a feasible option to conventional bridges for spans ranging from 20m to 50m due to many advantageous characteristics (Hurtado et al. 2012). The main advantages associated with FRP composites in terms of bridge applications are related to the properties such as light-weight, high tensile strength, resistant to corrosion and high resistance to fatigue (Tang & Podolny 1998; O’Connor 2009; Cytec n.d). Other advantages related to FRP composites in comparison with conventional materials are: anisotropic, non-magnetic, engineer-able, durable and that they provide fast installations (O’Connor 2009; Hurtado et al. 2012).

The major disadvantage with the implementation of FRP materials is that the knowledge of FRP composites in field of structural engineering is not fully developed. Data comes from the aerospace, defence and automobile industry may not be directly applicable in civil engineering applications (Hastak, Halpin & Hong 2004). The differences between applications concerns for example different loading cycles, exposure to moisture and VU radiation, differences in service life etc. (Hastak, Halpin & Hong 2004).

7.1 Design Parameters

7.1.1 Design Standards

In comparison with the conventional construction materials, there is a lack of knowledge about the performance of FRP composite applications regarding material behaviour etc. (Potyrala 2011; Hastak, Halpin & Hong 2004). The lack of international codes and design standards is a large influencing factor to that FRP generally is not the preferred material in bridge applications (Potyrala 2011; Chlosta 2012). The knowledge about FRP composites is furthermore generally low for civil engineers and contractors in comparison with the knowledge about conventional materials as steel, concrete and timber (O’Connor 2009; Hollaway 2010). This generally results in high safety factors in design for FRP composites (O’Connor 2009; Hollaway 2010). In design, finite element analysis (FEA) is sometimes required which calls for knowledge of the civil engineers (O’Connor 2009). FRP composites are considered engineer-able, however the standard design is generally more cost effective so the characteristic of being engineer-able is seldom utilized (O’Connor 2009).

FRP composites are anisotropic and exhibit different properties in different direction which poses a possibility to tailor the material depending on the desired properties in each direction (Potyrala 2011; O’Connor 2009). In order to increase the structural efficiency it is possible to arrange the fibres in the same orientation as the principle stresses (Cytec n.d). This result in a more efficient use of the material compared to concrete and steel since the mechanical properties can be tailored depending on the specific need of the project (Chlosta 2012). Since steel and concrete are isotropic they don’t have this possibility (Potyrala 2011). However the anisotropy of FRP composites is disadvantageous when it comes to joining of components (Potyrala 2011).

The structural members consisting of FRP composites generally incorporate a lower weight than traditional construction materials which can be seen in Figure 133 and Figure 134 (Hastak, Halpin & Hong 2004; Cytec n.d; Chlosta 2012). FRP composites consisting of a thermoset resin and reinforcing fibres generally provide a material with outstanding mechanical properties at a weight lower than for conventional materials such as steel, which can be seen in Table 71 (Muniz & Bansal 2009).

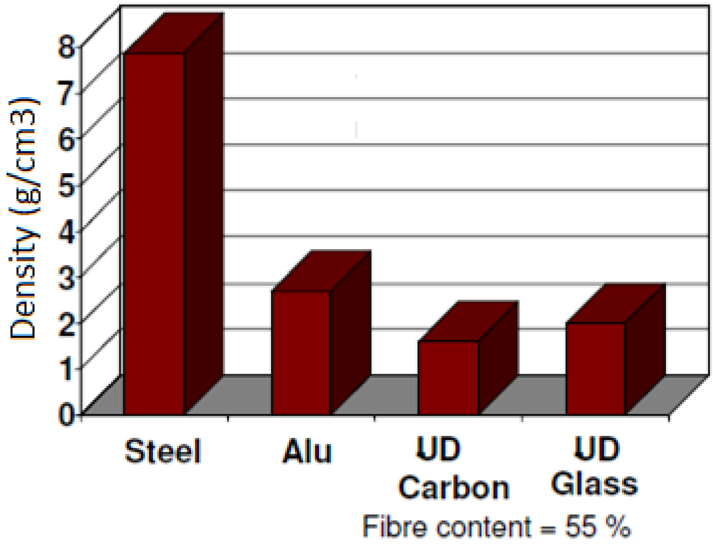

Figure 133 Comparison of density between metals and FRP composites (Yquel 2012, p. 4)

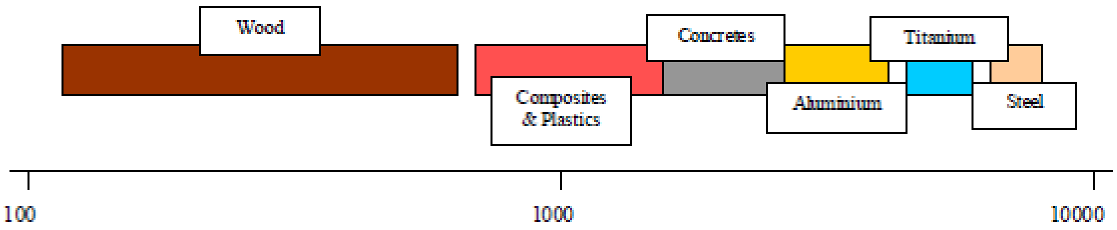

Figure 134 Comparison of density for different construction materials (Cytec n.d)

Regarding the vibration characteristics of FRP composite structures there has been little research until now (Chlosta 2012). Tests on FRP composite bridge decks have demonstrated better vibration and damping properties than conventional bridge structures (Cytec n.d; Chlosta 2012). The tests additionally demonstrated that the acceleration is higher in FRP composites than in concrete (Chlosta 2012). It is expected that the internal damping properties of FRP composites are high which results in a better vibration behaviour (Chlosta 2012). Since vehicular bridges mainly experiences short-duration transient loads, the high damping factor of FRP composites is relevant. The type of joint used, either bolted or bonded, also influences the dynamic behaviour of the FRP composite bridges. Bonded joints generally cause higher natural frequencies than bolted joints, and are thus improving the vibration resistance. The bonded joints have however the disadvantage of causing lower damping ratios due to the lower amount of friction in comparison with bolted joints (Chlosta 2012).

7.1.2 Structural Members

7.1.2.1 Decks

The benefits of FRP decks in comparison with conventional decks are extended service life and lowered maintenance costs, which ultimately improves the LCC efficiency (Hastak, Halpin & Hong 2004; Chlosta 2012). The service life of an FRP bridge deck can, without any maintenance work, exceed 75 years which is much longer than for corresponding concrete decks which have typical service life ranging from 25 to 50 years (Triandafilou & O'Connor n.d; Hastak, Halpin & Hong 2004). In order to ensure acceptable stiffness, during the entire service life, a strength reduction factor needs to be incorporated (Hastak, Halpin & Hong 2004). The FRP composite decks are furthermore lighter than conventional bridge decks but still incorporate sufficient strength to carry required loads (Triandafilou & O'Connor n.d). The low weight of the deck enables for higher load capacity ratings than for conventional bridge decks (Triandafilou & O'Connor n.d). Movable bridges as benefitted by low weight of the members since the operating expenses and energy consumption are lowered (Triandafilou & O'Connor n.d; Chlosta 2012). By replacing a heavy deck with a FRP bridge deck the load capacity of the bridge can be increased, which is beneficial since it provides extra capacity in case of unanticipated loading scenarios (Triandafilou & O'Connor n.d). Furthermore since FRP bridge decks are manufactured under controlled environments in factories where standards such as ISO-9001, that considers both safety and quality, are frequently used the finish product generally incorporates higher quality than conventional bridge decks constructed on-site (Triandafilou & O'Connor n.d).

The comparatively higher initial cost of bridge decks consisting FRP material in comparison with conventional concrete is one of the main issues that needs to be solved (Hastak, Halpin & Hong 2004; Triandafilou & O'Connor n.d). It is essential that the cost of the components of FRP bridge decks is lowered in order for FRP members to be competitive with conventional bridge decks (Hastak, Halpin & Hong 2004). Another disadvantage with FRP bridge decks are that there are few suppliers available and due to that an intermittent demand for FRP bridge decks the suppliers have had problems to remain in business (Triandafilou & O'Connor n.d). In addition it can be concluded that in order to get optimized FRP deck systems more development evolving an optimized cross section and establishing load paths are crucial (Tang & Podolny 1998; Hastak, Halpin & Hong 2004).

7.1.2.2 Superstructures

The outcome from completed superstructure projects consisting of FRP composites such as the Asturias road bridge (PUMACOM) and the M111 Bridge has shown similar benefits, namely a rapid installation and an expected long service-life and a rapid installation (Triandafilou & O'Connor n.d). Another advantage of FRP composite structures compared to steel- and concrete structures are that they always achieve higher load ratings (Triandafilou & O'Connor n.d). The performance of the superstructures has generally been satisfactory, except for the recurrent problem related to cracking and delamination of the wearing surface which is the most common maintenance problem in bridge applications with incorporated FRP (Triandafilou & O'Connor n.d; Hastak, Halpin & Hong 2004).

The disadvantages with superstructures consisting of FRP composites are however that they are more expensive than conventional bridge decks (Triandafilou & O'Connor n.d). The LCC are seldom quantified and considered since there is a lack of knowledge of the service life and maintenance costs. A disadvantage related to design is that finite element analysis is commonly required (Triandafilou & O'Connor n.d).

7.1.2.3 Connections

The basic criteria of joints are that they should provide sufficient durability, deformability and be simple (Potyrala 2011). A general concern in design is that there is a lack of information regarding connections. The design of FRP composite connections is mainly adopted from metallic connections and generally not developed in terms of the failure modes and performance criteria of FRP composites. The main extent of the available joint information originates from the aerospace industry and there is a lack of knowledge about the how well the information confirms with infrastructure applications (Potyrala 2011).

The areas of connection design that need to be developed are related to flexible joints, field connections and attachments (Potyrala 2011). FRP composites can be designed so they are thermally stable, particularly if carbon fibres are incorporated (Chlosta 2012). This measure eliminates the need for an expansion joint (Chlosta 2012). In bridge applications there is some concern related to the long-term integrity of joints when subjected to fatigue loading (Tang & Podolny 1998). Hence the areas related to bonded joints, anchorages and detailing of connections in terms of long-term durability need more attention and research (Tang & Podolny 1998; Hastak, Halpin & Hong 2004).

Today in most bridge applications, structural members are generally joined and connected through the epoxy adhesive bonding as well as using bolts (Tang & Podolny 1998; Clarke 1996). For steel, the members are commonly connected with bolts, which generally cause high peak stresses and subsequent local yielding (Clarke 1996; Chlosta 2012). Since FRP composites have a brittle behaviour until failure the peak stresses in the material can cause local crushing of the material (Clarke 1996). Furthermore, if the fibres of the FRP composites are arranged unidirectional, forming a hole can cause significant reduction of the strength of the composite. Regarding adhesive joints the quality of adhesive bonds is largely influenced by the workmanship. A significant difference between the adhesive bonds of steel and FRP composites is that the surface layer of FRP composites will generally have lower strength than the rest of the component, which is not the case for steel. If a FRP composite bonded joint is loaded in another direction then axially there is a risk of failure by peeling of the FRP composite since the through-thickness strength is lower than the in-plane strength (Clarke 1996).

7.2 Construction Parameters

7.2.1 Aesthetics and Dimensional Stability

Compared to traditional materials FRP composites provide the benefit of flexible design and ability to meet exact needs. Flexibility in manufacturing, for example possibility of manufacturing large and complex shapes is another advantage that FRP materials offer (Hastak, Halpin & Hong 2004; Cytec n.d; Chlosta 2012). FRP composites provide the possibility of achieving better geometric efficiency as well as better aesthetics compared to conventional materials (Chlosta 2012). Furthermore, if FRP composites are subjected to alternating temperatures, stress and moisture, they will keep the dimensional stability better than conventional materials (Chlosta 2012). An innovative solution that is very promising is to provide high quality fibres in effective regions of the cross-section of the member which is more optimizing (Tang & Podolny 1998).

7.2.2 Construction and Installation

Traditional construction methods using conventional construction materials are generally associated with complexities both in terms of manufacturing and installation (Potyrala 2011). This generally leads to inconvenience for road users, e.g. lane blockage and speed limits, delay in opening of the facilities etc. (Potyrala 2011). An advantage offered by FRP composites is that they generally enable quick project delivery in comparison with conventional materials (Tang & Podolny 1998; Hastak, Halpin & Hong 2004; Triandafilou & O’Connor n.d). The quick project delivery for FRP composites include faster, easier and less expensive manufacture and installation (Chlosta 2012). This is mainly due to fact that FRP composites are light weight and therefore could be manufactured off-site in factories and be assembled on-site using light equipment which ultimately reduces the costs in terms of site work and transportation (Potyrala 2011; Hastak, Halpin & Hong 2004). Since FRP composites are manufactured off-site, there are benefits of reduced time on-site of the components and improved safety for the workers and the components itself (Triandafilou & O'Connor n.d). FRP composites also enable modular construction which reduces the construction and installation time (Triandafilou & O'Connor n.d). Since the components generally are cured off-site, the need for curing on-site is eliminated which is advantageous in comparison with concrete (Triandafilou & O'Connor n.d). The light weight of the members also allows for installation in environmentally restrictive and inaccessible areas (Tang & Podolny 1998; Hurtado et al. 2012; Mostostal Warszawa S.A. et al. 2012). Another advantage associated with light weight of FRP composites is that longer spans and fewer pillars are necessary since the weight of the deck and beams are considerably lower (Mostostal Warszawa S.A. et al. 2012). Larger sections can thus be manufactured and transported, in comparison with conventional building materials, which reduces the transportation and assembly cost (Chlosta 2012).

By using FRP composites instead of conventional construction materials the weight of the structure can be reduced with roughly 70% to 80% (Tang & Podolny 1998; Hastak, Halpin & Hong 2004). The weight of FRP composites are generally in the range of $15kN/m^3$ to $20kN/m^3$ which enables manufacturing of components that has considerably lower weight than concrete with a unit weight of $23.6kN/m^3$ (Hurtado et al. 2012). Examples have shown that the replacement of an old bridge structure and installation of a new FRP composite bridge structure can be achieved in a matter of hours or days, the corresponding time for conventional bridge structures are commonly days or months (Tang & Podolny 1998; Hastak, Halpin & Hong 2004; Triandafilou & O'Connor n.d). An example is the PUMACOM Bridge that consists of three 46m long bridge girders consisting of FRP composite (Muniz & Bansal 2009).The weight of each girder is 0.1 ton/m, if the girders would have consisted of conventional materials the corresponding weight would have been 16ton/m (Muniz & Bansal 2009). The installation time of the PUMACOM Bridge was 2 days and the corresponding time for a conventional alternative would have been approximately 40 days (Muniz & Bansal 2009).

The low weight of FRP composites poses another advantage which is that excessive loading of long span bridges in terms of dead weight is eliminated (Tang & Podolny 1998). This enables for an improved live load capacity which is beneficial since the traffic ratings is constantly increasing (Potyrala 2011; Hastak, Halpin & Hong 2004). In addition with FRP composites the construction is not as limited to the season as for conventional materials due to that the production occurs in the factories (Potyrala 2011; Triandafilou & O'Connor n.d). If using conventional materials, the construction can be stagnated for periods of time due to the weather conditions (Potyrala 2011). Since FRP composites are prefabricated in factories it is possible for year-round installation. An uncertainty regarding FRP composites is related to field joining of structural components consisting of FRP and the influences of moisture, temperature and varying pressure (Potyrala 2011).

Another problem that is common during construction with conventional building materials such as reinforced concrete is to achieve accurate dimensions of the members (Potyrala 2011). FRP composites manufactured with the pultrusion process ensure full repetition of forms that are dimensionally accurate (Potyrala 2011). Furthermore, FRP composites manufactured with the pultrusion process are able to compete in terms of properties such as strength and weight with the traditional construction materials such as steel and aluminium (Hastak, Halpin & Hong 2004). In addition, using the pultrusion process, it is possible to achieve the required surface colour and texture (Potyrala 2011). Another advantage with the pultrusion process is that the manufacturing cost is reduced due to the decreased labour (Potyrala 2011).

Furthermore manufacturing in factories generally results in components with improved quality control (Triandafilou & O'Connor n.d). The VARTM manufacturing process is beneficial since the design specification of infrastructure applications varies from project to project and reductions in manufacturing costs can be achieved (Potyrala 2011).

There is a big potential with the use of FRP composites, today however the production techniques are complex which results in that the full capacity is not reached (Jäger & Kluth 2013). It is essential that the manufacturing processes are industrialised and that automated off-site processes are further developed in order to get a cost effective integrated construction process (Jäger & Kluth 2013; Hurtado et al. 2012). This will create cost savings in terms of labour and material, enhance the durability, improve the quality and productivity and instil reliability to the performance of the structure (Hastak, Halpin & Hong 2004).

7.2.3 Inspection and Maintenance

The cross sections commonly used in infrastructure applications are enclosed which complicates field inspections (Tang & Podolny 1998). In order to monitor the in-service condition of FRP composite deck despite the enclosed cross section fibre optic sensors and NDE and NDT devices have been incorporated (Tang & Podolny 1998).

FRP composites require less maintenance work during the service life compared to conventional materials (Chlosta 2012). In addition, it is generally less expensive to repair a FRP composite structure in case of damaged, compared to a steel structure (Cytec n.d).

7.2.4 Cost

The cost of FRP composites varies substantially and can range from 2€/kg to more than 200€/kg (Chlosta 2012). For bridge construction the cost is generally divided in short- and long-term costs (Chlosta 2012; Potyrala 2011). The short-term cost generally includes design, construction and installation and the long-term cost include modifications, maintenance, demolition and disposal of the products (Chlosta 2012; Potyrala 2011). Further subdivisions of these groups are indirect and direct costs (Chlosta 2012). Direct costs mainly include parameters such as production and raw materials while indirect costs include environmental impact, traffic disruption, depreciation and resale value (Chlosta 2012).

If comparing FRP composites to the conventional construction materials it can be concluded that FRP still is more expensive in terms of initial costs (Chlosta 2012; Hastak, Halpin & Hong 2004; Potyrala 2011; O'Connor 2009). The major part of the initial cost consists of the cost of the raw materials which generally comprises 40% to 90% of the total cost for the finished product (Chlosta 2012). Since the manufacturing techniques generally are not able to achieve mass quantities the price per component is still rather high (Chlosta 2012; Hastak, Halpin & Hong 2004; Tang & Podolny 1998). The high prices are generally justified in the aerospace industry, however not in civil engineering applications (Chlosta 2012). Development of new applications will probably be limited by the high cost of FRP materials since the civil engineering market is very price sensitive (Mostostal Warszawa S.A. et al. 2012). By developing the process and making it more efficient and cost-effective, FRP composites will be able to compete with the conventional materials in civil engineering applications (Tang & Podolny 1998; Hastak, Halpin & Hong 2004). Even though the FRP composites are currently regarded as relatively expensive, the prices have decreased during the last 20 years (Chlosta 2012). An example of this is that the prices of FRP decks have dropped roughly 50% since the 1990s, and the prices are in some cases similar to corresponding concrete decks. The price gap between FRP composites and conventional materials has decreased mainly due to better manufacturing techniques that have resulted in FRP composites being more competitive in bridge applications (Chlosta 2012).

The prices of the materials are generally quoted per unit weight (Clarke 1996). Since the conventional materials have a much higher density than FRP composites, which can be seen in Table 71, this quoting is misleading. Since FRP composites have low densities the net price is generally lower than expected regarding the high unit price. An example to demonstrate this is an application incorporating 175 kg steel which can be replaced by 6.2 kg CFRP which even though having a unit cost approximately 50 times higher only causes an increased net cost of 80% i.e. a factor of 1.8 (Clarke 1996).

Since the installation time is significantly reduced with the light-weight FRP composites, this enables cost savings in terms of reduced traffic interruption and less labour effort (Tang & Podolny 1998; Potyrala 2011; Hastak, Halpin & Hong 2004). Reducing traffic interruption, and consequently improve safety and reduce congestion, is a large priority in bridge projects today (Hurtado et al. 2012). The costs associated with maintenance are less for bridges consisting of FRP materials than for conventional materials, which consequently reduce the long-term costs (Hurtado et al. 2012).

Through the Trans-IND project the cost of a FRP composite bridge will be approximately 10% lower in the future than conventional bridges, due to optimizations in terms of automation throughout the whole process (Mostostal Warszawa S.A. et al. 2012). The predicted improvements of the Trans-IND projects are displayed in Figure 135.

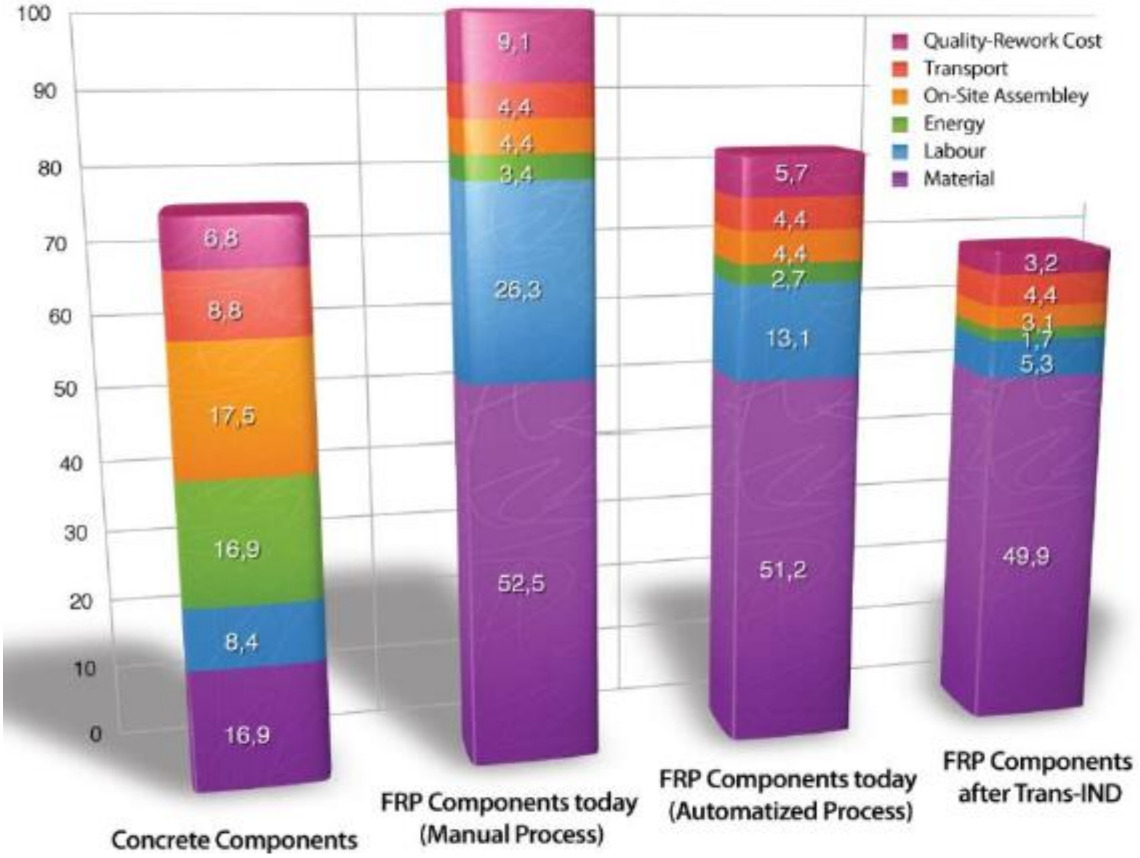

Figure 135 Comparison of normalized costs for bridge elements in arbitrary units (Mostostal Warszawa S.A. et al. 2012, p. 6)

7.3 Characteristics and Material Properties

7.3.1 Strength and Stiffness

FRP composites have the advantage of having a high tensile strength (R_m) and specific strength (R_m/ρ) which can be seen in Table 71 and Figure 136 (Tang & Podolny 1998). Since FRP composites generally are lighter than conventional construction materials they show improved stiffness-to-weight (specific stiffness) and strength-to weight ratios (specific strength) (Potyrala 2011; Hastak, Halpin & Hong 2004; Muniz & Bansal 2009; Cytec n.d; Chlosta 2012). The benefit enabled for the designer with a high specific strength in combination with high stiffness, which FRP composites incorporate, is more choices in design with regard to thickness and weight in comparison with steel and concrete (Potyrala 2011; Clarke 1996).

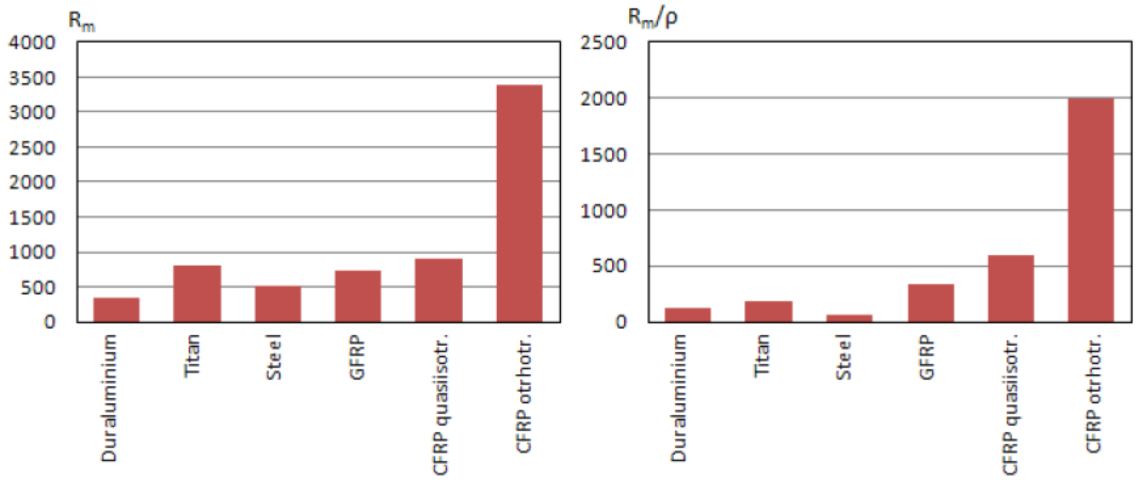

Figure 136 Comparison between FRP composites, steel, titan and aluminium of tensile strength and specific strength (Potyrala 2011)

The saving in weight and the higher strength and stiffness provides advantages in terms of seismic resistance, decreased need for large substructures as well as easier installation (Potyrala 2011; Mostostal Warszawa S.A. et al. 2012; Chlosta 2012). Smaller and consequently less expensive substructures (i.e. foundations and bearings etc.) are beneficial if the soil has a low bearing capacity (Hurtado et al. 2012; Chlosta 2012). In addition FRP composites also exhibit a high resistance if attacked by flooding (Triandafilou & O'Connor n.d). In design, the determining parameter is generally related to requirements regarding stiffness, with respect to deflection and buckling, rather than tensile strength (Tang & Podolny 1998; Hastak, Halpin & Hong 2004). This result in that the stiffness and stability of a section generally controls the design which is not optimized in terms of strength of the composite, however it ensures that SLS is reached before ULS (Tang & Podolny 1998; Hastak, Halpin & Hong 2004). The modulus of elasticity for steel is, as can be seen in Table 71 and Figure 137, very high which makes them very resistant in terms of deformation (Chlosta 2012). In order for FRP composites to achieve the same stiffness (EI) as steel the second moment of area (I) needs to be greater, which ultimately results in larger dimensions (Chlosta 2012). Another disadvantage with FRP composites is that the shear strength generally is low in comparison to the tensile strength (O'Connor 2009). Some FRP composites incorporate a relatively low modulus of elasticity, as can be seen in Table 71, which generates low stiffness's (O'Connor 2009). Table 71 displays a comparison of properties for FRP composites, aluminium and steel.

Table 71 Comparison of properties for different construction materials (Potyrala 2011)

Typical properties	Material				
	Duraluminium	Steel St52	GFRP	CFRP Vf=60 %	CFRP Vf=80 %
Density ρ [g/m^3]	2.80	7.80	2.10	1.5	1.70
Tensile strength Rm [MPa]	350	510	720	900	3 400
Specific strength Rm/ρ [MPa*cm^3/g]	125	65	340	600	2 000
Young's modulus E [GPa]	75	210	30	80	235
Specific Young's modulus E/ρ [GPa*cm^3/g]	27	27	14	59	138

In addition the tensile strength is much higher for unidirectional carbon fibre reinforced composites compared to conventional building materials, which have resulted in an increased use of CFRP in structural components carrying tensile forces (Potyrala 2011). Furthermore CFRP has a modulus of elasticity similar to steel, but with a density that is five times lower which can be seen in Table 71. GFRP has inferior performance in terms of strength and stiffness in comparison with CFRP, however it incorporates a tensile strength generally higher than steel but with an unsatisfactory stiffness which is demonstrated in Figure 137 (Potyrala 2011). Glass fibres generally have a tensile strength higher than steel and stiffness in the range of reinforced concrete (Clarke 1996). The advantages of GFRP in comparison with CFRP are related to cost and shear strength (Potyrala 2011). Other advantages with glass fibres are that they have good thermal and electrical insulation properties (Potyrala 2011). The reason however to the limited number of FRP composite bridges is generally related to the low stiffness of the GFRP girders (Leo, Chakrabortty & Khennane 2010). The low stiffness generally results in cross section that is very thick for GFRP girders which is visible in Figure 103 for the Tech21 Bridge (Leo, Chakrabortty & Khennane 2010).

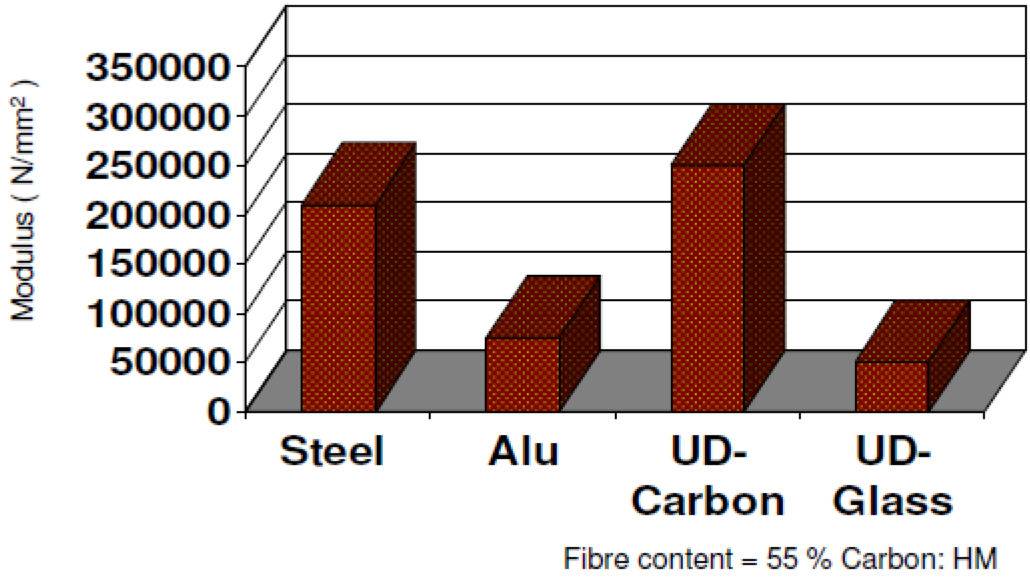

Figure 137 Comparison of stiffness for metals and FRP composites (Yquel 2012, p.4)

The consequences of improper curing of the resins in combination with exposure to UV and/or absorption of moisture can influence the structural system in terms of strength and stiffness (Tang & Podolny 1998; Hastak, Halpin & Hong 2004). If the composite is cured at high temperatures, it will generally comprise excellent properties and quality (Tang & Podolny 1998).

7.3.2 Ductility

Unlike steel, FRP composites do not display yielding and are hence brittle (Potyrala 2011; Hollaway 2010). Due to the brittle nature of FRP composites there will no warning if there is a problem with the structure or if dissipation of energy occurs in case of impact (Potyrala 2011). This problem can however be overcome by designing the composites so they exhibit a progressive failure (Potyrala 2011). The fact that FRP composites has a linear elastic relation until failure is however not a problem since the capacity design philosophy is that the deck should remain in the elastic range in case of an earthquake (Hurtado et al. 2012).

The fracture strain of glass fibres are low and consequently experience a brittle failure (O'Connor 2009; Chlosta 2012). For steel the fracture-strain is high and has a ductile behaviour (Chlosta 2012). It can furthermore be noted that FRP composites have higher impact strength than conventional materials (Chlosta 2012).

7.3.3 Fatigue

The fatigue life of a structural component is generally expressed with S-N diagrams (Potyrala 2011). FRP composites are generally assumed to be resistant to the effects of fatigue, and are generally neglected in design (Potyrala 2011; Hastak, Halpin & Hong 2004). This creates possibilities in innovative design especially in areas subjected to seismic activities (Potyrala 2011).

Unidirectional CFRP composites have excellent performance when subjected to tension fatigue, even at high stress levels, in comparison with metals and other composites (Clarke 1996; Cytec n.d; Chlosta 2012). For quasi-isotropic composites (i.e. laminates are stacked 0°, -45°, 45° and 90°) the fatigue resistance is higher than steel and aluminium by factors ranging from two to four (Clarke 1996). The number of cycles to failure (N) for FRP composites is much higher than for metals such as mild steel and alloys, generally specified as 10^6 to 10^7 for

FRP composites and 10^5 to 10^6 for metals (Potyrala 2011). It can be concluded that metals unlike glass and carbon fibres show a weakness under fatigue loading (Chlosta 2012).

A disadvantage with FRP composites in comparison with metals is that FRP composites experience loss in stiffness or gradual softening as a consequence of microscopic damage without any sign of cracks (Potyrala 2011).

Fatigue and fretting fatigue can furthermore cause significant distress to bridges through cracking and other types of damage (Potyrala 2011). There is little information of the fatigue resistance of bolted and bonded connections and these may ultimately control the life of the structure (Potyrala 2011).

7.3.4 Creep

FRP composites, such as cables and tendons, are generally susceptible to creep under sustained loading (Hastak, Halpin & Hong 2004; O'Connor 2009; Tang & Podolny 1998). The resistance to long-term creep for CFRP is however considered good if subjected to tensile stresses (Clarke 1996). Glass fibres however have the disadvantage of being susceptible to creep rupture, which is of special attention when it comes to prestressing applications (Tang & Podolny 1998). A measure to avoid creep rupture is by conducting a proper selection of fibres and by establishing specific design criteria's (Tang & Podolny 1998).

7.3.5 Long-Term Durability

All construction materials will degrade over time; FRP composites however have a larger resistance towards degradation than the majority of the conventional building materials (Hollaway 2010; Triandafilou & O'Connor n.d; Chlosta 2012). This is mainly because FRP composites are not susceptible to electrochemical corrosion which is one of the main sources of degradation of the conventional structural systems consisting of steel and concrete (Bisby 2006; Cytec n.d; Chlosta 2012). FRP composites are attractive in applications where there is a concern for corrosion, since they provide higher corrosion resistance than conventional materials such as steel, wood and reinforced concrete (Potyrala 2011; Hastak, Halpin & Hong 2004). The high corrosion resistance enables a long service life for the FRP composites and is also beneficial since the maintenance costs are low (Potyrala 2011; Triandafilou & O'Connor n.d; Hollaway 2010). Vinyl esters have the benefits of a high resistance towards solvents and corrosive environments as well as capability of elevated temperatures and have furthermore a LCC comparable with metals (Clarke 1996). It can be further noted that corrosion of steel girders is the single largest maintenance cost of bridges in the US and is especially severe in regions where the environmental conditions favour the phenomenon of corrosion (Hurtado et al. 2012). Examples of such environmental conditions are cold climate and coastal regions where the use of de-icing salt is common (Hurtado et al. 2012). Another advantage of FRP composites in terms of durability in comparison with conventional materials is the high resistance towards weathering and atmospheric degradation (Chlosta 2012). De-icing salt can be a serious problem for applications incorporating steel, FRP composites however are resistant to the effects of de-icing salts (Potyrala 2011).

The main concern regarding the long-term durability of FRP composites for bridge applications is the lack of historical performance data (Tang & Podolny 1998; Potyrala 2011; Hastak, Halpin & Hong 2004). In addition the data used to predict the long-term durability is based on information collected from the aerospace industry and are possibly not compatible with the civil engineering industry (Potyrala 2011). Hence further research is required regarding the long-term effects in order to get a clearer view of the characteristics of FRP (Chlosta 2012).

The environmental conditions having the largest negative impact on FRP composites are effects related to: moisture, alkali, thermal, creep and relaxation, fatigue, UV and fire (Hastak, Halpin & Hong 2004).

7.3.5.1 Alkali

There are resins that are ineffective if subjected to moisture (Hastak, Halpin & Hong 2004). Glass fibres are furthermore susceptible absorption of moisture and if subjected to alkali solution they can be severely degraded (Tang & Podolny 1998; Hastak, Halpin & Hong 2004).

7.3.5.2 Electromagnetic Transparency

FRP composites are suitable for applications such as bridges in factories and footbridges over railway tractions, where there is a risk of electric shock, since they does not conduct electricity (Potyrala 2011; Chlosta 2012).

7.3.5.3 UV Radiation

FRP composites are generally susceptible to UV radiation and thus require UV protection that needs to be considered in design (O'Connor 2009).

7.3.5.4 Temperature

FRP composites generally have a good resistance toward freeze-thaw conditions (Potyrala 2011; Chlosta 2012). A disadvantage with deck structures consisting of FRP composites is that they are generally more sensitive to thermal changes than deck structures consisting of the conventional materials steel and concrete, and hence needs special consideration (Hastak, Halpin & Hong 2004).

7.3.5.4.1 Fire

A major disadvantage with FRP composites is that they have low resistance towards fire, are combustible and may emit unhealthy gases (Potyrala 2011; Chlosta 2012). The toxic gases that are released during the FRP fire are regarded as greatest health hazard (Chlosta 2012). These disadvantages can be counteracted with choosing FRP composites that are self-extinguishing, fire retardant and that don't develop toxic fumes, but for these composites the strength is generally lowered (Potyrala 2011). FRP composites experience a reduction in strength at lower temperatures than steel, generally in the range of 80°C, and experience creep and distortion at temperatures of 100°C to 200°C (Potyrala 2011; Chlosta 2012). The relation between tensile yield stress and temperature for steel and FRP can be seen in Figure 138. As can be seen in Figure 138 it is crucial with fire protecting measures for FRP composites since all strength is lost at a temperature of approximately 540°C, the corresponding value for steel is 816°C (Chlosta 2012).

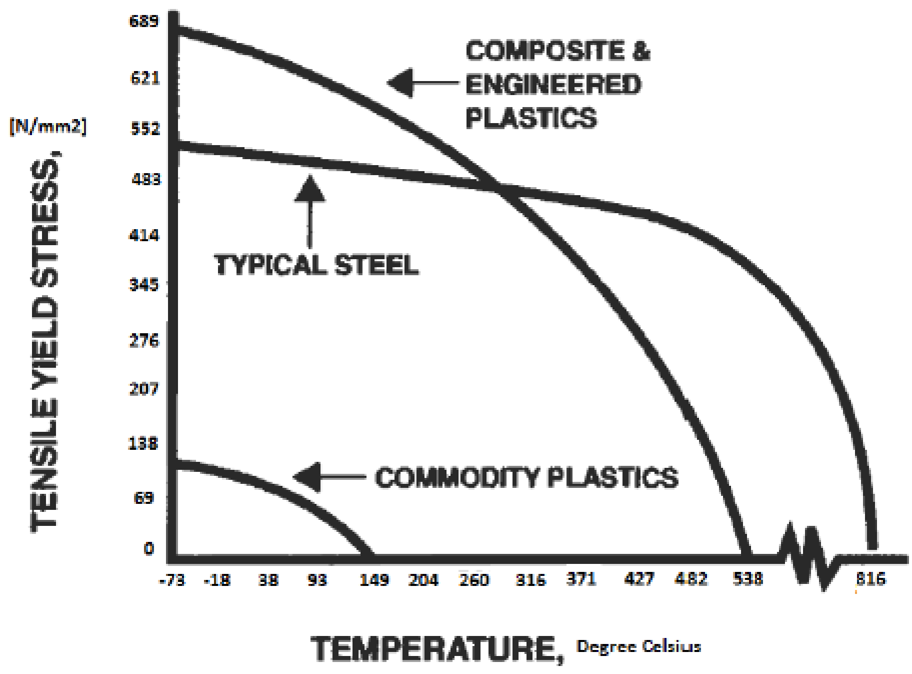

Figure 138 Relation between tensile yield stress and temperature for steel and FRP (Chlosta 2012)

FRP composites generally have higher thermal insulation in comparison with conventional materials (Cytec n.d; Chlosta 2012). In addition they conduct heat at a lower rate than metals (Chlosta 2012). Another advantage with FRP composites is that they have higher resistance against pyrolysis than conventional materials. Lastly it can be noted that the burn-through resistance of FRP composites generally is better than for metals such as aluminium alloys (Chlosta 2012).

7.4 Sustainability

Sustainability of a material is commonly measured in factors such as: use of resources, impact on the environment, health risks of human and environment, strategies for a sustainable site design and performance of the material (Lee & Jain 2009). The ideal use of a material or structure would be if it had a closed life cycle. A closed life cycle means that renewable resources, energy are used where there is no waste and where the social and environmental perspective is considered (Lee & Jain 2009).

The parameter of FRP composites that mostly influence the sustainability in a positive way is the strength to weight ratio (Chlosta 2012).

7.4.1 Environmental Impact

FRP composites generally have a lower carbon footprint than conventional building materials (Triandafilou & O’Connor n.d). FRP composites require less energy in terms of transportation and production than conventional materials steel and concrete (Chlosta 2012). In addition it can be noted that FRP composites incorporate more embedded energy compared to conventional materials such as concrete, steel and virgin aluminium (Chlosta 2012).

7.4.2 Material Usage

The polymer in FRP composites are generally produced from raw materials such as crude oil, natural gas, chlorine and nitrogen which are waste products from the oil industry (Lee& Jain 2009; Muniz & Bansal 2009). The amount of material required for FRP applications is comparatively insignificant even though if the demand would increase. This is due to that lower amount of material is required due to the combination of low weight and high strength and stiffness (Potyrala 2011; Hollaway 2010). Since less material is required, the waste production is also lower in comparison with conventional materials (Hollaway 2010). The use FRP composites in civil engineering application are considered to be at least as sustainable as the conventional materials steel, concrete and timber (Potyrala 2011). An alternative to using fossil fuels is the bio-based polymers, see chapter: 2.3.1.3.3 Green Composites (Lee & Jain 2009). Thermoset polymers are the most commonly used resins today and compared to thermoplastic polymers they can only be limitedly recycled (Potyrala 2011; Muniz & Bansal 2009). This is the reason why it is an ongoing shift towards thermoplastic resins (Potyrala 2011).

The manufacturing of fibres is however considered to be a concern when it comes to sustainability (Muniz & Bansal 2009). The required temperature is in general high when constructing the fibres used in civil engineering applications, namely carbon, glass and aramid (Lee & Jain 2009). The temperatures required for constructing glass fibres are generally in the range of 1400°C and 1200°C to 2400°C for carbon fibres (Lee & Jain 2009; Hollaway 2010). FRP is often considered a more environmental friendly than the conventional building materials, which is questionable if only considering the energy and material resources in production (Lee & Jain 2009; Hollaway 2010). Other environmental concern associated with the manufacturing process of FRP composites besides the depletion of fossil fuels are the emissions of air pollutions, acidification and generation of smog (Lee & Jain 2009). However if more parameters are considered such as the higher strength, lighter weight, better durability, its ability to increase life span of existing structures, better seismic properties, higher performance etc. in comparison with the conventional building materials, then FRP composites can be regarded as a more sustainable option (Lee & Jain 2009; Hurtado et al. 2012).

Even though glass fibres require a relatively high temperature during manufacture, they are regarded as ecological and sustainable since the raw materials are consisting of limestone and quartz powder which are inexhaustible (Potyrala 2011). Furthermore if comparing the glass fibre/polyester composite with steel and aluminium with regard to the energy consumption during manufacture, the composite requires one-fourth that of steel and one-sixth that of aluminium (Potyrala 2011). The total energy consumption for FRP composites is still two to three times higher for aluminium respectively steel even though recycled material is incorporated in steel and aluminium which can be seen in Table 72 (Chlosta 2012). A conclusion that can be drawn from Table 72 is that there are room for improvement regarding manufacturing of FRP composites, which is the main source of energy consumption. The embodied-energy footprint of a general FRP composite is furthermore approximately 50% higher than for timber. By incorporating more fibres and thus increasing the fibre volume fraction of the composite the embodied-energy of FRP composite will be lowered. This poses a great sustainability advantage in bridge engineering since high strength is required which mainly is provided by the fibres (Chlosta 2012). Since carbon fibres require a large amount of energy during production they are more problematic to justify when it comes to the environmental impact (Potyrala 2011).

Table 72 Total energy consumption of steel, aluminum and GFRP (Chlosta 2012)

Property	Unit	Steel	Aluminum	GFRP
Primary raw materials		25% recycled	50% recycled	glass and resin mix

Energy raw materials	MJ/kg	26	101	70-74
Secondary operations		Hot/Cold/Section roll	Extrusion or other	Composite manufacture
Energy secondary operations	MJ/kg	4-6	40-50	4-6
Field installation		Blast and paint		
Energy field installation	MJ/kg	30-35	0	0
Maintenance and use phase		Blast and paint		
Energy maintenance and use phase	MJ/kg	30-35	0	0
Total	MJ/kg	90-106	141-151	74-80
Total compared to a composite	MJ/kg	270-318	169-181	74-80
Element of 1.9 kg weight		at 3.5 kg	at 1.2 kg	at 1.0 kg

7.4.3 Human and Environmental Health Risks

Smoke, heat and gases released during combustion in case of a FRP fire is one of the main reasons to the limited use of FRP composites in the infrastructure sector since it is hazardous for the fire fighting crew and the people close by (Chlosta 2012). The substances generally released is for example carbon monoxide which is deadly to humans if exposed for one hour to a concentrations as low as 1 500ppm (Chlosta 2012).

7.5 Recommended Applications

It can be concluded that FRP composites should be used in applications where they are more beneficial than conventional materials (Clarke 1996). Areas where FRP composites are more beneficial are when requirements are set regarding durability, weight saving and corrosion resistance (Mostostal Warszawa S.A. et al. 2012). Examples of applications where FRP composites are more beneficial than conventional construction materials are (Triandafilou & O'Connor n.d; Cytec n.d):

- Replacing an existing concrete bridge deck with a FRP bridge deck which results in benefits of increased live load capacity
- The fast construction generally results in lowered costs and less disturbance of traffic. Benefits from less traffic disturbance are lowered levels of noise and air pollutants as well as less fuel consumption.

- In high traffic areas it is beneficial to replace a decommissioned bridge deck with a FRP deck instead of a concrete deck in order to reduce traffic delay
- By incorporating FRP composites in moveable bridges there will be less mass to swing hence less requirements on the mechanical system
- Structural FRP composites are beneficial in areas subjected to earthquakes since the mass of the structure is reduced
- FRP composites are more durable and have a longer lifespan than concrete which results in that FRP composite decks can be designed to last as long as the life of the bridge as supposed to a concrete deck that has to be replaced at least once. This results in a lower carbon footprint of the FRP composite deck since unnecessary bridge projects are avoided and thus reducing emissions of pollution and fuel consumption etc.

7.6 Future Research

The main areas that need to be addressed in the future are related to (Hastak, Halpin & Hong 2004; Triandafilou & O'Connor n.d):

- Connections such as panel-to-panel joints and how to attach decks to stringers
- Develop design standards and guidelines
- How material properties change due to variations in temperature
- At which rates materials degrade over time
- Repairing techniques
- Resistance to fire
- Resistance to impact and blast

It is furthermore important that the manufacturing and production processes are developed in order for the projects to be more cost effective (Hastak, Halpin & Hong 2004). Consideration for safety sustainability and performance are needed and should be implemented in the design standards (Hollaway 2010; Lee & Jain 2009). In addition is more information of FRP composites is required in terms of the mechanical and hygrothermal behaviour (Lee & Jain 2009).

7.7 Conclusion

7.7.1 Advantages

The main advantages with FRP composites in comparison with conventional materials are that they can increase the service life for existing structures and provide better resistance for structures that are subjected to severe environmental conditions such as weathering, aging and degradation (Hollaway 2010; Lee & Jain 2009). In addition they are advantageous compared to conventional materials since they incorporate a high corrosion resistance, provide an easy construction, are engineer-able and can be tailored in order to suit the performance requirements etc. (Lee & Jain 2009).

The low weight of FRP composites is another major benefit that generally reduces the construction cost, faster installation and lowered impacts on the environment (Lee & Jain 2009). Since FRP composites have high strength and stiffness in comparison with low weight, less material is required to achieve the same performance in comparison with conventional materials (Lee & Jain 2009). This is advantageous in a sustainable point of view since less material and waste is produced (Lee & Jain 2009). In general it can be concluded that FRP composites have a higher durability than conventional materials (Chlosta 2012). In Table 73 is a summary of the advantages provided with FRP composites compared to conventional materials.

Table 73 Summary of advantages of FRP composites compared to conventional materials

Advantages FRP composites compared to conventional materials
Mechanical properties
Outstanding mechanical properties
Superior strength to weight ratio
Better stiffness to weight ratio
High tensile strength
Better vibration and damping properties
High impact strength - ability to absorb energy
Better seismic resistance
Fatigue resistant
High resistance to weathering and atmospheric degradation
Good resistance against freeze-thaw conditions
Higher performance
Design properties
Flexible design that is able to meet exact needs
Aesthetic possibilities
Structural efficiency by arranging fibres in direction of principle stress
Possible to achieve better geometric efficiency
Low density (light weight)
Higher capacity of live loads
Low thermal expansion coefficient
Good dimensional stability

Non-magnetic
Engineer-able
Anisotropic (high directional strength with ability to tailor)
Reduced energy consumption and size of mechanism for moving bridges
Improved live load capacity
Higher thermal insulation
Conduct heat at a lower rate
Better burn-through resistance
Higher resistance against pyrolysis
Higher fibre volume fraction lowers embedded energy of FRP
Cost
Lower LCC and whole-of-life cost (WOL)
Lower user costs
Cost savings due to reduced traffic delay and traffic control
Less maintenance costs
Prices of FRP components continue to decrease
Manufacture
Possibilities of mass production
Full repetition of forms
Good quality of components due to prefabricated in controlled environment
Achieves required surface color and texture
Large, prefabricated and complex shapes possible
Less labour for automated manufacturing processes such as pultrusion

Construction and installation
Fast installation
Easy installation
Economic installation due to inexpensive machinery
Less labour due to lower weight of components
Reduced transportation and assembly costs due to larger sections
Smaller and less expensive substructures (bearings, foundations etc.)
Installation possible in inaccessible areas
Construction not as limited to weather conditions - year-round installation
Reduced traffic interruptions
Intelligent positioning systems and robots available
Optic sensors and NDE/NDT devices available
Safer construction
Maintenance
Easy to maintain damaged structures
Reduced maintenance requirements
Generally less expensive to repair compared to metallic structures
Durability
High durability
Longer service life
Chemical resistant
Resistant to de-icing salts
Corrosion resistant

Less degradation
Good weather resistance
Higher resistance to impact from floods and earthquakes
Resistance to atmospheric degradation
Increased life span
Sustainability
Lower carbon footprint
Reduced energy consumption for transportation and manufacturing
Less material required due to high strength to weight ratio
Lower waste production
GFRP lower energy consumption than aluminium and steel
Other
Can be thermally stable (no need for expansion joints)
Can be electrically non-conductive

7.7.2 Disadvantages

In Table 74 is a summary of the main disadvantages associated with FRP composites in comparison with conventional materials.

Table 74 Summary of disadvantages for FRP composites in comparison with conventional materials

Disadvantages FRP composites compared to conventional materials
Mechanical properties
Shear strength generally low in comparison with tensile strength
Low stiffness of GFRP
Susceptible to creep under sustained loading
GFRP susceptible to creep rupture

Softening due to fatigue loading
Lack of information of fatigue resistance of connections
Design
Lack of international codes and design standards
the low modulus of elasticity of FRP composites the design is mainly driven by deflection
Larger dimensions of cross sections due to low stiffness
FEA sometimes required
Anisotropic (connections)
Closed sections complicates field inspection
Limited experience in civil engineering application
Ductility
No yield line - brittle
Low fracture-strain
No warning if problem with structure
Cost
High initial cost
High unit cost of FRP materials
Expensive raw materials
Rather high price per component
Manufacturing
No standardised manufacturing process
Concern if improper curing of resins
Construction and installation

Durability problem with field joining
Durability
More sensitive to thermal changes than steel and concrete
Failure of wearing surface (delamination and cracking)
Lack of long-term performance data
Susceptible to absorption of moisture
Glass fibres susceptible to alkali solutions
Susceptible to UV radiation
Some resins are ineffective if subjected to moisture
Combustible
Low fire resistance
Emit unhealthy gases (CO2, CO)
Fire retardant additives lower mechanical properties
Experience reduction in strength at lower temperatures than steel
Smoke dangerous for people and firefighting crew
Sustainability
Raw materials and depletion of fossil fuels
Thermoset resins not recyclable
High temperatures required during manufacture of fibres
Emissions of air pollutants, smog and acidification during manufacture of fibres
50% higher energy consumption than timber
Carbon fibres hard to justify in terms of environmental impact

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8 Introduction to Existing Guidelines

At the present there are no accepted official international codes available regarding design of FRP composites for infrastructure application. However since the use of FRP composites in the civil engineering industry has considerably increased since 1970s, many countries have developed individual guidelines and recommendations (Chlosta 2012). Some existing guidelines for design of FPR structures are:

- The European approach of the "European Structural Polymeric Composites Group" (EUROCOMP) from 1996 called "Eurocomp Design Code and Handbook"
- The Dutch approach of the "CUR96 Aanbeveling" conducted by the "Civieltechnisch Centrum Uitvoering Research en Regelgeving" from 1999
- The approach from Denmark called the "Fiberline Design Manual"
- The United Kingdom approach called the "Design manual for road and bridges" – Part 17 from 2005
- Design of FRP bridges and Highway Structures BD90/05

8.1 Eurocomp Design Code and Handbook

The EUROCOMP design code and handbook was designed for the construction industry and cover a wide range of FRP composites for structural applications (Chlosta 2012). The Eurocomp is suited for designers and engineers that previously have worked with conventional building materials (Chlosta 2012). The layout of the Eurocomp design code and handbook is similar to the Eurocodes and does not have a legal status even though the information is based on scientific information (Chlosta 2012). The limitations of the Eurocomp design code and handbook is that it only covers design of glass fibre reinforced polymers and that structural parts such as components and connections are considered separately and not as an entity (Chlosta 2012). The Eurocomp design code and handbook is officially called "Structural Design of Polymer Composites" and includes three parts called: The Eurocomp Design Code, The Eurocomp Handbook and a third part consisting of technical reports (Chlosta 2012).

8.1.1 Eurocomp Design Code

The Eurocomp design code was developed for glass fibre reinforced composites for civil engineering structures, however other fibres are also applicable (Chlosta 2012). Furthermore the design codes only covers requirements related to serviceability, resistance and durability of structures (Chlosta 2012). It can be noted that the Eurocomp design code does not cover seismic design (Chlosta 2012). An advantage with the Eurocomp design codes are the consistency with the Eurocodes where the actions acting on FRP composite structures are calculated according to "Eurocode 1: Actions on Structures" (Chlosta 2012).

The topics covered in the Eurocomp design codes are (Chlosta):

- Chapter 2 "Basis of Design" which covers the fundamental requirements, limit states, material properties, design values for actions and failure warnings
- Chapter 3 "Materials" covers the constituents of the FRP composite such as resins, fibres, cores, honeycombs, foam, gel coats and additives
- Chapter 4 "Section and member design" which covers design parameters related to FRP composites such as ultimate and serviceability limit state, members in compression, members in tension, members in shear members in flexure, stability, plates, combination,

members laminate design, laminate strength, laminate stiffness, fatigue, rupture, creep design for impact, design for explosion, chemical attack and fire design

- Chapter 5 “Connection design” which covers parameters related to joints such as joint geometry, bonded joints, mechanical joints, laminated joints, tee joints, moulded joints, cast in joints, combined joints and bonded insert joints
- Chapter 6 “Construction and Workmanship” which covers parameters related to manufacture, fabrication, delivery, erection, connections, maintenance, repair, health and safety.
- Chapter 7 “Testing” related to testing parameters such as compliance testing, testing for verification and for design
- Chapter 8 “Quality control”

8.1.2 Eurocomp Design Handbook

The Eurocomp design handbook provides guidance for the designer to get supplementary information to the Eurocomp Design code regarding understanding of the choices made (Chlosta 2012). The Design Handbook should be utilized alongside the Eurocomp Design Code for the best results. The handbook is included with sufficient of documents and data that will precise the design clauses as well. The Eurocomp Design handbook furthermore gives additional information regarding the fibre type’s aramid and carbon (Chlosta 2012).

8.1.3 Eurocomp Test Reports

The Eurocomp test reports includes information from five major tests that were conducted during the Eurocomp research project (Chlosta 2012). The reports includes the tests on GFRP panels for road bridges, bonded joints, nominally pinned connections for pultruded frames, tubular form of GFRP member in trusses and pultruded GFRP pinned base rectangular portal frame (Chlosta 2012).

8.2 CUR96 Aanbeveling

The Dutch recommendation is called “CUR96 Aanbeveling”, or in short “CUR96”, was developed by the committee “Civieltechnisch Centrum Uitvoering Research and Regelgeving” (Civil Engineering Centre for the Implementation of Research and Regulation) in 1996 (Chlosta 2012). The recommendations cover the design of FRP composites for civil engineering structures. The layout of the CUR96 document is divided in two parts namely the CUR96 recommendations and the CUR 2003-6 Achtergrondrapport which is a background report (Chlosta 2012).

Both part of the Dutch recommendations where conducted by the committee which consisted of representatives from the scientific world, the civil engineering industry and the government (Chlosta 2012). Unlike the Eurocodes the CUR96 recommendations are not compulsory by law to follow, but are however recommended to follow by the Dutch Infrastructure authority (Chlosta 2012)

8.2.1 CUR96 Recommendation

As for the Eurocomp design codes, the CUR96 recommendation only covers design of glass fibre reinforced polymers composite structures (Chlosta 2012). A disadvantage of the CUR96 recommendations in comparison with the Eurocomp design codes are that it does not cover design of connections. The focus of the CUR96 recommendations is mainly on material properties, partial safety factors and calculations of strength and stiffness. The topics covered in the CUR96 recommendations are (Chlosta 2012):

- Chapter 5 “Demands of and for FRP structures” which is related to demands and durability of FRP structures
- Chapter 6 “Calculation methods and material properties” which covers parameters such as material factors, loads, safety factors, characteristic material properties and conversion factors
- Chapter 7 “Materials” which covers the constituents of FRP composites such as laminates, resin types and reinforcement types
- Chapter 8 “Construction and manufacturing” which is related to the available production methods
- Chapter 9 “Calculations” which covers calculations of stiffness, fatigue, stability and strength for different structural elements
- Chapter 10 “Inspection and control”

A requirement of the CUR96 recommendations is that the fibre volume fraction of the GFRP should be at least 20% (Chlosta 2012). In comparison with the Eurocomp Design Code the CUR96 recommendations is more compact and has a smaller coverage of areas such as creep and impact damage (Chlosta 2012).

8.2.2 CUR 2003-6 Background Report

The CUR 2003-6 Background Report has the same layout as the Eurocomp Handbook, and contains supplementary information to the CUR96 Recommendations (Chlosta 2012). The recommendations are mainly focused of the report is related to material properties, conversion- and material factors (Chlosta 2012). The CUR 2003-6 Background report gives a detailed explanation of how to calculate structures subjected to fatigue loading (Chlosta 2012).

8.3 Fiberline Design Manual

The Fiberline Design Manual was conducted by the well-known Danish FRP composite manufacturing company Fiberline (Chlosta 2012). The design specifications of the Fiberline Design Manual are mainly focused on the available Fiberline profiles which come in different shapes and dimensions are manufactured with the pultrusion process (Chlosta 2012). The fibre volume fraction of Fiberline profiles are furthermore generally in the range of 60% with E-glass fibres (Chlosta 2012). The matrix materials used in Fiberline profiles are (Chlosta 2012):

- P2600 Isophtalic polyester
- P3510 Vinyl ester (high temperature resistance)
- P4506 Isophtalic polyester (fire retardant)

A disadvantage of the Fiberline Design Manual is that it was developed for Fiberline profiles and is hence only applicable for structures that are built with Fiberline profiles (Chlosta 2012).

The topics covered in the Fiberline Design manual are (Chlosta 2012):

- Chapter 2 “Coefficients” which covers values and definitions, profiles, static calculations, deformation limits, loads and material properties
- Chapter 3 “Profiles used as beams and columns” gives examples of tensile-, compressive- and flexural strength

- Chapter 4 “Bolted joints” which covers calculation of bolted joints in terms of longitudinal and transverse capacity of bolts, tensile capacity of bolts and presents several examples of calculations
- Chapter 5 “Glued joints”
- Chapter 6 “Profile tables” gives detailed tables of the available profiles: L-profiles, IL-profiles, U-profiles, UL-profiles, Square tube, T-profile, L-profile, Pipe profile and handrails

In contrast to the other design codes and handbooks, the Fiberline Design Manual covers information related to fire properties, environmental, recycling and chemical resistance of the profiles (Chlosta 2012).

8.4 BD 90/05 UK standard

The UK standard called BD 90/05 is developed for design of highway bridges and re-decking, of existing bridges, with FRP materials (Clark, Howison, Parker & Allister 2005). The standard is suited for designers with previous knowledge of FRP composite materials, however expertise knowledge regarding FRP bridges is not required (Clark et al. 2005).

The topics that are covered in the BD 90/05 UK standard are (Clark et al. 2005):

- Chapter 2 “Components and sub-assemblies”
- Chapter 3 “Material characteristic of different FRP types” covers properties such as tensile strength, elastic modulus, elongation at failure and density
- Chapter 4 “Design requirements “ which covers parameters such as loading, design life, ultimate and serviceability limit states, deflection, vibration, fatigue limit state (local and global effects) and partial safety factors for loads and materials (ULS and SLS)
- Chapter 5 ”General requirement” which covers parameters such as durability, detailing, parapets, movement joints, resistance to fire and surface finishing
- Chapter 6 “Construction and maintenance”

8.5 Comparison of Recommendations

A comparison of advantages and disadvantages between the different unofficial codes is displayed in Table 75.

Table 75 Comparison of advantages and disadvantages for the Eurocomp, CUR96 and BD 90/05 UK standard

Standard types	Advantage	Disadvantage
Eurocomp	• Wide-range of applications for FRP structural performances • Design focus on serviceability, resistance and durability of structures • Can use Eurocode1 for calculations of actions • Can be used the fibre types aramid and carbon • Considers design of joints	• Developed for GFRP composites • Design code do not cover the seismic design of GFRP structures

CUR 96	• Design focused on material properties, calculation of strength and stiffness values and safety factors when designing GFRP composites	• Only for GFRP • Limited information regarding creep and impact damage • No information of design of connection
Fiberline	• Including specific FRP composite profiles and detail of the design of using • Carry out information of sustainable aspects for their profile information	• Only for pultrusion FRP structures component • Too specific profiles
UK BD 90/05	• Focus on FRP composite road bridges and re-decking of existing bridges with FRP	• Knowledge about FRP composite materials are required of the designer

8.6 Partial Safety Factors for FRP Composites

8.6.1 Material Partial Safety Factors - Eurocomp

In general the design value of material property X_d is defined as:

$$X_d = X_k/\gamma_m$$

Where X_k the characteristic material value is represented by a fractile and γ_m is the materials partial safety factor defined as material partial safety factors

Table 76 Partial safety factors for materials (Clark 1996)

Partial safety coefficient	Description (condition i)	Value of γ_{mi}		Notes
		Max	Min	
γ_{m1}	Derivation of material properties from test values (level of uncertainty)	2.25	1.0	(a), (b), (c)
γ_{m2}	Material and production process	2.7	1.1	(a), (b), (d)
γ_{m3}	Environmental effects and duration of loading	3	1	(a), (b), (e)

Notes for Table 76:

a) The partial safety factor of FRP material includes three different γ_m values, due to the difference in manufacturing techniques and material properties. The FRP materials partial safety factors are appropriate to use if the actions are persistent or transient (Clarke 1996).

For the Ultimate Limit State, the partial safety factor (γ_m) for material properties is given by the expression (Clarke 1996):

$$\gamma_m = \gamma_{m1}\gamma_{m2}\gamma_{m3}$$

The partial safety factors coefficients of $\gamma_{m1}, \gamma_{m3}\ and\ \gamma_{m3}$ can be obtained in Table 76. For ULS should γ_m be in the range of 1.5 and 10 and for SLS not less than 1.3 for building structures (Clarke 1996; Zoghi 2013).

b) Due to the consideration of accidental loading, the calculation of γ_m in (a) might needed to reduce with maximum one-third of the value (Clarke 1996). However more detailed or tested data justified with a bigger reduction (Clarke 1996).

c) The partial safety factor γ_{m1} is related to the uncertainty of deriving the laminate and values are given in Table 77, unless if more detailed information and test data are available, resulting in a lower value (Clarke 1996). The value of γ_{m1} should be in the range of 1.0 < γ_{m1} < 2.25 (Zoghi 2013).

Table 77 Values for γm1 (Clark 1996)

Derivation of properties	γ_{m1}
Properties of constituent materials (i.e. fibre and matrix) are derived from test specimen data	2.25
Properties of individual laminate are derived from theory	2.25
Properties of the laminate, panel or pultrusion are derived from theory	2.25
Properties of individual plies are derived from test specimen data.	1.5
Properties of the laminate, panel or pultrusion are derived from theory.	1.5
Properties of the laminate, panel or pultrusion are derived from test specimen data.	1.15

d) The partial safety factor γ_{m2} is related to the material and the manufacture process, which is given in Table 78. The value of γ_{m2} should be in the range of 1.1 < γ_{m2} < 2.7 (Zoghi 2013).

Table 78 Values for γm2 (Clark 1996)

Method of manufacture	γ_{m2}	
	Fully post-cured at works	Not fully post-cured at works
Hand-held spray application	2.2	3.2
Machine-controlled spray application 1.4 2.0	1.4	2.0
Hand lay-up	1.4	2.0
Resin transfer moulding	1.2	1.7

Prepreg lay-up	1.1	1.7
Machine-controlled filament winding	1.1	1.7
Pultrusion	1.1	1.7

e) The partial safety factor γ_{m3} is related loading duration and the environmental effect, which is given in Table 79. The value of γ_{m3} should be in the range of 1.0 < γ_{m3} < 3.0 (Zoghi 2013).

Table 79 Values of γm3 (Clark 1996)

Operating design temperature (°C)	HDT (°C)	γ_{m3}	
		Short-term loading	Long-term loading
25-50	55-80	1.2	3.0
	80-90	1.1	2.8
	>90	1.0	2.5
0-25	55-70	1.1	2.7
	70-80	1.0	2.6
	>80	1.0	2.5

HDT is referred to the heat distortion temperature and the operating design temperature should be retrieved through special advice (Clarke 1996).

8.6.2 Partial Safety Factor Related to Fatigue - Eurocomp

A FRP composite element which is subject by fatigue loading, the stress cycles n shall be achieve by following criteria (Clarke 1996):

For normal stress:

$$\gamma_{Ff}\Delta\sigma < \Delta\sigma_R/\gamma_{mf}$$

For shear stress:

$$\gamma_{Ff}\Delta\tau < \Delta\tau_R/\gamma_{mf}$$

Where:

$\Delta\sigma$ is the nominal normal stress range ($= \sigma_{max} - \sigma_{min}$), $\Delta\sigma_R$ is the normal fatigue strength, $\Delta\tau$ is the nominal shear stress range ($= \tau_{max} - \tau_{min}$), $\Delta\tau_R$ is the shear fatigue strength, σ_{max} and τ_{max} are the maximum stresses, σ_m and τ_m are the mean stresses, σ_{min} and τ_{min} are the minimum stresses, σ_R is the characteristic normal strength, τ_R is the characteristic shear strength, γ_{Ff} is the partial safety factor for fatigue actions with a value of 1.0 unless otherwise is determined or agreed

The partial safety factor γ_m for material properties if considering fatigue, where an extra partial safety factor γ_{m4} is considered, is given by the expression (Clarke 1996):

$$\gamma_{mf} = \gamma_{m1}\gamma_{m2}\gamma_{m3}\gamma_{m4}$$

Where:

$\gamma_{m1}, \gamma_{m2}, \gamma_{m3}$ are defined in Table 76 and γ_{m4} is defined in Table 80

Table 80 Partial safety factors γm_4 for fatigue strength (Clark 1996)

Inspection and access	"Fail-safe" components	Non "fail-safe" components
Component subjected to periodic inspection and maintenance. Detail accessible.	1.5	2.0
Component subjected to periodic inspection and maintenance. Poor accessibility of detail.	2.0	2.5
Component not subjected to periodic inspection and maintenance.	2.5	3.0

For a "Fail-safe" component local failure does not result in failure of the structure, which is not ensured for a non "fail-safe" components (Clarke 1996).

8.6.3 Material Partial Safety Factors According to CUR96

The safety factors for CUR96 recommendation for FRP composite is similar to Eurocode on FRP structural design, the design shows below is a general formula regarding to all design of calculation on FRP (CUR 1996; Chlosta 2012).

$$S\gamma_f \leq \frac{R}{\gamma_m \gamma_c}$$

Where:

γ_f is define as the load factor, γ_m is define as the material factors, γ_c is define as the conversion factors, S is define as the effect of the imposed design loads, R is define as the characteristic strength of the structures

The material partial safety factors γ_m are defined with the following formula:

$$\gamma_m = \gamma_{m1}\gamma_{m2}$$

Where:

γ_{m1} is equal to 1.35 and accounting for uncertainties involved in obtaining the material properties which, $\gamma_{m2}$is taking into consideration for uncertainties in material properties and depends on the production method. These values are presented in Table 81.

Table 81 Value of partial safety factors γ_{m2} (Chlosta 2012)

Method of manufacture	γ_{m2}	
	Fully post-cured at works	Not fully post-cured at works
Fibre spraying	1.6	1.9
Hand lay-up	1.4	1.7
Vacuum assisted resin transfer moulding (VARTM) or resin transfer moulding (RTM)	1.2	1.4
Filament winding	1.0	1.3
Prepreg lay-up	1.0	1.3
Pultrusion	1.0	1.3

Notes for Table 81:

Regarding to stability checks, the value of γ_m and γ_f shall be taken at least $\gamma_m, \gamma_f \geq 2.5$ or otherwise checked in section 9.2.1 in CUR 96 (CUR 1996; Chlosta 2012). For tests of the extreme limit state of strength the material factor γ_m should be larger 1.5 (CUR 1996).

8.6.3.1 Conversion Factors

The recommendation of CUR 96 suggests that conversion factor should be used which accounts for foreseen long-term effects and fatigue (CUR 1996).

The calculation of the conversion factors for FRP composites subjected to different conditions is given with the following formula (CUR 1996):

$$\gamma_c = \gamma_{ct} \cdot \gamma_{cv} \cdot \gamma_{ck} \cdot \gamma_{cf}$$

Where:

γ_c is the total conversion factor, γ_{ct} is defined as the effects of temperature, γ_{cv} is defined as the effects of moisture, γ_{ck} is defined as the effects of creep and γ_{cf} is defined as the effects of fatigue

Values of the conversion factors used in CUR96 can be seen in Table 82. Table 83 displays the areas where the respective conversion factor should be considered.

Table 82 More information about conversion factors (CUR 1996)

Conversion factors	**Description**	**values**
γ_c	total conversion factor	-
γ_{ct}	an effect of temperature	1.1

γ_{cv}	an effect of moisture	For GFRP structure exposed in dry condition	1.0
		For GFRP structure exposed in variation humidity condition (suitable for traffic bridge)	1.1
		For GFRP structure exposed in wet condition	1.3
γ_{ck}	an effect of creep		See (CUR 96)
γ_{cf}	an effect of fatigue		1.1

Table 83 Shows where application of the conversion factor should be taken into account (CUR 1996; Chlosta 2012)

	Extreme limit state			**Utility limit state**		
	Strength	Stability	Fatigue	Deformation	Vibration	First cracking
Conversion factor for temperature	x	x	x	x	x[3]	x
Conversion factor moisture	x	x	x	x	x[3]	x
Conversion factor creep[1]	x	x		x		x
Conversion factor fatigue		x		x	x[3]	x

8.7 Material Partial Safety Factor According to UK BD 90/05

The UK design manual is focused on re-decking with FRP composites of conventional bridges (Clark et al. 2005). The design manual also includes the material partial safety factors. The following recommendations are related to the structural performance of the FRP components decks and beams (Clark et al. 2005).

8.7.1 Ultimate Limit State

Table 84 shows the material partial factors that are applicable for design of the capacity of FRP structural components (Clark et al. 2005).

Table 84 The application of material partial factors for ULS (Clark et al. 2005)

	FRP deck		**FRP main beam**	
Material/ Loading type	**Transient**	**Permanent**	**Transient**	**Permanent**

Glass FRP (GFRP)	1.7	3.0	3.0	4.5
Aramid FRP (AFRP)	1.7	3.0	3.0	4.5
Carbon FRP (CFRP)	1.5	2.0	2.5	4.5

Notes for Table 84 and Table 85:

- The partial factors should be multiplied with 1.1 for automated processes such as pultrusion (Clark et al. 2005).
- The partial factors should be multiplied with 1.3 for manual and semi-automated techniques, such as hand lay-up, prepreg moulding and rein transfer moulding (Clark et al. 2005).

The partial factors should be considered for effects such as stress rupture, temperature variation, moisture, creep and general degradation (Clark et al. 2005).

8.7.1.1 Serviceability Limit State

Table 84 displays the material partial factors that are used in serviceability limit state design of FRP structural components. The factors are more appropriate applied to strength and modulus (Clark et al. 2005)

Table 85 The application of material partial factors for SLS (Clark et al. 2005)

	FRP deck		FRP main beam	
Material/ Loading type	**Transient**	**Permanent**	**Transient**	**Permanent**
Glass FRP (GFRP)	1.2	1.5	1.8	2.5
Aramid FRP (AFRP)	1.2	1.5	1.8	2.5
Carbon FRP (CFRP)	1.1	1.25	1.5	2.3

8.7.2 Design of FRP Structural Members

The information of this section will most provide the design criteria and limiting values for structural members of FRP material. Most of the information is referred from Eurocomp Design Code which covers all design areas.

Figure 139 displays the assumed coordinate system of the Eurocomp Design Code, used for the elements and components (Clarke 1996).

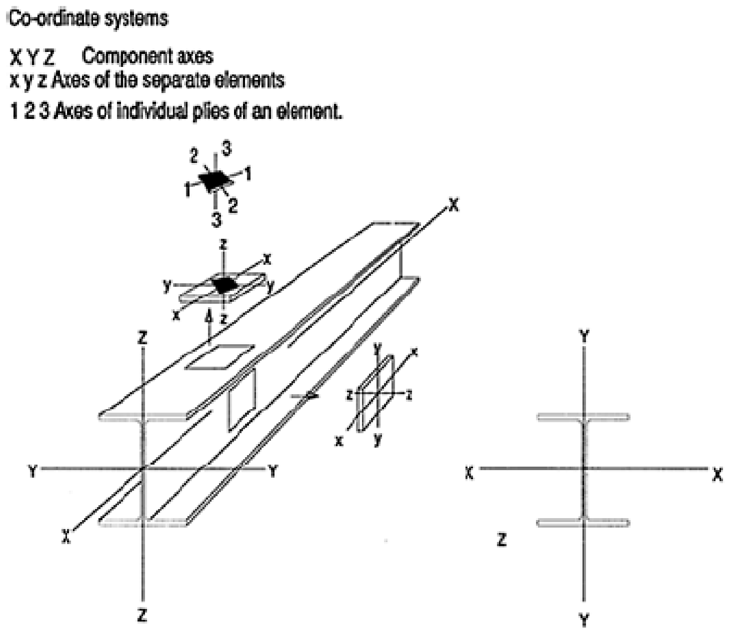


Figure 139 Coordinate system from the Eurocomp Design Code (Clarke 1996)

8.7.2.1 Laminate Design

Laminate design should fulfil the conditions of both the ultimate lime state and the serviceability limit state (ZRMK, TNO, UNIVPM, Mostostal, Acciona & Huntsman 2013). There are many methods to calculate the stiffness parameters of a laminate ply, examples are through experimental testing, the Halpin-Tsai method and the Simple Rule of Mixtures etc. (ZRMK et al. 2013). The design strength of a laminate can be determined through experimental testing or through data from manufacturers and is subsequently divided by the appropriate partial safety factor (ZRMK et al. 2013). Appendix B displays recommendation of standardisation related to the testing methods of laminates. The reader is referred to the Eurocomp Design Code for more information about laminate design (Clarke 1996).

8.7.2.2 Service Limit State

The factors considered in the serviceability limit state are (Clarke 1996):

- Deformations or deflections in the magnitude that the use and appearance of the structure is affected
- Damage and discomfort subjected to buildings and occupants due to the effects of vibrations, sway or oscillation
- All the affects mentioned above which causes damage to non-structural elements

To avoid the effect of damage from deformation, deflection and vibration it is important to set limiting values (Clarke 1996). The limiting values seen in Table 86 should be used by designer if the client, designer and authority have not given specific limiting values (Clarke 1996).

8.7.2.3 Deflection Limits

According to the SLS, the deflection of the beam is necessary to be checked (Clarke 1996). Figure 140 illustrates the deflection of a simply supported beam and the limiting values of the vertical deflection (Clarke 1996).

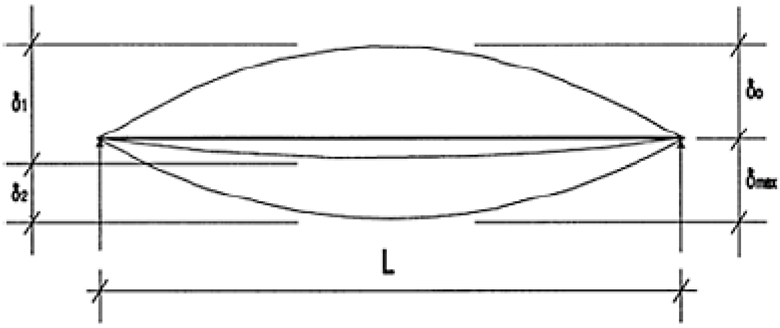


Figure 140 Vertical deflections (Clark 1996)

Where:

δ_{max} is defined as the maximum deflection, δ_1 is the variation of the deflection of the beam caused by permanent loads immediately after loading, δ_2 is a variation of the deflection of the beam because of the variable loading with time dependent deformations due to the permanent load, δ_0 is defined as the deflection due to the beam at the unloaded state

The following limits for deflections can be seen in Table 86 and are suited for different types of condition.

Table 86 Recommendation limiting values for deflection (Clark 1996)

Typical conditions	**Limits (see Figure 140)**	
	δ_{max}	δ_2
Walkways for occasional non-public access	L/150	L/175
General non-specific applications	L/175	L/200
General public access flooring	L/250	L/300
Floors and roofs supporting plaster or other brittle finish or non-flexible partitions	L/250	L/350
Floors supporting columns (unless the deflection has been included in the global analysis for the ultimate limit state)	L/400	L/500
Where $\boldsymbol{\delta_{max}}$ can impair the appearance of the structure	L/250	-

8.7.2.3.1 Deflection from Bending and Shear

The following of equations are calculation for bending and shear of isotropic, homogeneous beams which can be used for composite materials (Clarke 1996).

$$\text{Deflection (bending)} = k_1 F_v L^3 / (EI)$$

Where:

k_1 (see Table 87) is a factor that takes into account the end conditions and loading type of the beam, F_v is defined as the total vertical load applied on the beam, L is span length of the beam and EI is the appropriate flexural stiffness of the full section of the beam

$$\text{Deflection (shear)} = k_2 F_v L / A_v G_{xy}$$

Where:

k_2 (see Table 87) is a factor that takes into account the end conditions and loading type of the beam, F_v is the total vertical load applied on the beam, A_v is the area of the web and G_{xy} is defined as the web in-plane shear modulus

Values for k_1 and k_2 can be found in Table 87 (Clark 1996).

Table 87 Selected values for k_1 and k_2 (Clark 1996)

End conditions	Loading type	k1	k2
Cantilever	Point load at end	1/3	1
Cantilever	Uniformly distributed	1/8	1/2
Supported at ends	Point load at centre	1/48	1/4
Supported at ends	Uniformly distributed	5/384	1/8
Fixed at ends	Uniformly distributed	1/384	1/24

8.7.2.4 Ultimate Limit State

The following expression should be satisfied for the ultimate limit state (ULS) (Clarke 1996):

$$E_d \leq R_d$$

Where:

E_d is defined as effect of actions and R_d is defined as the design resistance

Table 88 displays equations for calculations of the flexural rigidity of isotropic and orthotropic plates.

Table 88 Plate stiffness equations (Clarke 1996)

Isotropic plates	$\boldsymbol{D = \dfrac{Et^3}{12(1-\nu^2)}}$
Specially orthotropic plates	$D_x = \dfrac{E_x t^3}{12(1-\nu_{xy}\nu_{yx})}$ $D_{xy} - D_{yx} = \dfrac{\nu_{yx} E_x t^3}{12(1-\nu_{xy}\nu_{yx})}$

$$D'_{xy} = \frac{G_{xy}t^3}{12}$$

$$D_y = \frac{E_y t^3}{12(1 - \nu_{xy}\nu_{yx})}$$

Where:

t is the thickness of the laminate, D_{xy} is the shear stiffness, E is the modulus of elasticity in bending, E_x is the modulus of elasticity in bending (x-direction), E_y is the modulus of elasticity in bending (y-direction), G_{xy} is the in-plane shear modulus, ν_{xy} is the major Poisson's ratio, ν_{yx} is the minor Poisson's ratio

8.7.2.5 Members in Tension

The following criterion is only focus on element which is subject to tensile forces (Clarke 1996). Tensile members have their longitudinal axis aligned parallel to the x-axis which can be seen in Figure 139 (Clarke 1996).

The design requirements that should be satisfied for all cross-sections of tensile members are (Clarke 1996):

$$N_{t,Sd} \leq N_{t,Rd}$$

Where:

$N_{t,Sd}$ is defined as the design tensile force and $N_{t,Rd}$ is defined as the design tension resistance of the cross-section

Where $N_{t,Rd}$ should be taken as the smaller of (Clarke 1996):

- The minimum gross cross-section

$$N_{t,Rd} = A\sigma_{x,t,k}/\gamma_m$$

Where:

A is defined as area of the cross-section, $\sigma_{x,t,k}$ is defined as tensile strength of laminate for gross cross-sectional area and γ_m is partial safety factor for material resistance

- The net cross-section at holes

$$N_{t,Rd} = 0.9A_{net}\sigma_{x,t,k}/\gamma_m$$

Where:

A_{net} is defined as the net cross-section area, $\sigma_{x,t,k}$, is defined as the as tensile strength of the laminate of the gross cross-sectional area and γ_m is the partial safety factor for material resistance

8.7.2.6 Members in Compression

For all cross-section of the member the member subjected to axial compression should satisfy the following expression (Clarke 1996):

$$N_{c,Sd} \leq N_{c,Rd}$$

Where:

$N_{c,Sd}$ is defined as the design compression force and $N_{c,Rd}$ is defined as the design compression resistance of the cross-section.

The design compression resistance, $N_{c,Rd}$, should be taken as the smallest value of the three conditions (Clarke 1996):

- The cross-sections ultimate design resistance:

$$N_{c,Rd} = A\sigma_{c,R}/\gamma_m$$

Where:

A is the cross-section area, $\sigma_{c,R}$ depends on the characteristic compressive strength of the laminate, i.e. $\sigma_{x,c,k}$ or $\sigma_{y,c,k}$ and γ_m is the partial safety factor of the material resistance

- The buckling resistance of the member:

$$N_{c,Rd} = k\pi^2 E_{x,d} I_{zz}/L^2\gamma_m$$

Where:

I_{zz} is the second moment of area (weak axis), where $k = 1$ is for columns with pinned ends and $k = 4$ is for columns with built-in ends

- The cross-sections for design local buckling resistance:

$$N_{c,Rd} = A_{eff}\sigma_{c,cr}/\gamma_m$$

Where:

A_{eff} is the effective cross-section area, γ_m is the partial safety factor for the material resistance and $\sigma_{c,cr}$ is defined as the buckling strength of the section

The least critical buckling resistance of the element in the section,$\sigma_{c,cr}$, can be determined for different boundary conditions as (Clarke 1996):

- For a rectangular plate with longer sides simply supported:

$$\sigma_{c,cr,y} = 2\pi^2[(D_x D_y)^{\frac{1}{2}} + H_0]/tb^2$$

$$H_0 = \frac{1}{2}(\nu_{xy}D_y + \nu_{yx}D_x) + 2(\frac{G_{xy}t^3}{12})$$

Where:

b is defined as effective width of the plate element, t is defined as thickness of the plate element, D_x and D_y are plate stiffnesses and are given in Table 88.

- A long rectangular plate with one long side simply supported and the other free:

$$\sigma_{c,cr,y} = \pi^2[(D_x\left(\frac{b}{a}\right)^2) + (\frac{12D'_{xy}}{\pi^2})]/tb^2$$

Where:

b is the effective width of the plate element, t is the thickness of the plate element and D_x, D_y and D'_{xy} are the stiffness of the orthotropic plate which was given in Table 88.

- For isotropic tubular sections and r/t>10:

$$\sigma_{c,cr,y} = 0.25E_{x,c,k}tr$$

Where:

$E_{x,c,k}$ is the characteristic axial compressive modulus, t is the thickness of the tube and r is the mean radius of the tube.

8.7.2.7 Members in Flexure

The design resistance of the member should be equal or larger for the following ultimate limit states (Clarke 1996):

- Axial strength
- Shear strength
- Flexural strength
- Bearing stress
- Web buckling due to shear
- Web buckling due to flexure
- Web buckling due to flexure and shear
- Web crippling
- Lateral torsional buckling
- Compression flange buckling

It can be noted that the last six items are covered under the chapter: 8.7.2.9 Stability.

8.7.2.7.1 Flexural Strength - Strength in Bending

For all sections of the member the internal bending moment M_{sd} should be equal or lower than the design moment resistance M_{Rd} (Clarke 1996):

$$M_{Sd} \leq M_{Rd}$$

The design moment resistance, M_{Rd}, should be taken as the lowest value of the following four conditions (Clarke 1996):

• The gross sections design ultimate resistance moment:

$$M_{Rd} = W_t\sigma_{t,k}/\gamma_m$$

Where:

W_t is the as section modulus in tension, $\sigma_{t,k}$ is the characteristic tensile strength and γ_m is the partial safety factor

• The gross sections design local buckling resistance:

$$M_{Rd} = M_{c,cr}/\gamma_m \text{ or } M_{Rd} = W_c\sigma_{c,k}/\gamma_m$$

Where:

$M_{c,cr}$ is the local buckling resistance of the cross-section, W_c is the section modulus in compression, $\sigma_{c,k}$ is the characteristic compression strength and γ_m is the partial safety factor

• The members lateral torsional buckling resistance moment:

$$M_{Rd} = M_{b,cr}/\gamma_m$$

Where:

$M_{b,cr}$ is the lateral torsional buckling resistance moment of the member and γ_m is the partial safety factor

8.7.2.8 Shear Strength - Member in Shear

The shear strength requirement is that for each cross-section of the member the shear force V_{Sd} should be equal or lower than the design shear resistance V_{Rd} (Clarke 1996):

$$V_{Sd} \leq V_{Rd}$$

The members design shear resistance V_{Rd} can be calculated as (Clarke 1996):

$$V_{Rd} = A_v \tau_{xy,k}/\gamma_m$$

Where,

A_v defined as area of shear and $\tau_{xy,k}$ is defined as the characteristic in-plan shear of the laminate

The shear area for different cross-sectional shapes can be taken as follows (Clarke 1996):

- For fabricated shapes as I, H and hollow box sections, loaded parallel to the web the area is calculated as:

$$A_v = \Sigma(d_w t_w)$$

Where:

A_v is defined as the shear area, d_w is the depth of the web and t_w is the thickness of the web

- For fabricated shapes as I, H and channel sections, loaded parallel to flanges:

$$A_v = A - \Sigma(d_w t_w)$$

Where:

A is defined as cross-section area

- For circular hollow sections and tube shapes with uniform thickness:

$$A_v = 2A/\pi$$

- For solid bars and plates:

$$A_v = A$$

It can be noted that (Clarke 1996):

- For other shapes than those already mentioned A_v should be established in a similar way as above
- If the thickness of the web is not constant, the minimum value of the thickness shall be used for t_w

- The shear buckling resistance should be further checked according to the following chapter: Web Buckling due to Shear – Critical Shear Stress in the Web
- Splices and end connection should be appropriately designed in terms of shear forces that are transferred across the joint

8.7.2.9 Stability

The requirement due to bending stress and shear stress in the web should be taken into account regard to the stability.

8.7.2.9.1 Web Buckling due to Flexure – Critical Flexural Stress in the Web

The requirement of in-plane bending stress is (Clarke 1996):

$$\sigma_{x,b} \leq \sigma_{x,cr,b}$$

Where:

$\sigma_{x,b}$ is the in-plane bending stress and $\sigma_{x,cr,b}$ is the critical buckling in-plane bending stress without shear stress

For a rectangular panel subjected to in-plane flexure, the critical buckling stress can be calculated as (Clarke 1996):

For isotropic material (Clarke 1996):

$$\sigma_{x,cr,b} = \frac{k\pi^2 E\left(\frac{t_w}{d_w}\right)^2}{12\left(1-\nu_{xy}^2\right)}$$

Where:

$k = 23.9$ and ν_{xy} is the Poisson's ratio

For special orthotropic materials (Clarke 1996):

$$\sigma_{x,cr,b} = \frac{k\pi^2 D_x}{d_w^2 t_w}$$

Where:

$k = 50$ if $\frac{D_y}{D_x} = 1$ i.e. web is fully clamped to the flange and $k = 20$ if $\frac{D_y}{D_x} = 0.5$ i.e. the web is partly clamped to the flange, D_x and D_y are the stiffness of the plate see Table 88

8.7.2.9.2 Web Buckling due to Shear – Critical Shear Stress in the Web

The requirement of shear stress in the web should be satisfy by the expression (Clarke 1996):

$$\tau_{xy} \leq \tau_{xy,cr,b}$$

Where:

τ_{xy} is the shear stress in x-, y-plane and $\tau_{xy,cr,b}$ is the critical buckling stress of an rectangular plate subjected to in-plane shear stress

The critical buckling stress can be taken as (Clarke 1996):

For isotropic materials:

$$\tau_{xy,cr,b} = \frac{k\pi^2 E\left(\frac{t_w}{d_w}\right)^2}{12(1-\nu^2)}$$

Where,

$k = 5.35$ for simply supported edges and $\frac{a}{b} > 10$ and $k = 8.98$ for built-in edges with $\frac{a}{b} > 10$, where a is the length of plate i.e. in the longitudinal direction and b is the width of plate i.e. in the transverse direction

For special orthotropic materials:

$$\tau_{cr} = 4k\left(D_x D_y^3\right)^{0.25} / d_w^2 t_w$$

Where:

$k = 8$ and D_x and D_y is defined as the stiffness of the plate, see Table 88

8.7.2.9.3 Web Buckling due to Flexure and Shear – Combined Shear and in-plane Bending in the Web

The criteria of combined shear and bending subjected to a web members should satisfy (Clarke 1996):

$$\left(\frac{\tau_{xy}}{\tau_{xy,cr,b}}\right)^2 + \left(\frac{\sigma_{b,x}}{\sigma_{x,cr,b}}\right)^2 \leq 1$$

The minimum value of the second moment of inertia I_s about the plane of the web of the stiffener should satisfy (Clarke 1996):

$$I_s = 0.34 d_w^4 \left(\frac{t_w}{b_s}\right)^3$$

8.7.2.9.4 Web Crippling - Buckling Resistance of the Web

For the sections I, H and U the design buckling resistance $R_{b,Rd}$ can be calculated by approximating the web as a compression member with the effective width b_{eff} (Clarke 1996):

$$b_{eff} = (h^2 + S_s^2)^{0.5}$$

The critical buckling stress, σ_{cr}, can be calculated as (Clarke 1996):

$$\sigma_{cr} = k\pi^2 \sqrt{D_x D_y} / b_{eff}^2 t_w$$

Where:

$$k = 2\left(1 + \frac{H}{\sqrt{D_x D_y}}\right)$$

$$H_0 = \frac{1}{2}\left(\nu_{xy} D_y + \nu_{yx} D_x\right) + \frac{G_{xy} t^3}{6}$$

I can be noted for an isotropic material that: $D_x = D_y = H_0$ and $k = 4$

8.7.2.9.5 Compression Flange Buckling - Buckling of Compression Flange

For all point in the member the following relationship should be fulfilled with regard to compression flange buckling (Clarke 1996):

$$\sigma_{c,x} \leq \sigma_{x,cr,c} / \gamma_m$$

Where:

$\sigma_{c,x}$ is the stress in any point of the longitudinal compression flange, $\sigma_{x,cr,c}$ is the critical buckling stress and γ_m is the partial safety factor

For isotropic plates where the flange is considerably longer than the wide the critical buckling stress can be calculated according to (Clarke 1996):

$$\sigma_{x,cr,c} = G_{xy,d}\left(\frac{2t_f}{b_f}\right)^2$$

Where:

$G_{xy,d}$ is the shear modulus of the flange in the plane

For orthotropic plates whit one pinned and one free longitudinal edge the local buckling stress can be calculated according to (Clarke 1996):

$$\sigma_{x,cr,b} = \pi^2\left[\left(D_x\left(\frac{b_f}{a}\right)^2\right) + \left(\frac{12D'_{xy}}{\pi^2}\right)\right]/t_f b_f^2$$

Where:

a is the half wavelength of the buckling length of the flange

8.7.2.9.6 Lateral Torsional Buckling

The calculation of critical buckling moment is defined as (Clarke 1996):

$$M_b C_1 = P_{ey}\left[K\frac{I_w}{I_{zz}} + \frac{GJ}{P_{ey}}\right]^{0.25}$$

Where:

C_1 is defined as a factor depending on the loading and end restraint conditions which can be retrieved from Table 89, K is the effective length factor referring to the end rotation about the minor axis, G_{xy} is the shear modulus of the flange material, J is the torsion constant, I_w is the warping constant (see equation below) and P_{ey} is the Euler column buckling load about the weak axis

The Euler buckling load can be calculated according to (Clarke 1996):

$$P_{ey} = \frac{\pi^2 E_{z,b,d} I_{zz}}{(kL)^2}$$

Where:

I_{zz} is the second moment of area about minor axis, L is the length of beam between points with lateral restraint, $E_{z,b,k}$ is the modulus of elasticity bending about minor axis and k can be retrieved from Table 89

Table 89 Values for k and C_1 (Clarke 1996)

Load condition	k	C_1
Uniformly distributed loading	1	1.132
Uniformly distributed loading	0.5	0.972

Central concentrated point load	1	1.365
Central concentrated point load	0.5	1.070

Where k = 0.5 corresponds to full fixity and k= 1 corresponds to no fixity

It can be noted that the equation of critical moment is only suited for doubly symmetrical cross-sections with the load subjected through the shear centre and end warping having no fixity.

$$I_w = I_f \frac{(D-t)^2}{2}$$

$$I_f = \frac{b_t^t}{12}$$

8.8 General Information of Structural Members

8.8.1 Trans-IND Beams

The Trans-IND project has presented three different types of beams which are commonly used FRP bridge design today (Warszawa 2012). The three types are divided in: the open-shaped beam, the close-shaped beam and the U-shaped beam (Warszawa 2012). Advantages posed with FRP composite components, such as beams, in comparison with conventional materials are that they have better advantages due to fatigue, corrosion and are lighter (Warszawa 2009).

8.8.1.1 Open-Shaped FRP Beam

The shape of the open-shaped FRP beam presented by the Trans-IND projects can be seen in Figure 141.

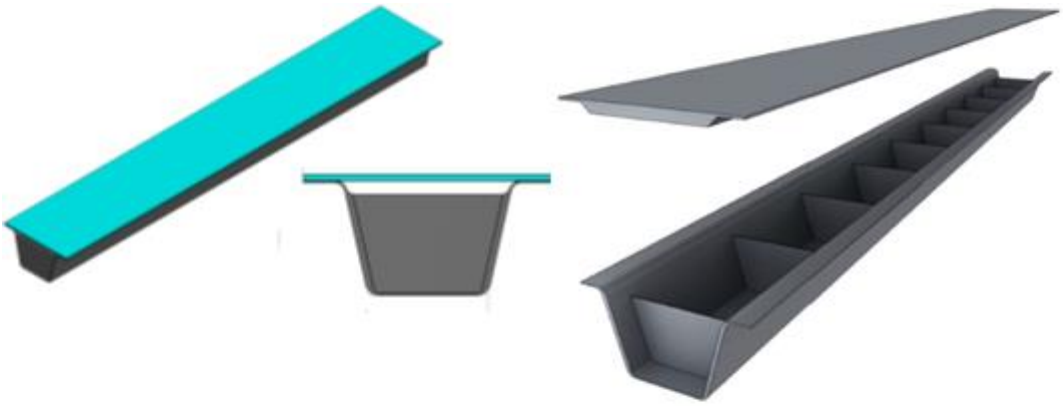


Figure 141 Cross-Section detail of open-shaped beam (Warszawa 2009)

The general information of the open-shaped beam is presented in Table 90. One example where the open-shaped Trans-IND beam has been used was for the PUMACON Bridge, which was mentioned in chapter: 6.1.3 Asturias Road Bridge.

Table 90 General information of Trans-IND open-shaped beam (Warszawa 2009)

Information about open-shaped beam	
Ideal span	10 - 15 m

Depth	1.2m
Width of top flange	2.5 m
Width of bottom flange	1.2m
Weight	1.7 kN/m – 9.8 kN/m
Material	Glass and carbon fibre, light core
Optimal load	5 - 9 kN/m^2
Decks	Continuous and discontinuous
Joints	Bolted connection
Use	Vehicular and pedestrian bridge

8.8.1.2 Close-Shaped FRP Beam

The shape of the close-shaped FRP beam presented by the Trans-IND projects can be seen in Figure 142.

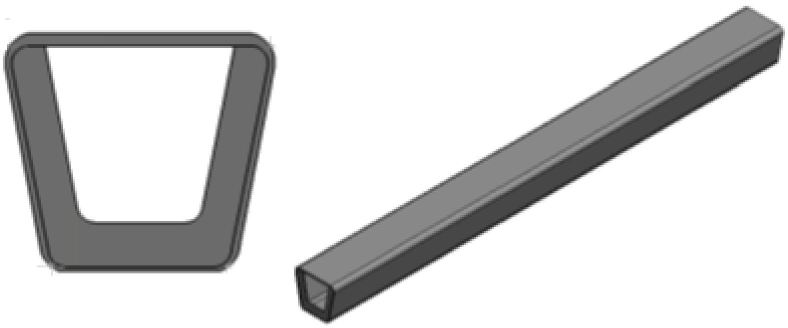


Figure 142 Close-shaped Trans-IND beam (Warszawa 2009)

The general information of the close-shaped beam is presented in Table 91.

Table 91 General information about closed-shaped beam (Warszawa 2009)

Information about closed-shaped beam	
Ideal span	20 - 35 m
Depth	1.5m
Width top flange	1.8 m
Width bottom flange	1.2 m
Weight	2.1 kN/m – 7.9 kN/m
Material	Glass and carbon fibre, light core

Optimal load	5 - 9 kN/m^2
Decks	Continuous and discontinuous
Joints	Embedded connection
Use	Vehicular and pedestrian bridge

8.8.1.3 U-Shaped FRP Beam

The shape of the U-shaped FRP beam presented by the Trans-IND projects can be seen in Figure 143.

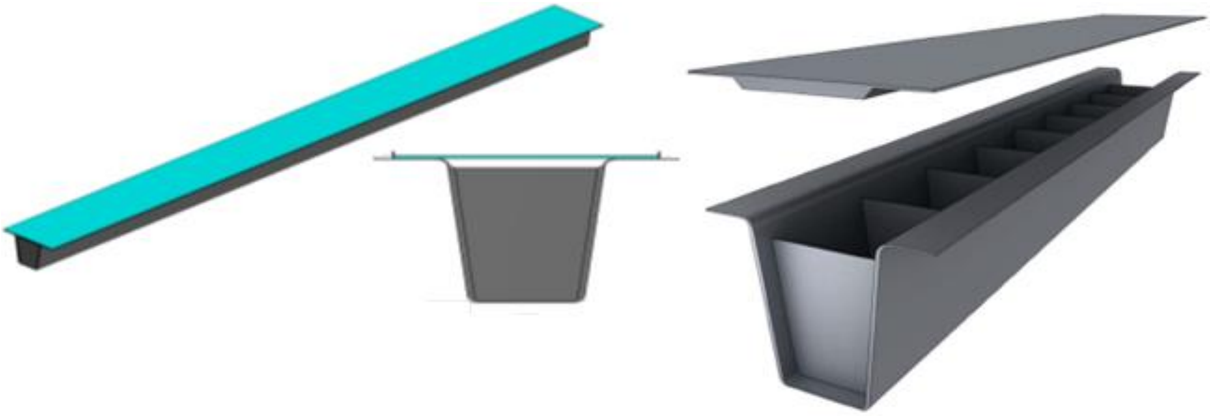


Figure 143 U-shaped Trans-IND beam (Warszawa 2009)

The general information of the U-shaped beam is presented in Table 92.

Table 92 General information about U-shaped beam (Warszawa 2009)

Information about open-shaped beam	
Ideal span	35 - 40 m
Depth	2.2m
Width of the top flange	3.2 m
Width of the bottom flange	1.2
Weight	3.7 kN/m – 7.4 kN/m
Material	Glass and carbon fibre, light core
Optimal load	5 - 9 kN/m^2
Decks	Continuous and discontinuous
Joints	Bolted connection

Use	Vehicular and pedestrian bridge

8.8.1.4 Design Guidelines for Trans-IND – Selection of Beam

The illustration in Figure 144 is represents a scheme so that the most suitable and cost-effective beam is chosen for the specific application (Warszawa 2009). The q specified as the y-axis of the illustration is the super imposed load, which is the combination of the dead load and the live load (Warszawa 2009).

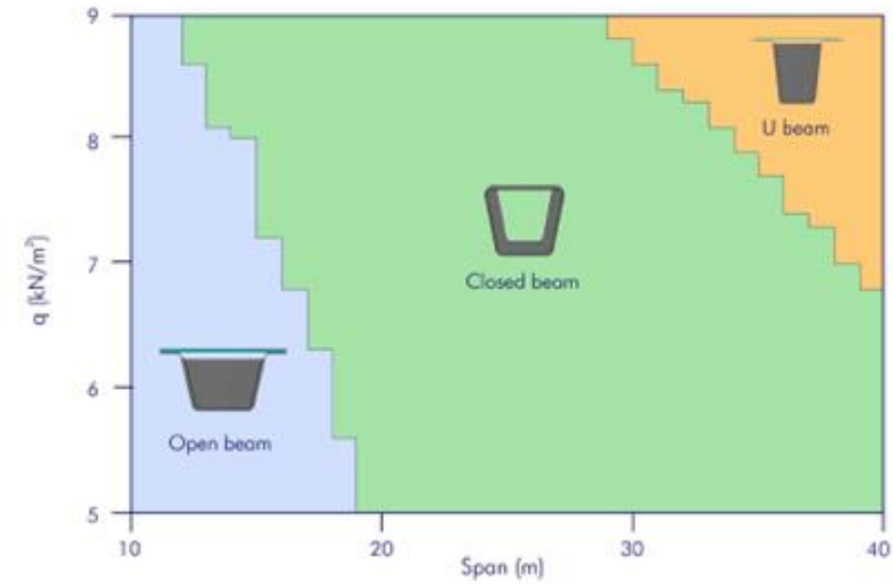


Figure 144 Optima selection to bridge requirement (Warszawa 2009)

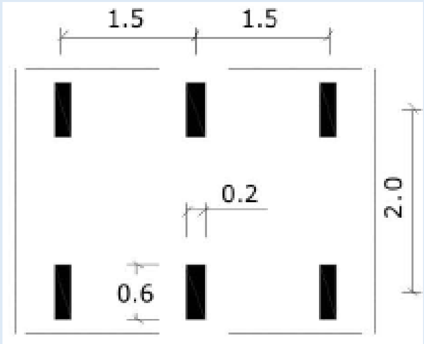
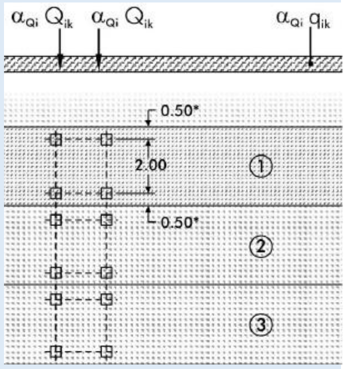
The factors that have to be considered when selecting the beam are (Warszawa 2009):

- The bridge should have a span ranging from 10m to 40 m
- The width of the bridge should be smaller than 12 m
- The beams should be simply supported
- When considering the loads the Spanish regulations called “Instruction on actions to be considered in the design of road bridge (IAP-98)” should be followed

As have been mentioned earlier there are no available European standards related to FRP composites (Warszawa 2009).The group called ACCIONA Infrastructures have through a series of theoretical and field work studies come up with a methodology for the design of road and pedestrian bridges consisting of FRP composite materials (Warszawa 2009). The methodology is summarized in Table 93 (Warszawa 2009). It can be noted that the effects of snow, seismic and wind loads are not considered in the beam calculations (Warszawa 2009).

Table 93 Beam design standards collected by ACCIONA (Warszawa 2009)

Parameter	Standard used in the design of the beams in the catalogue	Eurocode

Load	“Instruction on actions to be considered in the design of road bridge (IAP-98)”. (Spain); chapter 3.	Vehicle load: Q= $4 kN/m^2$ plus 600 kg Over 6 wheels with 100 kg each 	 Key (1) Lane Nr.1: Q_{1k}=300kN; q_{1k}=$9kN/m^2$ (2) Lane Nr.2: Q_{2k}=200kN; q_{1k}=$2,5kN/m^2$ (3) Lane Nr.3: Q_{3k}=100kN; q_{1k}=$2,5kN/m^2$ *For w_1=3.00 m EU 1, part 2, section 4.
Load Combination	“Instruction on actions to be considered in the design of road bridge (IAP-98)”. (Spain); chapter 4.	There is a coincidence between the load combinations that have to be considered in both cases.	EN 1990:2002, section 6
Material partial safety factors	J.L. Clarke; "Structural design of polymer composites: EUROCOMP design code and handbook"; 1996; ISBN- 13: 9780419194507.	$\gamma_m = \gamma_{m1}\gamma_{m2}\gamma_{m3}$ $\gamma_{m1} = 1.5$ $\gamma_{m2} = 1.2$ $\gamma_{m3} = 1.0$	N.A

Buckling (composite plates)	NASA Technical Reports Server; NTRS. (USA)	-Handbook of structural stability part II, buckling of composite elements, NASA Technical Note 3782. -Buckling behavior of long symmetrically laminated plates subjected to shear and linearly varying axial edge loads, NASA Technical paper 3659.	N.A
Service limits	"Recomendaciones para A el proyecto de puentes mixtos para carreteras; RPX- 95". (Spain).	Deflection: Maximum variation deflection at permanent load between time zero and infinity: L/200 Vibration: 1.65 Hz>f>2.35 Hz	Deflection: EN 1994, part 2,section 7. Vibration: 1.6 Hz>f>2.4 Hz
Physical, chemical and mechanical properties of materials	American Society for Testing and Materials; ASTM. (USA).	-ASTM D3039: Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials. -ASTM D3410: Standard Test Method for Compressive Properties of Polymer Matrix Composite Material with Unsupported Gage Section by Shear Loading. -ASTM D7078: Standard Test Method for Shear Properties of Composite Materials by V-Notched Rail Shear Method. -AST D2344: Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates.	N.A

Table 94 Beam design standard collected by ACCIONA (Warszawa 2009)

Parameter	Standard used in the design of the beams in the catalogue		Eurocode
Service limits	"Recomendaciones para el proyecto de puentes mixtos para carreteras; RPX- 95". (Spain).	Deflection: Maximum variation deflection at permanent load between time zero and infinity: L/200 Vibration: 1.65 Hz>f>2.35 Hz	Deflection: EN 1994, part 2,section 7. Vibration: 1.6 Hz>f>2.4 Hz
Buckling (composite plates)	NASA Technical Reports Server; NTRS. (USA).	-Handbook of structural stability part II, buckling of composite elements, NASA Technical Note 3782. -Buckling behavior of long symmetrically laminated plates subjected to shear and linearly varying axial edge loads, NASA Technical paper 3659.	N.A
Physical, chemical and mechanical properties of materials.	American Society for Testing and Materials; ASTM. (USA).	-ASTM D3039: Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials. -ASTM D3410: Standard Test Method for Compressive Properties of Polymer Matrix Composite Material with Unsupported Gage Section by Shear Loading. -ASTM D7078: Standard Test Method for Shear Properties of Composite Materials by V-Notched Rail Shear Method. -AST D2344: Standard Test Method for Short-Beam	N.A

	Strength of Polymer Matrix Composite Materials and Their Laminates.

8.8.2 Bridge Decks

As have been mentioned earlier the FRP composite decks pose advantages over conventional bridge decks in terms of the low weight which ultimately results in a higher load capacity (Potyrala 2011). A bridge deck consisting of GFRP generally has a weight approximately 80% lower than that of conventional materials (Chlosta 2012; Potyrala 2011). Other advantages with FRP decks, in comparison with decks consisting of conventional materials, are that they have a higher resistance against fatigue and corrosion and have a shorter and easier installation (Potyrala 2011). General information of summary on advantage and disadvantage of FRP deck is presented in Table 95.

Table 95 Comparison of advantages and disadvantages (Chlosta 2012)

Advantages of FRP Bridge Decks	Disadvantages of FRP Bridge Decks
Low weight	High initial cost
Resistance to de-icing salts and other chemicals	Deflection driven design due to FRP low stiffness
Fast installation	No standard manufacturing process
Good durability	Little knowledge on thermal behaviour
Lower user costs (lower maintenance costs)	Some failure of the wearing surface (i.e. cracking, debonding)
Long service life	The resultant tendency to creep over time
Fatigue resistance	Lack of long term performance data
Good quality due to fabrication in a controlled environment	Limited FRP experience within the engineering- and construction industry
Ease of installation	Lack of design standards

The most common constituents of FRP composites bridge decks are vinyl-ester- or polyester-resin with E-glass reinforcement (Chlosta 2012; Potyrala 2011). The general manufacturing techniques used for manufacturing of decks are pultrusion, hand lay-up and VARTM (Chlosta 2012). The different manufacturing techniques enables for different advantages and disadvantages, pultrusion for example offers a high dimensional tolerances and high quality of the products, however to a relatively high cost (Chlosta 2012). The hand lay-up method is cheaper and easier to customize in terms of fibre orientation and thickness of sheets and core, but has lower quality and dimensional tolerance than pultrusion (Chlosta 2012; Liu 2007). The VARTM method enables for special features, the dimensional tolerances and the quality are however low (Chlosta 2012).

As a FRP bridge deck design gives a large influence due to the strength and stiffness performance (Potyrala 2011). The bridge deck design should have sufficiency to managing the traffic loads, deflections and deck failure (Warszawa 2009). Since FRP material in general has high strength and low stiffness the design will be stiffness derived (Chlosta 2012). This will result in an incomplete utilization of the materials strength and the failure modes will be characterized by local buckling. The failure will usually appear on the sandwich face panel and in the web of pultruded section due to applied compression (Chlosta 2012).

Bridge decks can be divided in two groups namely sandwich structures and adhesively bonded pultruded shapes which will be discussed in the following chapters (Liu 2007).

8.8.2.1 Sandwich Decks

Sandwich decks, also called multilayer FRP decks consists of strong and stiff skins, which are able to carry flexural loads, enclosing the core that is shear resistant (Liu 2007). In general sandwich decks have bi-directional load-carrying capacity which is favourable in terms of concentrated loads subjected to the structure (Chlosta 2012). FRP sandwich decks are generally produced with the VARTM and hand lay-up method and have a typical thickness in the range of 170mm to 230mm (Potyrala 2011; Mara 2014).

The face sheet of the sandwich deck generally consist of E-glass mat or roving infused with a vinyl ester or polyester resin (Liu 2007, NYSDOT 2002). The design of sandwich core is determine by the manufacturer and fabrication process (Meyer 2006). The core material either consists of a rigid foam or a thin-walled cellular FRP material which can be seen in Figure 145 (Liu 2007; NYSDOT 2002). The thin-walled core's geometry is usually designed as a honeycomb, corrugated or sinusoidal shapes which can see in Figure 146 (Mara 2014).

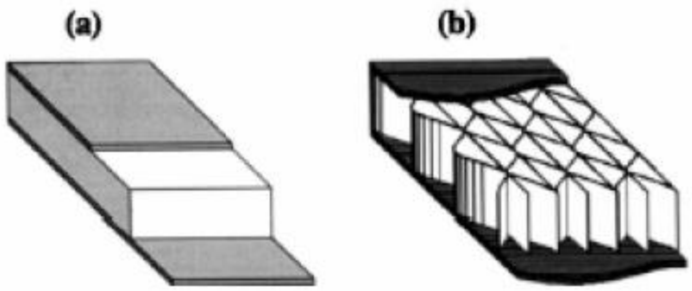


Figure 145 a) Generic (rigid) foam core b) Corrugated core (Liu 2007)

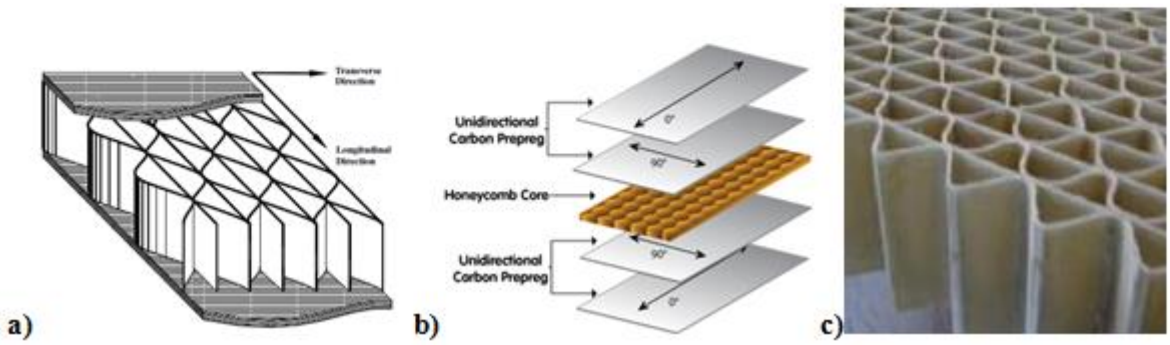


Figure 146 a) Sandwich deck with sinusoidal core configuration (Chen & Davalos 2009), b) Honeycomb sandwich deck (ACP composites 2010), c) corrugated core (FHWA 2013)

Regarding the long-term performance of FRP decks several critical durability conditions should be considered with regard to the face sheets, which are (Meyer 2006):

- Debonding, cracking, and loss of adhesion on the wearing surface
- Porosity in the laminate caused by moisture
- Blistering or bubbles on the surfaces
- Detachment between face sheet and core caused by traffic loads

The core is the most hidden part of the deck, which could lead complication due to inspection (Meyer 2006). The foam material provides low stiffness, however face sheet could prevent the physical problem as long as no moisture accumulate (Meyer 2006).

8.8.2.2 Pultruded Shaped Decks

A pultruded deck is manufactured with the pultrusion method (Mara 2014). The pultrusion method results in finish products incorporating properties such as continuous length, high performance and constant cross-section (Liu 2007). Pultruded profiles are furthermore easy and cheap to produce, however larger parts such as bridge deck panels cannot be produced (Mara 2014; Liu 2007; Zoghi 2013). The pultruded shaped decks are commonly constructed by joining pultruded shapes with adhesively bonding, wet lay-up, mechanical fasteners or a combination of these (Liu 2007; Zoghi 2013). An advantage with the joining method is that it provides large flexibility for the designer in terms of choosing constituents and size and shape of the cross-section (Liu 2007). The most common joining method is adhesively bonding which provides advantages of a faster assembly on-site and maximum stiffness (Zoghi 2013). Disadvantages are however that it is more expensive to adhesively bonding than the other joining methods (Zoghi 2013). Advantages with decks consisting of pultruded shapes are that they exhibit high stiffness and strength in the longitudinal direction, shorter fabrication time, consistent quality of the components and lowered costs due to reduced labour (Zoghi 2013). Disadvantages are that they require drilling on-site if mechanical joints are used which can lead to durability problems and high stress concentrations (Zoghi 2013). Typical cross-sections of pultruded shaped decks can be seen in Figure 147 .

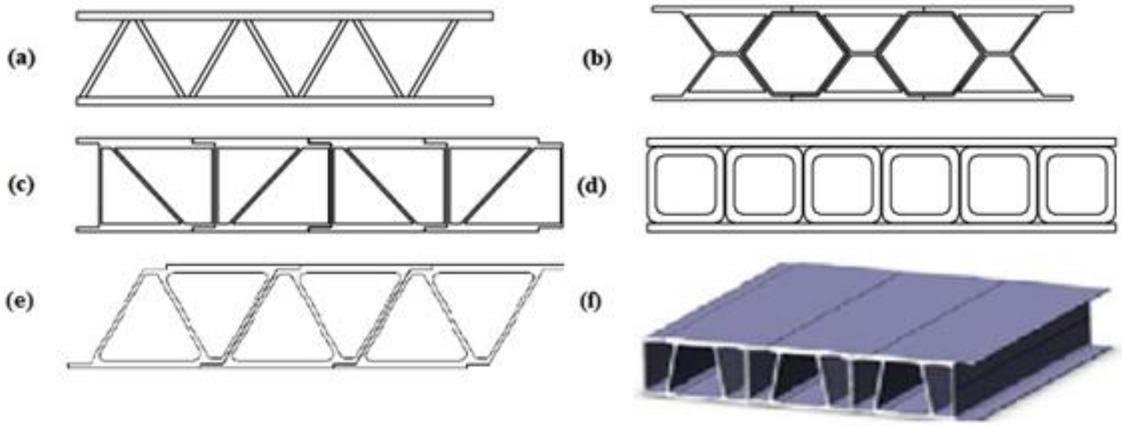


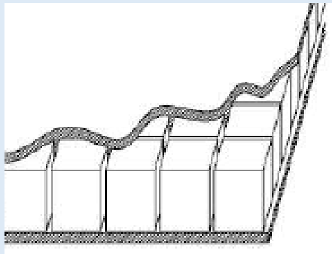
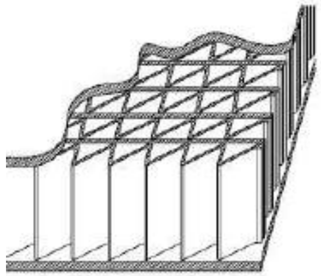
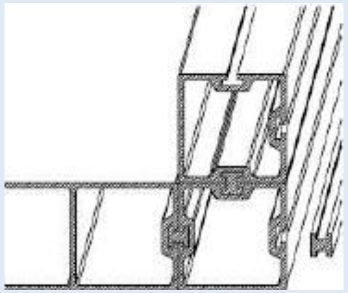
Figure 147 a) EZ-span deck, b) Superdeck, c) Dura span, d) Strong well, e) ASSET, f) Delta deck (Liu 2007)

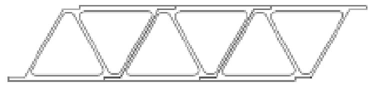
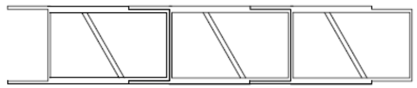
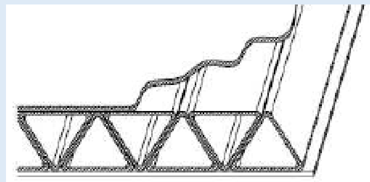
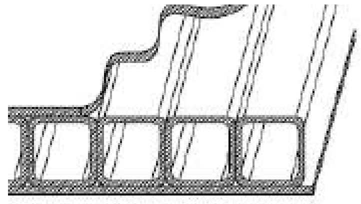
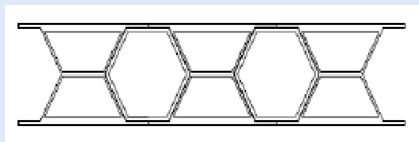
8.8.3 General Deck Types Used in the Industry

The two most common bridge deck types used in civil engineering applications are the sandwich structure deck and the adhesively bonded pultruded shapes (Liu 2007). Both kinds have been used frequently in recent projects of the infrastructure (Liu 2007).

In Table 96 several types of FRP deck designs will be presented, which are examples of the most used FRP composite decks in the industry today where some of them have been used in Trans-IND projects.

Table 96 General information about FRP Bridge decks (Bernard Potyrala 2011 & Mara 2014)

System	Manufacture Method	Manufacturer	Deck Thickness (mm)	Deck Weight (kN/m²)	Connection Between Deck Slab	Configuration
Hardcore	VARTM	Hardcore Composites (USA)	Various	Various	Glued	
Kansas	Hand lay-up	Kansas Structural Composite Inc. (USA)	Various	Various	Glued	
ACCS	Pultrusion	Maunsell Structural Platstics Ltd. (UK)	Various	-	Glued/ Mechanical	

ASSET	Pultrusion	Fiberline A/s (Denmark)	225	0.93	Glued	
Delta deck	Pultrusion	Korea	200	-	Glued	
DuraSpan	Pultrusion	Martin Marietta composite (USA)	195	1.05	Glued/ Mechanical	
EZ-span deck	Pultrusion	Creative pultrusion Inc. (USA)	216	0.96	Glued	
Strongwell	Pultrusion	Strongwell (USA)	170	-	Glued/ Mechanical	
Superdeck	Pultrusion	Creative Pultrusion Inc. (USA)	203	1	Glued	
F10	Filament winding, Pultrusion	-	220	-	Glued	-

8.8.3.1 Trans-IND Deck

The aim with the Trans-IND project is to achieve decks with sufficient strength in order to carry the traffic loads and sufficient stiffness in order to prevent excessive deflections (Warszawa 2009). The decks designed by the Trans-IND projects are both applicable for pedestrian and road bridges (Warszawa 2009). An Illustration of the Trans-IND deck can be seen in Figure 148.

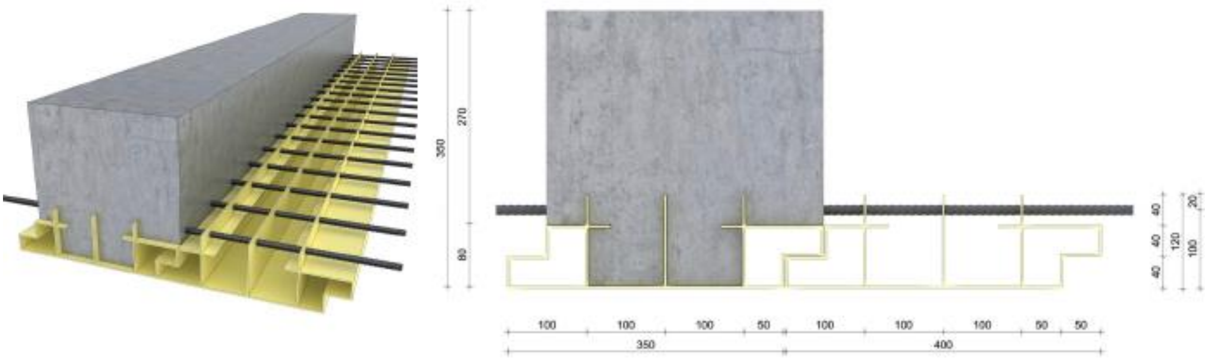


Figure 148 Trans-IND design deck and section view (Warszawa2009)

The Trans-IND decks are designed for construction of new bridges and are compatible with the Trans-IND beams discussed previously (Warszawa 2009). It can be noted that all the Trans-IND decks also are compatible with the standard load classes defined in Eurocode 1, EN1991-2-1 (Warszawa 2009). The characteristics of the Trans-IND beam are displayed in Table 97.

Table 97 General information about Trans-IND deck design

Information about Trans-IND	
Ideal span	2 - 3 m
Depth	0.35 m
Weight	3.3 kN/m
Optimal load	5 – 7,5 kN/m^2
Joints	Embedded connection
Material	Glass, Epoxy Resin, Concrete C30/37

8.8.3.1.1 Deck Installed on an Open-Shaped Beam

The deck that is compatible with the open-shaped beam discussed in the previous chapter: 8.8.1.1 Open-Shaped FRP Beam can be seen in Figure 149.

Figure 149 A section view of the deck position on open-shaped beam and an overview of the deck position on open-shaped beam (Warszawa 2009)

In order to decide the thickness of the deck installed on an open-shaped beam, Figure 144 in combination with Table 98 can be used (Warszawa 2009).

Table 98 Thickness selection (Warszawa 2009)

Thickness of deck profile (cm)					
Load (kN/m^2)	Span (m)				
	1.5	2.0	2.5	3.0	3.5
2.5	3.0	3.0	4.5	4.5	4.5
5.0	3.0	4.5	4.5	4.5	4.5
7.5	4.5	4.5	4.5	4.5	6.0
10.0	4.5	4.5	4.5	6.0	6.0

8.8.3.1.2 Deck Installed on a Close-Shaped Beam

The deck that is compatible with the close-shaped beam discussed in the previous chapter: 8.8.1.2 Close-Shaped FRP Beam can be seen in Figure 150.

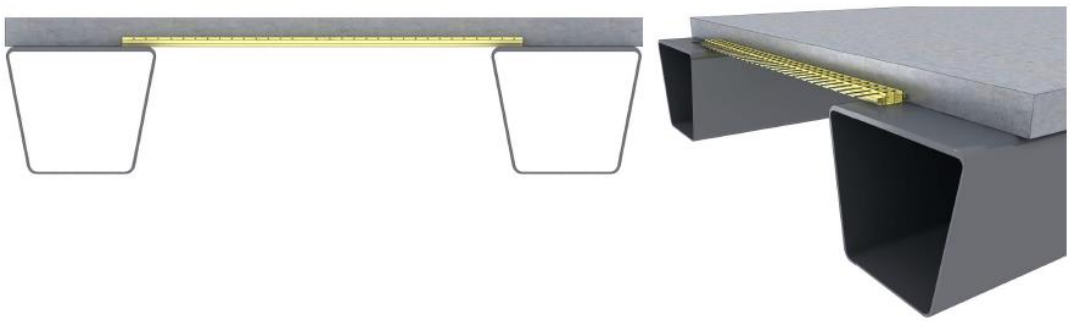


Figure 150 A section view of the deck position on close-shaped beam (Warszawa 2009)

The optimal thickness of the deck installed on a close-shaped beam can be estimated in the same manner as for the deck installed on an open shaped beam, i.e. with Figure 144 and Table 98 (Warszawa 2009).

8.8.3.1.3 Deck Installed on a U-Shaped Beam

The deck that is compatible with the U-shaped beam can be seen in Figure 151.

Figure 151 A section view and an overview of the position of a U-shaped beam (Warszawa 2009)

In order to decide the thickness of the deck installed on a U-shaped beam, Figure 144 in combination with Table 99 can be used (Warszawa 2009).

Table 99 Thickness selection (Warszawa. M 2009)

Thickness of deck profile (cm)					
Load (kN/m^2)	Span (m)				
	1.5	2.0	2.5	3.0	3.5
2.5	3.0	3.0	4.5	4.5	4.5
5.0	3.0	4.5	4.5	6.0	6.0
7.5	4.5	4.5	6.0	4.5	6.0
10.0	4.5	4.5	6.0	6.0	6.0

8.8.4 Comparison of Decks

Table 100 displays a comparison between decks manufactured with different manufacturing techniques.

Table 100 Comparison of different FRP deck manufacturing methods (Ettouney & Alampalli 2009; NYSDOT 2002, p. 4)

	Feature				
Manufacturing method	**Ability to get custom sizes**	**Adherence to dimensional tolerances**	**Cost attractiveness**	**Ability to incorporate special features**	**Overall quality**
Pultruded	L	H	L	L	H
VARTM	H	L	H	H	M
Open mould	H	M	H	M	M

Note: where H=high, M=medium and L=low

A comparison in between sandwich deck and adhesively bonded pultrusion decks can be seen in Table 101. There is currently no standardisation regarding deck deflections and no consensus between the manufacturers (Liu 2007). The recommendations for deflection for steel, concrete and aluminium set through the load and resistance factor design (LRFD) by the American Association of State Highway and Transportation Officials (ASSHTO) is a limiting deflection of span/800 for road bridges subjected to traffic loads (Zoghi 2013; AASHTO 2012; Liu 2007). As can be seen in Table 101 most of the adhesively pultruded decks have problems to meet the deflection requirement set by ASSHTO (Liu 2007).

Table 101 Comparison between sandwich deck and adhesively bonded pultrusion deck (Liu 2007)

	Deck system	Depth (mm)	Kg/m^2[a]	Cost ($\$/m^2$)	Deflection (reported)[b]	Deflection (normalized)[c]
Sandwich construction	Hardcore composite	152-710	98-112	570-1184	L/785[d]	L/1120
	KSCI	127-610	76[e]	700	L/1300[f]	L/1300
Adhesively bonded pultrusion	DuraSpan	194	90	700-807	L/450[g]	L/340
	Superdeck	203	203	807	L/530[h]	L/530
	EZSpan	229	229	861-1076	L/950[i]	L/950
	Strongwell	120-203	120-203	700[j]	L/605[k]	L/325

Notes to Table 101:

a) Without wearing surface, b) Assumes plate action, c) Normalized to HS201IM for a 2.4-m centre-to-centre span between supporting girders, d) HS20+IM loading of a 203-mm-deep section at a centre-to-centre span between girders of 2.7 m, e) For a 203-mm-deep deck targeted for RC bridge deck replacements, f) HS20+IM loading of a 203-mm-deep deck at a centre-to-centre span between girders of 2.4 m, g) HS20+IM loading of a 203-mm-deep deck at a centre-to-centre span between girders of 2.2 m, h) HS20+IM loading at a centre-to-centre span between girders of 2.4 m, I) HS20+IM loading at a centre-to-centre span between girders of 2.4 m, j) For a 171-mm-deep deck with a wearing surface under experimental fabrication processes, k) HS20+IM loading of a 171-mm-deep section at a centre-to-centre span between girders of 2 m.

Another comparison with FRP decks are between DuraSpan deck and ASSET deck's properties of the deck flange can be seen in Table 102. The geometry design of the deck has great influence with regard to the strength performance (Mara 2014). A triangular formed deck gives a better strength with regard to shear loads and consequently higher shear stiffness (Mara 2014). As can be seen in Table 102 the ASSET deck has better performance than the DuraSpan deck in terms of the compression and shear (Mara 2014).

Table 102 A comparisons of bridge deck properties (Mara 2014)

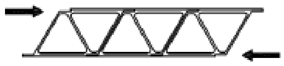
	Compression		Shear		Tension	
						
	Failure stress (MPa)	E-modulus (GPa)	Failure stress (MPa)	G-modulus (GPA)	Failure stress (MPa)	E-modulus (GPa)
Flange	~-170	NA	~70	2.6~5.0	200-300	18-23
DuraSpan deck	-34	11.7	0.13	0.005	18	9.6
ASSET deck	-41	16.2	0.61	0.47	NA	NA

Table 103 summarizes the failure modes associated with the two different deck types mainly used in civil engineering applications.

Table 103 Failure modes of typical bridge deck (Mara 2014)

Deck System		Failure Mode
Pultruded	Superdeck	Punching failure + delamination of pultruded shapes
	DuraSpan	Punching failure + delamination +web buckling
	Strongwell	Localized bending failure of plates and webs
	ASSET deck	Buckling of the webs and delamination
Sandwich	Hardcore	Web buckling + debonding of the flanges
	Honeycomb deck	Web buckling + debonding/delamination of the flanges

8.8.5 Connections

A disadvantage with FRP composite is the brittle fibres and anisotropic material which ultimately makes them difficult to join (Potyrala 2011). In order for the structure to work properly concern has to be taken when choosing the connection method (Potyrala 2011). Properties that have to be considered are: influence of chemicals and temperature, sensitivity to UV radiation and mechanical properties (Potyrala 2011). Figure 152 illustrates some common configurations of joints.

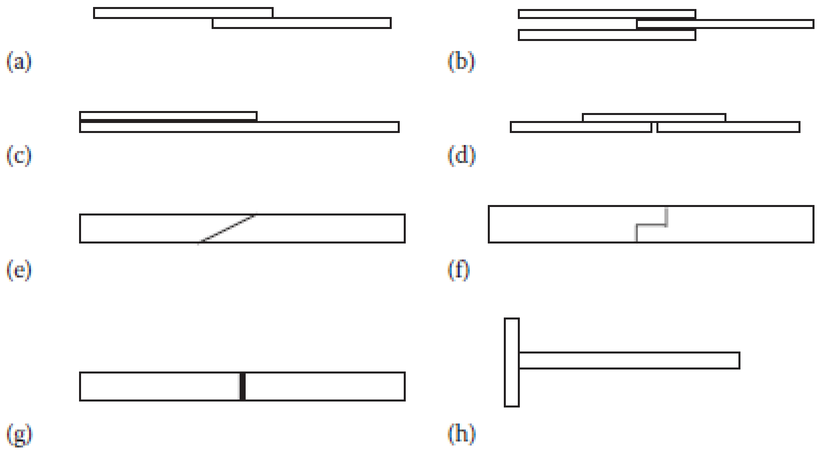


Figure 152 Typical joint configurations a) Single-lap joint, b) double-lap ,c) lap-strap joint , d) single-strap joint, e) scarf joint, f) stepped, (g) butt joint, and h) tee joints (Zoghi 2013).

The design of connection in FRP composite structures generally includes the following steps (Zoghi 2013):

1. Identify design requirements of the joint
2. Select the category of the joint and a joint technique i.e. bonded, mechanical or a combination
3. Select configuration of joint
4. Detailed design of the joint
5. Do an analysis and verification of the chosen design

There are mainly three categories of connection used in joining FRP composite elements which are: bonded connections and mechanical connection or combination of these (Potyrala 2011).

8.8.5.1 Bonded Connections

Bonded connections imply that two components are joined together by the means of an adhesive (Potyrala 2011). As can be seen in Figure 153, which is illustrating different types of bonded connection, the load between FRP composites joined with bonded connections is transferred through shear (Chlosta 2012).

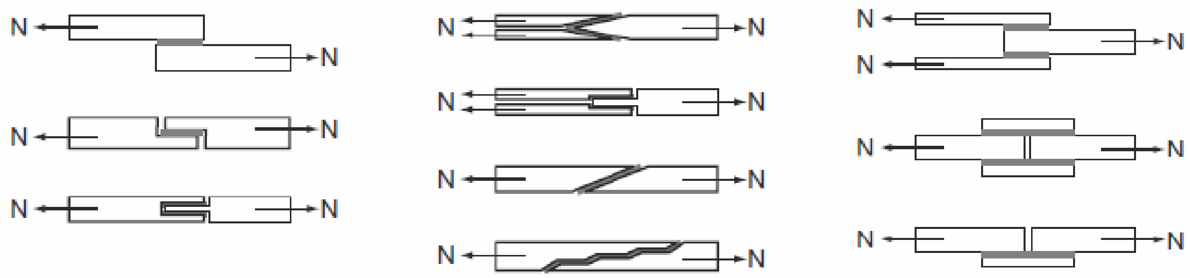


Figure 153 Various bonded connection types (Potyrala 2011)

The most common glues used are polyester, acrylic, epoxy, phenolic and polyurethane and the choice is dependent on the constituent polymer matrix of the FRP composite (Potyrala 2011; Chlosta 2012). Acrylic and thermoplastic polyurethane are considered thermoplastic adhesives and phenolics, epoxies and thermoset polyurethanes are considered thermoset adhesives (Zoghi 2013). The advantages and disadvantages of the three glue types epoxy, polyurethane and acrylic can be seen in Table 104. Adhesives used for structural applications are either ductile or brittle, where thermoset adhesives mainly behave in a brittle way (Zoghi 2013).

Table 104 Adhesive advantages and limitations (Zoghi 2013)

Adhesive types	Advantages	Limitations
Epoxy	• High strength • Good resistance towards solvent • Good capability to fill gaps • Good resistance towards elevated temperatures • Many formulations available • Relatively inexpensive	• Exothermic reaction • To achieve the optimum properties exact proportions are needed • Short pot life • Requires special care for storage and curing
Polyurethane	• Cure time varies • Tough • Provides excellent flexibility even at low temperatures • Cure can be achieved at both room temperature and at elevated temperatures • Cost is moderate	• Sensitive towards moisture • Resistance is poor at elevated temperatures • Short pot life • Special equipment is required for mixing and dispensing
Acrylic	• Good flexibility • Goof peel and shear strength • Mixing is not required • It is possible to bond dirty surfaces • Can cure at room temperature • Cost is moderate	• Low strength at elevated temperatures • Toxic • Flammable • Emit odour • Open time is limited • Dispensing equipment is required

8.8.5.1.1 Design of Bonded Connections

The condition that should be satisfied in design of bonded connection are (Zoghi 2013; Clarke 1996):

- The joint failure should occur either in the adherence or in the adhesive, however not in the interfaces
- The allowed peeling and shear stresses are not allowed to be exceeded
- Acceptable through-thickness tensile stress and out-of-plane shear stress should not be exceeded

Since the out-of-plane shear strength and the through-thickness tensile strength is considerably lower than the corresponding in-plane values it is important to consider the through-thickness parameters of the adherends in design (Zoghi 2013). Table 105 comprises a summation of the design parameters that has to be considered for adhesively bonded joints (Zoghi 2013):

Table 105 A summarized design parameters for adhesively bonded joints (Zoghi 2013)

	Design Parameters for Adhesively Bonded Joints
Material parameters of the FRP components	The properties of the layer adjacent to the adhesives such fibre orientation and presence of reinforcement in the through-thickness direction.
Material parameters of structural adhesives	(a) Mechanical properties: properties of the adhesive, ductile or brittle, pot life and requirements regarding preparation of primer and surface (b) Curing requirements (c) Temperature and moisture (or water) resistance
Design parameters	(a) Geometry: geometry parameters of the FRP adherends such as width, thickness and length, bondline thickness, area available for bonding, length of the overlap (b) The parameters related to the type of joint, type of loading and expected lifetime and environment are the same as for mechanically fastened joints
Fabrication parameters	(a) The preparation before bonding: treatment of the surface (b) Curing and post-curing: the applied clamping pressure (vacuumed assisted or not) and the control of the environments

In order to verify the design of adhesive joints either testing or calculations should be performed (Zoghi 2013). The limiting states that should be considered in design for bonded joins can be seen in Table 106 (Zoghi 2013).

Table 106 Limit states for adhesively bonded joints (Zoghi 2013)

	Limit States for Adhesively Bonded Joints
Serviceability limit states	(a) Deformation of the bonded assembly (b) Onset of nonlinear load-deformation behaviour of the joint under constant static load; onset of increasing deformation under cyclic fatigue loading or environmental effects (c) Fatigue resistance of adhesive and FRP members (d) Weather tightness of joints and durability of adhesive
Ultimate limit states	(a) Maximum resistance of the complete joint (b) Static or progressive failure of adhesive joints (c) Long-term endurance of FRP members, adhesives, and

	interfaces

The mechanical properties of the adhesive bonds that are of greatest importance are: shear modulus and strength, maximum shear strain, tensile modulus and strength and maximum tensile strain, and are generally attained from the manufacturer (Zoghi 2013). As have been mentioned earlier there is a lack of long-term data regarding durability of bonded connection which have resulted in that they have been limited to non-structural applications (Zoghi 2013).

Table 107 displays the partial safety factors that should be regarded in design of adhesively bonded connection, the factors which are acquired from the Eurocomp Design Code (Clarke 1996).

$$\gamma_m = \gamma_{m1}\gamma_{m2}\gamma_{m3}\gamma_{m4}$$

Table 107 Partial safety factors for adhesively bonding (Zoghi 2013; Clarke 1996)

Partial safety factors	
Source of Adhesive Properties (γ_{m1})	
Typical or textbook values	1.5
Values obtained by testing	1.25
Method of Adhesive Application (γ_{m2})	
Manual application, no adhesive thickness control	1.5
Manual application, adhesive thickness controlled	1.25
Established procedure with controlled parameters	1.0
Typical of loading (γ_{m3})	
Long-term	1.5
Short-term	1.0
Environmental Conditions (γ_{m4})	
Service conditions outside the adhesive test conditions	2.0
Adhesive properties determined for service conditions	1.0

8.8.5.1.2 Failure Modes of Bonded Connections

The primary failure modes associated with adhesive bonding are (Clarke 1996; Zoghi 2013; Chlosta 2012):

- Adhesive failure

- Cohesive failure of adhesive, i.e. rupture of the glue
- Cohesive failure of adherent, i.e. rupture of the composite

Measures to avoid adhesive failure are choosing the suitable adhesive and by thoroughly cleaning the surface that should be bonded (Chlosta 2012). Figure 154 illustrates a summation of the general failure modes of adhesively bonded connections.

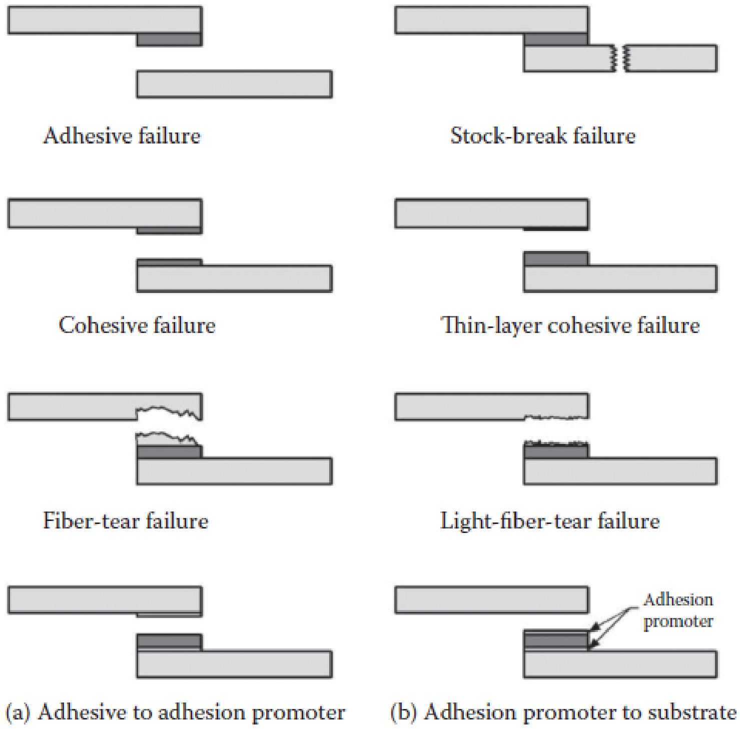


Figure 154 Failure modes for adhesively connection a) concrete-filled FRP girder and b) steel girder (Zoghi 2013)

Figure 155 illustrates the most likely failure mode where the strength of the bonded joint and the thickness of the adherent are considered (Chlosta 2012). As can be seen in the Figure 155 the scarf and stepped-lap joint is the strongest and that the single-lap joint is the weakest due to eccentricity. The most efficient range of adhesive layer is in the range of 0.1 mm to 0.25 mm. If the layer of adhesive is greater than 1.5 mm, it is necessary to taper the adherents (Chlosta 2012).

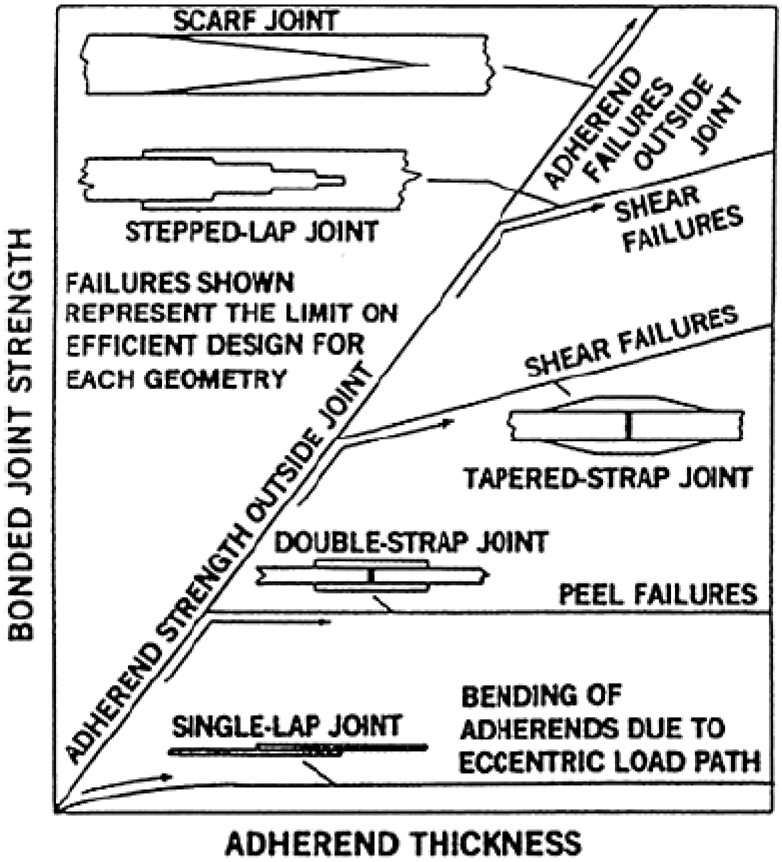


Figure 155 Failure modes of bonded joint where strength is plotted in relation to thickness of the adherent (Chlosta 2012)

The criteria's set regarding cohesive failure can be described with the maximum stress criterion where the maximum shear or tensile stress (σ_{max}, τ_{max}) in adhesive shall be less or equal to the maximum allowable adhesive shear or tensile stresses ($\sigma_{allow}, \tau_{allow}$) (Zoghi 2013). Overall the adhesive shall be considered as isotropic (Zoghi 2013).

$$\sigma_{max} \leq \sigma_{allow} \text{ and } \tau_{max} \leq \tau_{allow}$$

For more details of the design of adhesive bonding see the Eurocomp Design Code Section 5 (Clarke 1996).

8.8.5.2 Mechanical Connections

The design of mechanical connections of FRP composites are based on solutions used for metals (Potyrala 2011). However since FRP composites are anisotropic, brittle and heterogeneous the discontinuity, as a result of holes, of the fibres will cause a reduction of the load carrying capacity (Potyrala 2011). In contrast to FRP composites steel is isotropic, homogenous and continuous (Potyrala 2011).

Mechanical connections are common in applications such as FRP trusses, multicellular FRP bridge structures, beams and braced frame structures (Zoghi 2014). The mechanical connectors can either consists of FRP composite or metal (Zoghi 2013). The metal fasteners should consist of stainless or galvanized steel and screws and threaded bolts should be avoided (Chlosta 2012; Zoghi 2013). For mechanical connections, cut-outs are required in the FRP composite (Zoghi 2013). Mechanical connections are advantageous over bonded connections in terms of easier design due to that their working rules are defined (Potyrala 2011).

Figure 156 and Figure 157 shows typical mechanical connections of FRP composites where Figure 156 shows pultruded profiles connected with stainless steel fasteners and Figure 157 shows typical connections of steel girders and FRP composite decks (Potyrala 2011).

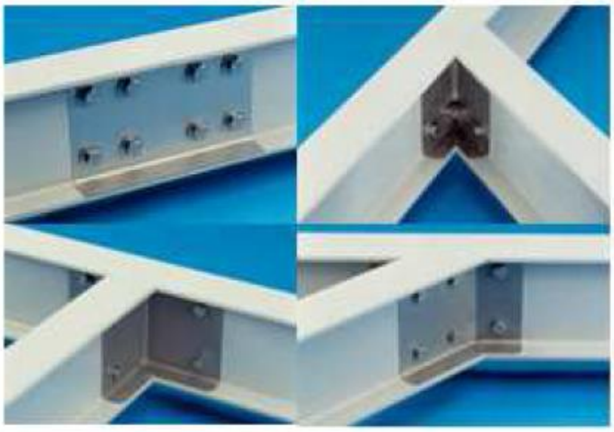


Figure 156 Stainless steel connection of pultruded members (Potyrala 2011)

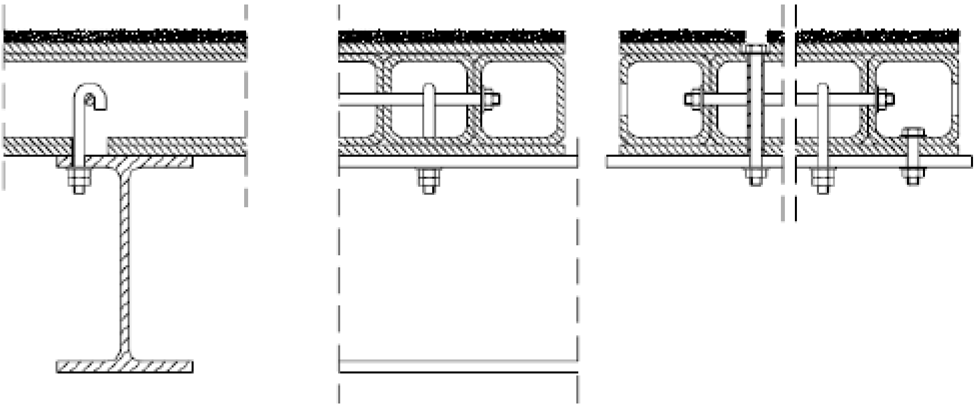


Figure 157 Mechanical connections between FRP composite decks and steel girders designed by Strongwell Virginia Tech (Potyrala 2011)

8.8.5.2.1 Design of Mechanically Fastened Joints

The parameters that should be considered in design of mechanical connections of FRP composites is summated in Table 108.

Table 108 A summarize of design parameters for mechanically fastened joints (Zoghi 2013)

Design Parameters for Mechanically Fastened Joints	
Material parameters of the FRP Components	(a) Material properties, also anisotropy or orthotropic, viscoelasticity, inhomogeneity, brittleness and environmental degradation (b) Type and form (i.e. unidirectional, woven, random or fabric) of the fibre (c) Type of resin (i.e. vinyl ester, polyester, phenolic resin or

	epoxy) (d) Scheme and architecture of fibre, such as sandwich or laminate construction and stacking sequence
Design parameters	(a) Geometry, includes size of rivet or bolt, geometry of the FRP components (i.e. width, thickness and length), shape and pattern of the cut-outs (oval or circular), size of the cut-out, spacing between cut-outs, distance to edge and arrangement (pitch and gage values) (b) Type of joint, such as tee joint, single lap, double lap or other (c) Type of loading (i.e. centrically or eccentrically loaded and compressive, tensile, shear) (d) Environment and lifetime, including environmental effects (temperature, moisture, chemical solutions) and dynamic fatigue loads
Fabrication parameters	(a) The material of the fastener (i.e. metallic or FRP) (b) Type of fastener (screw, bolt or rivet) (c) Type of tightening (clamping force or bolting torque, size of washer and clearance)

The Eurocomp Design code has provided a partial safety factor, in order to design the mechanical connection, which can be calculated with the following equation (Zoghi 2013):

$$\gamma_m = \gamma_{m1}\gamma_{m2}\gamma_{m3}$$

See Table 77, Table 78 and Table 79 for values of γ_{m1}, γ_{m2} and γ_{m3}. Other methods to design mechanical joints are the limit state design (LSD) and allowable stress design (ASD) (Zoghi 2013). For the ASD method the recommended value for the partial safety factor for all connection parts are set to 4 (Zoghi 2013).

According to limit sate design is illustrated a list regard to the requirement for SLS and ULS for the mechanically connection design shall be satisfied (Zoghi 2013; EUROCOMP section 5.2.2.2), see Table 109:

Table 109 Limit State for mechanically fastened joints

Limit States for Mechanically Fastened Joints	
Serviceability limit states	(a) Deformation of the assembly due to slippage of fasteners or excessive deformation of cut-outs (b) Onset of nonlinear load-deformation behaviour of the joint under constant static load (c) Onset of increasing deformation under cyclic fatigue loading

	or environmental effects (esp. the effects of temperature and moisture) (d) Fibre debonding or matrix cracking under load or due to fabrication techniques (e) Fatigue resistance of FRP members and fasteners (f) Weather tightness and durability of unsealed edges
Ultimate limit states	(a) Maximum resistance of the complete joint (b) Static failure of joined parts or fasteners (c) Progressive failure of cut-out edges (d) Long-term endurance of FRP members and fasteners (under long-term fatigue loading and environmental effects)

8.8.5.2.2 Failure Modes of Mechanical Connections

The failure modes associated with mechanical connections can be seen in Figure 158 and consists of the modes (Zoghi 2013; Potyrala 2011; Chlosta 2012):

- Shear-out failure
- Bearing failure
- Net-section tension failure
- Cleavage or splitting failure
- Pull through failure
- Fastener failure

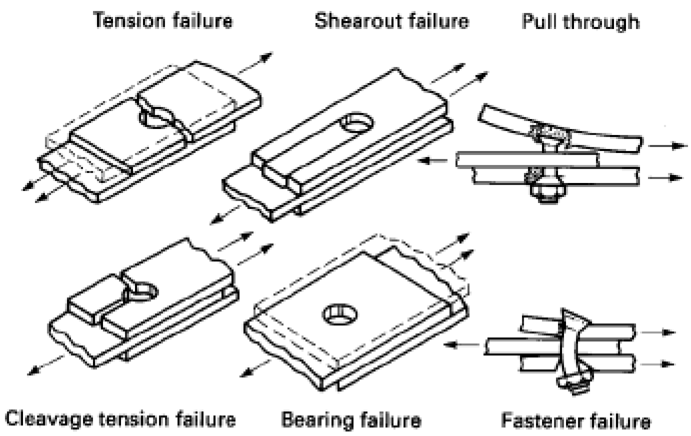


Figure 158 Typical failure modes of mechanical connection (Chlosta 2012)

The failure mode is mainly dependant on the location of the hole in relation to the fibre direction (Potyrala 2011). The failure modes seen in Figure 158 can be avoided by choosing appropriate diameter of the bolt, distance to the edge, thickness of the composite and head configuration (Chlosta 2012). In order to prevent failure of the fastener the ratio between diameter of the fastener (d) and thickness of the composite (t) that should lie in the range of (Chlosta 2012):

$$1.5 < {}^{d}/_{t} < 3.0$$

Tensile failure can either occur as tearing of the bolt or as shear fracture of the composite (Chlosta 2012). Tensile failure of the bolt can be calculated according to (Chlosta 2012):

$$P_d \leq \frac{A_s f_{yk}}{\gamma_m}$$

Where:

P_d is the design load, A_s is the stress area of the bolt, f_{yk} is the tensile strength of the bolt and γ_m is the partial safety factor

Tensile failure for the composite in a bolted connection can be calculated according to (Chlosta 2012):

$$P_d \leq \frac{2d\pi t f_\tau}{\gamma_m}$$

Where:

P_d is the design load, d is the diameter of the bolt, t is the thickness of the composite, f_τ is the shear strength of the laminate and γ_m is defined the partial safety factor

Calculation of shear failure presented here only considers shear in longitudinal direction and transversal direction of pultruded profile (Chlosta 2012). For other shear failure modes see the Eurocomp Design Code or the "Fiberline Design Manual" (Chlosta 2012). The equations used to calculate the shear strength in the longitudinal and transversal direction originates from the "Fiberline Design Manual" (Chlosta 2012)

Shear strength in longitudinal direction (0°):

$$P_{B,d,0} \leq \frac{dt f_{cB,0}}{\gamma_m}$$

Where:

$f_{cB,0} = pin - bearing\ strenght = 150N/mm^2$ and $\gamma_m = 1.3$

Shear strength in the transverse direction (90°):

$$P_{B,d,90} \leq \frac{dt f_{cB,90}}{\gamma_m}$$

Where:

$f_{cB,90} = pin - bearing\ strenght = 70N/mm^2$ and $\gamma_m = 1.3$

A failure analysis should consist of analysing the failure modes: net-section failure, bearing failure, shear failure of fasteners and shear-out failure (Zoghi 2013). The critical limit states for these failure modes are compared with the following criterion (Zoghi 2013):

$$\sigma_{cr} = k\sigma_{lim}$$

Where:

σ_{cr} is the critical design stress (tensile, compressive, or shear), σ_{lim} refers to the strength of a material for each critical limit state and k is defined as a factor considering stress concentrations (k = 0.9 for net-section tensile failure through the cut-out and k = 1 for all other cases)

The performance of mechanical connections is largely influenced by the loading direction and the large local stresses, caused by the holes (Chlosta 2012). The failure mode of pultruded profiles in the longitudinal direction are bearing failure which ultimately can cause progressive shear-out failure due to that the profile acts ductile in this direction (Zoghi 2013). Pultruded profiles loaded in the transversal direction acts in a brittle manner and the failure mode is generally brittle net-tension failure (Zoghi 2013). In addition if metallic fasteners are used the weight is increased and the corrosion resistance is decreased, which can pose a problem in structures consisting of trusses (Chlosta 2012). Another disadvantage with mechanical connections are that the gel-coat surface is damaged due to the drilling and which results in vulnerability (Chlosta 2012).

The detail of design with different load cases and resistance load can be found in Eurocomp Design Code Section 5 (Clarke 1996).

8.8.5.3 Combined Connections

The combined connection is a combination of both bolts and bonded joints, where the bolts prevent propagation of cracks which reduces the risk of failure in the glue (Potyrala 2011). In general the adhesive bonding is stiffer than mechanical connection and thus takes all of joint loads, hence the mechanical connection acts as a back-up element which is rather uneconomical (Potyrala 2011). Choosing a combined fastened-bonded joint is related to performance requirements where the SLS is satisfied by the bonded connection and the ULS is satisfied by the mechanical connection (Zoghi 2013).

8.8.5.4 Comparison of the Connection Types

Table 110 displays some typical properties of the different connection categories.

Table 110 Typical properties for the three different connection types used to connect FRP members (Chlosta 2012; Clarke 1996).

	Mechanical	Bonded	Combined
Stress concentration at joint	High	Medium	Medium
Strength/weight ratio	Low	Medium	Medium
Seal (water tightness)	No	Yes	Yes
Thermal insulation	No	Yes	No
Electrical insulation	No	Yes	No
Aesthetics (smooth joints)	Bad	Good	Bad
Fatigue endurance	Bad	Good	Good
Sensitive to peel loading	No	Yes	No
Disassembly	Possible	Impossible	Impossible

Inspection	Easy	Difficult	Difficult
Heat or pressure require	No	Yes/No[1]	Yes/No[1]
Tooling cost	Low	High	Low
Time to develop full strength	Immediate	Long	Long

Notes:

[1] No if cold curing two-part adhesive is used in an appropriate environment, see more information in Clarke 1996 chapter 6.

Table 111 furthermore displays a summation of the advantages and disadvantages for the three typical connections categories.

Table 111 Advantages and disadvantages for different connection types (Chlosta 2012)

Mechanical connections	
Advantages	**Disadvantages**
• Requires no special surface preparation • Can be disassembled • Easy inspection	• Low strength with regard to stress concentrations • Special practices required in assembly • Time consuming assembly • For moisture and weather tightness special gaskets or sealants normally is required • Risk of corrosion for metallic fasteners
Bonded connections	
Advantages	**Disadvantages**
• High joint strength can be achieved • Low number of parts required • High moisture and weather tightness • Minimized risk of corrosion problems • Smooth external surfaces	• Cannot be disassembled • Requires special surface preparation • Difficulty in terms of inspection • Temperature and high humidity can affect joints strength
Combined connections	
Advantages	**Disadvantages**
• Bolts provides support and pressure during assembly and curing • Growth of bonding defects is hindered by the bolts	• Structurally bolts act as backup elements- in an intact joints bolts carry no load

Bonded connections pose advantages over mechanical joints since they generally have a greater safety margin and in addition a simpler design (Liu 2007).

8.8.5.5 Examples of Different Types of Deck Connections

There are mainly three levels of connections which are (Mara 2014; Liu 2007):

- Component-to-component level connections used to form modular deck panels
- Pane-to-panel level connections used to form bridge deck systems
- System-level connections (or deck-to-support connections) used to form bridge superstructures

An additional connection type is the guard rail connections which are of importance for bridge structures in terms of safety reasons (Mara 2014).

The connection has an influence of the performance of the FRP deck system in terms of the properties: strength, stiffness and service time (Liu 2007). In order to utilize the full capacity of the FRP deck system the connections need to be properly designed and constructed (Liu 2007).

8.8.5.5.1 Component-to-Component Level Connection

Component-to-component level connection (CCL) is generally used to join deck elements in order to form modular bridge deck panels (Liu 2007; Mara 2014). The element usually consists of pultruded shapes and sandwich core and face sheets which are joined together with an adhesive bond (Liu 2007; Mara 2014). The advantages of adhesive bonded component-level connections are that they provide a smooth load transfer and ensure integrity of the deck (Mara 2014).

The design criterion of adhesively bonded CCL connections are failure should occur in the FRP substrate and avoided in the interface and adhesive (Liu 2007). Typical failure modes for adhesively bonded CCL connections are plate bending failure, punching shear failure, buckling of the FRP component and delamination (Liu 2007). Figure 159 illustrates a typical adhesively bonded CCL connection.

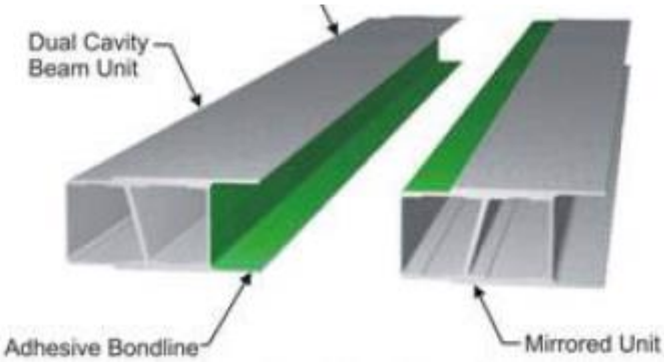


Figure 159 Example of component-to-component level connection (Meyer 2006)

Other means of CCL connections are mechanical fastening or interlocking connection (Mara 2014). A disadvantage with a mechanically fastened FRP deck is durability problems associated with penetration of salt and moisture in the drilled holes. Fatigue loading can also lead to stiffness degradation (Mara 2014). The interlocking connection member is better choice for a deck structure, such as advanced composite construction system (ACCS) and snap-fit connection. The main advantage of interlocking connections is that they are easy to assemble and replace (Mara 2014). A disadvantage associated with interlock connections are however that they are need to be fabricated with tight dimensional tolerances (Mara 2014).

8.8.5.5.2 Panel-to-Panel Level Connection

The design of panel-to-panel level connections is to achieve an efficient transfer of shear forces and bending moments between the modular panels (Liu 2007). Panel-to-panel level connections are used to assemble deck panels into an entire deck and are generally performed on the construction site (Mara 2014). The techniques commonly used are: mechanical shear connectors or adhesively bonded tongue and groove connections which can be seen in Figure 160 (Liu 2007; Mara 2014).

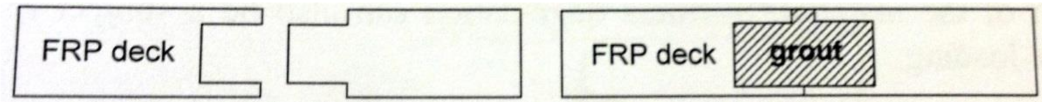


Figure 160 Left: tongue groove connection, Right: shear key connection (Mara 2014)

A disadvantage of the mechanical shear connection is that it is sensitive towards dynamic vehicle loading which ultimately can result in cracks (Mara 2014). The adhesively bonded panel-to-panel level connections have an efficient load transfer between the deck panels and in addition a high fatigue resistance (Mara 2014). Problems associated with adhesively bonded joints are however that the adhesive requires time to cure and develop sufficient strength which prolongs the assembly time (Mara 2014). The quality control of adhesively bonded panel-to-panel level connections is furthermore difficult to perform in field (Mara 2014). The disassembly is in addition impossible in terms of adhesively bonded joints (Mara 2014). Since individual components cannot be replaced for adhesively bonded connections a full replacement of the deck would be required which is very expensive (Mara 2014).

Figure 161 illustrates an example of panel-to-panel level connection called Superdeck™ which is constructed by assembling pultruded tubes using a combination of adhesive bonding and shear key interlocking connection (Liu 2007). This deck system which has presented the carry capacity enough for HS20-44 loading (Liu 2007).

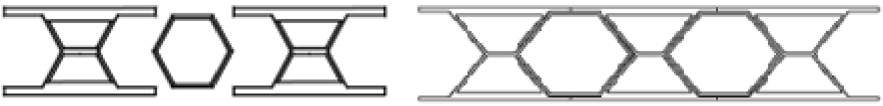


Figure 161 Superdeck produced by Creative Pultrusion Inc. (Liu 2007)

The DuraSpan deck, produced by the Martin Marietta Composites, has a similar panel-to-panel level connection as the Superdeck™ (Liu 2007). Tests consisting of fatigue, static and environmental durability on DuraSpan decks with adhesive joints have shown that the failure mode will occur in the composite material and not in the adhesive or interface (Liu 2007). An illustration of the DuraSpan deck can be seen in Figure 162.

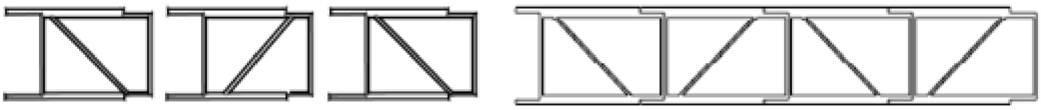


Figure 162 DuraSpan deck with panel-to-panel connection (Liu 2007)

An example of a panel-to-panel level connection of for sandwich panels is illustrated in Figure 163. The FRP-2 is produced by Hardcore Composites is a sandwich deck consisting of two E-glass fabric face sheets and a core constructed with multiple wrapped cells (Liu 2007). The panel-to-panel level connection consists of FRP splice plates. The FRP-3 deck system consists of a corrugated core sandwich system with shear keys connections (Liu 2007).

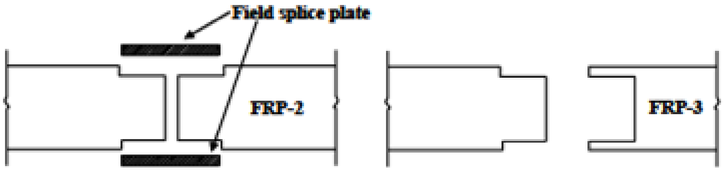


Figure 163 Two sandwich panel connection (Liu 2007)

Figure 164 illustrates two different panel-to-panel connections for the ASSET Fiberline deck system (Liu 2007). The two alternatives of connection consist of an adhesively bonded connection and a bolted connection. The adhesively bonded connection is generally stronger, easier to design and less expensive than the mechanically bonded connection (Liu 2007).

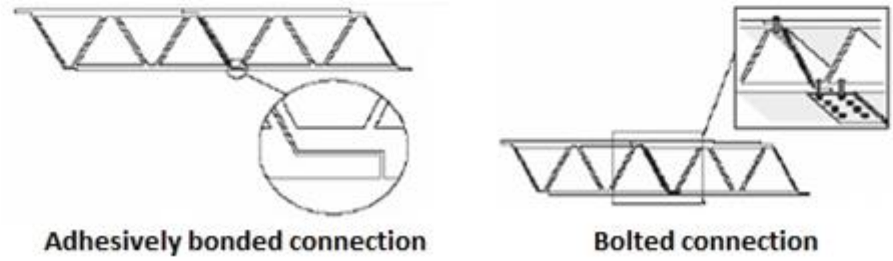


Figure 164 Left: ASSET Fiberline deck with adhesive bond, Right: ASSET Fiberline deck with bolted connection (Liu 2007)

The panel-to-panel level connections for the Strongwell deck system can be seen in Figure 165. The connections illustrated in Figure 165 are bolted connection and adhesive shear-key (Liu 2007). Both field- and laboratory testing have been done by the Virginia Polytechnic Institute and the State University (Virginia Tech) which have shown that the bolted joint are more sensitive to fatigue loading than the adhesive joints. Over-sizing of the holes was required during assembly which resulted in deflection problems. The damage associated with cyclic loading was furthermore wearing of the contact surfaces due to that the panels where sliding past each other and slope in the connections related to that the bolts constantly stroked against the tub walls (Liu 2007).

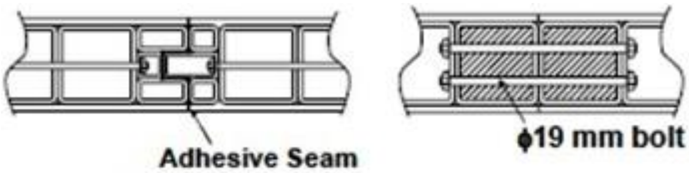


Figure 165 Two different connection methods of Strongwell decks (Liu 2007)

8.8.5.5.3 Deck-to-Girder (Stringer) Connections

The deck-to-girder connection is one of the most challenging areas related to joining FRP decks (Zhou & Keller 2004; Mara 2014). Three common connection techniques are (Mara 2014; Liu 2007):

- shear-stud connections

- adhesively bonded joints
- mechanical connection (bolts or clamping)

The deck-to-girder connections can be designed in order to incorporate composite action or not (Mara 2014). Connections incorporating composite action are adhesively bonded joints and shear stud connections. Connections not exhibiting composite actions are generally mechanical fasteners such as bolts (Mara 2014).

Shear-stud connections, similar to those used for concrete decks, are appropriate in systems such as Superdeck or DuraSpan (Liu 2007; Mara 2014). This type of system can be seen in Figure 166, the purpose of the designed connection is to prevent both transverse movement and uplifting of the deck (Mara 2014). In general shear-stud connections are installed in cut-outs, visible in Figure 166, which causes a discontinuous load transfer which ultimately can lead to stress concentrations (Mara 2014).

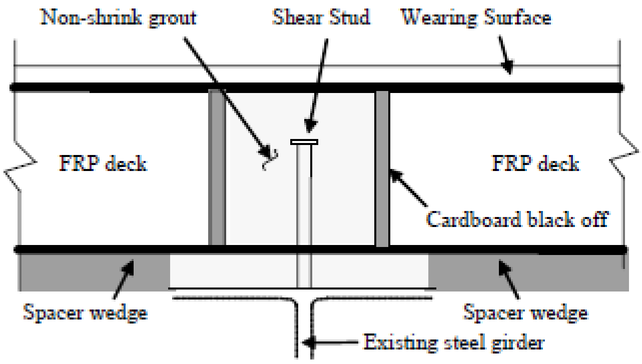


Figure 166 Superdeck shear-stud connection (Hastak, Halpin & Hong 2004)

The benefits of adhesively bonded joints are that they have a high capacity of transferring shear force, easy to construct and gives more uniform stress distribution to the structure than shear studs (Liu 2007; Mara 2014). Some disadvantages with adhesively bonded joints applied in field are lack of fatigue performance and durability (Liu 2007). Deck-to-girder connections where a FRP deck and steel girders should be adhesively joined, which can be seen in Figure 167, concern has to taken to the thermal properties of the materials (Mara 2014). Other parameters that have to be considered for the adhesive and interface of adhesively bonded connections are the effects of the environmental and service conditions. Information of the long-term performance and effects of environment of adhesively bonded joints for steel girders bonded to FRP deck is still in the study phase, and requires further research to be fully understood (Mara 2014).

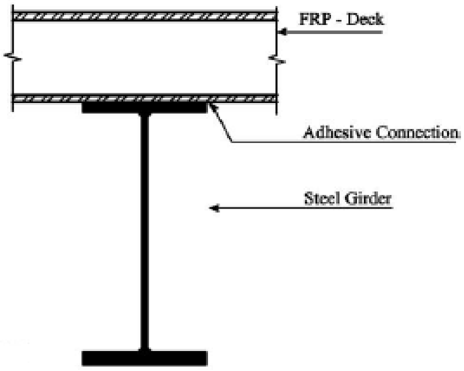


Figure 167 Adhesively bonding of FRP deck and steel girder (Zhou & Keller 2004)

Mechanical connections generally consist of clamps or bolts, which can be seen in Figure 168 and Figure 169 (Liu 2007). Clamped connections are often used in sandwich decks such as the Kansas Structural composite Inc. (KSCI) seen Table 96. The clamping system is fixed underneath the top flange of the girder and secured with bolts which are illustrated in Figure 168 (Liu 2007).

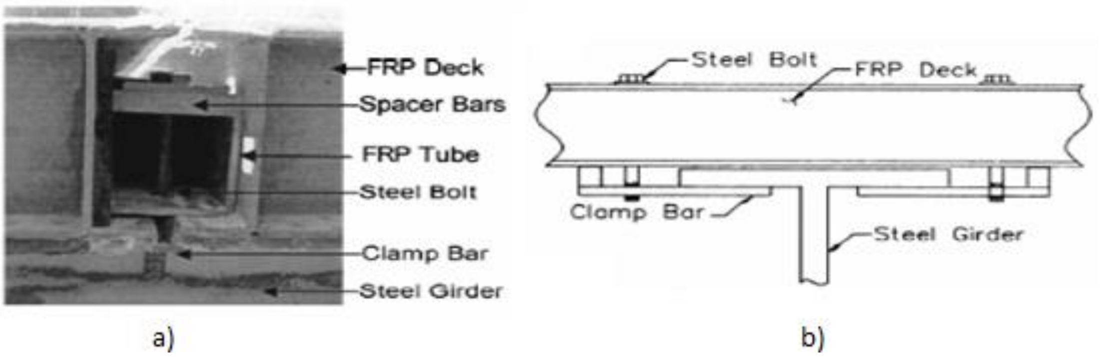


Figure 168 Clamped connection a) elevation view b) the cross section (Liu 2007)

The bolted connection illustrated in Figure 169 is rather difficult to install but have the advantages of sufficiently restraining the deck from up-lifting and rotation when the deck is subjected to static and dynamic loads (Liu 2007).

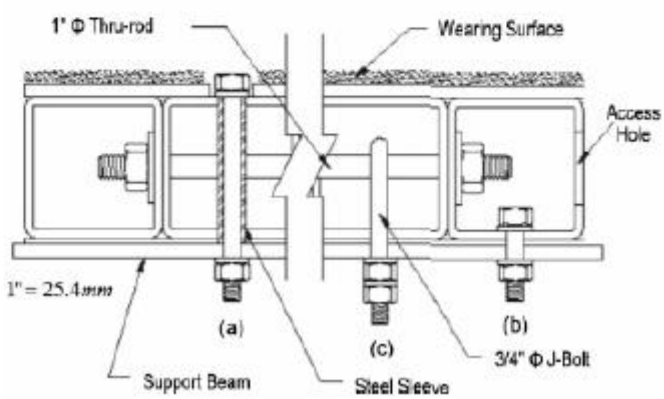


Figure 169 Bolted connection of Strongwell deck system (Liu 2007)

A comparison between adhesively bonded connection, bolted connection and shear-stud connection for deck-to-girder connections can be seen in Table 112.

Table 112 Comparison between different connections (Mara 2014)

Criteria	Adhesive bonding	Bolted connection	Shear-stud connection
Stress concentration	low	high	high
Sensitivity to peel loading	yes	no	no
Strength/weight ratio	medium	low	low
Fatigue resistance	high	low	medium
Corrosion resistance	high	low	medium
Accommodate thermal expansion	yes	no	no
Failure	brittle	quasi-ductile	ductile
Time to develop strength	long	immediate	medium
Dynamic resistance	good	low	low
Aesthetic joints	good	bad	bad
Sealing (water tightness)	yes	no	no
Special surface preparation	yes	no	no
Inspection possibility	low	high	low
Disassembly	no	yes	no

8.8.5.6 Guard Rail Connections

The guard rail connection should also be considered in bridge design (Mara 2014). The purpose of the guard rail is to carry the load from impact without damaging the bridge. The guard rail have until now been attached to the steel girder or to the concrete curbs. The guard rail generally consists of either concrete, steel or FRP. The FRP railings are generally attached to the FRP decks by means of adhesion or mechanical fasteners and are generally not designed to resist impact loading (Mara 2014). An illustration of a concrete guard rail system can be seen in Figure 170.

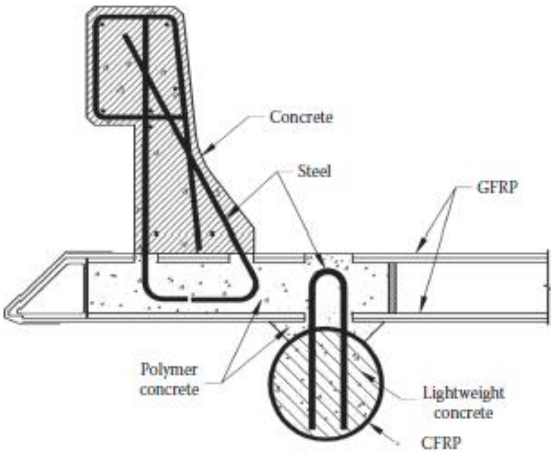


Figure 170 A concrete guard rail system (Zoghi 2013)

The steel guard rail can be assembled with bolts into the deck or to the girders as a cantilever element which can be seen in Figure 171. The steel guardrail connection is still in the development phase and requires further research (Mara 2014).

Figure 171 Guardrail with steel connection (Hastak et.al 2004)

8.9 References

8.9.1.1 Design

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8.9.1.2 Structural Components

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9 Optimal Design of All-Composite Bridge

This chapter presents the optimized design of the investigated bridge in this thesis. The optimization mainly regards the cross section of the girders to fulfil the requirements for ULS and SLS. The bridge which the design will be based on is called Rokån which was constructed in 1948 and is located in the north of Sweden. The Rokån bridge has previously been analysed by Mara 2014 where two bridge alternatives where studied as an alternative to the exploited existing bridge. The two refurbishing alternatives analysed by Mara 2014 included one with a full replacement of the superstructure with steel girders and concrete deck and the other with a replacement of the concrete deck to an ASSET FRP deck.

9.1 Case Study – Rokån Bridge

The Rokån Bridge was a two lane road bridge located in the northern part of Sweden and was constructed in 1948. The bridge had a span of 12 m, a width of 6 m and was simply supported. It was comprised of a 265mm thick concrete deck placed upon two steel girders as can be seen in Figure 172 (Mara 2014). An assessment of the bridge conducted in 2002 showed that the bridge was in need of rehabilitation since the deck was seriously deteriorated and the steel girders were deemed to have insufficient load-carrying capacity (Mara 2014). Data of the Rokån Bridge can be seen in Table 113.

Table 113 Dimension of the original Rokån Bridge

Information of original Rokån Bridge	
Span length	12 m
Free width	6 m
Number of lanes	2
Material of deck	Concrete (265 mm)
Material of girders	Steel

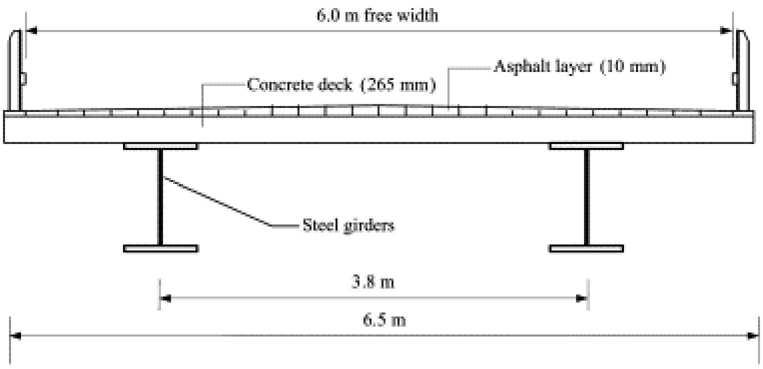

Figure 172 Original Rokån Bridge (Mara 2014)

The road authorities decided that the whole superstructure was in need of replacement, and the bridge was replaced with a prefabricated concrete deck and two steel girders in 2002 (Mara 2014). An alternative to the solution chosen by the road authorities consisting of an all-composite bridge will in the following be designed.

The all-composite bridge concept consists of FRP composite ASSET deck, manufactured by the Danish company Fiberline Composites, which is placed on four glass fibre reinforced girders. A 40mm asphalt wearing surface was considered in the design. The cross-section of the all-composite concept can be seen in Figure 173.

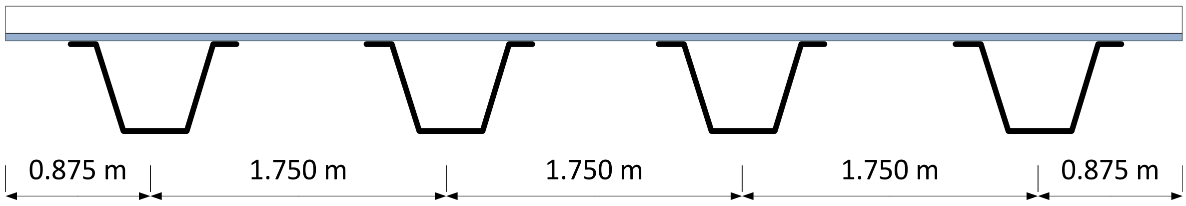

Figure 173 Cross-section of the all-composite bridge

GFRP composites have low stiffness and it was shown that the girders had sufficient load bearing capacity, however could not fulfil the requirements for SLS. Subsequently four carbon reinforced polymer (CFRP) cables were incorporated on the bottom flange of each girder to increase the stiffness as can be seen in Figure 174.

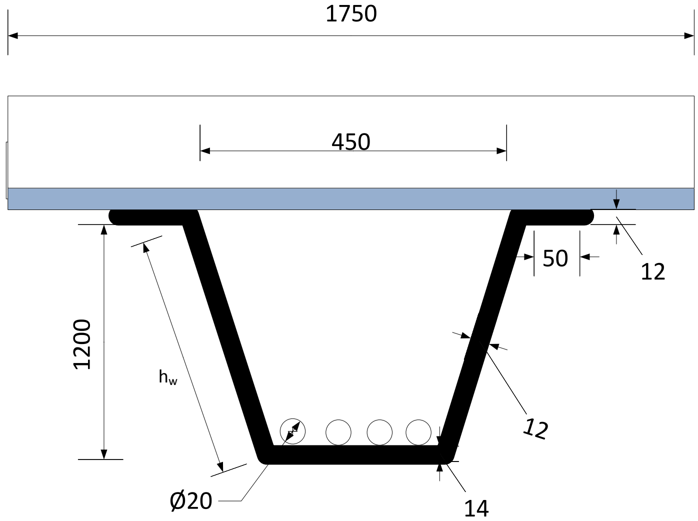

Figure 174 Dimensions and configuration of the bridge deck

Since FRP is comparatively expensive in comparison to conventional materials, with regards to initial costs, the optimization process aimed at minimizing material usage. The methodology of the optimization process was to first perform hand calculations to get reasonable dimensions, which can be seen in Appendix A. Secondly to model the bridge using the FE software ABAQUS (ver.6.11-3) and verifying the hand calculations. Thirdly the FE model was redefined and optimized with regard to SLS and ULS requirements.

9.2 The FE Model

The four FRP girders, the top plate and the Asset deck are modelled by 3D-deformable shell elements. The dimensions and the geometry of the Asset deck can be seen in Figure 175 and was designed by Fiberline Composites Inc. (Mara 2011).

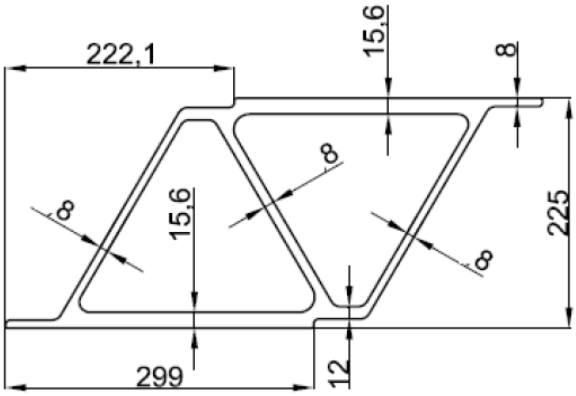

Figure 175 ASSET deck dimension (Mara 2011)

The real model of the ASSET deck is designed with curved lines between the webs and the flanges, which assist to reduce concentration of stresses. In the FE model however the ASSET deck is modelled, as in Figure 176, for simplification.

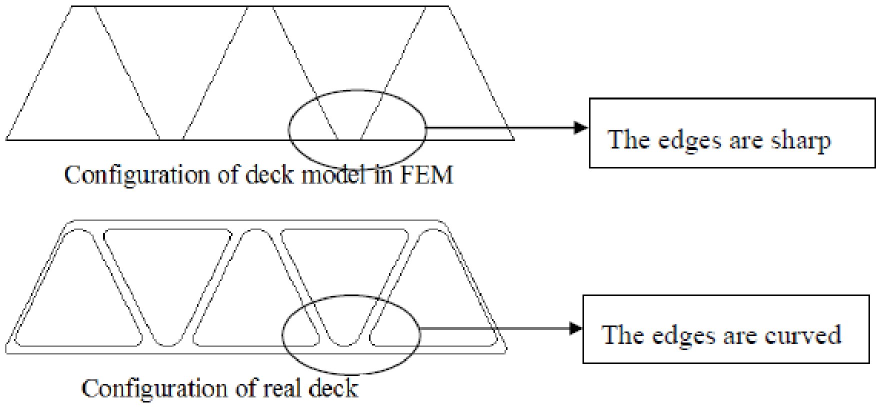

Figure 176 The configuration between in FEM model and real deck geometry (Mara 2011)

The adhesively bonded connections between the deck components were not considered in the FE model. The FRP deck was furthermore modelled with 3D orthotropic material properties and the characteristics properties which were given by Fiberline Composites. The material properties and the material local coordinate system of the ASSET deck can be seen in Table 114 and Figure 177. The self-weight of the wearing surface are furthermore applied as an equivalent density to the ASSET deck, which is explained in Appendix A.

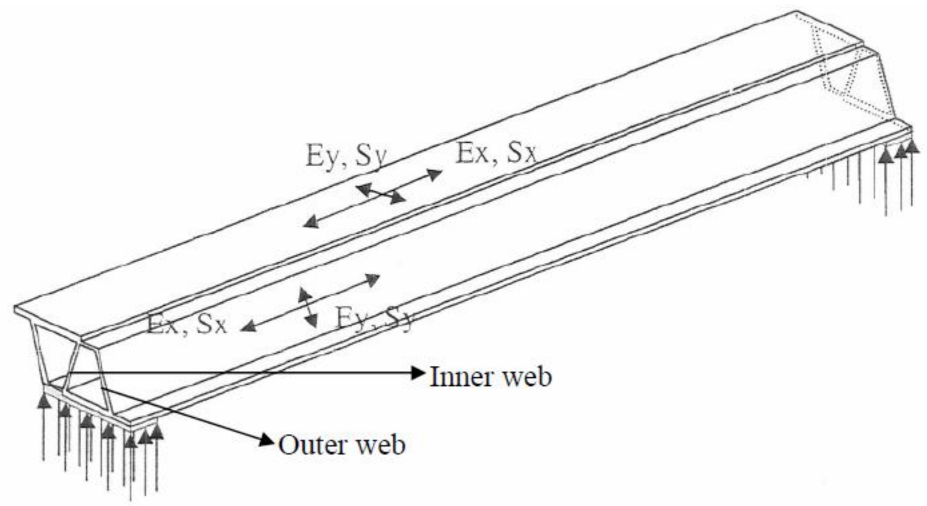

Figure 177 Orientation of the Asset deck (Mara 2011)

Table 114 The characteristics material properties of the Asset deck (Mara 2011)

Property	Flange plate	Outer web plates	Inner web plates
E_x [MPa]	23000	17300	16500
E_y [MPa]	18000	22700	25600
G_{xy} [MPa]	2600	3150	2000
G_{xz} [MPa]	600	600	600
G_{yz} [MPa]	600	600	600
ν_{xy} [-]	0.3	0.3	0.3
Note: x is the pultrusion direction, y is transversal direction and z is the vertical direction			

The values of the material properties are characteristic and should be changed to design values as input data in ABAQUS by considering the material partial safety factor γ_m. Worth noticing is that the partial safety factor γ_m should be calculated for both SLS and ULS conditions which can be seen in Table 115. This is related to that the traffic load is considered as a short-time load in SLS and hence the γ_{m3} differs between ULS and SLS.

Table 115 Partial safety factors for SLS and ULS

	ULS	SLS
γ_{m1} [1]	1.15	1.15
γ_{m2} [2]	1.2	1.2
γ_{m3}	2.5 [3]	1 [4]

[1] Properties of the laminate, panel or pultrusion are derived from test specimen data [2] Resin transfer moulding [3] Long term loading [4] Short time loading

The cross-section design of the GFRP girders is modelled as open-shaped beam from the recommendations from the Trans-IND catalogue (Warszawa 2009). The bridge cross-section also includes a GFRP top plate which is installed between the GFRP girders and the ASSET deck. The dimensions of the cross-section of girders, top plate and ASSET deck can be seen in Figure 178 and are based on dimensions from the preliminary hand design calculations. The cross-section has been verified with hand calculations for capacity checks with regard to the ULS and SLS which can be seen in Appendix A.

In the FE model the CFRP cables where incorporated as an equivalent GFRP thickness in the bottom flange of the girders which can be seen in Figure 178.

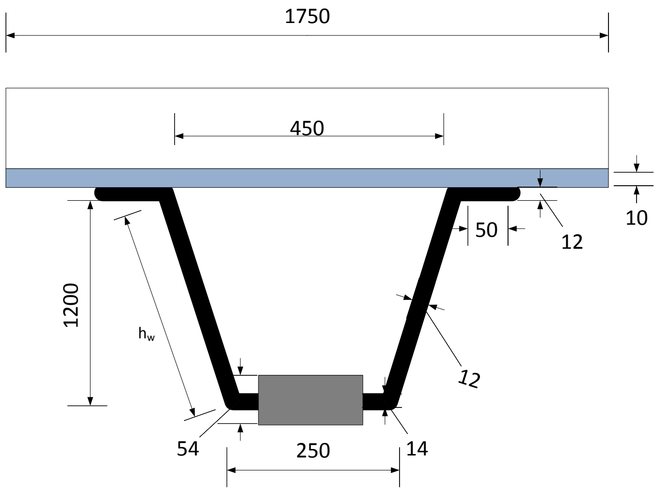

Figure 178 FE model with equivalent CFRP thickness

The characteristic material properties used for the top plate and the GFRP girders can be seen in Table 116. The values of E_x and E_y are based on values retrieved from Agarwal, Broutman & Chandrashekhara 2006. The characteristic and design strength of the GFRP can be seen in Table 117. When assigning the properties to the FE model, the design values of the material properties should be used by accounting for the partial safety factors.

Table 116 The characteristic material properties for the girders and top plate (Agarwal, Broutman & Chandrashekhara 2006)

Property	Girders
E_x [MPa]	25000
E_y [MPa]	15000
G_{xy} [MPa]	4140
G_{xz} [MPa]	6063
G_{yz} [MPa]	6063

$\boldsymbol{\nu_{xy}}$ [-]	0.237

Table 117 Characteristic and design strengths for epoxy and glass fibre FRP

Strengths	σ_k	σ_d (ULS)
$\boldsymbol{\sigma_{LU}}^1$	1062	307.8
$\boldsymbol{\sigma'_{LU}}^2$	610	176.8
$\boldsymbol{\sigma_{TU}}^3$	118	34.2
$\boldsymbol{\sigma'_{TU}}^4$	31	8.9
$\boldsymbol{\tau_{LTU}}^5$	72	20.9

Note: [1] Tension longitudinal, [2] Compression longitudinal, [3] Compression transversal, [4] Tension transversal, [5] Shear

9.2.1 Interaction

For the connections between the structural components adhesive bonding was modelled by considering interaction between the glued elements. The connections were applied between the ASSET deck and the top plate and between the top plate and the top flange of the girders. In ABAQUS the "Tie constraints" method was used since it provides full bond between the parts and is suitable for connecting shell elements. The location of interactions could be seen in in Figure 179.

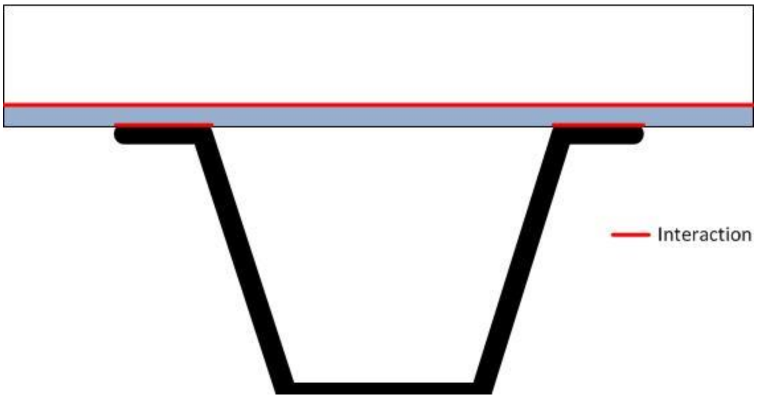

Figure 179 Interaction between ASSET deck and top plate and the top plate and top flange of GFRP girders

9.2.2 Boundary Conditions

The bridge is designed to be simply supported as can be seen in Figure 180. The boundary conditions were applied at the edges of the girders which can be seen in Figure 181. The bottom flanges of the girders are pinned (fixed in x- and y-direction) on one side and roller support on the other side (fixed in y-direction) which is illustrated in Figure 180 and Figure 181. For the web of the girders, both edges are fixed in z direction which can be seen in Figure 181.

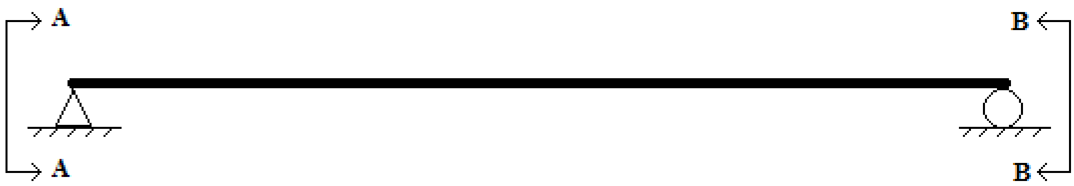

Figure 180 Structural system and boundary conditions for the Rokån Bridge

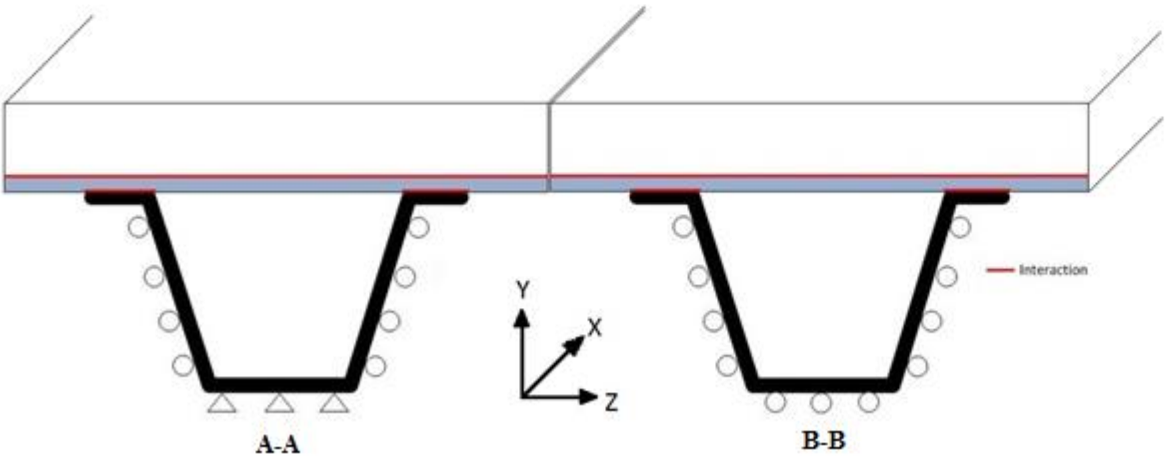

Figure 181 Boundary conditions for both sides of the bridge

9.2.3 Load

In the model, different configuration giving the critical values with regard to design parameters were applied depending on the purpose of the analysis, i.e. whether ULS or SLS. Traffic loads, both vertical and horizontal (traction), and the self-weight of whole structure were considered in the model. Wind, snow, railings etc. was not considered in the FE model or the hand calculations.

9.2.3.1 Self-Weight

For each component of the bridge structure is assigned with corresponding density according to the material properties. In the load module in ABAQUS gravity was applied for the entire model in the vertical direction (y-direction).

9.2.3.2 Traffic Loads

The traffic loading was performed according to "EN1992-2-traffic loads on road bridges and footbridges" with load model "LM 1" which is illustrated in Figure 182 and Figure 183.

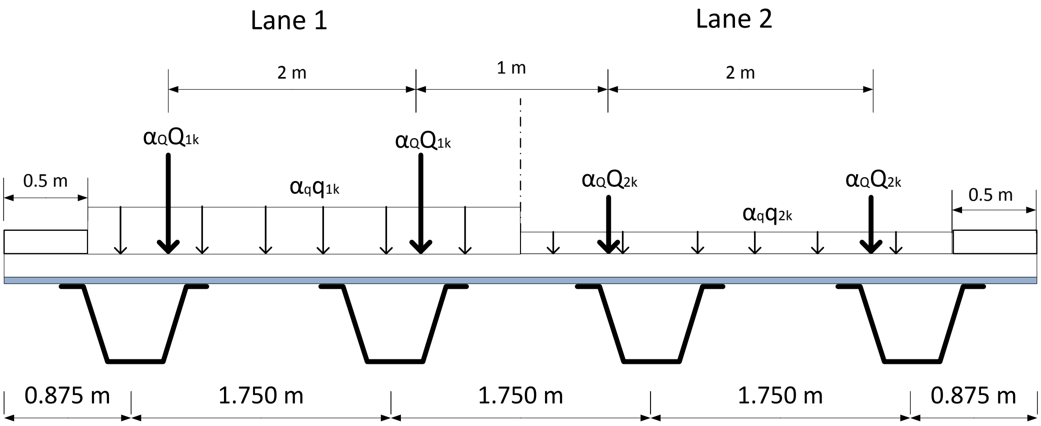

Figure 182 LM 1 in the transversal traffic direction according to Eurocode 1992-2

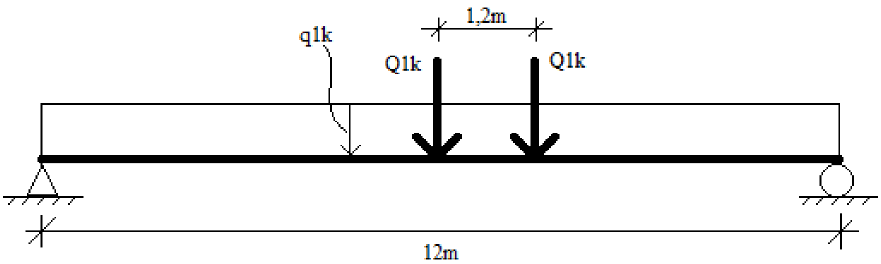

Figure 183 The LM1 model seen from the longitudinal traffic direction

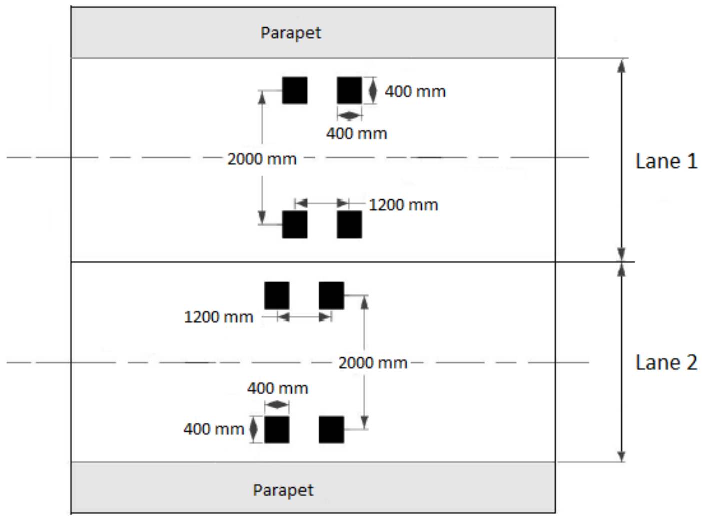

Figure 184 LM1 seen from above

The defined values of Q_{1k} and q_{1k} can be taken as Table 118. The adjustment factors α_Q and α_q defined in from the LM1 model are taken for class 1 vehicles i.e. international heavy vehicle traffic. The distance 2m from Figure 182 and 1.2m from Figure 183 represents the distances between the wheel axels of the car which can be seen in Figure 184.

Table 118 Load model 1 (LM1) according to EC1

Location	Axle loads Q_{1k} [N]	Uniform load q_{1k} [N/mm^2]	Adjustment factor α_Q	Adjustment factor α_q

Lane 1	300	9	1	1
Lane 2	200	2.5	1	1

9.2.3.3 Vertical Loads

The axle loads were applied on an area of 400x400mm in the FE model, representing the wheels, as can be seen in Figure 184. The uniform loads were considered on the corresponding lane area along the bridge, i.e. 3m x 12m which can be seen in Figure 183.

9.2.3.4 Horizontal Loads

The horizontal loads, also called traction, are the resulting horizontal force from braking and acceleration of the cars and is acting on the deck surface. The traction was calculated according to LM1 from Eurocode 1992-1 and was applied as a "traction force" in the FE model on both lanes in one direction.

9.2.4 Ultimate Limit State (ULS)

The ULS loading configurations consisted of two cases, one to analyse the shear effects such as shear buckling and shear stresses in the web and the other to analyse the bending stresses in different parts of the cross-section which can be seen in Figure 185 and Figure 186.

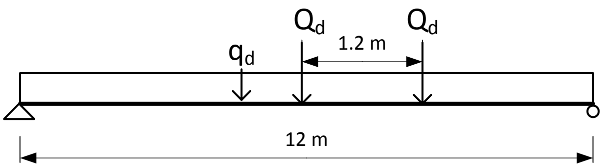

Figure 185 ULS configuration for maximum bending stresses

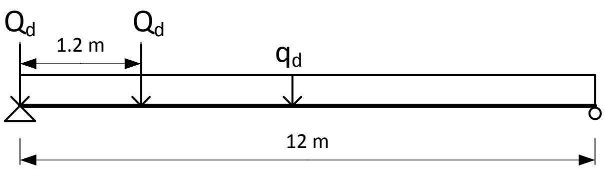

Figure 186 ULS load configuration for maximum shear stresses and buckling analysis

The buckling analysis of the FRP bridge was performed with a linear buckling analysis where the "step" was set to "Linear perturbation – Buckle". The "Lanczos" method was chosen as it generally is faster than the "Subspace" method. The critical buckling load can be calculated according to the following formula:

$$P_{cr} = \lambda \times P_{ref} \qquad (1)$$

Where:

P_{cr} is the critical buckling load, λ is the buckling factor and P_{ref} is the applied load on the structure

The design loads applied in the FE model for the ULS condition are calculated according to the formulas:

$$Q_{1d} = 1.35\alpha_Q Q_{1k} \qquad Q_{2d} = 1.35\alpha_Q Q_{2k} \qquad (2)$$

$$q_{1d} = 1.35\alpha_q q_{1k} \qquad q_{2d} = 1.35\alpha_q q_{2k} \qquad (3)$$

9.2.5 Serviceability Limit State (SLS)

The SLS loading configuration shown in Figure 187 was used to retrieve the largest deflection. For the Eigen frequency analysis only the gravity load was applied.

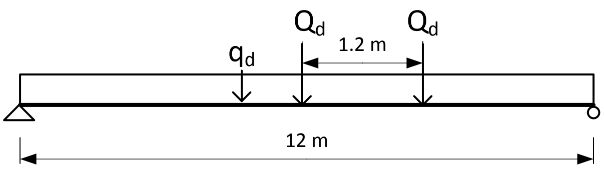

Figure 187 SLS configuration for maximum deflection

The frequent combination was used to calculate the SLS design load:

$$Q_{1d} = \psi_0 \alpha_Q Q_{1k} \qquad Q_{2d} = \psi_0 \alpha_Q Q_{2k} \qquad (4)$$

$$q_{1d} = \psi_0 \alpha_q q_{1k} \qquad q_{2d} = \psi_0 \alpha_q q_{2k} \qquad (5)$$

Where:

$$\psi_0 = 0.5$$

The limiting value for deflection is taken according to (Clarke 1996; Mara 2014):

$$\delta_{limit} = \frac{L_{span}}{400} = 30mm \qquad (6)$$

The limit related to the frequency analysis is that the Eigen frequencies of the FRP structure should be in the range of (Warszawa 2009):

$$1.65\ Hz > f > 2.35\ Hz \qquad (7)$$

9.2.5.1 Mesh

The FE model was assigned elements with approximate size of 100 mm with structured mesh control.

9.3 Validation of the FE Model

The FE model was verified to the hand calculations by comparing the bending stresses and maximum deflection for one girder assigned with steel properties for the most loaded girder in the ULS bending load configuration.

9.3.1 Verification by Assigning Steel Properties

The FE model was validated by comparing the stress and deflection parameters in several points from the FE model and comparing them with corresponding results from hand calculations. In order to avoid deviations of results due to orthotropic material models, which is not possible account in hand calculations, steel material was used for all parts. At hits stage, the FE model consisted of only one girder with corresponding ASSET deck and top plate which can be seen in Figure 188.

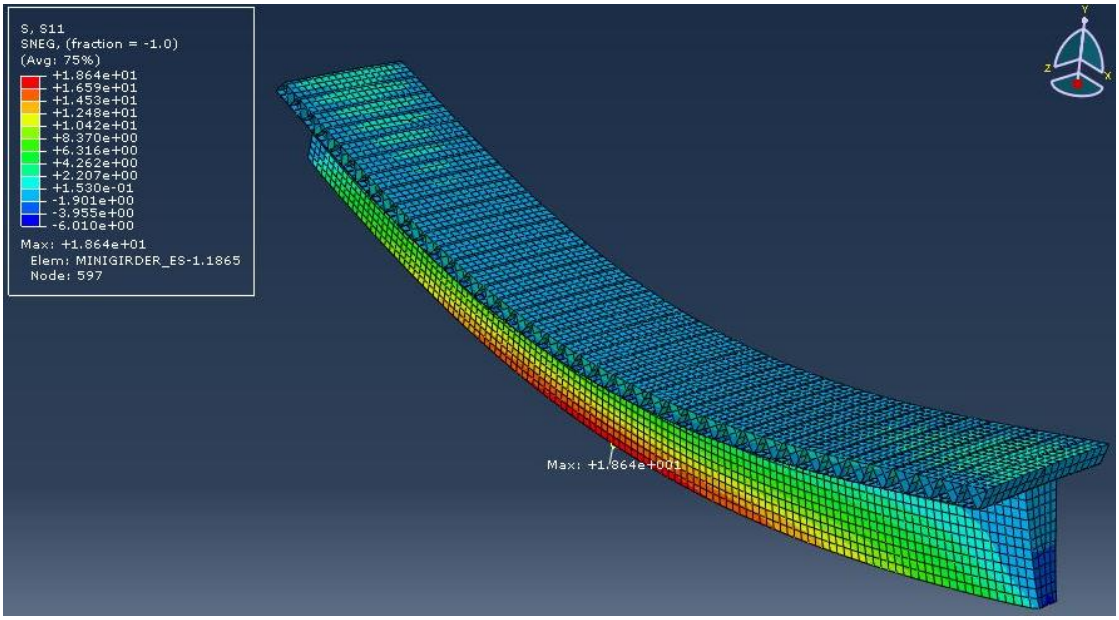

Figure 188 FE model of steel for verification (S11 bending stresses)

Both stresses at different locations in the girder and maximum deflections were compared in order to validate the FE model. The results are summarized in Table 119. The locations where the stresses were analysed can be seen Figure 189.

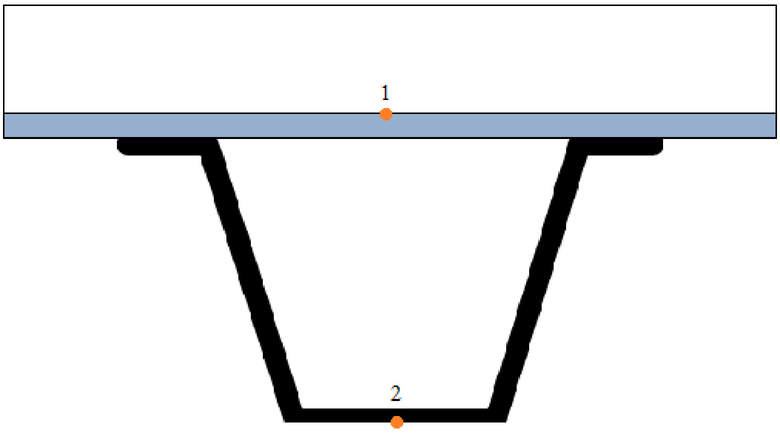

Figure 189 Location of the two points where bending stresses are compared

Table 119 Ratio for deflection and bending stresses for steel verification model

	Hand calculation	Abaqus	Ratio [%]
Deflection [mm]	1.36	1.408	96.6
	Stresses [MPa]		
Location 1	2.603	2.833	91.9
Location 2	18.305	18.640	98.3

It can be seen that the results from the FE model corresponds well with hand calculations and deviation is less than 8%. Hence the FE model is supposed to provide accurate results.

When the stress was checked in the point above the ASSET deck the variation of stresses between hand calculations and the FE model was in the magnitude of 450%. This is because in the hand calculations, full interaction between the flanges of the FRP decks is assumed, i.e. planes remain plane assumption, while in reality the webs of the FRP deck are not able to provide this full interaction and this phenomenon can be captured in the FE model. Therefore, stresses from hand calculations are not valid on the top of the FRP deck as the strain distribution is not proportional with respect to the rest of the section.

9.4 Results

9.4.1 Verification of FE Model

9.4.1.1 Check of Reaction Forces and Stresses

According to the load distribution factors, from the hand calculations seen in Appendix A, the reaction forces were largest for the interior girder under lane 1. The reaction forces were calculated according to Appendix and were subsequently compared to the reaction forces of the corresponding girder in the FE model. The values of the reaction forced can be seen in Table 120.

Table 120 Comparison reaction forces between hand calculations and FE model

	Hand calculations		FE model		Ratio [-]
	Support A	Support B	Support A	Support B	
Reaction forces [kN]	528.5	597.4	265.6	333.3	1.88

The correction factor from the comparison of the reaction forces is equal to 1.88 and the difference is related to the error inherent in the load distribution model considered in the hand calculations.

The bending stresses are compared in the four locations as seen in Figure 190.

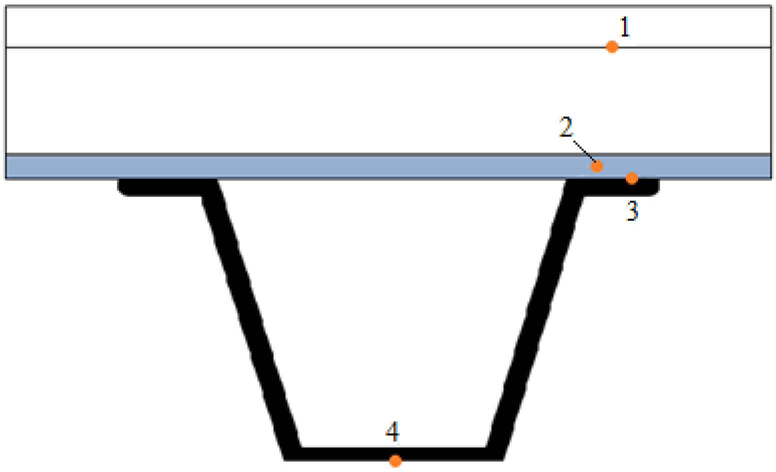

Figure 190 The four levels where bending stresses are analysed

The comparison of bending stresses can be seen in Table 121.

Table 121 Comparison bending stresses between hand calculations and FE model

	Hand calculations [MPa]	FE model [MPa]	Ratio [-]
Level 1	41.1	25.4	1.62
Level 2	33.4	19.2	1.74
Level 3	32.9	21.5	1.53
Level 4	91.5	57.7	1.59

The large differences are related to that the material models considered for the hand calculations and FE model i.e. orthotropic in the FE model and isotropic in the hand calculations. The model has already been validated when steel properties were assigned.

9.4.2 Ultimate Limit State

9.4.2.1 Bending stresses

The bending stresses obtained from the FE model for the four different locations seen in Figure 190 and design material strength of the GFRP composite are presented in Table 122.

Table 122 Comparison bending stresses from FE model

	FE model [MPa]	Material design strength [MPa]	Utilization ratio [%]
Level 1	25.4	307.8	8.2
Level 2	19.2	176.8	10.9
Level 3	21.5	307.8	7.0
Level 4	57.7	307.8	18.7

Figure 191 and Figure 192 illustrates the results from the bending stress analysis.

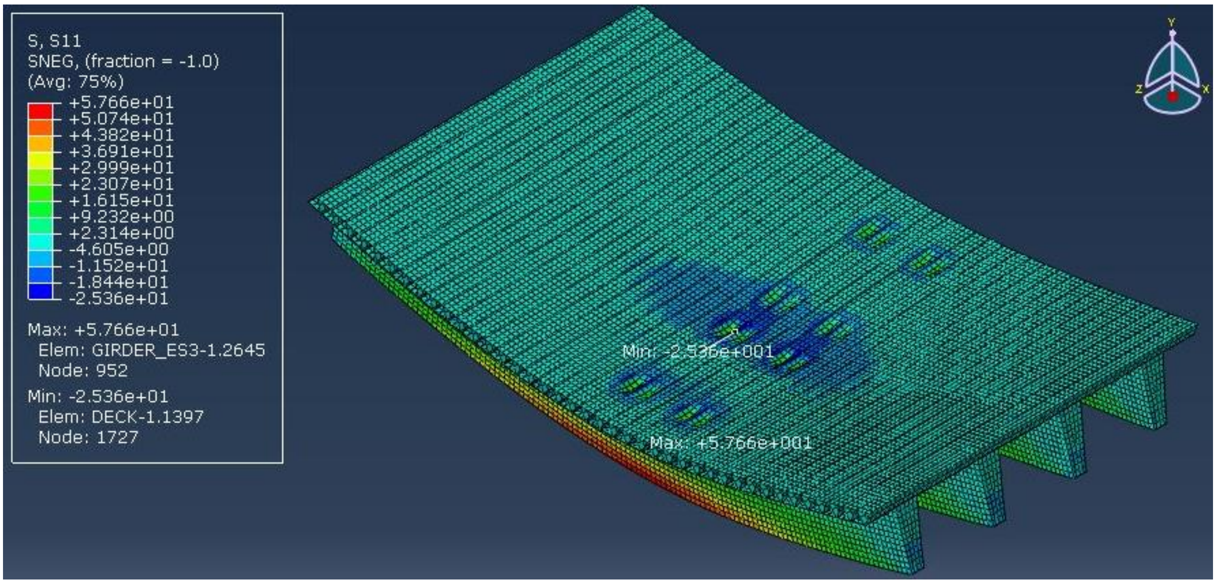

Figure 191 Bending stresses of the bridge – deformed shape

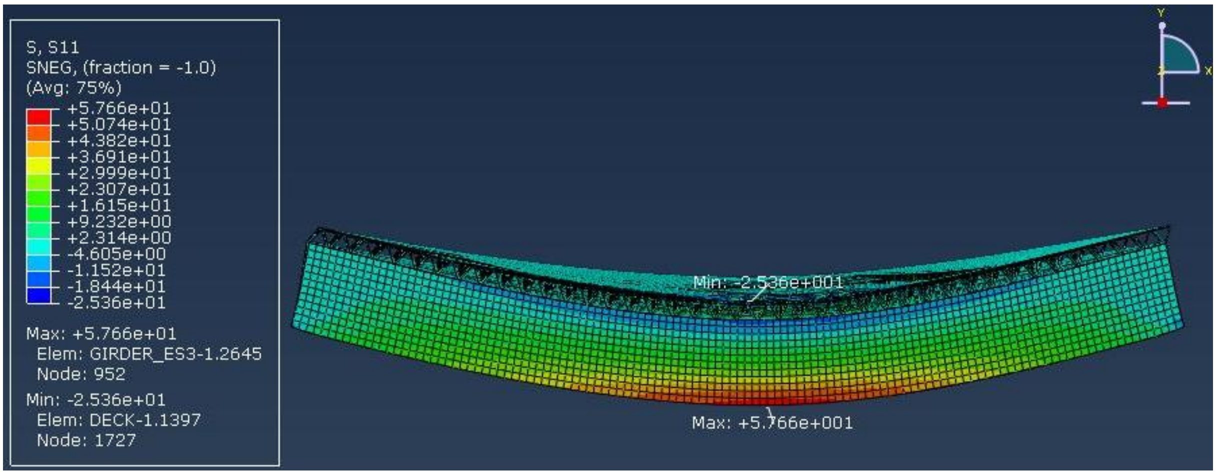

Figure 192 Bending stresses in the longitudinal direction – deformed shape

9.4.2.2 Shear Stresses

The shear stress from the FE model was obtained in the point of neutral axis of the interior girder under lane 1 close to support A, as seen in Figure 193. This point was chosen because the largest shear stress was presumed to take place at this location.

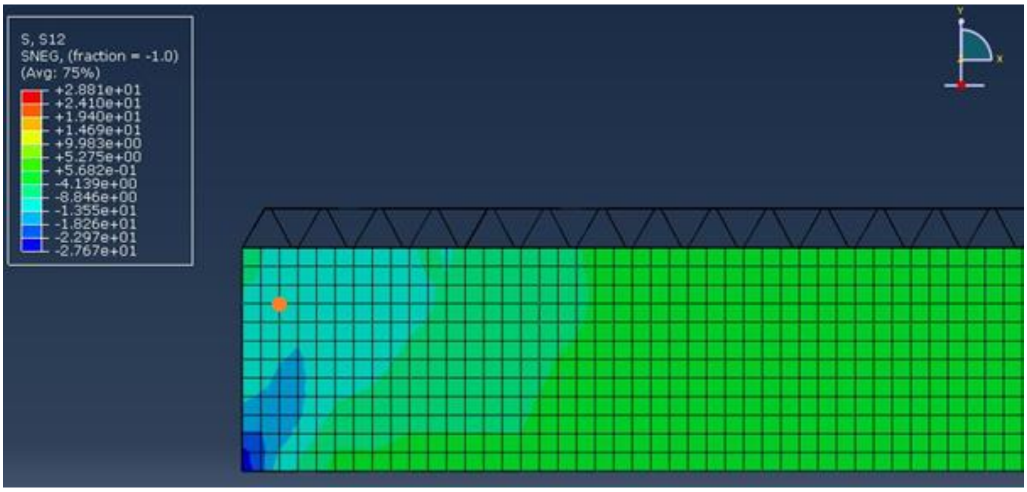

Figure 193 Point in the FE model where the shear stress is measured

The shear stress and corresponding utilization ratio of the FRP composite bridge in the specified point can be seen in Table 123.

Table 123 Shear capacity of the FE model

	FE model [MPa]	Material design strength [MPa]	Utilization ratio [%]
τ_{12}	11.35	20.9	54.3

The shear stress in the web is well below the design shear strength of the material, i.e. the cross-section has sufficient shear capacity.

9.4.2.3 Buckling Analysis

The ULS shear load configuration was applied in order to obtain the buckling modes of the structure. The first ten buckling modes with corresponding eigenvalue can be seen Table 124.

Table 124 First ten buckling modes with corresponding eigenvalues

Mode	Eigenvalue λ
1	1.1030
2	1.2300
3	1.2838
4	1.2952
5	1.4014
6	1.4154
7	1.4415
8	1.5215

9	1.5303
10	1.5870

Figure 194 and Figure 195 illustrates the first buckling mode, occurring in the interior girder, from below and from the side.

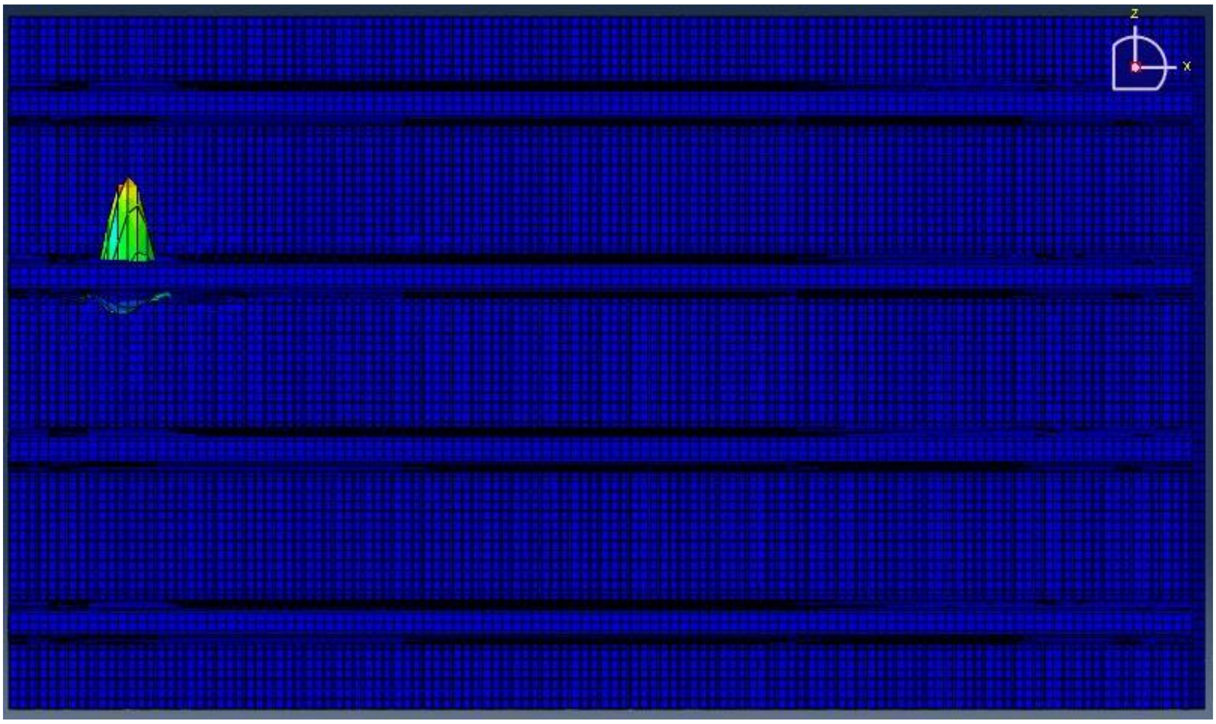

Figure 194 First buckling mode (shear buckling) of the interior girder seen from below

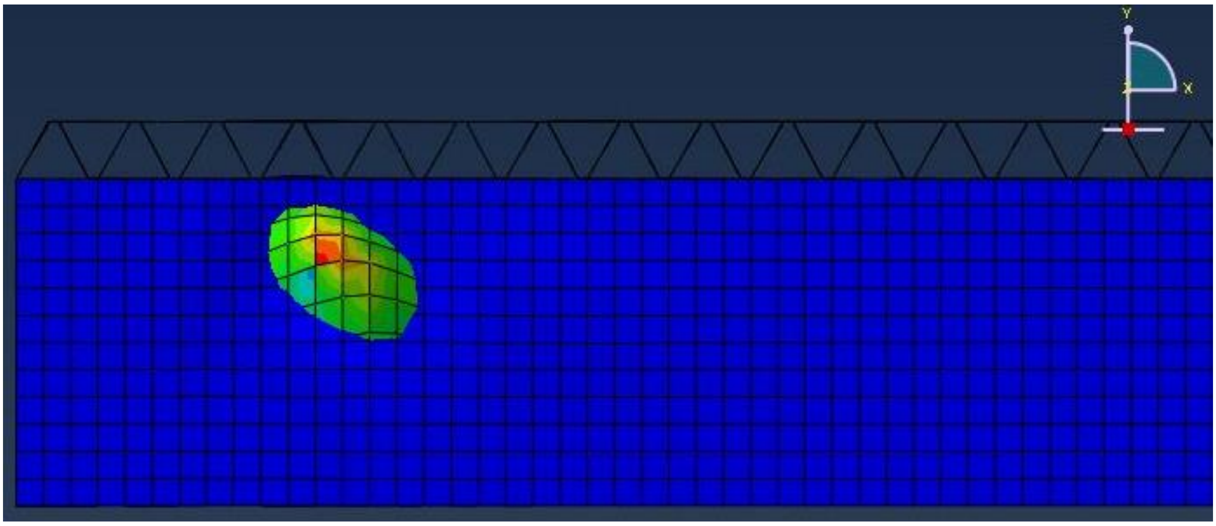

Figure 195 First buckling mode (shear buckling) of the interior girder seen from the side

The FRP bridge has sufficient capacity since all buckling factors (λ) are larger than one. The cross-section can be considered relatively optimized since the first buckling mode is close to one.

9.4.3 Serviceability Limit State

9.4.3.1 Deflection

The deformed shape of the maximum deflection of the FRP bridge can be seen in Figure 196 and Figure 197 when subjected to the SLS loading configuration demonstrated in Figure 187.

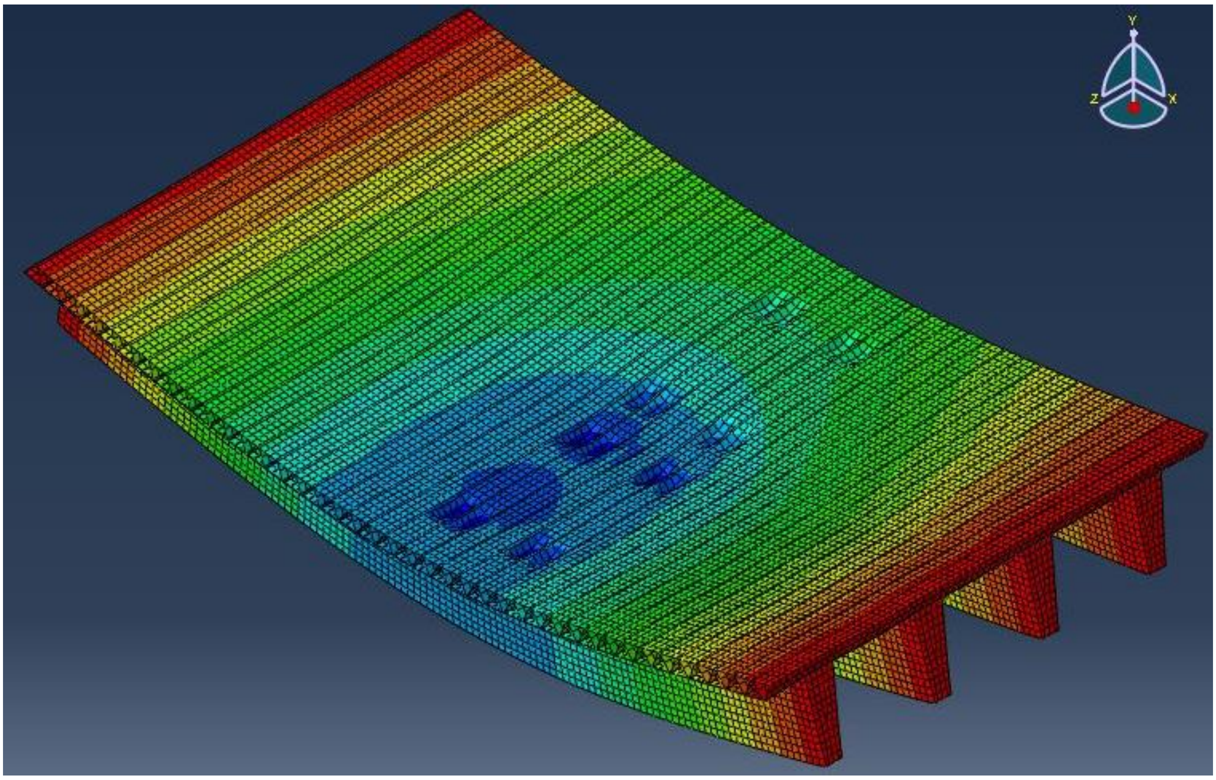

Figure 196 The maximum deflection of the bridge – deformed shape

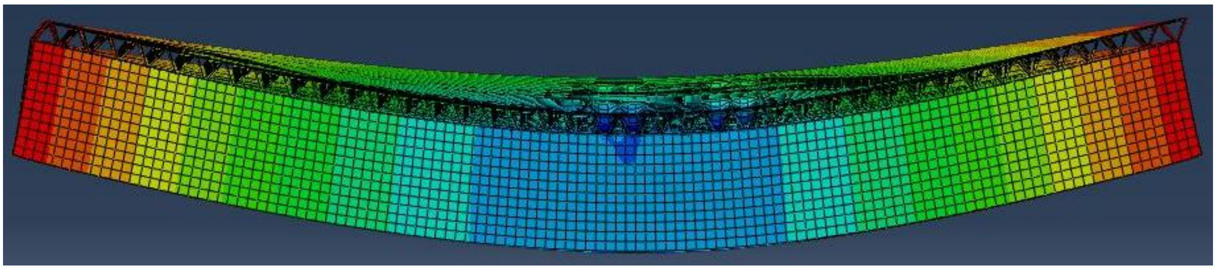

Figure 197 The maximum deflection of the bridge seen from the side – deformed shape

The maximum deflection obtained in the bottom flange of the interior girder can be seen in Table 125.

Table 125 The maximum deflection of the most loaded girder - value obtained from bottom flange

	FE model [mm]	Limiting value [mm]	Utilization ratio [%]
Deflection	27.7	30	92.2

The deflection of the bridge is close to the limiting value which indicates an optimized cross-section.

9.4.3.2 Frequency Analysis

The ten first frequencies of the FRP bridge can be seen in Table 126.

Table 126 Ten first Eigen frequencies of the FRP bridge

Mode	Frequency [Hz]
1	0.30
2	0.35
3	0.48
4	0.53
5	0.56
6	0.57
7	0.62
8	0.66
9	0.67
10	0.67

As can be seen in the Table 126 the first Eigen frequency is equal to 0.3 which is well below the limit interval defined in equation 6. Hence the dynamic behaviour of the bridge is satisfactory.

9.4.4 Conclusion and Discussion

To ensure that the FE model was correct, steel properties were assigned in both the hand calculations and the FE model. The results from the FE model indicated very good correlation with hand calculations. Hence a conclusion can be drawn that the FE model is accurate and could be used for the detailed design of the bridge for ULS and SLS. The comparison of the reaction forces and bending stresses indicated that the values obtained from the hand calculations were approximately 1.88 larger than the FE model. A possible explanation to the factor of 1.88 is inaccurate assumptions when performing the load distribution factors in the hand calculations.

The design of the all-composite FRP bridge can be presumed to be optimized since the utilization factor is approximately 92% for the deflection. The utilization factors for bending stresses are low, in the range of 7% to 18%, which is reasonable since FRP composites have a high strength however relatively low stiffness. The shear capacity of the FRP composite bridge is sufficient and the utilization ratio is higher than for the bending stresses. This is reasonable since the shear strength is lower than the compressive and tensile strength in the longitudinal direction which was presented in Table 117.

The shear load configuration was chosen for the buckling analyse since the area close to the end-supports is more critical in terms of buckling. The first buckling mode consisted of shear buckling which can be seen in Figure 195 and had an eigenvalue (λ) of 1.1. Hence the critical buckling load is relatively close to the ULS shear load and it can be concluded that the cross-section is optimized in terms of buckling.

The frequency analysis demonstrated that the dynamic response of the FRP bridge is satisfactory since the first Eigen frequency is equal to 0.3 which is substantially lower than 1.65 which was the limiting value.

9.5 References

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Mara V. (2014): *Fibre reinforced polymer bridge decks: Sustainability and a novel panel-level connection.* Ph.D. Thesis. Department of Civil and Environmental Engineering, Division of Structural Engineering, Chalmers University of Technology, Publication no 14:01,Gothenburg, Sweden, 2014.

Mara V. (2011): *Fibre reinforced polymer bridge decks: A feasibility study in upgrading existing concrete-steel bridges*. Master Thesis, Department of civil and Environmental engineering. Chalmers University of technology.Gothenburg Sweden.

Warszawa M. (2009): New industrialised Construction Process for Transport Infrastructures Based on Polymer Composite Components. Trans-IND

10 Life Cycle Cost Analysis

The life cycle cost (LCC) analysis is an approach used to estimate all the costs incurred throughout the structures life cycle (Bisby et al. 2006). The LCC analysis is a tool for the designer to perform a comparative cost assessment including all relevant economic factors (Salokangas 2013). The costs considered when conducting a LCC analysis are generally divided in agency costs and social costs, which can be seen in Figure 198 (Mara 2014). The agency costs are further divided in initial construction costs, operation and maintenance costs and disposal costs. The social costs are further subdivided in user costs and society costs (Mara 2014).

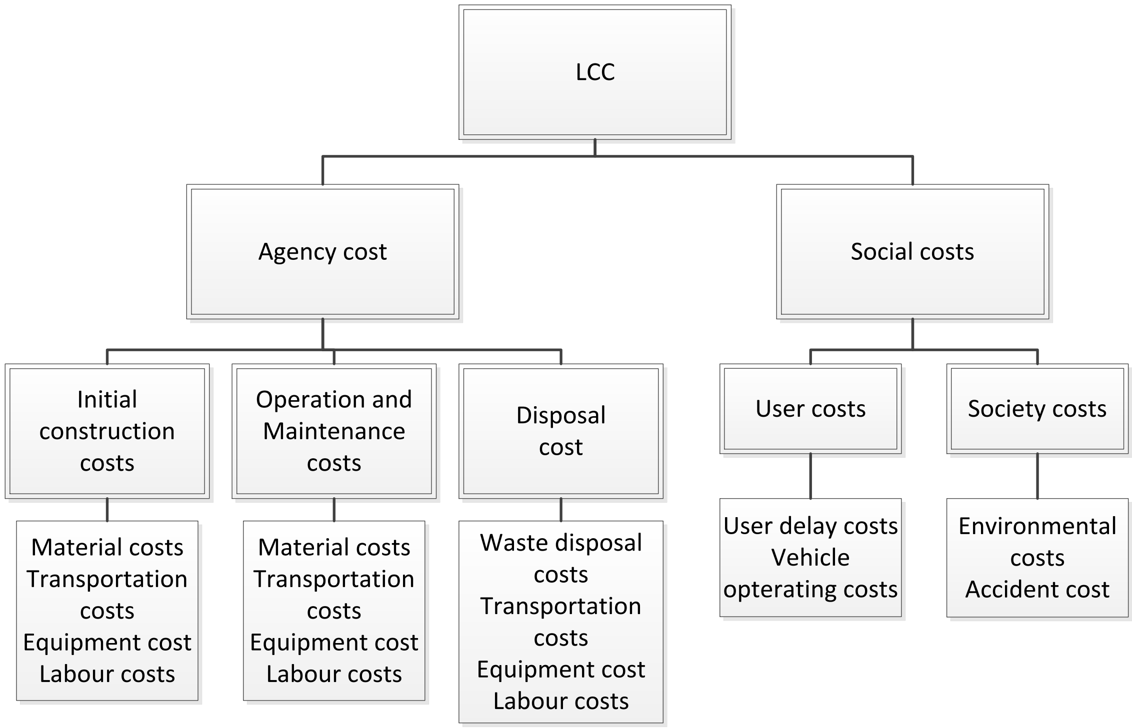

Figure 198 Life cycle cost analysis (Mara 2014)

Since bridges have a lifespan of up to 100 years one of the most critical elements of LCC is how the value of money changes with time (Murphy 2013). The net present value (NPV) method accounts for how the value of money changes with time and makes it possible to compare past, present and future costs (Murphy 2013). In the NPV method the “time value of money” is accounted for with a discount rate (d) (Murphy 2013).

The following formula can be used to calculate the expected cost after a specified time period, also called net present value, life cycle cost or owner costs (Banthia et al. 2006; Murphy 2013):

$$NPV = LCC_T = \sum_{n=1}^{L} \frac{C_n}{(1+d)^n} \qquad (1)$$

Where:

LCC_T is the life cycle cost at present value, C_n is the cost incurred in year n, d is the discount (inflation) rate, n is the year considered and L is the service life span

The discount rate d is generally set to 3.5% which is a reasonable value (Mara 2014; Murphy 2014).

10.1 Case Study – Rokån Bridge

The aim with the case study was to investigate the competitiveness of, the previously designed and optimized, all-composite bridge in comparison with a steel-concrete composite bridge. The case study was again based on an original bridge called the Rokån Bridge.

The road authorities decided that the whole superstructure was in need of replacement, and the bridge was replaced with a prefabricated concrete deck and two steel girders in 2002 (Mara 2014). The solution chosen by the road authorities will in the following be compared with the all-composite bridge alternative designed in the previous chapter: 9 Optimal Design of All-Composite Bridge.

The two bridge concepts that will be compared are:

- Alternative 1 – Concrete deck with steel girders
- Alternative 2 – FRP ASSET deck with GFRP girders

A design requirement set was that the bridge deck should be widened by 1m for both bridge alternatives i.e. increase the bridge width from 6m to 7m (Mara 2014). General data for the new Rokån Bridge can be found in Table 127.

Table 127 General information about the new Rokån Bridge (Mara 2014)

The New Rokån Bridge	
Service life (years)	80
Effective width of bridge (m)	7
Length of bridge (m)	12
Average daily traffic (ADT) (vehicles/day)	796
Hourly time value of drivers, w (EUR/h)	28
Hourly vehicle operating cost, r (EUR/h)	21

10.1.1 Alternative 1 – Concrete Deck and Steel Girders

Alternative 1 represents the alternative chosen by the road authorities and consists of a full replacement of the whole superstructure (Mara 2014). The steel girders required to be replaced due to insufficient load carrying capacity as a result of the increased traffic loads (Mara 2014). The original concrete deck was severely deteriorated and thus required to be replaced. The new alternative was a prefabricated concrete deck acting compositely with the two new steel girders which can be seen in Figure 199 (Mara 2014).The new steel/concrete bridge was assembled in 35 days close to the original Rokån Bridge (Mara 2014). The total closure of the new bridge was estimate to 30 hours and the drivers were then redirected to a 16km longer alternative route which took approximately 15 minutes to drive (Mara 2014).

Figure 199 Alternative 1 with the prefabricated concrete deck and steel girders (Collin 2009)

10.1.2 Alternative 2 – FRP ASSET Deck and GFRP Girders

Alternative 2 represented a full replacement of the bridge with a FRP ASSET deck and four GFRP composite girders. The ASSET deck, produced by the Danish company Fiberline Composites, can be seen in Figure 200.

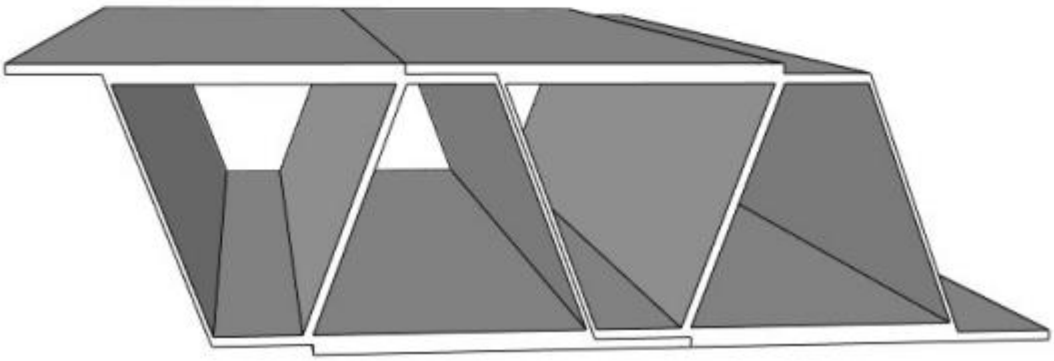

Figure 200 Cross-section of a Fiberline ASSET bridge deck system (Engdahl & Desha Rousstia 2012)

The cross-section of the girders and the geometry of alternative 2 can be seen in Figure 201. Since the stiffness of the GFRP girders were relatively low, four carbon fibre cables were incorporated in each GFRP girder, which can be seen in Figure 202. The carbon fibre cables had a diameter of 20mm.

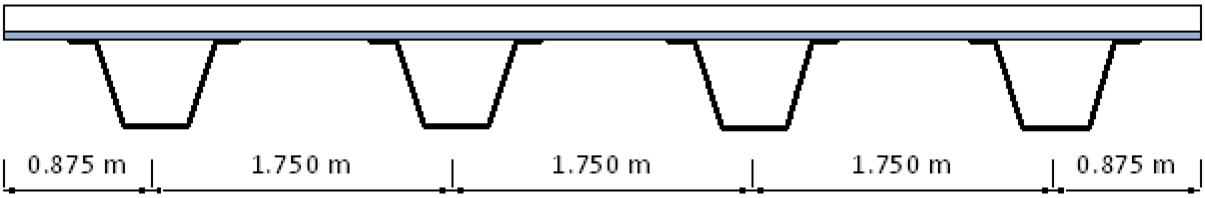

Figure 201 Cross-section of alternative 2 with dimensions

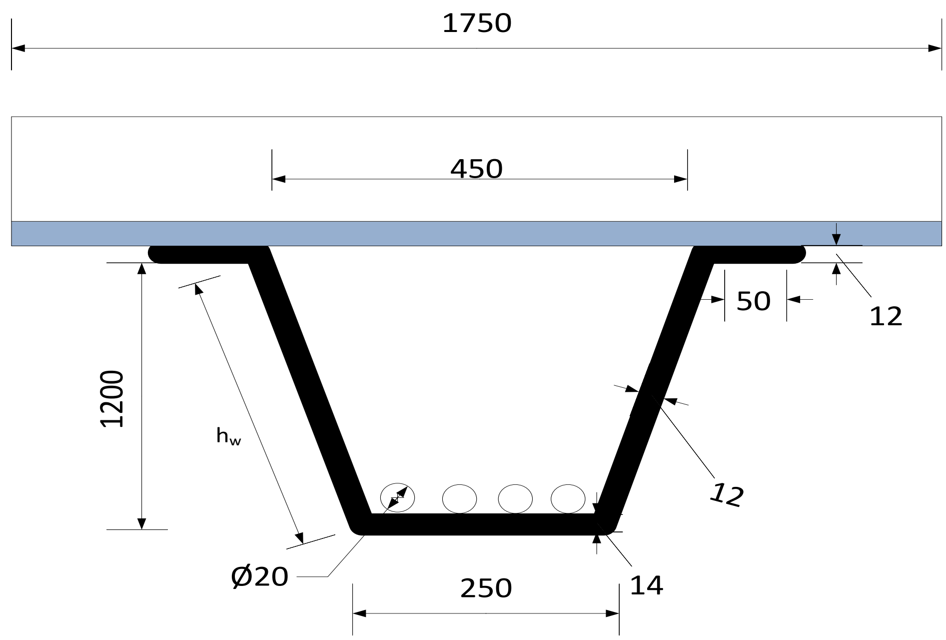

Figure 202 Cross-section of alternative 2 with dimensions

The time required to replace the original Rokån Bridge with the all-composite alternative was assumed to take 20hours. The elapsed time included demolition of the old deck and girders and assembly of the new FRP superstructure (Mara 2014). The demolition of the original deck took approximately 3 hours and assembly of the new deck and girders roughly 17 hours.

10.2 Input Values for the LCC Analyse

10.2.1 Agency Costs

The costs associated with agency costs are the initial costs of the material, manufacturing, maintenance and finally disposal of the materials (Mara 2014).

10.2.1.1 Initial Costs

The initial costs of an FRP bridge are generally divided in the following categories (Nishizaki et al. 2006; Banthia et al. 2006):

- Raw material
- Production method (i.e. hand lay-up, pultrusion, VARTM etc.)
- Assembly
- Transportation

10.2.1.1.1 Cost of Raw Materials

The cost of the different deck systems and wearing surfaces used for the LCC calculations of the two alternatives can be seen in Table 128.

Table 128 Project cost parameters (Mara 2014; Murphy 2013)

Item	Prefabricated concrete deck with steel girders	FRP ASSET deck with GFRP girders

Cost of the deck (EUR/m^2)	522	805
Thickness of wear surface (mm)	90	40
Cost of wear surface including surfacing (Euro/m^2)	42	105[1]

Note: [1] 75EUR/m^2 for applying the surfacing and 30EUR/m^2 for wearing surface material

The cost of the epoxy resin, used in the GFRP girders of alternative 2, has been assumed to 100SEK/litre. The typical cost of the reinforcing fibres carbon and E-glass, which are used in alternative 2, can be seen in Table 129. Even though GFRP is the least expensive fibre type it is generally more expensive than conventional reinforcement i.e. having a higher initial cost (Bisby et al. 2006). The cost of CFRP is generally taken as 20 times the cost of GFRP, which can be seen in Table 129. It is important to consider the total LCC of the structure and not only the initial costs (Bisby et al. 2006). An advantage of GFRP in comparison with conventional reinforcement is less maintenance of the deck as GFRP is non-corrosive (Bisby et al. 2006).

Table 129 Typical cost of reinforcing fibres used in FRP composite structures (Chlosta 2013)

Fibre type	Cost (EUR/kg)
Carbon	10-45
E-glass	1.25-2.5

Cost of common FRP composite bridge deck systems can be seen in Table 130.

Table 130 Cost for typical FRP bridge deck systems (Chlosta 2013)

Bridge deck type	Costs (EUR/m^2)	Depth (mm)	Weight (kg/m^2)	Limit deflection
Hardcore composites (sandwich)	570-1184	152-710	98-112	L/1120
KSCI (sandwich)	700	126-610	76	L/1300
DuraSpan (Adhesively bonded pultruded profiles)	700-807	194	90	L/340
Superdeck (Adhesively bonded pultruded profiles)	807	203	107	L/530
EZSpan (Adhesively bonded pultruded profiles)	761-1076	223	98	L/950
Strongwell (Adhesively bonded	700	120-203	112	L/325

pultruded profiles)

10.2.1.1.2 Construction, Transportation and Assembly

The construction cost is difficult to estimate since the prices vary between manufacturers, sizes of the projects and countries (Murphy 2013). Studies have shown that the cost of construction and assembly of FRP composite decks are lower than for concrete decks (Murphy 2013). There is currently lack of reliable data however an approximate value is that the construction cost of a FRP composite deck generally is 30% lower compared to a concrete deck (Murphy 2013). The manufacturing cost of the GFRP girders through the RTM method have been assumed to be approximately 4000SEK/m^2 (444EUR/m^2)

10.2.1.2 Maintenance and Repair Costs

Two factors that are important to consider when it comes to the maintenance costs are (Nishizaki et al. 2006):

- Inspection
- Repair

The cost of maintenance and repair of large civil engineering projects such as bridges generally comprises a large part of the total cost during the lifespan (Bisby et al. 2006).

10.2.1.2.1 Inspection

The regulations of bridge inspections differ between countries (Murphy 2013). In Sweden there are mainly four types of inspections which are carries out, namely (Murphy 2013):

- Yearly inspection
- General inspection
- Main inspection
- Special inspection

The yearly inspections is brief and conducted in order to verify that the maintenance is correctly performed (Murphy 2013). The general inspection is generally conducted every third year, mainly on bridge elements not submerged, in order to check for structural damages (Murphy 2013). The inspection is also conducted as a follow up to the previous inspection in order to ensure that damages have been fixed (Murphy 2013). The main inspection is a thorough inspection of the structural performance of the entire bridge which is conducted every sixth year (Murphy 2013). The special inspection is conducted if requested and can for example consist of inspection of submerged elements (Murphy 2013).

Table 131 Cost of different inspection procedures (Murphy 2013)

Type of inspection	Performed every (years)	Cost (EUR)
Yearly inspection	1	110
General	3	555

inspection		
Main inspection	6	1110
Special inspection	when required	-

An approximation commonly made is that the inspection costs and intervals are independent of the bridge type, i.e. FRP composite or concrete bridge (Murphy 2013).

10.2.1.2.2 Repair

The maintenance and repair assumed for the bridge alternative 1 is related to surface maintenance and replacement of insulation (Mara 2014). The interval of replacement of the wearing surface is assumed to be approximately every 10 years (Mara 2014). The replacement of the insulation is assumed to be conducted every 40 years (Mara 2014).

The required maintenance and repair work presumed for alternative 2 is related to surface maintenance of the deck during the expected life span. The wearing surface applied on the FRP deck should be replaced every 20 years (Mara 2014). The maintenance activities and expected corresponding duration of the two alternatives can be seen in Table 132.

Table 132 Construction and maintenance activities for the two alternatives of the Rokån Bridge (Mara 2014)

Alternative 1					
Construction activity		**Frequency**	**Description**	**Duration**	**Traffic disturbance**
Initial	Replacement of the superstructure	Once	Replacement of the old superstructure	30 hours	All lanes closed
Future	Surface maintenance	Every 10 years	Removal and replacement of the asphalt	24 hours	1 lane closed
	Replacement of insulation (waterproofing)	Every 40 years	Replacement of the insulation (waterproofing)	2 weeks	1 lane closed
	Repainting of steel girders	Every 30 years	Painting	24 hours	1 lane closed
Alternative 2					
Initial	Replacement of the superstructure	Once	Replacement of the old superstructure	30 hours	All lanes close

Future	Surface maintenance	Every 20 years	Removal and replacement of the wearing surface	24 hours	1 lane closed

10.2.1.3 Disposal Costs

The disposal costs are also referred to as decommissioning costs (Bisby et al. 2006). The parameters included in the disposal costs are related to costs associated with the end of life for the bridge (Mara 2014). If the material can be recycled, as for steel, the disposal cost is a profit (Mara 2014). However in the case of concrete and thermoset polymers the material is generally disposed to a landfill (Mara 2014). The FRP composite ASSET deck can be disposed to a fee of 110 EUR/tonne, which can be seen in Table 133 (Mara 2014). The steel will result in a profit of 50 EUR/tonne and the concrete disposed to the landfill will lead to a fee of 110 EUR/tonne (Mara 2014).

Table 133 Disposal costs for different materials (Sagemo & Storck 2013; Mara 2014)

Type	Unit price	
Concrete	110	EUR/ton
Steel	-50	EUR/ton
Asphalt	4.5	EUR/ton
FRP ASSET deck	110	EUR/ton

The transportation cost of the disposed material of the original bridge was obtained from the contractors of the original Rokån Bridge replacement as 960 EUR for alternatives 1 (Mara 2014). The same cost is assumed for alternative 2.

10.2.2 Social Costs

The social costs are generally divided in user costs and society costs (Mara 2014). The social costs are the costs associated with disturbances of the traffic during construction and maintenance work of the bridge, which can be seen in Table 132 (Mara 2014). Social costs are both accounted for during the initial construction phase and during maintenance and repair works.

10.2.2.1 User Costs

User delay costs and vehicle operating costs are parameters generally considered in the user costs and can be calculated with the following formulas (Mara 2014; Murphy 2013):

$$User\ delay\ costs = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) \cdot ADT \cdot N \cdot w \qquad (2)$$

$$Vehicle\ operating\ costs = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) \cdot ADT \cdot N \cdot r \qquad (3)$$

Where:

$\left(\frac{L}{S_a} - \frac{L}{S_n}\right)$ is yields the time loss (surplus driving time in comparison to normal conditions) for the road users during construction, ADT is the average daily traffic, N is the number of days of roadwork, w is the hourly time value of the drivers and r is the hourly vehicle operating cost

The ADT was in this case assumed to be constant during the whole life span of the bridge (Mara 2014). For alternatives 1 the traffic speed was limited from the original speed of 90 km/m to 70 km/m for 14 days and from 90km/h to 50km/h for seven days due to the total replacement of the superstructure, which contributed to the social costs (Mara 2014). The input data for the social costs accounted for during the initial construction can be seen in Table 134.

Table 134 Input data for social costs during the initial construction (Mara 2014)

Item	Alternative 1	Alternative 2
Average daily traffic (ADT)	796 vehicles/day	796 vehicles/day
Time loss of driver due to detour during closure of the bridge	15 minutes	15 minutes
Hours of closure of the bridge	30 hours	20 hours
Hourly time value of drivers	28 €/h	28 €/h
Hourly vehicle operating cost	21 €/h	21 €/h
Normal traffic speed	90 km/m	90 km/m
Traffic speed during assembly of the superstructure for 14 days	70 km/m	-
Traffic speed during assembly of the superstructure for 7 days	50 km/m	-
Length of the affected roadway	200 m	-

10.2.2.2 Society Costs

Costs considered in the society costs are generally environmental costs and accident costs (Mara 2014).

The accidental costs can be calculated with the following formula (Mara 2014):

$$Accident\ cost = L \cdot ADT \cdot N \cdot (A_a - A_n) \cdot C_a \qquad (5)$$

Where:

L is the length of the affected roadway where the cars are driving, A_a is the accident rate during construction, A_n is the normal construction rate and C_a is the cost per accident

The probability of an accident is generally so small that the influence of accident costs on the total LCC is minimal, hence the accidental costs are omitted from the calculations (Murphy 2013). The accident costs are only regarded for alternative 1 since the construction and assembly of the bridge is laborious in comparison with alternatives 2 which incorporate a FRP composite deck.

10.2.2.3 Environmental Costs

The environmental costs accounts for the damage to the environment caused by the pollutants, such as carbon emissions (Mara 2014). The amount of for example carbon emitted can be converted to a cost and included in the total LCC (Mara 2014). The pollutants considered in this thesis are related to CO_2 produced through the mechanisms: processing of materials, transportation and diversions of traffic (Mara 2014). The general value of the cost of the damage caused by CO_2 is estimated to 6.64 EUR/tonne (Mara 2014).

10.3 Total LCC - Comparison of Alternative 1 and 2

The calculations of the life cycle costs of alternative 1 and 2 can be seen in Appendix C and the total LCC for the two alternatives are summarized and displayed in Table 135 and Figure 203. Both in the different life-cycle phases of the bridge and by cost entity it can be noted that the total cost for both categories are the same.

Table 135 Comparison of total LCC cost (in EUROS) of the two alternative bridge systems (Mara 2014)

Cost category	**Alternative 1**	**Alternative 2**
By life-cycle phase		
Initial costs	158121	160072
Maintenance and repair costs	30238	10979
End-of-life costs	1303	895
Total costs	**189661**	**172189**
By cost entity		
Agency costs	176004	163901
Social and environmental costs	13657	8288
Total costs	**189661**	**172182**

It can be concluded from Table 135 that alternative 2 has a lower total cost than alternative 1 and the difference is approximately 9.2%. It can furthermore be noted that all costs of alternative 2, except for the initial cost, are lower than for alternative 1.

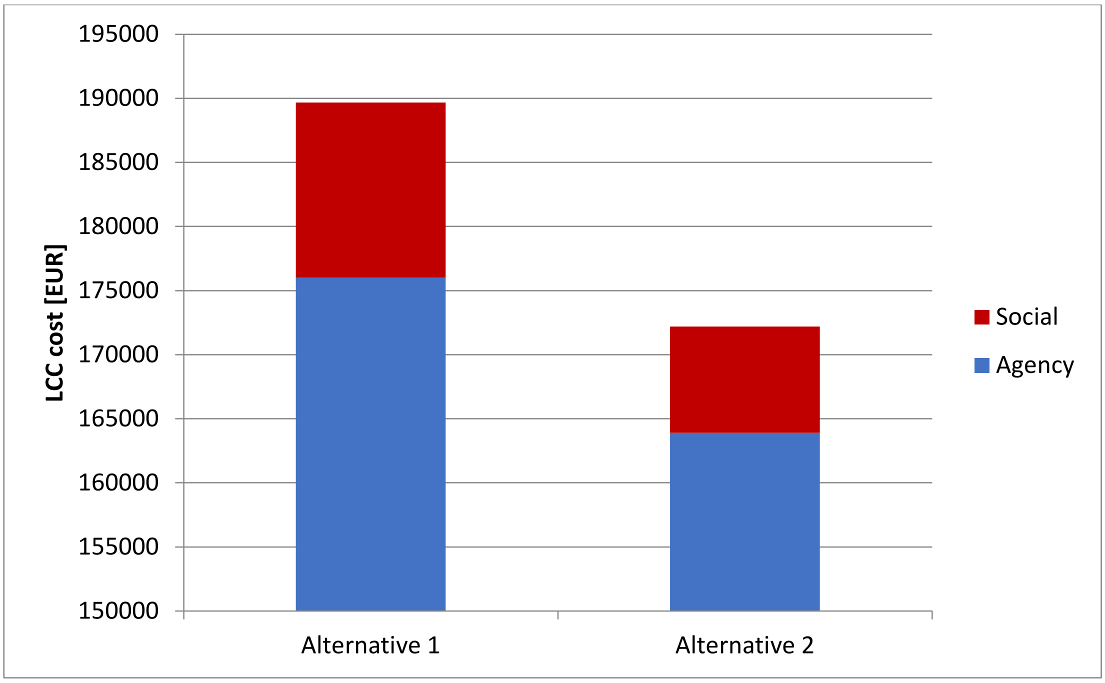

Figure 203 Total LCC cost of alternative 1 and 2

Figure 204 and Figure 205 illustrates the cost breakdown for alternative 1 and 2. It can be concluded that the by life-cycle phase of alternative 2 is 93% comprised by the initial costs. The corresponding value for alternative 1 is 83% which subsequently has a higher maintenance and repair cost. The maintenance and repair costs of alternative 2 are approximately 62.9% lower than for alternative 1. This is a result of that alternative 2 require fewer maintenance activities which additionally are conducted at a lower frequency than alternative 1. This ultimately leads to reduced social costs due to less traffic disruptions.

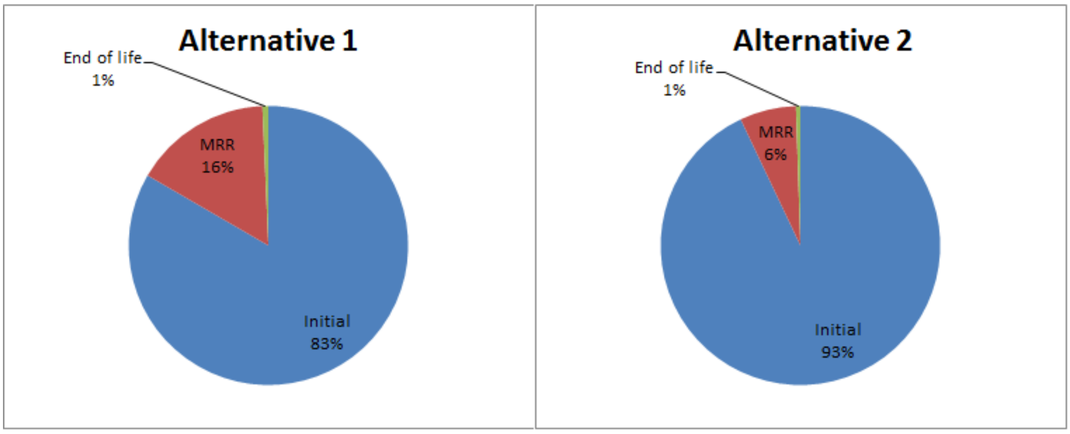

Figure 204 Alternative 1 and 2: by life-cycle phase

The percentage of the agency costs are similar for alternative 1 and 2 and represent 93% respectively 95% and the social and environmental costs represent approximately 7% of the total costs for alternative 1 and 5% for alternative 2. The reason why the percentage is so low is that the Rokån Bridge is located in a rural area with a low ADT. The total social costs of alternative 2 are approximately 39.3% lower than for alternative 1 which is related to less disruption of the traffic during construction and maintenance for alternative 2. Alternative 2 enables for a rapid construction and less maintenance activities in comparison with alternative 1 due to the lightweight of the FRP elements.

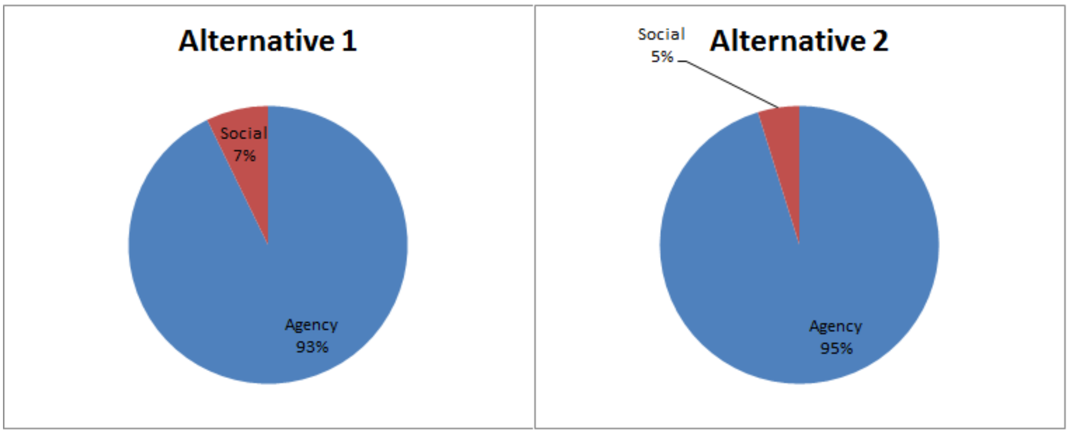

Figure 205 Alternative 1 and 2: by cost entity

A sensitivity analysis was conducted in order to estimate the social and total costs for different ADT's. Figure 206 displays the social costs for different ADT's.

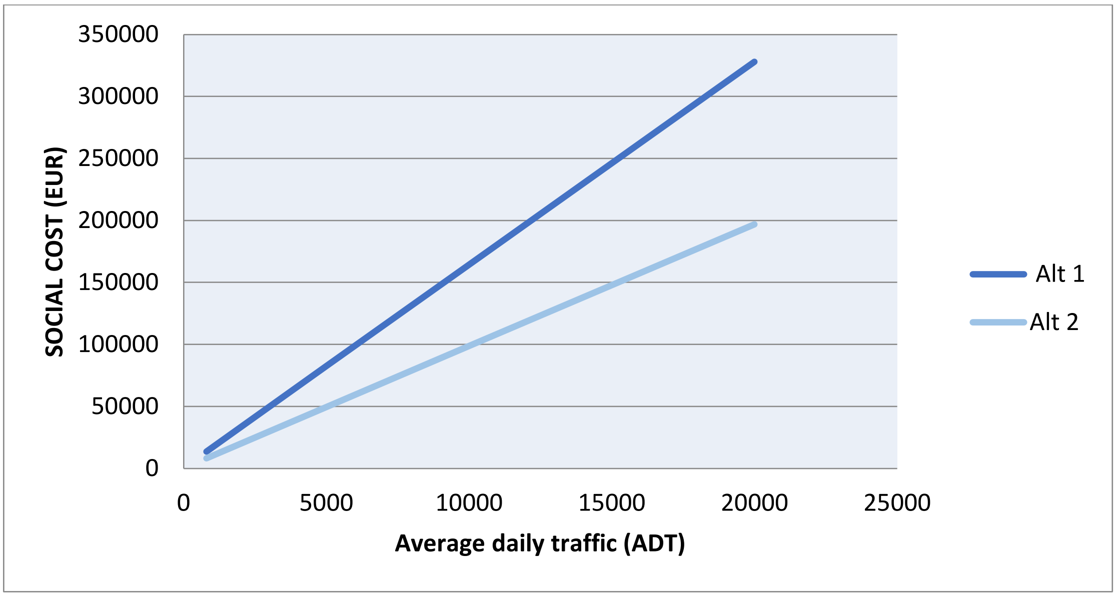

Figure 206 Social costs of alternative 1 and 2 for different ADT's

The difference in the total costs, which include agency costs and social costs, between alternative 1 and 2 for different ADT's can be seen in Figure 207. The difference in total costs between alternative 1 and 2 for an ADT of 796vehicles/day is approximately 9.2%. For an ADT of 20000vehicles/day the difference in total costs is approximately 28.4%.

Figure 207 Total costs of alternative 1 and 2 for different ADT's

Figure 208 a summation of the total costs for alternative 1 and 2 with varying ADT’s is shown. It can be noted that the agency costs are constant for different ADT’s which is due to that the agency costs are associated with material, construction and disposal costs.

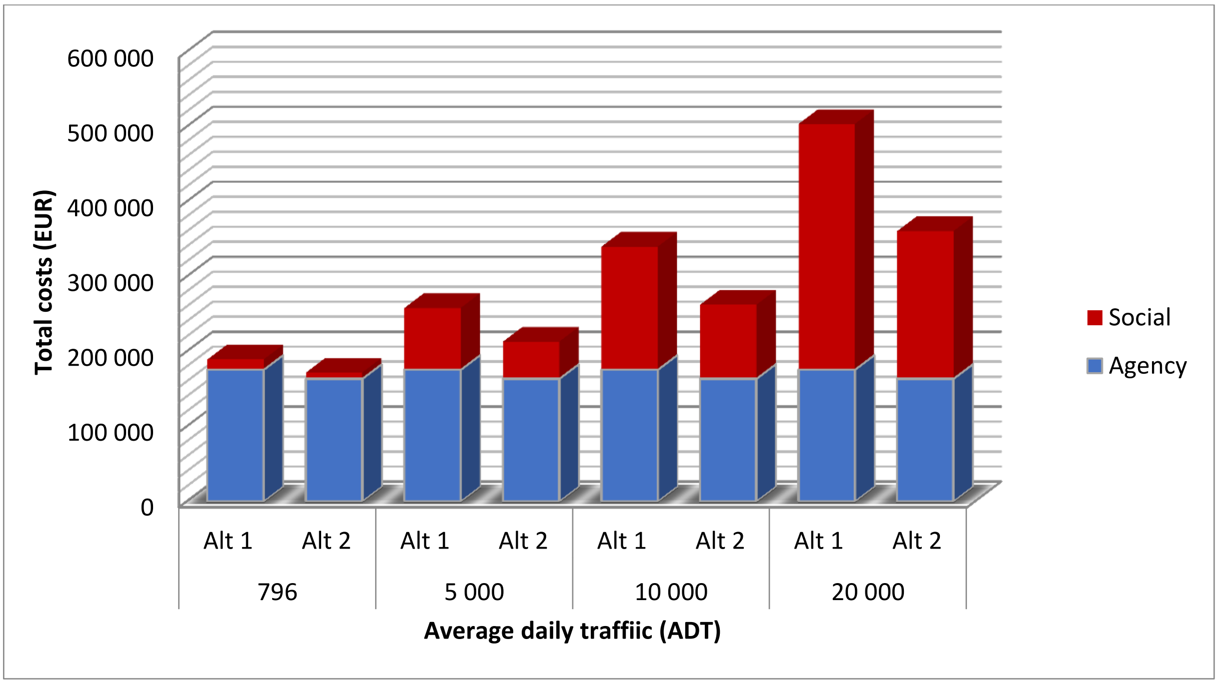

Figure 208 Social and agency costs for alternative 1 and 2 for different ADT's

10.4 Conclusion and Discussion

It is reasonable that the initial cost of alternative 1 is lower than for alternative 2. This is because FRP composites are generally more expensive than conventional construction materials and the application of FRP structures is a wide spread. . However the difference in initial cost between the two alternatives was approximately 1.2% which can be considered negligible. One reason to the small price difference is due the lightweight of alternative 2. Bridge alternative 1 would result in a weight of

115.1 ton and alternative 2 in 16.8 ton. It can be seen that even though FRP composites have a higher price/kg, the difference in initial costs is small due to the larger weight of conventional materials.

The largest difference between the alternatives is the maintenance and repair, where the difference is 62.9%. This is reasonable since the conventional bridge requires frequent maintenance activities such as repainting of steel girders, replacement of wearing surface and insulation which results in a high costs. However, since FRP composites is a relatively new material, where the oldest bridge is approximately 30 years, there is large amount of uncertainties and lack of knowledge about the long-term durability and maintenance requirements of the material. The large difference in maintenance costs can, for this reason, be somewhat overestimated..

An assumption made in the end-of-life phase is that the cost of dismantling alternative 2 is the same as for alternative 1. This is presumably an assumption on the safe side and the end-of-life costs of alternative 2 can be even lower. The light weight furthermore contributes to a lower end-of-life cost of alternative 2 since less material requires being demolished in comparison with the conventional bridge even though the steel is deposited with a profit.

As was determined in the sensitivity analysis, the difference in LCC between alternative 1 and 2 increased from 9.2% to 28.4% when the ADT was increased from 796vehicles/day to 20000vehicles/day. This is related to the fast assembly and lower amount of maintenance enabled with FRP composites, in comparison with conventional materials, which results in less disruption of traffic and lower levels of emissions. Consequently it can be established that FRP composite road bridges are more justified in urban areas where the ADT is high.

10.5 References

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11 Recommendations for Future Studies

During the master thesis, there were a couple of interesting questions which could be answered in future studies.

Regarding the case study, it would be interesting to further investigate the optimization design of the cross-section. One example would be to analyse a sandwich structure of the girders, with a foam core and skins. In the FE model the members were modelled with orthotropic material behaviour and another example could have been to analyse with different stack-up i.e. with different directions of the fibres in order to get more reasonable result. It would also have been interesting to investigate the fatigue performance of the cross-section and further develop connections.

The dimensions of the bridge in the case study were fixed to a width of 7m and a span of 12m. It would have been interesting to analyse a bridge with a longer span i.e. 20-25m. This is due to that problems such as deflections are more difficult to control and the design would have been more challenging.

Due to the shortage in time, the life cycle assessment analysis was not conducted as was intended. However this would be interesting to consider in future studies alongside the LCC analysis.

Appendices

Appendix A – Hand calculations for optimized cross-section and input data for LCC analysis

Appendix B – List of standardisations

Appendix C – LCC analysis Excel sheets

Appendix A

Hand Calculation for optimize cross-section

The Rokån bridge consists of a 7m wide FRP bridge deck with an asphalt wearing surface layer. The deck is supported on four GFRP girders with four incorporated carbon cables each. The bridge has furthermore two lanes and a span of 12m.

Cross-section of FRP Girders

The open shape of the GFRP girders is retrieved from the "Trans-Ind catalogue"

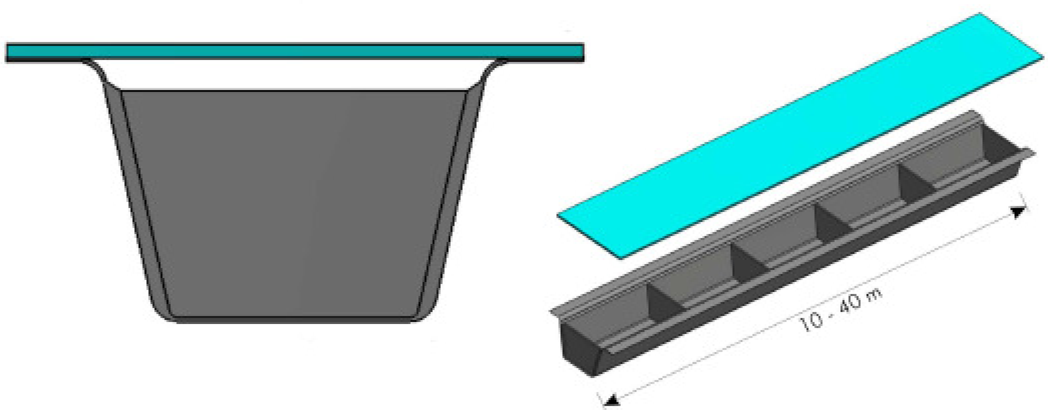


Figure 1. Cross section of the FRP girder

Material parameters:

Both the top flange and the open shape beam of the GFRP bridge girder consists of glass fibre reinforced polymer and the cables from carbon fibres. The polymer of the FRP composite is furthermore epoxy.

$E_{GFRP.girder.0} := 25GPa$	Modulus of elasticity unidirectional fibres with load acting transversally (Applied in span where moment is high)
$E_{GFRP.top.plate.0} := 25GPa$	Modulus of elasticity for unidirectional fibres with load acting transversally (Applied in span where moment is high)
$E_{GFRP.90} := 15GPa$	Modulus of elasticity for bidirectional fibres with load acting transversally (Applied in span where moment is high)
$E_{asset.0} := 23GPa$	Modulus of elasticity for ASSET deck in longitudinal direction
$E_{asset.90} := 18GPa$	Modulus of elasticity for ASSET deck in the transversal direction
$G_{xy} := 4.14GPa$	Shear modulus of GFRP
$\nu_{23} := 0.237$	Poission ratio of GFRP

Geometry of the bridge:

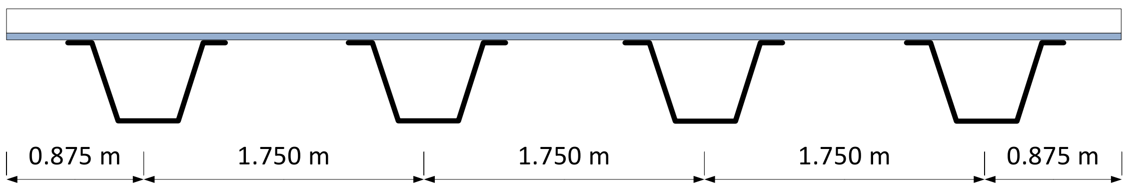


Figure 2. Cross-section of the bridge - position of the girders

Dimensions:

$L_{span} := 12m$ Length of bridge

$w_{deck} := 7m$ Width of bridge

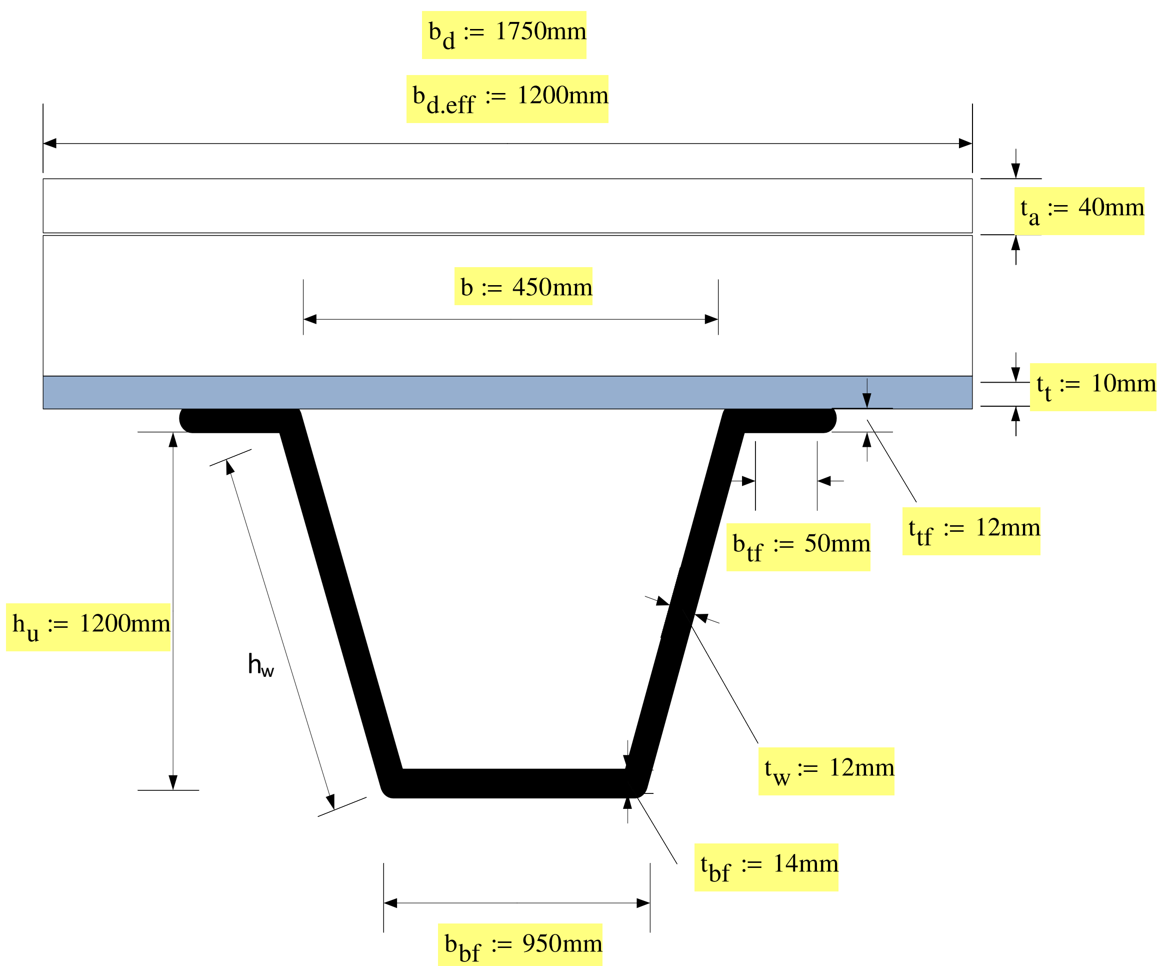


Figure 3. Dimensions of the girder, top plate and ASSET deck

GFRP Girders:

Note: The width of the bottomflange correspond to 4 CFRP bars with the diameter with 20 mm and the E-modulus of 181 GPa.

$$\alpha_h := \operatorname{atan}\left(\frac{\frac{b-250mm}{2}}{h_u}\right) = 4.764\cdot deg$$ The inclination of the "webs" of the U-shaped beam

$$h_w := \frac{h_u}{\cos(\alpha_h)} = 1.204\,m$$ Height of the "webs"

ASSET Deck:

$t_{deck} := 0.225m$ Thickness of the ASSET deck

$t_{f.asset} := 15.5mm$ Thickness of the flanges of the ASSET deck, can be seen in Figure 4.

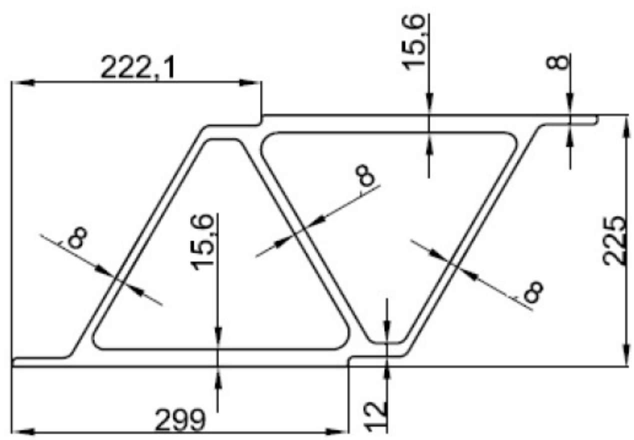


Figure 4. Cross-section of the ASSET deck

Concrete Asphalt Wearing Surface:

$t_{asphalt} := 40mm$ Thickness of the asphalt layer

$E_{asphalt} := 5GPa$ Modulus of elasticity of the wearing surface

Total thickness of the cross section of the bridge:

$$t_{tot} := t_a + t_{deck} + t_t + t_{tf} + h_u = 1.487\,m$$

Corresponding height of the carbon section in Abaqus:

$E_{carbon} := 181GPa$ — Young's modulus for GFRP

$E_{GFRP} := 25GPa$ — Young's modulus for carbon cables

Area carbon cables:

$d_{carbon} := 20mm$ — Diameter of carbon cables

$n_{carbon} := 4$ — Number of carbon cables

$$A_{carbon} := \frac{\pi \cdot d_{carbon}^{\ 2}}{4} = 3.142 \times 10^{-4}\,m^2$$

Equivalent distance of CFRP to GFRP:

$$b_{eq} := \left(\frac{A_{carbon} \cdot \dfrac{E_{carbon}}{E_{GFRP}}}{t_{bf}}\right) \cdot n_{carbon} = 649.861 \cdot mm$$

$V_{GFRP} := b_{eq} \cdot t_{bf} \cdot 12m = 0.109 \cdot m^3$ — Volume of the equivalent GFRP bottom flange

$t_{carbon} := \dfrac{V_{GFRP}}{12m \cdot 170mm} = 53.518 \cdot mm$ — Thickness of the carbon bottom flange used in Abaqus

Calculation of second moment of area of the FRP girders

Area of the open shaped U beam:

$A_{asphalt} := b_{d.eff} \cdot t_{asphalt} = 0.048\,m^2$ — Area of the asphalt layer

$A_{deck.plate} := b_{d.eff} \cdot t_{f.asset} = 0.019\,m^2$ — Areas of the flanges fo the ASSET deck

$A_{top.plate} := b_{d.eff} \cdot t_t = 0.012\,m^2$ — Area of the GFRP top plate

$A_{beam} := 2 \cdot h_w \cdot t_w + b_{bf} \cdot t_{bf} + 2 \cdot t_{tf} \cdot b_{tf} = 4.34 \times 10^4 \cdot mm^2$ — Total area of the one GFRP girder

$A_{tot} := 2 \cdot A_{deck.plate} + A_{top.plate} + A_{beam} + A_{asphalt} = 0.141\,m^2$ — Total area of the cross section seen in Figure 3.

$EA_{asphalt} := E_{asphalt} \cdot A_{asphalt}$

$EA_{deck} := E_{asset.90} \cdot A_{deck.plate}$

$EA_{top.plate} := E_{GFRP.top.plate.0} \cdot A_{top.plate}$

$EA_{beam} := E_{GFRP.girder.0} \cdot A_{beam}$

$EA_{tot} := EA_{asphalt} + 2EA_{deck} + EA_{top.plate} + EA_{beam}$

Distance to the center of gravity:

$$z_{tp} := \frac{\begin{array}{l} E_{asphalt} \cdot b_{d.eff} \cdot t_{asphalt} \cdot \dfrac{t_{asphalt}}{2} + E_{asset.90} \cdot b_{d.eff} \cdot t_{f.asset} \cdot \left(t_{asphalt} + \dfrac{t_{f.asset}}{2}\right) \ldots \\ + E_{asset.90} \cdot b_{d.eff} \cdot t_{f.asset} \cdot \left(t_{asphalt} + t_{deck} - \dfrac{t_{f.asset}}{2}\right) \ldots \\ + E_{GFRP.top.plate.0} \cdot t_t \cdot b_{d.eff} \cdot \left(t_{asphalt} + t_{deck} + \dfrac{t_t}{2}\right) \ldots \\ + E_{GFRP.girder.0} \cdot 2 \cdot b_{tf} \cdot t_{tf} \cdot \left(t_{asphalt} + t_{deck} + t_t + \dfrac{t_{tf}}{2}\right) \ldots \\ + E_{GFRP.girder.0} \cdot 2 \cdot h_w \cdot t_w \cdot \left(t_{asphalt} + t_{deck} + t_t + t_{tf} + \dfrac{h_u - t_{bf}}{2}\right) \ldots \\ + E_{GFRP.girder.0} \cdot b_{bf} \cdot t_{bf} \cdot \left(t_{tot} - \dfrac{t_{bf}}{2}\right) \end{array}}{EA_{tot}} = 0.577\,\mathrm{m}$$

$$n_{asphalt.deck} := \frac{E_{asphalt}}{E_{asset.90}} = 0.278$$

$$n_{deck.plate} := \frac{E_{asset.90}}{E_{GFRP.top.plate.0}} = 0.72$$

$$n_{plate.girder} := \frac{E_{GFRP.top.plate.0}}{E_{GFRP.girder.0}} = 1$$

Moment of Inertia:

Level arms:

$$d_1 := \frac{t_{asphalt}}{2} = 0.02\,\mathrm{m}$$

$$d_2 := t_{asphalt} + \frac{t_{f.asset}}{2} = 0.048\,\mathrm{m}$$

$$d_3 := t_{asphalt} + t_{deck} - \frac{t_{f.asset}}{2} = 0.257\,\mathrm{m}$$

$$d_4 := t_{asphalt} + t_{deck} + \frac{t_t}{2} = 0.27\,\mathrm{m}$$

$$d_5 := t_{asphalt} + t_{deck} + t_t + \frac{t_{tf}}{2} = 0.281\,\mathrm{m}$$

$$d_6 := t_{asphalt} + t_{deck} + t_t + t_{tf} + \frac{h_u - t_{bf}}{2} = 0.88\,\mathrm{m}$$

$$d_7 := t_{tot} - \frac{t_{bf}}{2} = 1.48\,\mathrm{m}$$

$$I_y := \frac{n_{asphalt.deck} \cdot b_{d.eff} \cdot t_{asphalt}^3}{12} + n_{asphalt.deck} \cdot b_{d.eff} \cdot t_{asphalt} \cdot (z_{tp} - d_1)^2 \ ... = 2.715 \times 10^{10} \cdot mm^4$$
$$+ \frac{n_{deck.plate} \cdot b_{d.eff} \cdot t_{f.asset}^3}{12} + n_{deck.plate} \cdot b_{d.eff} \cdot t_{f.asset} \cdot (z_{tp} - d_2)^2 \ ...$$
$$+ \frac{n_{deck.plate} \cdot b_{d.eff} \cdot t_{f.asset}^3}{12} + n_{deck.plate} \cdot b_{d.eff} \cdot t_{f.asset} \cdot (z_{tp} - d_3)^2 \ ...$$
$$+ \frac{n_{deck.plate} \cdot b_{d.eff} \cdot t_t^3}{12} + n_{deck.plate} \cdot b_{d.eff} \cdot t_t \cdot (z_{tp} - d_4)^2 \ ...$$
$$+ 2 \cdot \left[\frac{b_{tf} \cdot t_{tf}^3}{12} + b_{tf} \cdot t_{tf} \cdot (z_{tp} - d_5)^2 \right] ...$$
$$+ 2 \cdot \left[\frac{t_w \cdot h_w}{12} \cdot \left(h_w^2 \cdot \cos(\alpha_h)^2 + t_{bf}^2 \cdot \sin(\alpha_h)^2 \right) + t_w \cdot h_w \cdot (d_6 - z_{tp})^2 \right] ...$$
$$+ \frac{b_{bf} \cdot t_{bf}^3}{12} + b_{bf} \cdot t_{bf} \cdot (d_7 - z_{tp})^2$$

Section modulus's for the four different locations of the beam to be investigated:

$$W_1 := \frac{I_y}{z_{tp} - t_{asphalt}} = 0.051 \cdot m^3$$ Top of the deck

$$W_2 := \frac{I_y}{z_{tp} - t_{asphalt} - t_{deck} - \frac{t_t}{2}} = 0.088 \cdot m^3$$ In the middle of the deck top flange

$$W_3 := \frac{I_y}{z_{tp} - t_{asphalt} - t_{deck} - t_t} = 0.09 \cdot m^3$$ Top of the U girder

$$W_4 := \frac{I_y}{t_{tot} - z_{tp}} = 0.03 \cdot m^3$$ Bottom flange of the U girder

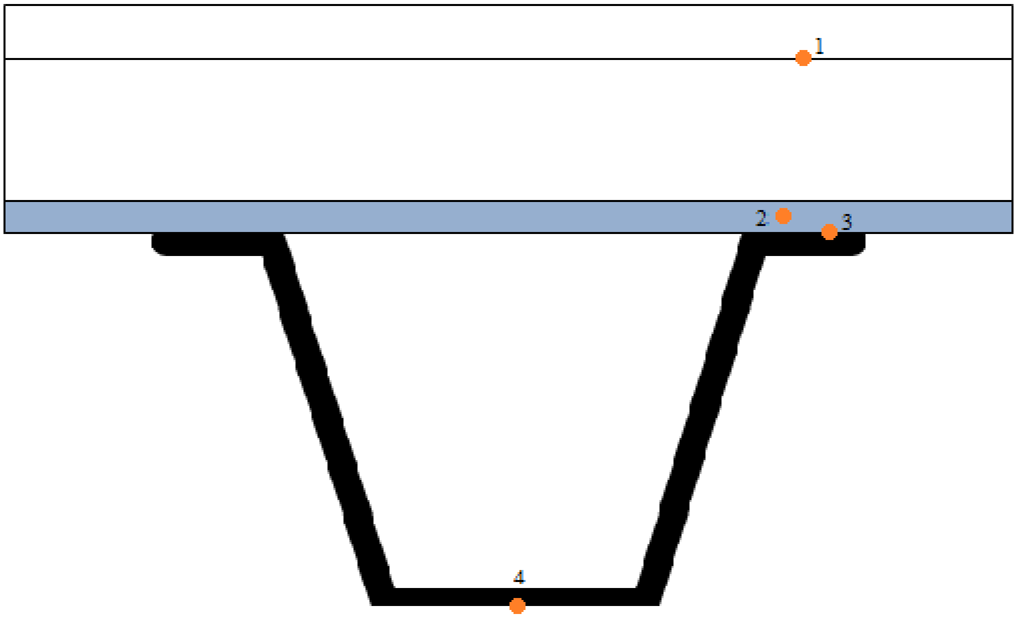


Figure 5. Four different location of the beam

Applied Loads

Self-Weight

FRP Deck:

The FRP deck consists of a ASSET deck manufactured by Fiberline Composites in Denmark

$g_{FRP} := 925 \frac{N}{m^2}$ The weight of the ASSET bridge deck (Fiberline)

The design self-weight of the FRP deck for one girder:

$G_{deck} := b_d \cdot g_{FRP} = 1.619 \cdot \frac{kN}{m}$

Asphalt Layer - Wearing surface:

$\gamma_{as} := 23 \frac{kN}{m^3}$

$G_{asphalt} := b_d \cdot t_{asphalt} \cdot \gamma_{as} = 1.61 \cdot \frac{kN}{m}$

In Abaqus the selfweight of the ASSET deck and the asphalt wearing surface is applied as a n equivalent density:

$A_{ASSET.1m} := 241.8mm \cdot 8mm \cdot 7 + 1m \cdot 15.6mm \cdot 2 = 0.045\,m^2$ Area of 1m (width) ASSET deck

$V_{ASSET.1m} := A_{ASSET.1m} \cdot 1m = 0.045 \cdot m^3$ Volume for 1m x 1m ASSET deck

$V_{asphalt} := 1m \cdot 1m \cdot t_{asphalt} = 0.04 \cdot m^3$ Volume asphalt for 1m x 1m

$m_{ASSET.1m} := \frac{g_{FRP} \cdot A_{ASSET.1m}}{g} = 4.22\,kg$ Mass of 1m x 1m ASSET deck

$\rho_{ASSET.1m} := \frac{m_{ASSET.1m}}{V_{ASSET.1m}} = 94.324 \frac{kg}{m^3}$ Density ASSET deck

$m_{1.asphalt} := \gamma_{as} \cdot V_{asphalt} = 920\,N$ Force comming from 1m x 1m asphalt

$\rho_{asphalt} := \frac{m_{1.asphalt}}{V_{ASSET.1m} \cdot g} = 2.097 \times 10^3 \cdot \frac{kg}{m^3}$ Equivalent density of asphalt

$\rho_{deck.asph} := \rho_{ASSET.1m} + \rho_{asphalt} = 2.191 \times 10^3 \frac{kg}{m^3}$ Combination of densities

$\rho_{deck.asph.ABAQUS} := \rho_{deck.asph} = 2.191 \times 10^{-6} \cdot \frac{kg}{mm^3}$ Equivalen density used in Abaqus

FRP Girders:

The self-weight of each girder (including the top plate):

$\rho_{GFRP} := 1800 \frac{kg}{m^3}$ The density of FRP composites generally lie in the range of 1200 to 1800 kg/m^3

$G_{girder} := \rho_{GFRP} \cdot g \cdot \left(A_{beam} + A_{top.plate}\right) = 0.978 \cdot \frac{kN}{m}$

Total self-weight of the FRP bridge structure:

The total self-weight per girder:

$G_{k.girder} := G_{deck} + G_{girder} + G_{asphalt} = 4.207 \cdot \frac{kN}{m}$

Total moment comming from the self-weigh:

Simply supported beam:

$M_{d.self.weight} := \frac{1.35 G_{k.girder} \cdot L_{span}^2}{8} = 102.222 \cdot kN \cdot m$

$$V_{d.self.weight} := \frac{1.35G_{k.girder} \cdot L_{span}}{2} = 34.074 \cdot kN$$

Traffic Loads

Traffic loads are calculated according to EN 1991-2 Load model 1 (LM1)

Input data:

$c_w := 1.2m$ Distance between the wheels

Lane 1:

$w := 3m$ The width of one lane

$Q_{1k} := 300kN$ Axle load for lane 1

$q_{1k} := 9\frac{kN}{m^2}$ Uniform distributed load

Eurocode 1 allows for assuming a value of alfaQ equal to 0.8 for the first conventional lane, we, however, consider this value to be unity. we also assume a value of 1 for alfaq.

National adjustment factors:

$\alpha_{Q1} := 1$

$\alpha_{q1} := 1$

Lane 2:

$Q_{2k} := 200kN$ Axle load for lane 2

$q_{2k} := 2.5\frac{kN}{m^2}$ Uniform distributed load

National adjustment factors:

$\alpha_{Q2} := 1$

$\alpha_{q2} := 1$

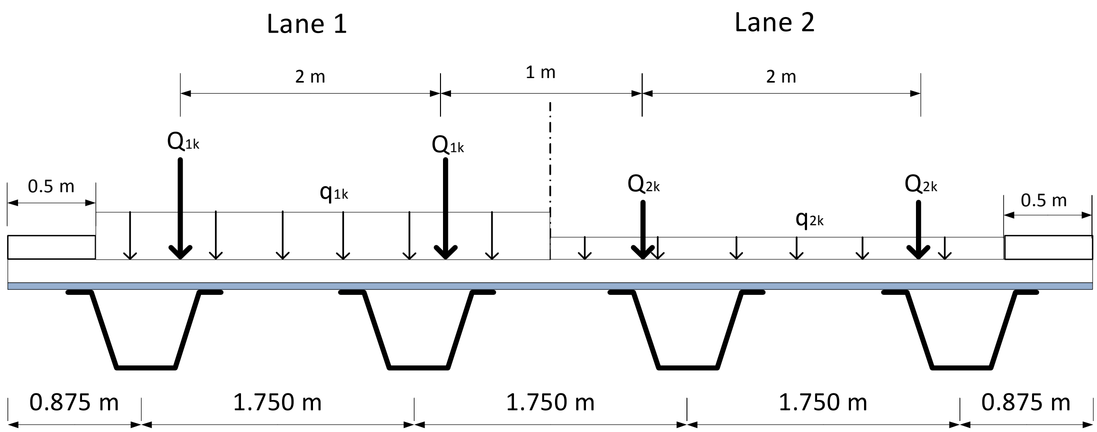


Figure 6. Load model 1

Load Combinations:

Load distribution factors for external girders:

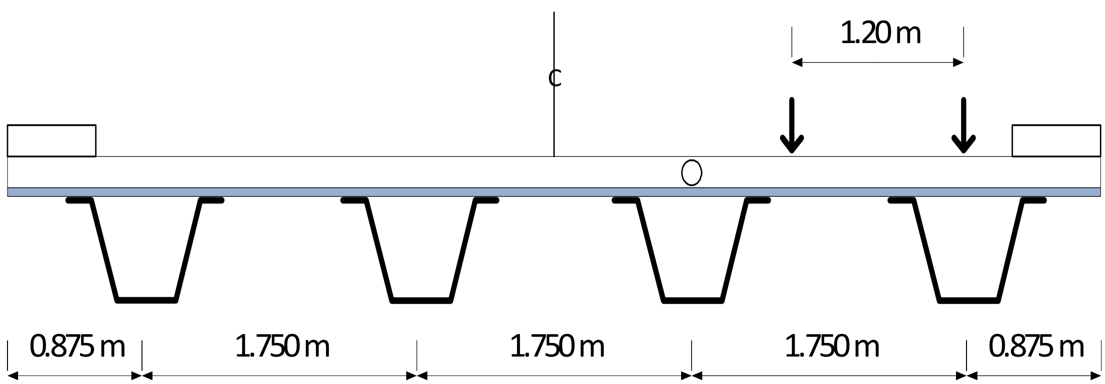


Figure 7. Arrangement of loads and hinge to calculate load distribution factor for external girders

$$R_{ext} := \frac{0.5Q_{1k} \cdot 1.750m + 0.5Q_{1k} \cdot 0.55m}{1.750m} = 197.143 \cdot kN$$

$\beta_{ext} := 1.2$ Multiple presence factor

$$R_{ext.girder} := \beta_{ext} \cdot R_{ext} = 236.571 \cdot kN$$

Load distribution factors for internal girders:

Case I) One lane loaded

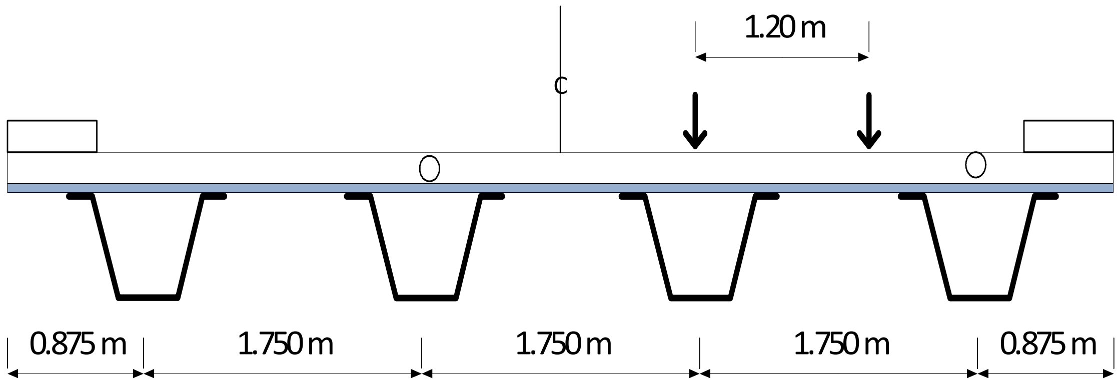


Figure 8. Arrangement of loads and hinges to calculate load distribution factor for internal girders

$$R_{int.1} := \frac{0.5Q_{1k} \cdot 1.750m + 0.5Q_{1k} \cdot 0.55m}{1.750m} = 197.143 \cdot kN$$

$\beta_{int.1} := 1.2$ Multiple presence factor

$R_{int.girder.1} := \beta_{int.1} \cdot R_{int.1} = 236.571 \cdot kN$

Case II) Two lanes loaded

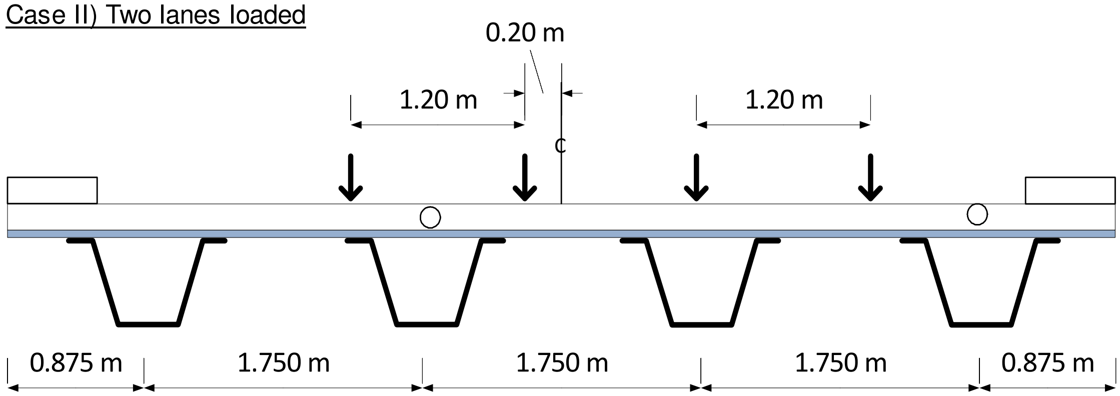


Figure 8. Arrangement of loads and hinges to calculate load distribution factor for internal girders

$$R_{int.2} := \frac{0.5Q_{1k} \cdot 1.750m + 0.5Q_{1k} \cdot 0.55m + 0.5Q_{1k} \cdot 0.675m}{1.750m} = 255 \cdot kN$$

$\beta_{int.2} := 1.0$ Multiple presence factor

$R_{int.girder.2} := \beta_{int.2} \cdot R_{int.2} = 255 \cdot kN$

$R_{int.girder} := \max(R_{int.girder.1}, R_{int.girder.2})$

$R_{ext.girder} = 236.571 \cdot kN$

$R_{int.girder} = 255 \cdot kN$ Governs the design

Characteristic loads:

$Q_k := R_{int.girder}$ Characteristic point load

$q_k := q_{1k}$ Characteristic uniform load

Note: for simplicity, it is assumed that girders carry a UDL equivalent to 9kN/m2 without accounting for load distribution.

The design ULS traffic load:

Point loads:

$Q_d := 1.35 \cdot \alpha_{Q1} \cdot R_{int.girder} = 344.25 \cdot kN$

Uniform loads:

$q_d := 1.35 \cdot \alpha_{q1} \cdot q_{1k} \cdot w = 36.45 \cdot \frac{kN}{m}$

Load effects

Maximum moment

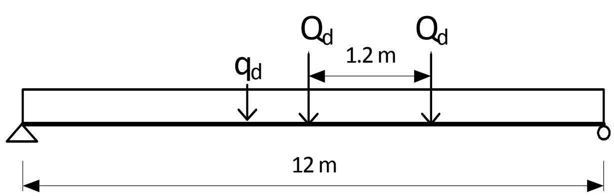


Figure 9. Load configuration of maximum bending moment in ULS

$$M_{d.max} := \frac{Q_d \cdot L_{span}}{4} + 0.2(Q_d \cdot L_{span}) + \frac{q_d \cdot L_{span}^2}{8} = 2.515 \times 10^3 \cdot kN \cdot m$$

Calculated with influence lines

Maximum shear

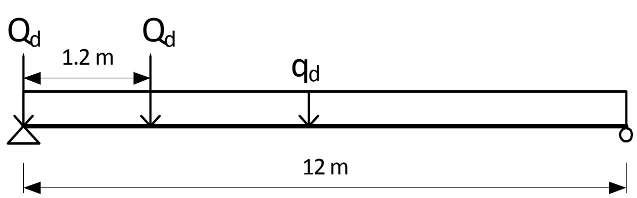


Figure 10. Load configuration of maximum shear moment in ULS

$V_{d.max} := Q_d + 0.9 \cdot Q_d + 6m\, q_d = 872.775 \cdot kN$

Calculated with influence lines

Design Values:

$M_{Ed} := M_{d.self.weight} + M_{d.max} = 2.617 \times 10^3 \cdot kN \cdot m$

$V_{Ed} := V_{d.self.weight} + V_{d.max} = 906.849 \cdot kN$

Horizontal actions - Traction

$F_t := 0.6 \cdot \alpha_{Q1} \cdot (2 \cdot Q_{1k}) + 0.1 \cdot \alpha_{q1} \cdot q_{1k} \cdot w \cdot L_{span} = 392.4 \cdot kN$

$$F_{t1} := \begin{cases} (180kN \cdot \alpha_{Q1}) & \text{if } F_t < 180kN \cdot \alpha_{Q1} \\ (900kN) & \text{if } F_t > 900kN \\ F_t & \text{otherwise} \end{cases}$$

$F_{t1} = 392.4 \cdot kN$

$F_{t1.d} := 1.35 \cdot \alpha_{Q1} \cdot F_{t1} = 5.297 \times 10^5 N$ The design traction load

Reaction forces from hand calculations:

$L_w := 1.2m$ Distance between wheels

$$R_B := \frac{Q_d \cdot (L_{span} + L_w) + q_d \cdot \dfrac{L_{span}^{\,2}}{2}}{L_{span}} = 597.375 \cdot kN$$ Reaction force support B

$R_A := 2 \cdot Q_d + q_d \cdot L_{span} - R_B = 5.285 \times 10^5 N$ Reaction force support A

$R_A + R_B = 1.126 \times 10^6 N$ Sum of reaction forces

Capacity checks

Partial safety factors for material

Partial safety factors ULS:

$\gamma_{m1} := 1.15$ Derived from material properties from test values

$\gamma_{m2} := 1.2$ Material and production process - Resin Transfer Moulding and fully post cured

$\gamma_{m3} := 2.5$ Long-term loading (traffic load)

$\gamma_{m.uls} := \gamma_{m1} \cdot \gamma_{m2} \cdot \gamma_{m3} = 3.45$

Partial safety factors SLS:

$\gamma_{m1.sls} := 1.15$ Derived from material properties from test values

$\gamma_{m2.sls} := 1.2$ Material and production process - Resin Transfer Moulding and fully post cured

$\gamma_{m3.sls} := 1$ Short-term loading (traffic load)

$\gamma_{m.sls} := \gamma_{m1.sls} \cdot \gamma_{m2.sls} \cdot \gamma_{m3.sls} = 1.38$

ULS checks:

Bending stresses

$M_{Sd} \le M_{Rd}$ where $M_{Rd} := \dfrac{W_s \cdot \sigma_{t.k}}{\gamma_m}$ From the book "Structural Design of Polymer Composites" (Clarke 1996)

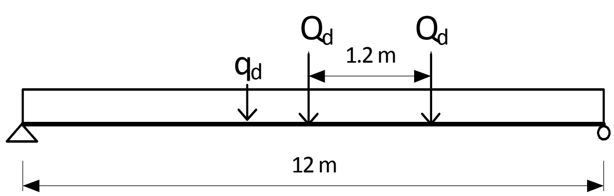


Figure 11. Load condition for ULS bending

The bending stresses are analysed in four different locations of the cross-section, seen in Figure 5.

The design strength of GFRP composite are retrieved from the book "analysis and performance of fiber composites", and are as follows:

<u>Longitudinal direction of the fibres:</u>

$\sigma_{b.ks} := 1062MPa$ $\sigma_{b.d} := \dfrac{\sigma_{b.ks}}{\gamma_{m.uls}} = 307.826 \cdot MPa$ Design tensile strength

$\sigma_{c.ks} := 610MPa$ $\sigma_{c.d} := \dfrac{\sigma_{c.ks}}{\gamma_{m.uls}} = 176.812 \cdot MPa$ Design compressive strength

Transversal direction of the fibres:

$\sigma_{t.k.t} := 118MPa$ $\qquad \sigma_{t.d.t} := \frac{\sigma_{t.k.t}}{\gamma_{m.uls}} = 34.203 \cdot MPa$ Design tensile strength

$\sigma_{c.k.t} := 31MPa$ $\qquad \sigma_{c.d.t} := \frac{\sigma_{c.k.t}}{\gamma_{m.uls}} = 8.986 \cdot MPa$ Design compressive strength

Design stresses in the four different locations:

Check:

$$\sigma_1 := \frac{n_{deck.plate} \cdot M_{Ed}}{W_1} + \frac{F_{t1.d}}{A_{tot}} = 41.054 \cdot MPa \qquad check_1 := \begin{vmatrix} \text{"OK"} & \text{if } \frac{\sigma_1}{\sigma_{b.d}} \le 1 \\ \text{"NOT OK"} & \text{otherwise} \end{vmatrix} = \text{"OK"}$$

$$\sigma_2 := \frac{M_{Ed}}{W_2} + \frac{F_{t1.d}}{A_{tot}} = 33.378 \cdot MPa \qquad check_2 := \begin{vmatrix} \text{"OK"} & \text{if } \frac{\sigma_2}{\sigma_{c.d}} \le 1 \\ \text{"NOT OK"} & \text{otherwise} \end{vmatrix} = \text{"OK"}$$

$$\sigma_3 := \frac{M_{Ed}}{W_3} + \frac{F_{t1.d}}{A_{tot}} = 32.896 \cdot MPa \qquad check_3 := \begin{vmatrix} \text{"OK"} & \text{if } \frac{\sigma_3}{\sigma_{b.d}} \le 1 \\ \text{"NOT OK"} & \text{otherwise} \end{vmatrix} = \text{"OK"}$$

$$\sigma_4 := \frac{M_{Ed}}{W_4} + \frac{F_{t1.d}}{A_{tot}} = 91.496 \cdot MPa \qquad check_4 := \begin{vmatrix} \text{"OK"} & \text{if } \frac{\sigma_4}{\sigma_{b.d}} \le 1 \\ \text{"NOT OK"} & \text{otherwise} \end{vmatrix} = \text{"OK"}$$

Utilization ratio bending stresses:

$$UR_1 := \frac{\sigma_1}{\sigma_{b.d}} = 0.133 \quad UR_2 := \frac{\sigma_2}{\sigma_{c.d}} = 0.189 \quad UR_3 := \frac{\sigma_3}{\sigma_{b.d}} = 0.107 \quad UR_4 := \frac{\sigma_4}{\sigma_{b.d}} = 0.297$$

OK!

Shear

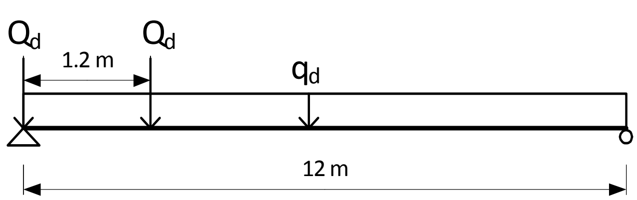


Figure 12. Load condition for ULS shear

$A_{web} := 2t_w \cdot h_w = 0.029\,m^2$ Area of the webs

$$\tau_{shear} := \frac{R_B}{A_{web}} = 20.671 \cdot MPa$$ Shear stress in the webs

$\tau_{xy.k} := 72MPa$ Characteristic shear strength of laminate

$$\tau_{xy.d} := \frac{\tau_{xy.k}}{\gamma_{m.uls}} = 20.87 \cdot MPa$$ Design shear resistance of the section

Utilization shear stress:

$$U_{shear} := \frac{\tau_{shear}}{\tau_{xy.d}} = 0.99$$ OK!

Utilization between hand calculations and Abaqus:

$\tau_{A.shear} := 11.3MPa$ Shear stress in neutral axis from Abaqus

$$U_{conv.shear} := \frac{\tau_{shear}}{\tau_{A.shear}} = 1.829$$ Same

Bearing capacity of supports:

$$S_s := \frac{V_{Ed}}{\left(b_{tf} \cdot \sigma_{c.ks}\right)} = 29.733 \cdot mm$$ The required width of the support

SLS check:

Deflection

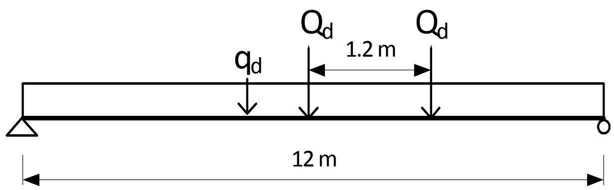


Figure 13.Load condition for SLS

Deflection limit for traffic bridge:

$$\delta_{lim} := \frac{L_{span}}{400} = 30 \cdot mm$$

End conditions	Loading type	k_1	k_2
Cantilever	Point load at end	1/3	1
Cantilever	Uniformly distributed	1/8	1/2
Supported at ends	Point load at centre	1/48	1/4
Supported at ends	Uniformly distributed	5/384	1/8
Fixed at ends	Uniformly distributed	1/384	1/24

Table 1. Selection factors k1 (bending) and k2 (shear) according to deflection behaviourof the beam

$\psi_1 := 0.5$ SLS - Frequent load combination

$q_{1d.sls} := \psi_1 \cdot q_{1k} \cdot w = 13.5 \cdot \frac{kN}{m}$ SLS design uniform load

$Q_{d.sls} := \psi_1 \cdot R_{int.girder} = 1.275 \times 10^5 N$ SLS design point load

Deflection due to bending:

$$\delta_{bending} := \frac{k_1 \cdot F_v \cdot L_{span}^3}{EI}$$

Equation to calculate deflection from bending (Clarke 1996)

Deflection from uniform load:

$$\delta_{bending.uniform} := \frac{5}{384} \cdot \frac{q_{1d.sls} \cdot L_{span}^4 \cdot \gamma_{m.sls}}{E_{GFRP.girder.0} \cdot I_y} = 7.412 \cdot mm$$

Deflection from point load:

$$\delta_{bending.point} := \frac{1}{48} \cdot \frac{2 \cdot Q_{d.sls} \cdot 11.4m \cdot \left[3 \cdot L_{span}^2 - 4 \cdot (11.4m)^2\right] \cdot \gamma_{m.sls}}{E_{GFRP.girder.0} \cdot I_y} = -10.818 \cdot mm$$

Total deflection from bending:

$$\delta_{bending} := \delta_{bending.uniform} + \left|\delta_{bending.point}\right| = 18.23 \cdot mm$$

Utilization factor:

$$u_{bending} := \frac{\delta_{bending}}{\delta_{lim}} = 0.608$$

Deflection due to shear:

$$\delta_{shear} := \frac{k_2 \cdot F_v \cdot L_{span}}{A_v \cdot G_{xy}}$$

Equation to calculate deflection from shear (Clarke 1996)

$A_v := A_{web} = 0.029\,m^2$

Area of the webs

$G_{xy} = 4.14 \cdot GPa$

Shear modulus of the GFRP composite

Deflection from point load:

$$\delta_{shear.point} := \frac{1}{4} \cdot \frac{\left[\left(2 \cdot Q_{d.sls}\right) \cdot L_{span}\right]}{A_v \cdot G_{xy}} = 6.394 \cdot mm$$

Deflection from uniform load:

$$\delta_{shear.uniform} := \frac{1}{8} \cdot \frac{\left(q_{1d.sls} \cdot L_{span}^{\ 2}\right)}{A_v \cdot G_{xy}} = 2.031 \cdot mm$$

Total deflection from shear:

$$\delta_{shear} := \delta_{shear.point} + \delta_{shear.uniform} = 8.425 \cdot mm$$

Total deflection of the bridge:

$$\delta_{tot} := \delta_{shear} + \delta_{bending} = 26.655 \cdot mm$$

ABAQUS input data ULS

Characteristic values of modulus of elasticity and shear modulus for GFRP girders and top plate:

$$E_{GFRP.girder.0} = 25 \cdot GPa$$

$$E_{GFRP.90} = 15 \cdot GPa$$

$$G_{12uls} := 4.14GPa$$

Design values of the GFRP girders and top plate used as input values in Abaqus:

$\gamma_{m.uls} = 3.45$ Material partial safety factor ULS

$$E_{GFRP.d.0uls} := \frac{E_{GFRP.girder.0}}{\gamma_{m.uls}} = 7.246 \cdot GPa$$

$$E_{GFRP.d.90uls} := \frac{E_{GFRP.90}}{\gamma_{m.uls}} = 4.348 \cdot GPa$$

$$G_{12.duls} := \frac{G_{12uls}}{\gamma_{m.uls}} = 1.2 \cdot GPa$$

$$G_{23} := \frac{E_{GFRP.d.90uls}}{2 \cdot (1 + 0.237)} = 1.757 \cdot GPa$$

Design values of ASSET deck

SLS- Characteristics values		gamma_M	1,38
Property	**Flange plate**	**Outer web plates**	**Inner web plate**
Ex [Mpa]	23000	17300	16500
Ey [Mpa]	18000	22700	25600
Gxy[Mpa]	2600	3150	2000
Gxz[Mpa]	600	600	600
Gyz[Mpa]	600	600	600
v_xy	0,3	0,3	0,3
SLS-Design values			
Property	**Flange plate**	**Outer web plates**	**Inner web plate**
Ex [Mpa]	16666,66667	12536,23188	11956,52174
Ey [Mpa]	13043,47826	16449,27536	18550,72464
Gxy[Mpa]	1884,057971	2282,608696	1449,275362
Gxz[Mpa]	434,7826087	434,7826087	434,7826087
Gyz[Mpa]	434,7826087	434,7826087	434,7826087
v_xy	0,3	0,3	0,3

Table 2. Characteristic and design values of the ASSET deck in ULS

Traffic load in ULS

Characteristic traffic loads (from LM1):

$Q_{1k} = 3 \times 10^{5}\,\mathrm{N}$ $\quad Q_{2k} = 2 \times 10^{5}\,\mathrm{N}$ $\quad$ Point loads

$q_{1k} = 9 \cdot \frac{\mathrm{kN}}{\mathrm{m}^2}$ $\quad q_{2k} = 2.5 \times 10^{3}\,\mathrm{Pa}$ $\quad$ Uniform loads

The ULS traffic design loads:

$point_{1d.uls} := 1.35 \cdot \alpha_{Q1} \cdot Q_{1k} = 4.05 \times 10^{5}\,\mathrm{N}$ $\quad point_{2d.uls} := 1.35 \cdot \alpha_{Q2} \cdot Q_{2k} = 2.7 \times 10^{5}\,\mathrm{N}$

$uniform_{1d.uls} := 1.35 \cdot \alpha_{q1} \cdot q_{1k} = 0.012 \cdot \frac{\mathrm{N}}{\mathrm{mm}^2}$ $\quad uniform_{2d.uls} := 1.35 \cdot \alpha_{q2} \cdot q_{2k} = 3.375 \times 10^{-3} \cdot \frac{\mathrm{N}}{\mathrm{mm}^2}$

Loads applied in Abaqus for ULS:

$$point_{1.uls} := \frac{\frac{point_{1d.uls}}{2}}{(400\mathrm{mm})^2} = 1.266 \cdot \frac{\mathrm{N}}{\mathrm{mm}^2} \qquad point_{2.uls} := \frac{\frac{point_{2d.uls}}{2}}{(400\mathrm{mm})^2} = 8.437 \times 10^{5}\,\mathrm{Pa}$$

$$uniform_{1.uls} := uniform_{1d.uls} = 0.012 \cdot \frac{\mathrm{N}}{\mathrm{mm}^2} \qquad uniform_{2.uls} := uniform_{2d.uls} = 3.375 \times 10^{-3} \cdot \frac{\mathrm{N}}{\mathrm{mm}^2}$$

$$F_{traction} := \frac{F_{t1.d}}{L_{span} \cdot 2w} = 7.357 \times 10^{-3} \cdot \frac{\mathrm{N}}{\mathrm{mm}^2}$$ Traction load

Strength of the material:

Design tensile strength:

$$\sigma_{Ab.d} := \frac{\sigma_{b.ks}}{\gamma_{m.uls}} = 307.826 \cdot \mathrm{MPa} \qquad \sigma_{At.d.t} := \frac{\sigma_{t.k.t}}{\gamma_{m.uls}} = 34.203 \cdot \mathrm{MPa}$$

Design compressive strength

$$\sigma_{Ac.d} := \frac{\sigma_{c.ks}}{\gamma_{m.uls}} = 176.812 \cdot \mathrm{MPa} \qquad \sigma_{Ac.d.t} := \frac{\sigma_{c.k.t}}{\gamma_{m.uls}} = 8.986 \cdot \mathrm{MPa}$$

ABAQUS Input data SLS

Characteristic values of modulus of elasticity and shear modulus for GFRP girders and top plate:

$E_{GFRP.girder.0} = 25 \cdot GPa$

$E_{GFRP.90} = 15 \cdot GPa$

$G_{12sls} := 4.14GPa$

Design values of the GFRP girders and top plate used as input values in Abaqus:

$\gamma_{m.sls} = 1.38$ Material partial safety factor ULS

$$E_{GFRP.d.0sls} := \frac{E_{GFRP.girder.0}}{\gamma_{m.sls}} = 18.116 \cdot GPa$$

$$E_{GFRP.d.90sls} := \frac{E_{GFRP.90}}{\gamma_{m.sls}} = 10.87 \cdot GPa$$

$$G_{12.dsls} := \frac{G_{12sls}}{\gamma_{m.sls}} = 3 \cdot GPa$$

$$G_{23sls} := \frac{E_{GFRP.d.90sls}}{2 \cdot (1 + 0.237)} = 4.394 \cdot GPa$$

Design values of ASSET deck

SLS- Characteristics values		**gamma_M**	1,38
Property	**Flange plate**	**Outer web plates**	**Inner web plate**
Ex [Mpa]	23000	17300	16500
Ey [Mpa]	18000	22700	25600
Gxy[Mpa]	2600	3150	2000
Gxz[Mpa]	600	600	600
Gyz[Mpa]	600	600	600
v_xy	0,3	0,3	0,3
SLS- Design values			
Property	**Flange plate**	**Outer web plates**	**Inner web plate**
Ex [Mpa]	16666,66667	12536,23188	11956,52174
Ey [Mpa]	13043,47826	16449,27536	18550,72464
Gxy[Mpa]	1884,057971	2282,608696	1449,275362
Gxz[Mpa]	434,7826087	434,7826087	434,7826087
Gyz[Mpa]	434,7826087	434,7826087	434,7826087
v_xy	0,3	0,3	0,3

Table 2. Characteristic and design values of the ASSET deck in SLS

Traffic load in SLS

The SLS traffic Design load:

Frequent load combination:

$\psi_1 = 0.5$

$\text{point}_{1d.sls} := \psi_1 \cdot Q_{1k} = 1.5 \times 10^5 \, N$

$\text{point}_{d2.sls} := \psi_1 \cdot Q_{2k} = 1 \times 10^5 \, N$

$\text{uniform}_{1d.sls} := \psi_1 \cdot \alpha_{q1} \cdot q_{1k} = 4.5 \times 10^{-3} \cdot \frac{N}{mm^2}$

$\text{uniform}_{2d.sls} := \psi_1 \cdot \alpha_{q2} \cdot q_{2k} = 1.25 \times 10^{-3} \cdot \frac{N}{mm^2}$

Loads applied in Abaqus for SLS:

$$\text{point}_{1.sls} := \frac{\frac{\text{point}_{1d.sls}}{2}}{(400mm)^2} = 0.469 \cdot \frac{N}{mm^2}$$

$$\text{point}_{2.sls} := \frac{\frac{\text{point}_{d2.sls}}{2}}{(400mm)^2} = 0.312 \cdot \frac{N}{mm^2}$$

$\text{uniform}_{1.sls} := \text{uniform}_{1d.sls} = 4.5 \times 10^{-3} \cdot \frac{N}{mm^2}$

$\text{uniform}_{2.sls} := \text{uniform}_{2d.sls} = 1.25 \times 10^{-3} \cdot \frac{N}{mm^2}$

Strengths in SLS:

Design tensile strength (longitudinal and transversal):

$$\sigma_{d.bl.sls} := \frac{\sigma_{b.ks}}{\gamma_{m.sls}} = 769.565 \cdot MPa \qquad \sigma_{d.tt.sls} := \frac{\sigma_{t.k.t}}{\gamma_{m.sls}} = 85.507 \cdot MPa$$

Design compression strength (longitudinal and transversal):

$$\sigma_{d.cl.sls} := \frac{\sigma_{c.ks}}{\gamma_{m.sls}} = 442.029 \cdot MPa \qquad \sigma_{d.ct.sls} := \frac{\sigma_{c.k.t}}{\gamma_{m.sls}} = 22.464 \cdot MPa$$

Vertification

Convergence study with steel material properties in FE model:

A convergence study was conducted in order to see if the FE model was correct. The properties of the members in Abaqus was replaced with the properties of steel. A uniform load of 0.01N/mm^2 was furthermore applied. Both stresses and deflection was compared between hand calculation and the FE model to ensure convergance and suitability of the FE model.

Input data for steel alternative:

$E_{steel} := 210\text{GPa}$ Young's modulus steel

$G_{steel} := 79.3\text{GPa}$ Shear modulus steel

$q_{steel} := 0.0100 \dfrac{\text{N}}{\text{mm}^2}$ Applies uniform load (chosen randomly)

$w_{steel} := 1.75\text{m}$ Width of the deck

$t_b := 250\text{mm}$ Width bottom flange of the girder

Section properties:

$A_{deck.plate.} := b_d \cdot t_{f.asset} = 0.027\,\text{m}^2$

$A_{top.plate.} := b_d \cdot t_t = 0.018\,\text{m}^2$

$A_{beam.} := 2 \cdot h_w \cdot t_w + t_b \cdot t_{bf} + 2 \cdot t_{tf} \cdot b_{tf} = 3.36 \times 10^4 \cdot \text{mm}^2$

$A_{tot.steel} := 2 \cdot A_{deck.plate.} + A_{top.plate.} + A_{beam.} = 0.105\,\text{m}^2$

Total area of the cross section seen in Figure 3.

Distance to the center of gravity:

$$z_{tp.steel} := \frac{b_d \cdot t_{f.asset} \cdot \frac{t_{f.asset}}{2} + b_d \cdot t_{f.asset} \cdot \left(t_{deck} - \frac{t_{f.asset}}{2}\right) \ldots + t_t \cdot b_d \cdot \left(t_{deck} + \frac{t_t}{2}\right) + 2 \cdot b_{tf} \cdot t_{tf} \cdot \left(t_{deck} + t_t + \frac{t_{tf}}{2}\right) \ldots + 2 \cdot h_w \cdot t_w \cdot \left(\frac{h_u - t_{bf}}{2} + t_t + t_{deck} + t_{tf}\right) \ldots + t_b \cdot t_{bf} \cdot \left(h_u + t_{tf} + t_t + t_{deck} - \frac{t_{bf}}{2}\right)}{A_{tot.steel}} = 377.155 \cdot \text{mm}$$

Moment of inertia:

$$I_{y.steel} := \frac{b_d \cdot t_{f.asset}^3}{12} + b_d \cdot t_{f.asset} \cdot \left(z_{tp.steel} - \frac{t_{f.asset}}{2}\right)^2 \dots$$
$$+ \frac{b_d \cdot t_{f.asset}^3}{12} + b_d \cdot t_{f.asset} \cdot \left[z_{tp.steel} - \left(t_{deck} - \frac{t_{f.asset}}{2}\right)\right]^2 + \frac{b_d \cdot t_t^3}{12} \dots$$
$$+ b_d \cdot t_t \cdot \left[z_{tp.steel} - \left(t_{deck} + \frac{t_t}{2}\right)\right]^2 \dots$$
$$+ 2 \cdot \left[\frac{b_{tf} \cdot t_{tf}^3}{12} + b_{tf} \cdot t_{tf} \cdot \left[z_{tp.steel} - \left(t_{deck} + t_t + \frac{t_{tf}}{2}\right)\right]^2\right] \dots$$
$$+ 2 \cdot \left[\frac{t_w \cdot h_w}{12} \cdot \left(h_w^2 \cdot \cos(\alpha_h)^2 + t_{bf}^2 \cdot \sin(\alpha_h)^2\right) \dots + t_w \cdot h_w \cdot \left(\frac{h_u - t_{bf}}{2} + t_{deck} + t_{tf} + t_t - z_{tp.steel}\right)^2\right] \dots$$
$$+ \frac{t_b \cdot t_{bf}^3}{12} + t_b \cdot t_{bf} \cdot \left[\left(t_{deck} + t_t + t_{tf} + h_u - \frac{t_{bf}}{2}\right) - z_{tp.steel}\right]^2$$
$$= 1.841 \times 10^{10} \cdot mm^4$$

Check deflection

Deflection from bending:

$$\delta_{bending.steel} := \frac{5}{384} \cdot \frac{q_{steel} \cdot w_{steel} \cdot L_{span}^4}{E_{steel} \cdot I_{y.steel}} = 1.222 \cdot mm$$

Deflection from shear:

$$\delta_{shear.steel} := \frac{1}{8} \cdot \frac{q_{steel} \cdot w_{steel} \cdot L_{span}^2}{A_v \cdot G_{steel}} = 0.137 \cdot mm$$

Total deflection:

$$\delta_{tot.steel} := \delta_{bending.steel} + \delta_{shear.steel} = 1.36 \cdot mm$$

Ratio between hand calcilations and FE model:

$\delta_A := 1.408mm$ Deflection from Abaqus

$$U_{steel.defl} := \frac{\delta_{tot.steel}}{\delta_A} = 96.562 \cdot \%$$ Ok!

Check bending stresses

Calculated bending moment from uniformly distributed load:

$$M_{ed} := \frac{q_{steel} \cdot w_{steel} \cdot L_{span}^{2}}{8} = 315 \cdot kN \cdot m$$

Section modulus for point between ASSET deck and top plate:

$$W_{hand.c1} := \frac{I_{y.steel}}{z_{tp.steel} - t_{deck}} = 0.121 \cdot m^{3}$$

Section modulus for point in bottom flange of GFRP girder:

$$W_{hand.c2} := \frac{I_{y.steel}}{\left(t_{deck} + t_{t} + t_{tf} + h_{u}\right) - z_{tp.steel}} = 0.017 \cdot m^{3}$$

Stresses in the point below the FRP deck (i.e between the deck and the top plate)

$$\sigma_{hand.c1} := \frac{M_{ed}}{W_{hand.c1}} = 2.603 \cdot MPa$$ Stress from hand calculations

$$\sigma_{Abaqus1} := 2.8332MPa$$ Stress from Abaqus

Check of stresses in the point below the GFRP girder (i.e outmost fibre of girders):

$$\sigma_{hand.c2} := \frac{M_{ed}}{W_{hand.c2}} = 18.305 \cdot MPa$$ Stress from hand calculations

$$\sigma_{Abaqus2} := 18.63MPa$$ Stress from Abaqus

Ratios between hand calculations and Abaqus:

$$U_{steel} := \frac{\sigma_{hand.c1}}{\sigma_{Abaqus1}} = 0.919$$ OK!

$$U_{steel2} := \frac{\sigma_{hand.c2}}{\sigma_{Abaqus2}} = 0.983$$ OK!

It can be concluded that the ratio between the hand calculations and the FE model since the values differs with less than 10% for both the stresses and deflection.

If checking in the point in the top flange of the ASSET deck we get a high ratio between the hand calculation and the FE model:

$$W_{1s} := \frac{I_{y.steel}}{z_{tp.steel}} = 0.049 \cdot m^3$$

$$\sigma_{1.1} := \frac{M_{ed}}{W_{1s}} = 6.453 \cdot MPa$$

$$\sigma_{A.1} := 1.43MPa$$

$$U_1 := \frac{\sigma_{1.1}}{\sigma_{A.1}} = 4.513$$

Conclusion:

When the beam tries to bend then the whole pressure is transferred to the deck system from the bottom flange. The deck consists of two plates where the bottom tries to shrink and if there is no good interaction to the top flange it will not shrink. Hence, the webs of the ASSET deck are not good enough to make the flanges work compositely. In the other direction the webs work as shear webs and works more compositely. It can be concluded that the difference between the hand calculations and value from Abaqus in point 1 is due to that full interaction is assumed for the hand calculations and thus the plates works perfectly compositely, while that is not the case in Abaqus where the flanges doesnt work together completly.

Check ratio between reaction forces for hand calculations and FE model:

Reaction forces from hand calculations:

$R_A = 528.525 \cdot kN$ Reaction force support A

$R_B = 597.375 \cdot kN$ Reaction force support B

Reaction forces from FE model:

The reaction forces from interior girder from Abaqus (ULS):

$$R_{AA} := 265559N$$

$$R_{AB} := 333302N$$

Ratio between reaction forces from Abaqus and hand calculations

$$\alpha_{reaction} := \frac{R_A + R_B}{R_{AA} + R_{AB}} = 1.88$$

Check ratio between bending stresses for hand calculationa and FE model:

Stresses in the four locations from Abaqus:

$\sigma_{As.1} := 25.3595MPa$

$\sigma_{As.2} := 19.1922MPa$

$\sigma_{As.3} := 21.502MPa$

$\sigma_{As.4} := 57.6599MPa$

$\alpha_1 := \dfrac{\sigma_1}{\sigma_{As.1}} = 1.619 \qquad \alpha_2 := \dfrac{\sigma_2}{\sigma_{As.2}} = 1.739 \qquad \alpha_3 := \dfrac{\sigma_3}{\sigma_{As.3}} = 1.53 \qquad \alpha_4 := \dfrac{\sigma_4}{\sigma_{As.4}} = 1.587$

$$\alpha_{stress} := \frac{\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4}{4} = 1.619$$

Correction factor between Abaqus and hand calculations:

$\alpha_{load.coeff} := \dfrac{\alpha_{reaction} + \alpha_{stress}}{2} = 1.749$ i.e approximately 1.8

Conclusion:

The abaqus model and the hand calculations are correct, which have been established by assigning steel properties for both analyses which retrieved corresponding deflections.

Both the bending stresses and the reaction forces differs with factor of approximately 1.8 which can be a consequence of assumptions with regard to load calculations.

LCC input data

Cost of GFRP is 20kr/kg and CFRP 20 times as much.

Weight of girders+top-flange:

$t_b := 250\text{mm}$ Width bottom flange

$A_{beam} := 2 \cdot h_w \cdot t_w + t_b \cdot t_{bf} + 2 \cdot t_{tf} \cdot b_{tf} = 3.36 \times 10^4 \cdot \text{mm}^2$

$A_{top.plate.} := b_d \cdot t_t = 0.018\,\text{m}^2$

$m_{girder.top} := \rho_{GFRP} \cdot \left(A_{top.plate.} + A_{beam.}\right) \cdot 4 \cdot L_{span} = 4.415 \times 10^3\,\text{kg}$

$m_{Eglass} := m_{girder.top} \cdot 0.6 = 2.649 \times 10^3\,\text{kg}$

With optimization half the bridge will be unidirectional and half the bridge will be bidirectional:

$m_{unidir.mat} := 0.800 \dfrac{\text{kg}}{\text{m}^2}$

$m_{bidir.mat} := 0.600 \dfrac{\text{kg}}{\text{m}^2}$ $12 \dfrac{\text{kr}}{\text{m}^2}$

Area GFRP mat required:

$$A_{GFRP.unidir} := \frac{\frac{m_{Eglass}}{2}}{m_{unidir.mat}} = 1.656 \times 10^3 \cdot \text{m}^2$$

$$A_{GFRP.bidir} := \frac{\frac{m_{Eglass}}{2}}{m_{bidir.mat}} = 2.208 \times 10^3\,\text{m}^2$$

Volume epoxy resin required:

$m_{epoxy} := m_{girder.top} \cdot 0.4 = 1.766 \times 10^3\,\text{kg}$

$\rho_{epoxy} := 1250 \dfrac{\text{kg}}{\text{m}^3}$

$v_{epoxy} := \dfrac{m_{epoxy}}{\rho_{epoxy}} = 1.413 \cdot \text{m}^3$ i .e. 1413 liters

Cost of epoxy resin is 100SEK/liter (11,9 EUR/liter)

Manufacturing costs:

Area of mould:

$$A_{mould.girder} := L_{span} \cdot \left(t_b + 2h_w + 2 \cdot b_{tf}\right) = 33.1\, m^2$$

$$A_{mould.topplate} := L_{span} \cdot w_{deck} = 84\, m^2$$

Cost of mould per m2 is 4000 SEK (443.8 EUR)

Cost of carbon cables:

$A_{carbon} = 3.142 \times 10^{-4}\, m^2$ Area carbon cables

$V_{carbon} := 4A_{carbon} \cdot L_{span} = 0.015 \cdot m^3$ Volume carbon cables

$\rho_{carbon} := 1800 \dfrac{kg}{m^3}$ Density carbon cables

Appendix B - Standardisations

Materials

Table 1 Summary of different Fibre types standards (ZRMK 2013)

Material	Standardisation	Description
	Fibre types	
Glass	ISO 1888 Textile glass	Determination of average diameter
Carbon	ISO 10119	Determination of density
	ISO 11567	Determination of filament diameter and cross-sectional area
	Rovings	
Textile Glass Rovings	BS EN 14020-3	Specific requirements
	BS EN ISO 9163	Manufacture of test specimens and determination of tensile strength of impregnated rovings
	BS EN 14020-1	Designation
	EN 14020-2	Methods of test and general requirements
	ISO 9163:2005	Specifies two methods for the determination of the tensile stress at break of an impregnated roving
	ISO 15039	Determination of solubility of size
	ISO 2797:1986	Basis for a specification
	ISO 3375:2009	Determination of stiffness of rovings
	ISO 1889:2009	Determination of linear density (Continuos filament yarns, staple fibre yarns, textured yarns and rovings (packeges))
Textile glass reinforced plastics rods	ISO 3597-1	General considerations and preparation of rods
	ISO 3597-2	Determination of flexural strength
	ISO 3597-3	Determination of compressive strength
	ISO 3597-4	Determination of apparent interlaminar shear strength
Filament winding	ISO 1268-5:2001	Fibre-reinforced plastics -- Methods of producing test plates
	Mats	
Textile Glass Mats	BS EN 14118-1	Designation
	BS EN 14118-2	Methods of test and general requirements
	BS EN 14118-3	Specific requirements
	ISO 2559:1980	Basis for a specification
	ISO 3374:1990, ISO 3374:2000	Determination of mass per unit area

	ISO 3616:1977	Determination of average thickness, thickness under load and recovery after compression
	ISO 3342:2011	Determination of tensile breaking force
Woven Rovings		
Fabrics		
Woven fabric	EN 13417-1	Designation
	BS EN 13417-2	Methods of test and general requirements
	BS EN 13417-3	Specific Requirements
Multi-axial multi-fly fabrics	EN 13473-1	Designation
	BS EN 13473-2	Methods of test and general requirements
	BS EN 13473-3	Specific requirements
Woven fabric - Textile glass	ISO 2113:1996, ISO 2113:1996/Cor 1:2003	Basis for specification
	ISO 4602:2010	Determination of number of yarns per unit length of warp and weft
	ISO 4603:1993, ISO 4603:1993/Amd 1:2010	Determination of thickness
	ISO 4606:1995	Determination of tensile breaking force and elongation at break by the strip method
Prepegs		
Carbon fibre - epoxy	DIN EN 6044-1	Aerospace series - Part 1: General requirements
	DIN EN 6044-2	Aerospace series - Part 2: Qualification program/batch release testing; unidirectional tape, 180 C curing class
Materials for interconnecting structures	DIN EN 61249-4-1	Part 4-1: Sectional specification set for prepreg materials, unclad (for the manufacture of multilayer boards) - Epoxide woven E-glass prepreg of defined flammability; German version prEN 61249-4-1:2005
Fibre reinforced plastics	ISO 10352	Moulding compounds and prepregs - Determination of mass per unit area (EN ISO 10352:1997 Identical)
	ISO 12115, EN ISO 12115:1997	Thermosetting moulding compounds and prepregs - Determination of flowability, maturation and shelf life
	ISO 11667	Moulding compounds and prepregs - Determination of resin, reinforced-fibre and mineral-filler content - Dissolution methods (EN ISO 11667:1999)
	ISO 1268-4	Methods of producing test plates - Part 4: Moulding of prepregs
	ISO 12114	Thermosetting moulding compounds and prepregs – determination of cure characteristics (EN ISO 12114:1997 Identical)

	DIN EN 6039	Aerospace series - Test method; determination of the exothermic reaction during curing of prepreg material
Textile-glass-reiforced plastics	ISO 1172	Determination of the textile-glass and mineral-filler content (Prepregs, moulding compounds and laminates)
Composites	ISO 15034	Determination of resin flow
	ISO 15040	Determination of gel time
Plastics	ISO 9782	Reinforced moulding compounds and prepregs - Determination of apparent volatile-matter content
	ISO 8604:1988	Definitions of terms and symbols for designations
	ISO 8606:1990	Bulk moulding compound (BMC) and dough moulding compound (DMC) -- Basis for a specification
Resin		
Unsaturated polyester resin	ISO 584:1982	Determination of reactivity at 80 degrees C (conventional method)
	BS 3532	Method of specifying unsaturated polyester resin systems
Phenolic resin	EN 2833-5	Areospace series Glass Fibre Thermosetting Preimpregnates Technical Specification Part 5: Glass Fabric/Phenolic Resin Preimpregnate
Epoxy	ISO 527-1	Determination of tensile properties – general principles (ISO 527-1:1993/Cor 1:1994) (ISO 527-1:1993/Amd 1:2005)
Plastics	ISO 527-2	Determination of tensile properties - Part 2: Test conditions for moulding and extrusion plastics (ISO 527-2:1993, including Corr. 1:1994); German version EN ISO 527-2:1996
	ISO 527-3	Determination of tensile properties - Part 3: Test conditions for films and sheets (ISO 527-3:1995 + Corr 1:1998 + Corr 2:2001) (includes Corrigendum AC:1998 + AC:2002); German version EN ISO 527-3:1995 + AC:1998 + AC:2002
	EN ISO 527-4	Determination of tensile properties. Test conditions for isotropic and orthotropic fibre-reinforced plastic composites (ISO 527-4:1997 Identical)
	EN ISO 527-5	Determination of tensile properties - Part 5: Test conditions for unidirectional fibre-reinforced plastic composites (ISO 527-5:2009 Identical)
	ISO/DIS 178	Determination of flexural properties; German version prEN ISO 178:2008 / Note: Date of issue 2008-06-30 * Intended as replacement for DIN EN ISO 178 (2006-04).
	ISO 604:2002	Determination of compressive properties
Laminate		
Pultrusion		
Reinforced plastic	EN 13706-1	Specifications for pultruded profiles - Part 1:

composites		Designation
	EN 13706-2	Specifications for pultruded profiles. Method of test and general requirements
	EN 13706-3	Specifications for pultruded profiles. Specific requirements
Fibre-reinforced plastic composites	EN 14125:1998/AC:2002	Fibre-reinforced plastic composites - Determination of flexural properties
	EN ISO 14129	Fibre-reinforced plastic composites - Determination of the in-plane shear stress/shear strain response, including the in-plane shear modulus and strength, by the +/- 45° tension test method
	EN ISO 14130	Determination of apparent interlaminar shear strength by short-beam method
	EN 2378	Determination of water absorption by immersion
	EN 2743	Standard procedures for conditioning prior to testing unaged materials
	DIN EN 2823	Determination of the effect of exposure to humid atmosphere on physical and mechanical characteristics
	EN 12576	Preparation of compression moulded test plates of SMC, BMC and DMC
Carbon fibre reinforced plastics	EN 2561	Aerospace series - Unidirectional laminate - Tensile test parallel to the fibre direction
	EN 2562	Aerospace series - Unidirectional laminate - Flexural test parallel to the fibre direction
	EN 2563	Aerospace series - Unidirectional laminate - Determination of the apparent interlaminar shear strength
	EN 2597	Aerospace series - Unidirectional laminate - Tensile test perpendicular to the fibre direction
Carbon fibre laminate	EN 2564	Determination of the fibre-, resin- and void content
Glass fibre reinforced plastics		
Flexural test	EN 2746	Aerospace series - Three point bend method
Tensile test	EN 2747	Aerospace series Tensile test
	EN ISO 527-4	Determination of tensile properties. Test conditions for isotropic and orthotropic fibre-reinforced plastic composites
	EN ISO 527-5	Determination of tensile properties - Part 5: Test conditions for unidirectional fibre-reinforced plastic composites
Shear strength	EN 2377	Aerospace series - Test method - Determination of apparent interlaminar shear strength
Textile glass reinforced plastics	EN ISO 7822	Determination of void content - Loss on ignition, mechanical disintegration and statistical counting

		methods
Textile Glass fibre laminate	DIN 18820-1	Unsaturated polyester and phenacrylic resins for load-bearing structural members (GF-UP, GF-PHA); structure, manufacture and characteristics
	DIN 18820-2	Unsaturared polyester and phenolic resins for load-bearing structural members (GF-UP, GF-PHA); physical parameters for standard laminates
	DIN 18820-3	Unsaturared polyester and phenolic resins for load-bearing structural members (GF-UP, GF-PHA); Schutzmaßnahmen für das tragende Laminat
	DIN 18820-4	Unsaturated polyester and phenacrylic resins for load-bearing structural members (GF-UP, GF-PHA); tests and quality control

Testing

Table 2 Standardisations of pultrusion properties with minimum requirement E17 and E23 (Bernard Potyrala 2011 p.30)

Standardisation	**Description**	**Minimum Requirement**	
GFRP Pultrusion			
Test methods		E17[1]	E23[2]
EN 13706-2	Modulus of elasticity for the whole unit [GPa]	17	23
	Pin-bearing strength - longitutional	90	150
	Pin-bearing strength - transverse [MPa]	50	70
EN ISO 527-4	Tensile modulus - longitutional [GPa]	17	23
	Tensile modulus - transverse [GPa]	5	7
	Tensile strngth - longitutional [MPa]	170	240
	Tensile strength - transverse	30	50
EN ISO 14125	Bending strength - longitutional [MPa]	170	240
	Bending strength - transverse [MPa]	70	100
	Shear strength – longitutional [MPa]	15	25
Note:[1] E17 – less strict requirement to the quality (i.e the Effective flexural modulus of the profile by testing) ,[2]E23 – have most strictest requirement to quality.			

Table 3 Testing method during production process (Clark 1996)

Standardisati	**Description**

ons	
Testing for quality assurance	
ISO 9000:1987	Quality Management and Quality Assurance Standards—Guidelines for selection
ISO 9001:1987	Quality systems—Model for quality assurance in design/development, production, installation and servicing.
ISO 9002:1987	Quality systems—Model for quality assurance in production and installation
ISO 9003: 1987	Quality systems—Model for quality assurance in final inspection and test
ISO 9004: 1987	Quality management and quality system elements Guidelines
The preparation and condition of test specimens	
ISO 291:1977	Plastics—Standard atmospheres for conditioning and testing
ISO 1268:1974	Plastics—Preparation of glass fibre reinforced, resin bonded, low-pressure laminated plates or panels for test purposes
The properties of the glass fibre and of the roving	
ISO 1889:1987	Textile glass—Continuous filament yarns, staple fibre yarns, textured yarns and roving (packages) – determination of linear density
ISO 2078:1985	Textile glass—Yarns—Designation
ISO 2797:1986	Textile glass—Rovings—Basis for a specification
ISO 3341:1984	Textile glass—Yarns—Determination of breaking force and breaking elongation
ISO 3375:1975	Textile glass—Determination of stiffness of rovings
ISO 3598:1986	Textile glass—Yarns—Basis for a specification
The properties of mats and woven of multi-axial fabrics	
ISO 2113: 1981	Textile glass—Woven fibres—Basis for specification
ISO 2559: 1980	Textile glass—Mats (made from chopped or continuous strands)—Basis for a specification
ISO 3342:1987	Textile glass—Mats—Determination of tensile breaking force
ISO 3374:1990	Textile glass—Mats—Determination of mass per unit area
ISO 3616:1977	Textile glass—Mats—Determination of average thickness, thickness under load and recovery after compression
ISO 4602: 1978	Textile glass—Woven fabrics—Determination of number of yarns per unit length of warp and weft
ISO 4603: 1978	Textile glass—Woven fabrics—Determination of thickness

ISO 4605: 1978	Textile glass—Woven fabrics—Determination of mass per unit area
ISO 4606:1979	Textile glass—Woven fabric—Determination of tensile breaking force and breaking elongation by the strip method
The properties of the fibre-based material used in manufacture process	
ISO 1886:1990	Reinforcement fibres—Sampling plans applicable to received batches
ISO 8604: 1988	Plastics—Prepregs—Definitions of terms and symbols for designations
ISO 8605:1989	Textile glass reinforced plastics—Sheet moulding compound (SMC)—Basis for a specification
ISO 8606: 1990	Plastics—Prepregs—Bulk moulding compound (BMC) and dough moulding compound (DMC) – basis for a specification
The manufacture of the laminate	
ISO 584: 1982	Plastics—Unsaturated polyester resins—Determination of reactivity at 80°C
ISO 1628: 1984	Determination of viscosity number
ISO 1675: 1985	Plastics—Liquid resins—Determination of density by the pyknometer method
ISO 2555: 1989	Plastics—Resins in the liquid state or as emulsions or dispersions—Determination of apparent viscosity by the Brookfield Test method
ISO 3219:1977	Plastics—Polymers in the liquid emulsified or dispersed state—Determination of viscosity with a rotational viscometer working at defined shear rate
ISO 6186: 1980	Plastics—Determination of pourability
Visual inspection of finish product	
ASTIM 2563	Classifying visual defects in glass-reinforced plastic laminate parts
Local inspection of finish product	
ISO 868: 1985	Plastics and ebonite—Determination of indentation hardness by means of a durometer (shore hardness)
ISO 20391: 1987	Plastics—Determination of hardness—Part 1: Ball indentation method
ISO 20392:1987	Plastics—Determination of hardness—Part 2: Rockwell hardness
ISO 66031: 1985	Plastic—Determination of multi-axial impact behaviour of rigid plastics—Part 1: Falling dart method
ISO 660312: 1989	Plastic—Determination of multi-axial impact behaviour of rigid plastics—Part 2: Instrumented puncture test

Table 4 Testing standard for adhesive bonded FRP composite joints (Zoghi 2013)

Standardisations	Description
Adhesive characterization	
ASTM D907-05, D4800-94(2005)	Standard terminology
ASTM D1084-97(2005), D7149-05, D2556-93a(2005)	Physical properties
ASTM D3983-98(2004), D4027-98(2004), D905-03, D4896-01	Strength and shear modulus
ASTM D5868-01	Bonding characteristics
ASTM D1183-03	Environmental aging
Joint Characterization	
ASTM D2093-03	Laminate surface preparation
D5573-99(2005)	Failure mode classification
ASTM D5868-01, D3163-01, D3164-03, D3165-00; ISO 4587:2003	Tensile shear loading
ASTM D897-01, D2095-96(2002); ISO 6922: 1987	Tensile loading (butt joint)
ASTM D1781-98(2004), D1876-01, D3167-03a(2004), D903-98(2004)	Peel loading
ASTM D1184-98(2004)	Flexural loading
ASTM D5041-98(2004), D950-03, D1062-02, D3433-99(2005), D3807-98(2004)	Cleavage loading
ASTM D1780-05, D2293-96(2002), D2294-96(2002)	Creep
ASTM D3166-99(2005)	Fatigue
ASTM D1151-00, D1828-01e1, D2918-99(2005), D2919-01e1, D3762-03, D3632-98(2004), D1144-99(2005), D904-99(2005), D896-04	Durability

Reference

1. Bernard Potyrala, P. (2011), *Use of Fibre Reinforced Polymer Composites in Bridge Construction*. State of the Art in Hybrid and All-Composite Structures. Master Thesis, Universitat Politécnica De Catalunya
2. ZRMK, TNO, UNIVPM, Mostostal, Acciona, Huntsman *(2013), Recommendation for standardisation* - Trans-IND
3. Clarke, J. (1996), *Structural Design of Polymer Composites*. London: E & FN SPON, P. 524
4. Zoghi, M 2013), *The international handbook of FRP composite in civil engineering.*

Appendix C - Life Cycle Cost analysis

Alternative 1

Convert the cost to present value		
Ct : cost today	C : cost at previous time	
Inflation rate i=4%	3,5%	
Time period (years) t=	10	
Formula	Ct=C*(1+i)^t	
All costs are given in Euros		(ref. thesis)

	Cost category	Sub-categories	Cost /C (2002)	Cost /Ct (2014)	%
CONSTRUCTION COSTS	**Material costs**				
		Prefab. concrete deck	40000	56424,0	
		Steel	25000	35265,0	
		Wearing surface	3200	4513,9	
		Miscellaneous elements	8500	11990,1	
		Total		**108192,9**	
	Installation and other costs				
	Stock for assemblage		1000	1410,6	
	Additional costs (labor, equipment costs etc)		12000	16927,2	
		Total		**18337,8**	
		Total construction costs		**126530,7**	**80,0**
SOCIAL COSTS	**User cost (from the thesis)**				
		User delay	5127,6	7233,0	
		Vehicle operating	4292,1	6054,4	
		Incidence of accidents	1932	2725,3	
	Environmental costs		1312,2	1851,0	
		Total Social costs		**16012,7**	**8,1**
Disposal costs	**Demolish the concrete deck**			9500,0	
	Dismantling the old bridge		2500	3526,5	
		Total demolition costs		**13026,5**	
	Disposal costs				
		Conrete		5500,0	
		Reinforcement steel		-250,0	
		Steel girders		-440,0	
		Disposal costs		**4810,0**	
	Transportation costs	**Transportation of disposal materials**		**960,0**	
		Total disposal costs		**18796,5**	**11,9**
TOTAL inital costs				**158120,5**	100%

Social costs according to Ehlen's equations for consistency							
Driver delay costs due to limited speed due to assemblage of the new bridge							
Number of days =	14	Normal traffic speed (Sn)	90	Limited traffic speed (Sa)	70	Length of the affected road L (km) =	0,2
Number of days =	7	Normal traffic speed (Sn)	90	Limited traffic speed (Sa)	50	Length of the affected road L (km) =	0,2
Driver delay time during closure of the bridge(h)	0,25	Number of days of closure (30h)	1,25				
ADT	796						
Hourly time value of drivers w (Euro/h)	26,80						
Hourly vehicle operating cost: r (Euro/h)	19,7						

User cost (calculated here)	
Driver delay costs	7121,965
Vehicle operating costs	5247,764
Environmental costs	423,6076
Total Social costs	**12793,34**

$$\text{Driver delay costs} = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) \times \text{ADT} \times N \times w \quad (2)$$

$$\text{Vehicle operating costs} = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) \times \text{ADT} \times N \times r \quad (3)$$

$$\text{Accident costs} = L \times \text{ADT} \times N \times (A_a - A_n) \times c_a \quad (4)$$

where L = length of affected roadway over which cars drive; S_a = traffic speed during bridge work activity; S_n = normal traffic speed; ADT = average daily traffic, measured in number of cars per day; N = number of days of road work; w = hourly time value of drivers; r = hourly vehicle operating cost; c_a = cost per accident; and A_a and A_n = during-construction and normal accident rates per vehicle-kilometer, respectively. Table

Alternative 2

Convert the cost to present value		
Ct : cost today	C : cost at previous time	
Inflation rate i=3,5%	3,5%	
Time period (years) t=	10	
Formula	Ct=C*(1+i)^t	
All costs are given in Euros		(ref. thesis)

	Cost category	Sub-categories	Cost
CONSTRUCTION COSTS	**Material costs**		
		FRP deck	67620
		E-glass fibres for girder and top plate	5881
		Epoxy resin	13984
		CFRP cables	1215
		Cost of mould	14690
		Wearing surface	2520
		Miscellaneous elements	17632
		Total	**123543**
	Installation and other costs		
	Surfacing cost		6300
	Additional costs (labor, equipment costs etc)		3385
		Total	**9685**
	Total construction costs		**133228**
Social costs	**User cost**		
		Driver delay	4445
		Vehicle operating	3275
	Environmental costs		328
	Total Social costs		**8047**
Disposal costs	Demolish the old deck		9500
	Dismantling the old bridge		3526
		Total demolition costs	**13026**
	Disposal costs		
		Concrete	5500
		Reinforcement steel	-250
		Steel girders	-440
		Disposal costs	**4810**
	Transportation costs	**Transportation of materials**	**960**
	Total disposal costs		**18796**
TOTAL inital costs			**160072**

Traffic Input Data			
Average daily traffic ADT =		796	
Hourly time value of drivers w (kr/h) 2002		19	
Hourly time value of drivers w (kr/h) 2012		26,8	
Hourly vehicle operating cost: r (kr/h) 2002		14,0	
Hourly vehicle operating cost: r (kr/h) 2012		19,7	
driver delay time due to detouring (ref.thesis)	15 min	0,25	hours
Number of days of closure (20 hours)		0,83	days

Material Input Data	
Area of the deck (m2)	84,0
Price of ASSET deck (euro/m2)	805,0
Price E-glass fibres (EUR/kg)	2,2
Weight of E-glass fibres (kg) Vf=60%	2649,0
Price epoxy resin (EUR/liter)	11,1
Amount of epoxy (liter)	1261,0
Price of CFRP cables (EUR/kg)	45,0
Weight of CFRP cables (kg)	27,0
Manufacturing - Mould area of one girder (m2)	33,1
Cost of moudling RTM method (EUR/m2)	443,8
Surfacing 75 euro/m2 (kr/m2)	75,0
Wearing surface 30euro/m2 (kr/m2)	30,0
Disposal cost (110 euro/ton)	110,0

MR and R Costs

	Life span (years)	80 years
MRR costs	Discount rate	3,5%

Alternative 1		Interval (years)	Cost (€/m²)	Quantity (m2)	Costs (€)	Frequency	LCC cost	Total
Surface maintenance	Material	10			4514	7	10004,2	
	Installation, equipment cost	10			1693	7	3751,6	
	Demolition cost	10	20	113,4	2268	7	5026,6	
	Disposal costs	10	110	23,5	2582	7	5722,8	
Replacement of insulation		40	170	113,4	19278	1	4869,1	
Repainting of steel girders		30	188	61	11468	2	5541,5	29374,3
Alternative 2								
Surface maintenance	Material	20			2625	3	2315,4	
	Installation, equipment	20			6901	3	6087,2	
	Demolition costs	20			2268	3	2000,5	
	Disposal costs	20	110	5,9325	653	3	575,6	
								10978,8

Input Data Traffic		
Average daily traffic ADT =		796
Hourly time value of drivers w (€/h) 2012		28
Hourly vehicle operating cost: r (€/h) 2012		21
Normal traffic speed (Sn)		90
Limited traffic speed (Sa)		70
Length of the affected road L (km) =		0,042
Waiting time when 1 lane closed(sec)		10
driver delay time detour (ref.thesis min)		15

$$\text{Driver delay costs} = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) \times \text{ADT} \times N \times w \qquad (2)$$

$$\text{Vehicle operating costs} = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) \times \text{ADT} \times N \times r \qquad (3)$$

$$\text{Accident costs} = L \times \text{ADT} \times N \times (A_a - A_n) \times c_a \qquad (4)$$

where L = length of affected roadway over which cars drive; S_a = traffic speed during bridge work activity; S_n = normal traffic speed; ADT = average daily traffic, measured in number of cars per day; N = number of days of road work; w = hourly time value of drivers; r = hourly vehicle operating cost; c_a = cost per accident; and A_a and A_n = during-construction and normal accident rates per vehicle-kilometer, respectively. Table

Social costs

Activity

Alternative 1	Duration (h)	Driver delay costs	LCC cost	Vehicle operating costs	LCC	Environmental costs	LCC (env)	Total
Surface maintenance	24	64,9	143,8	48,7	107,9	30,05	210,3	
Replacement of insulation	336	908,4	229,4	681,3	172,1			
Repainting of girders	24	64,9	23,1	48,7	23,5			
Total			**373,2**		**279,9**		**210,3**	**863,5**
Alternative 2								
Surface maintenance	24	64,9	57,2	48,7	42,9	45,52	136,6	
Total			**57,2**		**42,9**		**136,6**	**236,7**

End of Life (Disposal Cost)

Life span	**80 years**
Discount rate	**3,5%**

		Costs	LCC costs
Alternative 1	**Demolition of the bridge**	13026,5	831
	Disposal		
	concrete	7573,5	483
	reinforcement steel	-607,5	-39
	steel	-531,1	-34
	Transportation	960	61
	TOTAL		**1303**
Alternative 2	**Demolition of the bridge**	13026,5	831
	Disposal		
	FRP (incl transport)	1003	64
	TOTAL		**895**

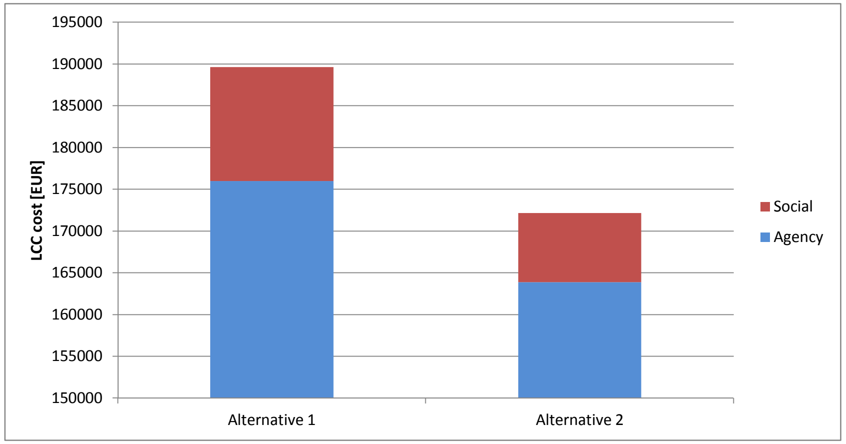
Note: Environmental costs are negligible here

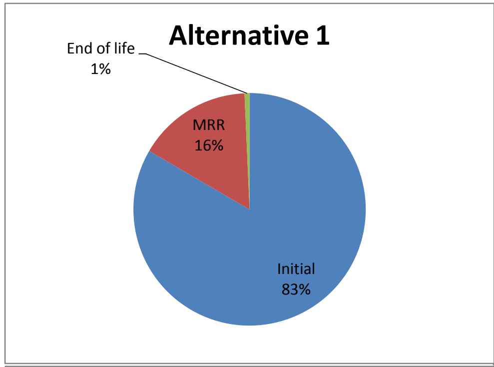
Costs Summary

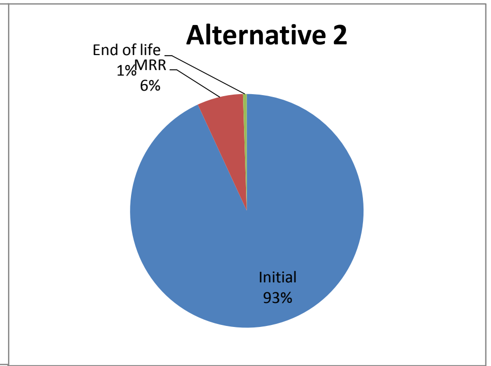
		Alternative 1	Alternative 2	Ratio [%
Initial	**Agency costs**	145327	152024	-4,6
	Social costs	12793	8047	37,1
	Total	**158121**	**160072**	-1,2
MRR	**Agency costs**	29 374	10979	62,6
	Social	863	237	72,6
	Total	**30238**	**11216**	62,9
End of life	**Agency costs**	1303	895	31,3
	TOTAL	**189661**	**172182**	9,2

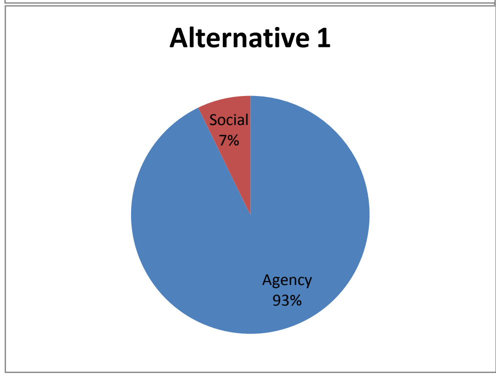
	Alternative 1	Alternative 2	Ratio [%]
Initial	158121	160072	-1,2
MRR	30238	10979	63,7
End of life	1303	895	31,3
TOTAL	**189661**	**171945**	9,3

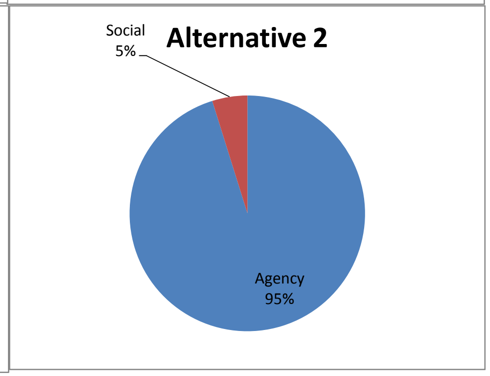
	Agency	Social	TOTAL
Alternative 1	176004	13657	189661
Alternative 2	163898	8284	172182
Ratio [%]	6,9	39,3	9,2





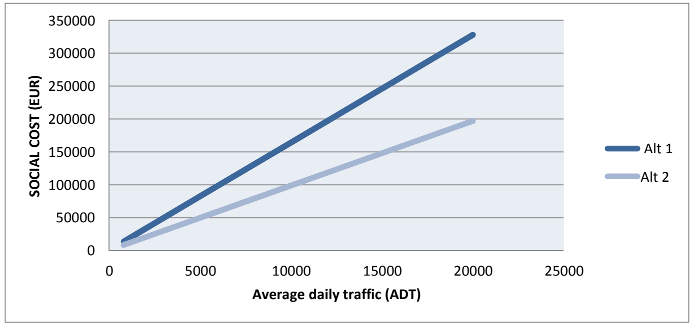


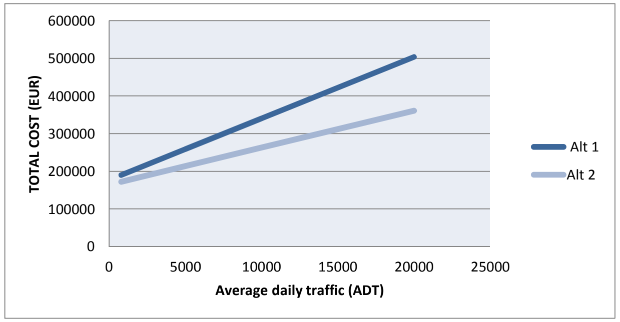




Sensitivity Analysis

	Social costs		Ratio	Agency costs		Total costs		Ratio
ADT	Alt 1	Alt 2		Alt 1	Alt 2	Alt 1	Alt 2	
796	13657	8284	39,342462	176004	163898	189661	172182	9,2
5000	82436	49583	39,852734	176004	163898	258440	213481	17,4
10000	164238	98701	39,903676	176004	163898	340242	262599	22,8
20000	327842	196938	39,92899	176004	163898	503846	360836	28,4





ADT	796		5 000		10 000		20 000	
	Alt 1	Alt 2	Alt 1	Alt 2	Alt 1	Alt 2	Alt 1	Alt 2
Social	13657	8284	82436	49583	164238	98701	327842	196938
Agency	176004	163898	176004	163898	176004	163898	176004	163898