A New Concept for Sustainable Refurbishment of Existing Bridges Using FRP Materials

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ABSTRACT: This paper presents a new strengthening concept proposed for road bridges in the project SUREBridge (Sustainable Refurbishment of Existing Bridges), co-funded by the European Commission through the ERA-NET Plus Infravation 2014 Call. The project proposes an innovative and holistic refurbishment approach by using fiber-reinforced polymer (FRP) materials. The approach is designed for bridge upgrading, including repair and strengthening actions in the most effective and efficient way in terms of reducing construction time, resource consumption, and traffic disruption.

SUREBridge concept consists of bonding prestressed carbon fiber reinforced polymer (CFRP) laminates to the tensile parts of flexural members (such as bottom flange of girders), and installing glass fiber reinforced polymer (GFRP) panels to the compressive parts (such as top of the existing concrete deck). A novel prestressing system is used to apply prestressed CFRP laminates eliminating the need for mechanical anchorage of the composite strips. The GFRP panels contribute by increasing the overall bending stiffness of the section and unloading the compressive concrete which might not be in a good condition. The GFRP panels are fabricated in a robust modified sandwich-type that ensures load-spreading onto the concrete. The bespoke design of the decks allows for widening the bridge and the incorporation of a curb to avoid further water ingress to the concrete substructure.

The effectiveness of the proposed technique is demonstrated through lab test of the stepwise prestressing method and a case study of strengthened prototype beams. Furthermore, a theoretical model has been set up to predict the strengthened cross section's ultimate bending moment.

1 INTRODUCTION

Bridge owners and traffic authorities in European countries deal a substantial number of old bridges which are becoming structurally deficient and geometrically insufficient. With the expected increase in the traffic volume, the existing bridges will be subjected to more severe load actions. Consequently, the need for refurbishment in bridge structures will increase dramatically in the future. The refurbishment, in this context, includes not only strengthening, repair and upgrading of bridge structures, but also geometric changes such as widening the bridge deck to provide more traffic volume capacity. A study conducted within the European "Sustainable

Bridges" project (PANTURA, 2012) revealed that – a top of priority from bridge management point of view is to develop non-disruptive strengthening and repair techniques for bridges.

1.1 SUREBridge project

SUREBridge project is proposed to meet the need for new upgrading techniques that can satisfy the requirements imposed by stakeholders and end users. Construction processes for bridges, especially in densely populated areas, clearly call for holistic innovative solutions with a minimum negative impact and the most efficient use of resources. Investigations show that approximately 70% of the problems in existing concrete and concrete-steel bridges are related to concrete decks (PANTURA, 2012).

One goal included in the framework of SUREBridge project is to realize and provide a solution using fiber reinforced polymer (FRP) materials to (1) utilize the remaining capacity of the superstructure in existing bridges by preserving the relevant structural elements such as girders and concrete deck, and (2) strengthening the bridge to the desired service level. The GFRP deck on the top and CFRP laminates for strengthening on the bottom will ensure an upgraded capacity and service performance of the superstructure in the remaining life of the bridge.

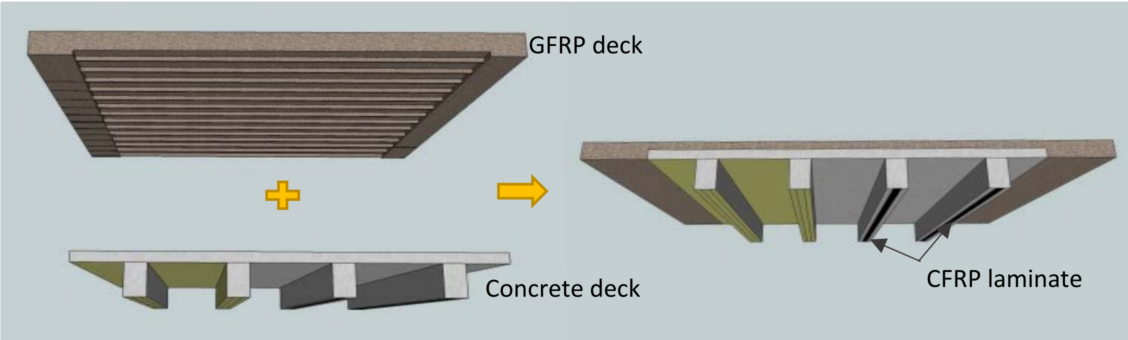


Figure 1. SUREBridge concept—externally bonded (EB) prestressed CFRP laminates on the bottom of girder (tensile part) and GFRP panels on the top of the existing concrete deck (compressive part)

1.2 SUREBridge solution and methodology

The SUREBridge solution is designed to form a package approach addressing innovations in refurbishment of bridge structures including areas such as strengthening using prestressed CFRP laminates and new lightweight FRP-concrete composite decking system. This goal is realized by adding a complementary tailor-made glass fiber reinforced polymer (GFRP) deck to be installed on top of the existing concrete deck, and (if necessary) strengthen the concrete deck from the bottom with prestressed CFRP laminate as illustrated in Figure 1. This strengthening operation could be extended to girders if they do not have enough capacity for carrying the desirable load levels.

The strengthening of the concrete deck and/or the girders from the bottom will also be a part of the solution package when higher flexural capacity is required. Externally bonded (EB) technique using CFRP laminates (passive or prestressed) has become widely popular for flexural strengthening of concrete members in the past two decades. Different from the traditional application od prestressed CFRP laminates which need mechanical anchorage at the ends of the laminate, the proposed method in SUREBridge eliminates this need of anchorage by using an innovative prestressing method.

According to the investigation (PANTURA, 2012), two major areas of problem in existing bridges are (a) the aging and lack of load bearing capacity of concrete decks, and (b) the need for wider decks for increased traffic demands. In the perspective of concrete deck, the refurbishment technique proposed in SUREBridge solution is installing a lightweight GFRP deck on the existing concrete deck to establish a FRP-concrete composite deck system.

1.3 Motivation/benefits of using GFRP panels

The conventional practice to tackle the problem with aged concrete decks—assuming the girders are in good condition—is to replace them with new concrete decks or with full FRP decks. Compared with these regular solutions, the FRP-concrete composite deck system gains the following benefits:

(1) Save and utilize the residual capacity of aged concrete deck;

(2) Increase the overall bending stiffness of strengthened concrete section;

(3) Potential to widen the bridge deck;

(4) Protect the concrete substrate against environmental impacts.

1.4 Specification and innovation in FRP decking system

The proposed GFRP decking is of the type that is already commonly in use as all-FRP bridge structure, or as a decking on a primary structure. The first type has seen hundreds of realizations, initially in low-risk usages such as pedestrian bridges, gradually moving towards more high-value applications. In movable structures, such as bascular and swing bridges the advantages of the low self-weight of FRP structures were also quickly identified. Now, more advanced structures use the material in hybrid, whereof a 142m long hybrid structure of an FRP deck spanning in transverse in between two steel trusses spanning longitudinally is a prime example (Veltkamp and Peeters, 2014)

When used as a deck-element on top of a primary structure, the main structure has to date typically been in steel that the FRP can be easily connected to, however hybrids with concrete are envisageable too. In the latter case, they could eliminate part of the typical high self-weight of reinforced concrete structures. In particular, in hybrid with high strength concrete grades, this could render such structures ‘lightweight’, challenging the traditional view of the material being ‘heavy’.

The deck proposed for SUREBridge is made using the InfraCore technology. This is a modified sandwich in which delamination has been eliminated as a failure mode due to the integral connection with continuous glass fibers between top skin and bottom skin. Structures are made in full through the infusion technique. Different to standardized FRP elements such as pultruded profiles, the infusion technique allows for a bespoke construction of structural components. The prefabrication in large components eliminates bonds and the associated risks.

2 STRENGTHENING TECHNIQUE USING PRESTRESSED CFRP LAMINATES

In the refurbishment case that requires to further upgrading the flexural capacity of superstructure, a combined use of GFRP deck on the top of original concrete deck with externally bonded CFRP laminates on the bottom of deck or girder is proposed in SUREBridge solution. To fully utilize the tensile strength of CFRP laminates and increase flexural performance in serviceability limit state, the CFRP laminate is suggested to be prestressed before bonding to concrete members. In the conventional prestressing technique, an anchorage system, for instance mechanical anchors, is required to be installed at the CFRP ends, due to the localized peaking shear stress and peeling effects that developed upon the removal of prestressing tools, see Figure 2 (Haghani and Al-Emrani, 2016). The core competence of the innovative prestressing method incorporated in the SUREBridge solution is that the need for anchorage system at CFRP ends could be eliminated, which is approached by applying the prestressing force with a gradually decreasing force profile towards the ends of CFRP laminate.

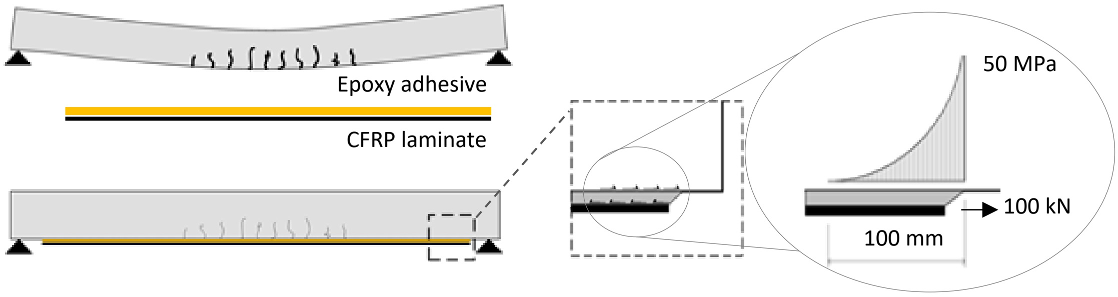


Figure 2. Interfacial shear stress concentration developed at each end of CFRP laminate upon releasing of prestressing force (Haghani and Al-Emrani, 2016; Haghani et al., 2009)

2.1 Stepwise prestressing method for externally bonded CFRP

The concept of using prestressed and gradually anchored CFRP (gradient anchorage method) for strengthening of concrete structures was first proposed in EMPA (Stöcklin and Meier, 2001; Meier and Stöcklin, 2006). Different from EMPA's gradient anchorage method that stepwisely cure the adhesive and bond the CFRP with decreasing the prestressing force at ends, the proposed stepwise prestressing method is able to—within one jack go—achieve a stepwise decreasing profile of prestressing force till the anchorage end. This stepwise prestressing method and a prestressing device based on it was first proposed by (Haghani et al., 2015). This innovative prestressing method was incorporated into the SUREBridge solution package. Figure 3 illustrated the developed prestressing device. The device was composed of a simple mechanism including several aluminum tabs interconnected with series of springs (steel bars with changing diameters). The tabs would be connected to the strengthening FRP laminates through a medium (a GFRP plate in Figure 3). When the prestressing force is applied, the force transferred from the prestressing device to the CFRP plate is dependent on the ratio of cross-sectional stiffness between the CFRP and springs (steel bars). Considering the increasing diameter of steel bars towards the CFRP ends, the novel prestressing device can achieve a gradually decreasing prestressing force profile towards the CFRP ends in only one go. Using this method, it is easily possible to manipulate the gradient of the prestressing force in the composite laminate by changing the number of steps (tabs).

The prestressing system was removed when the epoxy adhesive between CFRP and RC beam was cured after 24 hours. Upon the release of the prestressing device (aluminum tabs and steel bars), the prestressing force in CFRP would be transferred to concrete through cured adhesive layer. The shear stress was developed along the bond line, of which the magnitude is directly related to the axial pretension force in CFRP (Al-Emrani and Kliger 2006; Haghani, Al-Emrani, and Kliger 2009). Contributing to the decreasing prestressing level within the grip length, the shear and peeling stress developed were reduced to the such a level that the bond line was strength enough to allow force transfer to the concrete substrate. Previous numerical and experimental studies proved that it was possible to reduce the shear and peeling stresses in the bond line below 1.0 and 0.2 MPa, respectively, given a prestressing force of 80 kN distributed by eight steps (tabs). Since the application of this prestressing method eliminates the concentration of shear stress near, this prestressing method eliminates the need for mechanical anchorage systems at CFRP ends.

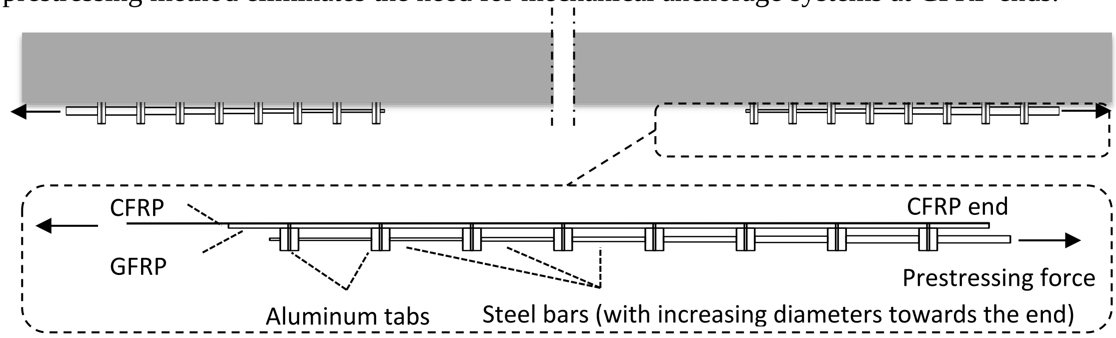


Figure 3. Applying stepwise prestressing force in CFRP laminate using the new technique

2.2 Experimental verification

The stepwisely prestressing method and the prestressing device were verified by laboratory test. A reinforced concrete beam was strengthened with externally bonded CFRP laminate using stepwisely prestressing method. The dimensions of RC beams were 4500 × 200 × 300 (Length × Width × Height, unit: mm). The CFRP laminate was 3.8-meter-long with cross-section of 80 × 1.4 (Width × Thickness, unit: mm). The average modulus of elasticity in tension and ultimate tensile strength were 210 GPa and 3300 MPa, respectively. The prestressing force in CFRP laminate was 80 kN, equivalent to 22 percent of ultimate tensile strength of CFRP laminate. The specimens were tested under four-point bending in displacement-control manner.

As a verification, the strains in CFRP between sequent tabs were monitored during the prestressing process. This was done through readings from 19 strain gauges placed along the CFRP laminate. **Error! Reference source not found.** shows the measured strain values in the CFRP laminate under different prestressing forces up to 80 kN. Given a certain prestressing force, it was clear to identify that in the middle section of CFRP the strain reached the highest level, while the strain started decreasing gradually towards the CFRP laminate ends within the "anchorage length". The results prove that a gradual force profile along the anchorage length can be achieved using stepwise prestressing device.

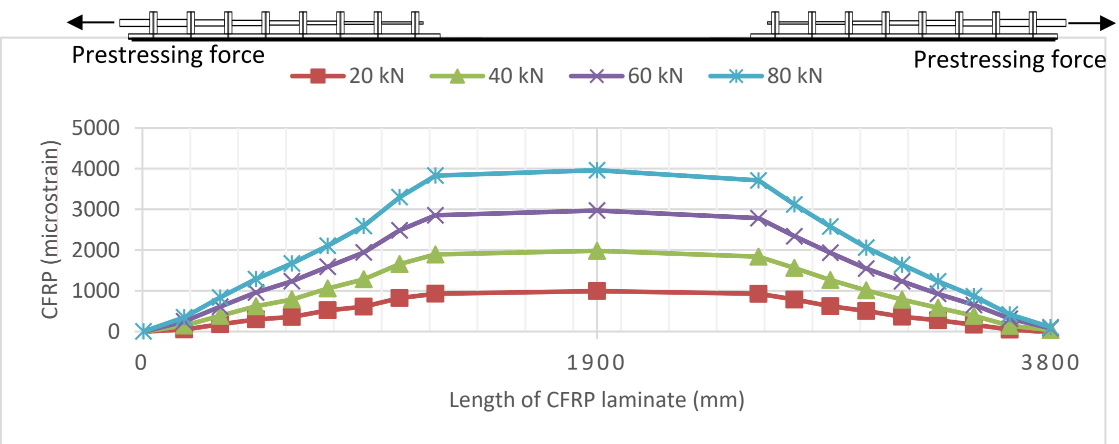
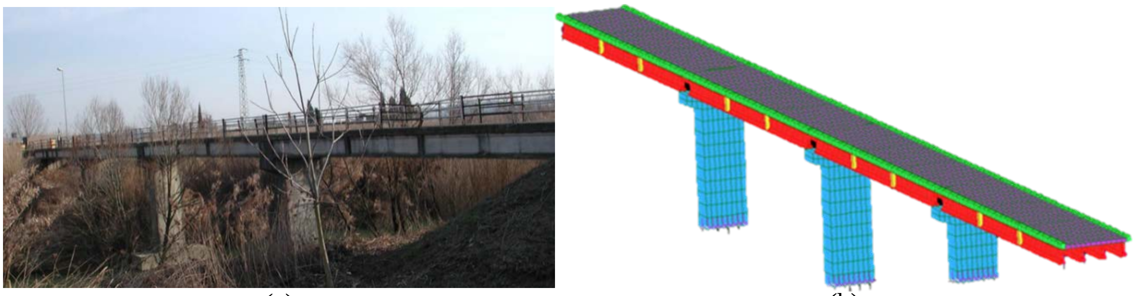


Figure 4. Tensile strain in CFRP laminate under prestressing force up to 80 kN in specimen B3

3 A CASE STUDY IN TUSCANY

3.1 Structural assessment of the San Miniato bridge

In order to evaluate the effectiveness of the SUREBridge solution, its application to a real bridge has been analyzed. The selected case study is a bridge located in San Miniato, Pisa (Italy), from now on referred to as the "San Miniato bridge" (Figure 5.a). The bridge, built in 1968, has a length of 60 m subdivided into four spans of 15 m each. The 3-meter-wide deck is composed of a 160-mm-thick cast-on-site concrete slab and four prefabricated pre-stressed concrete girders, 1 m high and 1 m distant one from another (Valvo et al. 2017).



(a) (b)

Figure 5. (a) Side view of the San Miniato bridge; (b) Finite element model of the San Miniato bridge

Structural assessment of the San Miniato bridge has been conducted by using a Standard Operating Procedure developed within the SUREBridge project (SUREBridge 2016a). The first step was the search for original design documentation. Then, in situ tests were carried out to obtain the actual material properties; dynamical acquisitions were performed to measure the natural frequencies and mode shapes of the bridge. The main problems affecting the structure turned out to be the corrosion and breakage of some pre-stressing wires in a border girder, as well as concrete spalling, reinforcement corrosion, and general degradation of concrete surfaces. A finite element model of the bridge (Figure 5.b) was developed to analyze the static behavior of the structure. The analysis revealed the lack of both flexural strength and shear strength in the longitudinal direction for the composite section (girder + slab) and in the transverse direction for the concrete slab. The current load-carrying capacity of the bridge was evaluated in the 51% of traffic loads imposed by current regulations. Furthermore, the road section width (3 m) was not sufficient for the road category assigned to the bridge by the Italian road regulations (SUREBridge 2016b).

3.2 SUREBridge solution for the San Miniato bridge

An intervention on the bridge has been designed including the widening of the existing lane from 3 m to 3.5 m and the addition of two lateral walkways, as shown in **Error! Reference source not found.**, where the existing and widened bridge cross sections are compared. A new finite element model of the widened bridge has been created to evaluate the internal forces in the new configuration, in particular the design bending moment, M_{sd}, on the strengthened section (CFRP + girder + slab + GFRP) under the full action of traffic load prescribed by current regulations.

The resisting bending moment of the composite section, M_{rd}, at the ultimate limit state has been evaluated according to the following hypotheses:

- no relative slip is considered between the concrete slab and the girder;
- no relative slip is considered between the concrete slab and the GFRP panel;
- the whole composite section remains plane after deformation;
- prestressing force in CFRP laminates has been limited to 100 kN (Haghani et al., 2015);

- the design strain of CFRP laminates has been limited to avoid intermediate delamination failure as prescribed by the Italian standard CNR-DT 200 R1/2013 (2014);
- GFRP/concrete delamination has not been considered.

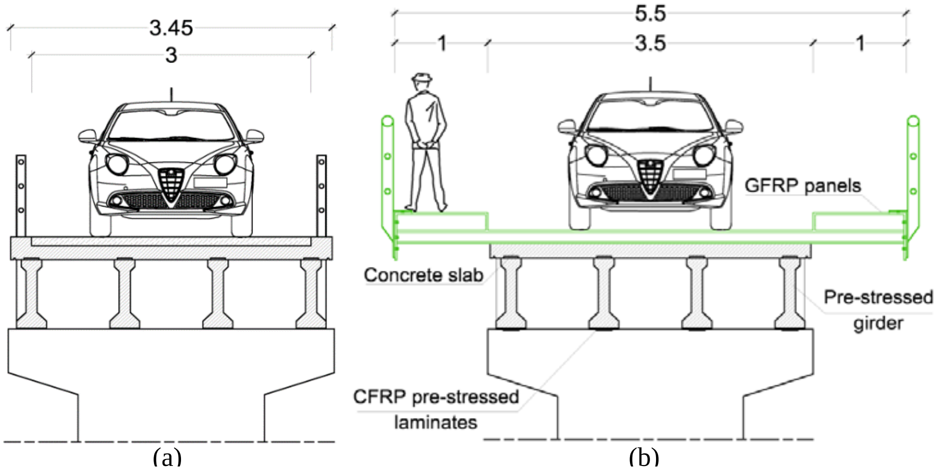


Figure 6. (a) Existing cross section, (b) widened cross section.

Table 1 shows the demand and capacity in terms of bending moment of the composite section obtained by using GFRP panels or CFRP laminates only, and the SUREBridge solution, which uses both. The benefits of the SUREBridge solution are clear: the ultimate bending moment can be increased by nearly 80% from 721 to 1298 kN·m, above the design value of 1291 kN·m. Furthermore, using the GFRP panels only would require very thick panels, while using CFRP only would imply too many laminates, with resulting economical and executive problems in both cases. In addition, the transverse disposition of the GFRP panels is needed to increase the bending moment of the concrete deck in that direction; adding only the GFRP panels in the transverse direction on the top of the section, would provide a proper strength for the internal girders, but it would not be sufficient for the damaged border girder.

Table 1. Required bending moment capacity of case study bridge and the design capacity strengthened with SUREBridge solution

Section	**Demand** **M_{sd} (kN·m)**	**Capacity** **M_{rd} (kN·m)**			
	Widened bridge	Existing section	+ GFRP	+ CFRP	+ GFRP + CFRP
Internal girder	1313	992	1342 (1)	1373 (3)	1418 (1) (5)
Border girder	1291	956	1296 (1)	1326 (3)	1379 (1) (5)
Damaged border girder	1291	721	1311 (2)	1395 (4)	1298 (1) (3)

(1) GFRP panel: H = 150 mm, webs in the transverse direction;
(2) GFRP panel: H = 200 mm, webs in the longitudinal direction;
(3) CFRP laminate: No. 4 laminates 80 mm x 1.4 mm;
(4) CFRP laminate: No. 6 laminates 80 mm x 1.4 mm;
(5) CFRP laminate: No. 3 laminates 80 mm x 1.4 mm.

4 CONCLUSION AND FURTHER STUDY

The SUREBridge solution aims to provide a strengthening approach for road bridges by using FRP materials. The lab test of RC beam that externally boned with stepwise prestressed CFRP demonstrated the achievement of a gradual decreasing profile of prestressing force towards the CFRP ends. The case study of applying SUREBridge solution to San Miniato bridge showed the efficiency of upgrading the load bearing capacity of deficient bridge.

Further study would include the full-scale test of prototype beams strengthened with SUREBridge solution originated from the geometry of San Miniato bridge. The experimental test will a) provide more evidence of the efficiency of this solution, b) be use to verify the modeling in FE analysis for optimal design, and c) help to develop a theoretical model to predict the ultimate bending capacity of strengthened cross-sections.

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6 REFERENCES

CNR-DT 200 R1/2013. 2014. Istruzioni per la Progettazione, l'Esecuzione ed il Controllo di Interventi di Consolidamento Statico mediante l'utilizzo di Compositi Fibrorinforzati. Roma: Consiglio Nazionale delle Ricerche.

fib - federation internationale du betonbeton, 2013. fib Model Code for Concrete Structures 2010 (John Wiley & Sons).

Haghani, R., and Al-Emrani, M. (2016). A New Method for Application of Pre-stressed FRP laminates for Strengthening of Concrete Structures. IABSE Congr. Stockh.

Haghani, R., Al-Emrani, M., and Kliger, R. (2009). Interfacial stress analysis of geometrically modified adhesive joints in steel beams strengthened with FRP laminates. Constr. Build. Mater. 23, 1413–1422.

Haghani, R., Al-Emrani, M., and Kliger, R. (2015). A new method for strengtheng concrete structures using prestressed FRP laminates. pp. 1153–1158.

Meier, U., and Stöcklin, I. (2006). A novel Carbon Fiber Reinforced Polymer (CFRP) system for post-strengthening. pp. 477–479.

PANTURA Project, Deliverable D5.3, Needs for maintenance and refurbishment of bridges in urban environments, FP7 Program, 2011-2014.

SUREBridge – Sustainable Refurbishment of Existing Bridges. 2016a. Deliverable D4.1 – Standard operating procedure for the assessment of existing bridges.

SUREBridge – Sustainable Refurbishment of Existing Bridges. 2016b. Deliverable D4.1 – Appendix – Assessment of San Miniato bridge.

Stöcklin, I., and Meier, U. (2001). Strengthening of concrete structures with prestressed and gradually anchored CFRP strips. In FRPRCS-5: Fibre-Reinforced Plastics for Reinforced Concrete Structures Volume 1, (Thomas Telford Publishing), pp. 291–296.

Valvo, PS, Davini, E, Alocci, C, Pasquale, A, Ricci, F, Miranda Santos, JC, Veltkamp, M, and Haghani, R, 2017, The European project SUREBridge – A case study in Tuscany, AIMETA 2017 – 23rd Congress of the Italian Association of Theoretical and Applied Mechanics (Salerno, Italy, 4–7 September 2017).

Veltkamp, M., and Peeters, J. (2014). Hybrid bridge structure composed of fibre reinforced polymers and steel. Struct. Eng. Int. J. Int. Assoc. Bridge Struct. Eng. IABSE 24, 425–427.