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APPLICATION OF PRE-STRESSED UN-BONDED CFRP FOR STRENGTHENING OF METALLIC STRUCTURES

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ABSTRACT

Application of carbon fiber-reinforced polymer (CFRP) composites for retrofitting reinforced concrete structures has been extensively investigated and used in practice. Many studies demonstrated the beneficial influence of such composite materials for the flexural and shear strengthening of concrete girders, as well as for confinement of concrete columns. However, the strengthening techniques and the accompanying theories for metallic structures have not been developed as thoroughly as those for concrete structures. There are several differences between the behavior of bonded joints in CFRP-strengthened concrete and metallic members, which will be briefly explained in this paper. Furthermore, one of the main aims of the paper is to give an overview on different techniques for carbon-fibre reinforced polymer (CFRP) strengthening of steel plates and beams. Different bonded and un-bonded retrofit systems will be discussed with particular focus on application of pre-stressed un-bonded retrofit (PUR) systems. Furthermore, some details about design and testing procedure of a new so called flat PUR (FPUR) system will be given. Finally, the paper gives some details about CFRP strengthening and wireless sensor monitoring of two old metallic bridges in Switzerland and Australia.

KEYWORDS

Carbon Fiber-reinforced Polymer (CFRP), Steel strengthening, Fatigue, Prestressing, Bonded, Pre-stressed Un-bonded Reinforcement.

INTRODUCTION

Application of carbon fiber-reinforced polymer (CFRP) composites for retrofitting reinforced concrete structures has been extensively investigated and used in practice. Many studies demonstrated the beneficial influence of such composite strips for the flexural and shear strengthening of concrete girders, as well as for confinement of concrete columns. However, the required theories and strengthening techniques for steel structures have not been developed as thoroughly as those for concrete structures (e.g., Ghafoori and Motavalli 2015b & c & a). There are several differences between the behavior of bonded joints in CFRP-strengthened concrete and metallic members, which will be briefly explained in this section.

Key differences between strengthening of steel and concrete structures

Failure mode: The main difference between CFRP–steel and CFRP–concrete bonded joints is that in the former, failure will likely occur in the adhesive layer and in the latter failure is expected to occur in the concrete substrate, proving proper surface preparation. Therefore, by providing an adequate bond length, the optimal bond strength is dependent on the fracture energy of the adhesive for the former and the fracture energy of the concrete substrate for the latter. In the FRP-strengthened steel structures, interfacial failure should happen within the adhesive layer in the form of cohesion failure to maximize the effectiveness of FRP strengthening and minimize variations of the interfacial bond capacity as a result of different surface preparations. Furthermore, it has been observed that the inappropriate surface preparation of the steel substrate prior to the bond application will result in an adhesion failure at the steel-to-adhesive interface (Fernando 2010). Assuming the adhesive as the weakest point of a CFRP-steel bond joint, Ghafoori and Motavalli 2016a have developed a prestressed unbonded reinforcement (PUR) system that can be used as an alternative to the bonded CFRP reinforcement. The developed PUR system functions without using an adhesive layer, hence the performance of the system is no longer dependent on the fracture energy of the adhesive. Strengthening using the PUR system is recommended for cases when the surface of the structure, which has to be retrofitted, is not smooth enough to be bonded to CFRP plates, or when there is a concern about the effects of high ambient temperatures, moisture, freeze/thaw cycles or fatigue behavior of the bonded CFRP-to-metal joint.

Stiffness and deformations: Recent experimental and numerical studies at Empa (Ghafoori and Motavalli 2015b & c) have shown that strengthening of steel beams with pre-stressed CFRP strips does not increase the stiffness of the retrofitted member significantly. This finding is in contrast to retrofitted concrete beams, in which the flexural and/or flexural-shear cracks are often initiated at even service load levels. In the latter case, applying pre-stressed laminates to the tension face of the member can close the existing cracks more efficiently than non-pre-stressed laminates, and thereby, the depth of the compression zone in the concrete beam is increased, which results in an increased stiffness. For the same reason, i.e. increasing the effective depth of the cross-section, utilizing pre-stressed laminates can increase the stiffness of the cracked steel members. Therefore, one of the main difference between the behavior of the CFRP bonded concrete and steel beams is that in the former the cracks are initiated at relatively low load levels in the tension face of the concrete beams, and the bonded CFRP laminate tends to keep the cracks close. However, in the latter, no crack initiates in the steel even after yielding, and the role of an adhesive layer between the CFRP laminate and the steel substrate is limited to transferring the shear stresses from the steel substrate to the CFRP laminate along the connection.

DIFFERENT CFRP RETROFITS SYSTEMS FOR STEEL STRUCTURES

Strengthening steel structures using pre-stressed bonded CFRP composites

Ghafoori and Motavalli 2015c have used bonded non-prestressed normal modulus (NM), high modulus (HM) and ultra-high modulus (UHM) CFRP strips for flexural strengthening of steel beams. It has been shown that UHM CFRP strips are effective in increasing the stiffness of the metallic girders and reducing the flexural deformations. Metallic members have been traditionally strengthened using non-pre-stressed CFRP plates. However, in non-pre-stressed retrofit systems, the dead loads are not transferred to the CFRP plates and only a portion of the live load is transferred to the CFRP plates. As an alternative, by using pre-stressed CFRP plates, a portion of the dead load is transferred to the CFRP plates in addition to the live load (Ghafoori 2013, Ghafoori and Motavalli 2013). It has been shown that prestressed CFRP strips can increase the flexural yield and ultimate load capacity of steel beams substantially. Ghafoori and Motavalli 2015b have shown that prestressed CFRP strips can be used for strengthening of steel beams that are prone to lateral-torsional buckling (LTB) to increase the LTB capacity. Moreover, Ghafoori et al. 2012b studied the performance of notched steel beams retrofitted with CFRP patches under high-cycle fatigue loading regime. The test results for a four-point bending test scheme with a cyclic loading frequency of 4.2 Hz showed that the application of CFRP reinforcements extended the fatigue life substantially, and in some cases, a complete fatigue crack arrest was achieved.

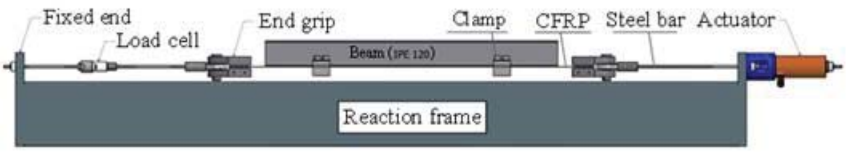
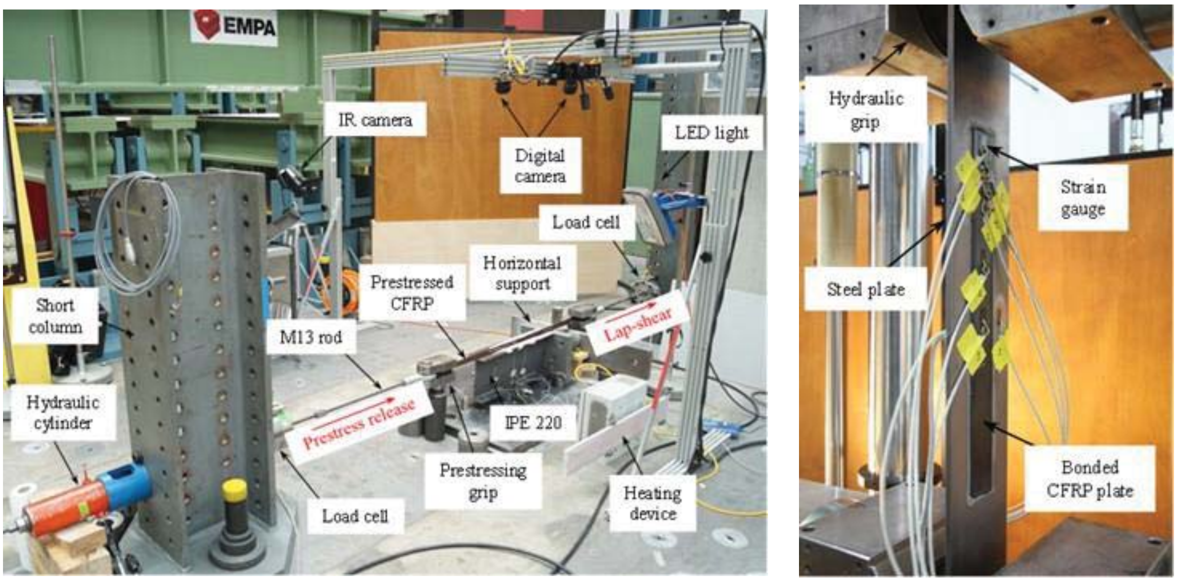


Figure 1. Elements of the pre-stressing set-up, which uses an independent reaction frame to pull the CFRP strip (Ghafoori and Motavalli 2015b).

Through an ongoing research topic at the Structural Engineering Research Laboratory of Empa, a setup for lap-shear and prestress release tests has been developed (see Figure 2a) to investigate the bond behavior of non-prestressed and prestressed CFRP plates to the steel substrate. The designed test setup allows lap-shear and prestress release tests to be systematically performed, while the test be monitored using a 3D digital image correlation (DIC) system. Based on the experimental results and 3D DIC measurements, performed on a set of lap-shear and prestress release tests using the aforementioned setup, it has been demonstrated that accelerated curing of the epoxy adhesive by heating, as an alternative to the conventional cold curing, leads to the same lap-shear strength as room-temperature cured CFRP-to-steel joints. Furthermore, in room-temperature cured joints, the debonding load of prestress release tests is slightly lower than that of lap-shear tests, because of the mixed-mode (I/II) state of the stresses within the bond in a prestress release test (Hosseini et al. 2017b).

It is known that although the existing knowledge on the bond behaviour of CFRP-to-steel obtained through lap-shear tests is crucial to realize the load transfer mechanism; the available models cannot be directly used for the strengthening of steel tensile members using prestressed CFRP plates. Thus, the bond behaviour of non-prestressed and prestressed CFRP plates to the steel substrate has been also studied using CFRP-strengthened steel plates under uniaxial tensile loading (See Figure 2b). An analytical model was developed by Hosseini et al. (2016) to predict the strain in steel and CFRP plates, which its predictions found to be in a good correlation with the performed experiments on CFRP-strengthened steel plates under uniaxial tension. Both the results of the analytical modelling and experimental tests revealed that neglecting the eccentricity in single-side CFRP-reinforced steel members, leads to an unsafe prediction of the stress levels in steel (Hosseini et al. 2017a).

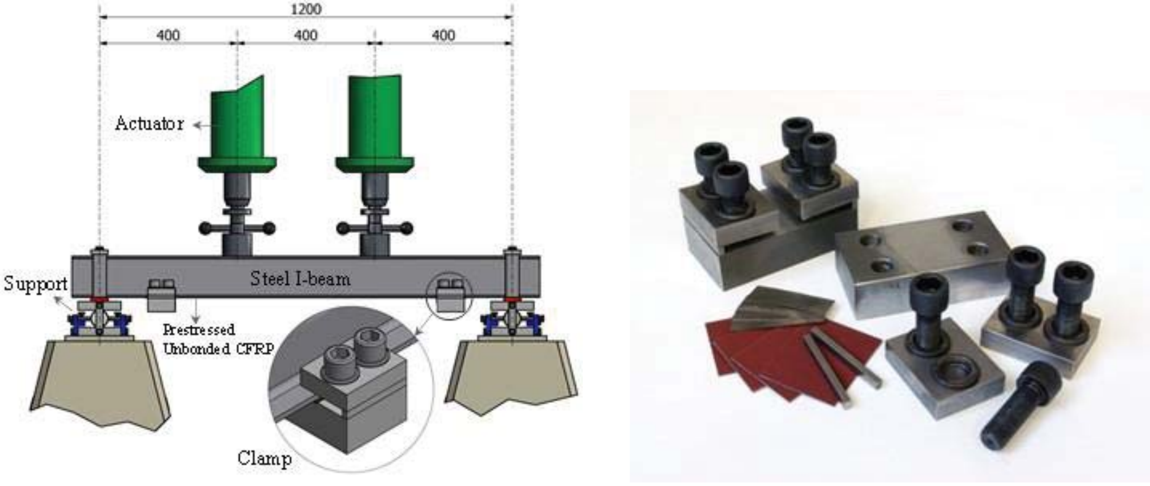


(a) (b)

Figure 2. (a) Lap-shear and prestress release test setup developed at Empa (Hosseini et al. 2017b). (b) Bonded CFRP-strengthened steel plate under uniaxial tensile loading (Hosseini et al. 2016).

Strengthening steel structures with prestressed unbonded CFRP composites

The majority of the existing research on CFRP strengthening of metallic members has used CFRP materials bonded to the steel substrate. As it has been discussed before, the efficiency of the bonded retrofit system is mainly dependent on the behavior of the CFRP-to-steel bond joint, while the bond strength is limited due to the premature debonding failure. Sophisticated surface preparation is required prior to bonding the CFRP to the steel member to maximize the efficiency of the composite system and reduce the risk of interface debonding.



(a) (b)

Figure 3. a) Test set-up (all dimensions in mm), b) components of the mechanical anchorage system (Ghafoori and Motavalli 2015b).

Many studies have raised concerns about the influence of environmental conditions (e.g., elevated or subzero temperatures, water and moisture and ultraviolet light) and dynamic loads (e.g., fatigue, impacts and earthquakes) on the behavior of the CFRP-to-steel bond joint. Because of these concerns, which are mainly associated with the long-term performance of the CFRP-to-steel bond joints, a pre-stressed un-bonded retrofit (PUR) system has been recently designed and tested at Empa (Ghafoori and Motavalli 2015b & c & a). In contrast to the pre-stressed bonded reinforcement (PBR) systems, the PUR system works without relying on the bond; instead, it uses a pair of friction-clamps to hold the prestressed CFRP plates to the steel member. An independent reaction frame to pull the CFRP strips was developed, as shown in Figure 1. The pre-stressed CFRP strip was then attached to the steel beam using mechanical clamps. The force in the actuator was then released and the extra CFRP strip, out of the mechanical clamps, was cut.

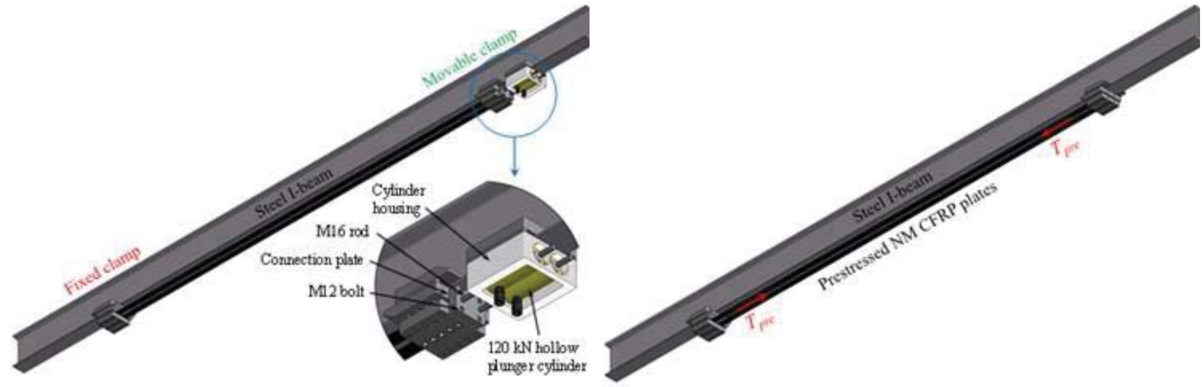
The retrofitted beams were tested in a four-point bending static loading test set-up, as shown in Figure 3a. Figure 3b depicts the elements of the mechanical anchorage system. It has been shown that prestressed unbonded and bonded CFRP strip have almost an identical effect on the stiffness improvement of steel beams. Prestressed unbonded CFRP strips could, however, prevent fatigue crack initiation (Ghafoori et al. 2015c) and propagation (Aljabar et al. 2016, Ghafoori et al. 2012a, Ghafoori and Motavalli 2016b, Hosseini et al. 2017a) in steel plates and beams. In summary, the results of the extensive tests have shown that the static and fatigue behavior of steel beams are strongly governed by the prestress level in the CFRP strip, rather than the effect of the adhesive bonding. Bonded and unbonded systems have shown relatively similar results, particularly in the linear-elastic domain (Ghafoori 2015).

Figure 4. Different elements of the trapezoidal retrofit system: a) initial state of the beam, b) clamps are fixed, and the CFRP plates are placed between the two clamps, c) using pre-stressing chair, the saddle pushes the CFRP plates away from the beam that induces pre-stress in the CFRP plates, d) two plates are positioned between the beam and the saddle, and e) the pre-stress chair is removed (Ghafoori and Motavalli 2015a).

Figure 3a shows a PUR system with straight CFRP strips. Ghafoori and Motavalli 2015a have recently developed and patented a trapezoidal PUR system for strengthening of a historical metallic railway bridge in Switzerland. A summary of the prestressing procedure is explained as follows. Assume an I-beam as shown in Figure 4a. First, the mechanical clamps are placed near two ends of the beam, and three parallel CFRP plates are placed and tightened inside the clamps, as shown in Figure 4b.

Each CFRP plate has dimensions of 50 mm width and 1.2 mm thickness. Each friction clamp is consisted of a lower plate, a middle plate and two upper plates. The middle and the lower plates consist of three hard plates, which provide a uniform stress distribution along the CFRP anchorage length. Each CFRP plate is anchored between the lower plate and the middle plate and is subjected to compressive force, which is applied by pre-tensioned bolts. The beam flange is also gripped between the middle plate and the upper plates and subjected to the compressive force of pre-tensioned bolts. A pre-stressing chair is used to increase the eccentricity between CFRP plates and steel beam, as shown in Figure 4c.

The pre-stressing chair consists of a saddle that can move along two vertical threaded bars. The distance between the saddle and the beam can be manually changed by turning the threaded rods using a wrench. Thus, by turning the threaded rods, the saddle pushes the CFRP plates away from the beam, and the CFRP pre-stress is increased. A larger eccentricity between the CFRP plates and the beam corresponds to a larger CFRP pre-stress level. After the desired pre-stress level is achieved, two plates are placed between the CFRP plates and the beam (see Figure 4d). Each plate is positioned between the saddle and a shoe. The two shoes are connected by two steel bars and four nuts, as shown in Figure 4e, and then the pre-stressing chair is removed. Figure 4e shows the final configuration of the strengthened beam. More details can be found in Ghafoori and Motavalli 2015a, Ghafoori et al. 2015a. More recently, Kianmofrad et al. 2017) have suggested four different variants of the prestressed PUR systems: trapezoidal PUR (TPUR), triangular PUR (TriPUR), flat PUR (FPUR), and contact PUR (CPUR) systems for steel I-beams, while another PUR system for fatigue strengthening of tensile steel members has been introduced at Empa by Hosseini et al. 2017a. The behavior of each system has been examined using numerical, analytical and experimental investigations and, certain advantages and drawbacks of each system have been discussed.



(a) (b)

Figure 5. The FPUR system: (a) installation of the prestressing system and applying the required prestressing level; (b) fastening the movable clamp and removing the prestressing system (Hosseini et al. 2018).

Furthermore, Hosseini et al. 2018 have developed and tested a FPUR system. The FPUR system relies on two sets of mechanical clamps i.e. the so called *fixed clamp* on one side, and the *movable clamp* on the other side of the beam (Figure 5). The two sets of the mechanical clamps are capable of transferring the prestressing force of the CFRP plates to the lower flange of a metallic I-shaped girder via friction. Each set of the mechanical clamps holds two prestressed normal modulus (NM) CFRP plates with cross-sectional dimensions of 50 × 1.4 mm (width × thickness). The strengthening procedure using the proposed FPUR system consists of the following three steps:

1) Installation of the mechanical clamps and the non-prestressed CFRP plates (see Figure 5): on both sides of the beam, the unstressed CFRP plates are sandwiched between 16-mm thick toothed plates installed inside the *lower plate* and *upper plate* with five prestressed bolts. The bolts generate a total gripping force. On one side of the beam (left side in Figure 5) the beam bottom flange is sandwiched between the upper plate and the over-flange plate by fastening eight bolts. This results in a full gripping force between the *fixed clamp* set and the beam bottom flange. On the other side of the beam, the unstressed CFRP plates are sandwiched in the *movable clamp*, while this clamp set is free to move horizontally along the beam axis for prestressing.
2) Installation of the prestressing system, applying the required prestressing force, and fastening the movable clamp (see Figure 5a): two hollow plunger cylinders are installed adjacent to the *movable clamp* using especial cylinder housing. The cylinder housing is anchored to the beam bottom flange in a similar way as the *fixed clamp* set. With the help of two threaded rods, the *movable clamp* can be pulled using the hollow plunger cylinders connected to a manual hydraulic pump, and subsequently, the CFRP plates can be prestressed. Upon reaching the desired prestressing level in the CFRP plates all the eight bolts of the *movable clamp* will be tightened, which leads to the design gripping force between the mechanical clamping system and the beam flange.
3) Removing the prestressing system to realize the final configuration as depicted in Figure 5b: after reaching the desired prestressing force in the CFRP plates, the hydraulic pressure can be released and the entire prestressing system consisting of the two hollow plunger cylinders and the cylinder housing can be removed.

STRENGTHENING OF METALLIC BRIDGES

Strengthening of a railway riveted bridge in Switzerland

The Münchenstein Bridge was constructed in 1875 by G. Eiffel. The bridge is located near Basel City over the river Birs in Switzerland. In 1891, after 15 years of service, the bridge suddenly collapsed when a passenger train was passing across it. The disaster took the lives of 73 passengers and is historically the worst railway accident ever in Switzerland. A single-span riveted bridge was then constructed in 1892, as a replacement for the collapsed one. The bridge, as shown in Figure 6a, consists of 10 frames and was constructed approximately 5 m above the water level. The total length of the bridge is approximately 45.2 m. The bridge is subjected daily to both passenger and freight trains. After successful laboratory tests of the TPUR system (see Figure 4), several cross-girders of the bridge were strengthened with the system. Figure 6b shows a riveted cross-girder of the bridge after strengthening. Furthermore, to ensure no slip occurs between the CFRP plates and the clamps and also between the friction clamps and the metallic beams, one strain gauge was glued on each CFRP plate and the prestrain level was monitored using a wireless sensor network (WSN) system. Because strain gauges do not automatically compensate for temperature, for each active strain gauge, a dummy strain gauge was used to compensate for the effects of temperature variations. The dummy strain gauges, which are identical to the active strain gauges, were mounted to unstrained CFRP plates and placed near the active gauges. To account for the temperature effects, the dummy strain gauges were wired into a Wheatstone bridge on an arm adjacent to the active strain gauge.

(a) (b)

Figure 6. (a) Münchenstein railway metallic Bridge (120-year-old) subjected to a passenger train. The bridge consists of 10 panels with the total length of 45.2 m, width of 5 m and height of 6.15 m and built on a 45-deg skew. (b) The cross-girders were retrofitted with pre-stressed un-bonded CFRP strips (Ghafoori et al. 2015b).

Strengthening of a roadway metallic bridge in Australia

After successful laboratory tests on the FPUR system (see Figure 5), the system was applied on two cross girders of a roadway metallic bridge called SN6091 Bridge over Diamond-Creek along Heidelberg-Kinglake Road in Victoria, Australia (see Figure 7a). The steel I-shaped cross girders were strengthened with the proposed FPUR system having a prestressing level of about 38%. A WSN system was installed on the bridge for long-term monitoring of the strain levels in prestressed CFRP plates. Figure 7b shows the applied FPUR and the WSN systems on the cross girders of the so called Diamond-Creek Bridge. Sets of truck loading (e.g., see Figure 7a) were performed before and after strengthening of the bridge, which showed the effectiveness of the FPUR system to reduce the bending stresses in the bottom flange of the girders (Ghafoori et al. 2018). The long-term performance of the system will be monitored at least for one year using the installed WSN system.

(a) (b)

Figure 7. (a) Diamond-Creek Bridge, Melbourne, Australia, (b) application of the FPUR system for CFRP strengthening of the bridge cross-girders (Ghafoori et al. 2018).

CONCLUSIONS

The two main differences between the behaviour of CFRP–concrete and CFRP–metal bonded members are concerned with the failure mode and the stiffness of the retrofitted members. These differences resulted in the development of different CFRP prestressing concepts for strengthening of concrete and metallic members, which were briefly explained in this paper. For strengthening of metallic members, laboratory test results showed that adhesive bond does not significantly improve the static and fatigue behaviour of retrofitted steel beams; however, CFRP prestressing plays an important role. Therefore, in order to minimize the concerns related to effects of high ambient temperatures, moisture, freeze/thaw cycles or fatigue loading on the performance of the CFRP-to-metal bonded joints, a PUR system has been recently developed. The PUR system includes a novel friction-based mechanical clamping system for strengthening of metallic I-beams. Furthermore, some details about strengthening of a 120-year-old railway metallic bridge in Switzerland as well as an old roadway bridge in Australia using prestressed unbonded CFRP strips were given.

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