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REPAIR AND STRENGTHENING OF STEEL STRUCTURES USING CFRP COMPOSITES: AN OVERVIEW

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ABSTRACT

Since decades, carbon fiber-reinforced polymer (CFRP) composites have been used for strengthening of concrete structures, for which the required design theories and techniques have been well developed. However, strengthening of steel structures still requires further development of relevant theories and techniques. In this paper, the main differences in design requirements for CFRP strengthening of concrete and steel members are discussed. In addition, an overview on the research at Empa on non-prestressed/prestressed bonded/ubonded strengthening systems using CFRP plates and rods for steel girders, plates and connections is given, and, a few projects for real application of the developed systems in steel bridges are briefly explained.

KEYWORDS

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

INTRODUCTION

Theoretical and technical requirements for application of carbon fiber-reinforced polymer (CFRP) composites for flexural and shear strengthening of concrete girders and columns have been extensively developed. However, such theories and techniques developed for concrete members are not necessarily applicable to steel structures (Ghafoori and Motavalli, 2015a-c). It stems from the fact that failure modes and structural behavior in terms of stiffness and deformation for steel and concrete members are different. In concrete members, failure is likely to occur in concrete substrate, while in steel members, the adhesive layer is prone to failure. In other words, in CFRP-strengthened steel members, fracture energy of the adhesive is the failure controlling parameter, while for such concrete members, fracture energy of the substrate (i.e., concrete) determines the failure. In addition, due to low tensile strength of concrete, flexural and/or flexural-shear cracks initiate at even service load, which results in stiffness reduction and deformation increase in concrete members. In this case, application of CFRP composites helps keeping the cracks closed and controlling the member deformations by carrying loads in tension face of the member. Application of prestressed CFRP reinforcements can bring further improvement by providing precompression to the concrete member. In steel structures, however, cracks are not developed even after yielding. Addition of CFRP reinforcements to steel components does not increase the member stiffness significantly (Ghafoori and Motavalli, 2015b-c). Therefore, application of prestressed CFRP reinforcements can be a more effective solution for steel structures. These considerations make a significant difference in design requirements for development of strengthening systems for steel and concrete members.

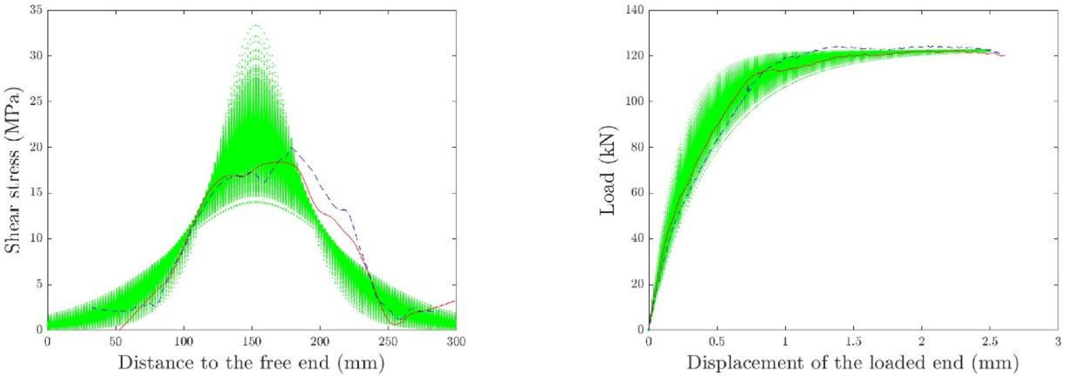
Effectiveness of strengthened steel members with bonded CFRP materials is mainly dependent on the bond strength. Characterization of proper adhesive, required bond length, bond strength, and effect of strengthening on the steel members has been investigated in various research studies in recent years (e.g., Li et al., 2022; Martinelli et al., 2019; Ghafoori et al., 2015c). In order to eliminate the dependence on the bond between CFRP and steel member, Ghafoori and Motavalli, 2016 introduced a prestressed unbonded reinforcement (PUR) system, which functioned purely through friction. Unbonded strengthening systems are more appropriate solutions for the cases, where the structure surface is not smooth to bond the CFRP plate, or when high ambient temperatures, moisture, freeze/thaw cycles or fatigue affect the behavior of CFRP-to-steel bonded joints. For unbonded strengthening systems, development of safe friction-based anchorages is essential. In the recent years, various types of mechanical unbonded anchorages for prestressed and non-prestressed CFRP plates and rods have been developed (Ghafoori and Motavalli, 2015a; Heydarinouri et al., 2021b; Hosseini et al., 2018b).

In this paper, the latest strengthening techniques developed for steel girders and connections using prestressed/non-prestressed bonded/unbonded CFRP plates and rods are introduced, and the results of numerical and experimental studies are briefly discussed. In addition, pilot applications of the developed systems for strengthening of steel bridge girders and connections are given.

PRESTRESSED AND NON-PRESTRESSED BONDED CFRP SYSTEMS

CFRP-to-steel interface bond behavior at ultimate loads

In bonded strengthening system, normal modulus CFRP can be used for both non-prestressed and prestressed strengthening, while ultra-high modulus CFRP is typically used for non-prestressed strengthening. Martinelli et al., 2019 examined the bond capacity of CFRP-steel interface, i.e., ultimate limit state, during the release of prestress, and found that the bond capacity at prestress release is lower than that of a bonded joint without any prestress force. The reduced bond capacity is attributed to the mixed-mode I/II (i.e., tensile/shear) fracture behavior of the bonded joint, with the presence of prestress force. When computing a bonded CFRP strengthening system, material properties are commonly defined as deterministic values. However, such properties in practice have an actual range, rather than single values. This brings some level of inaccuracy when a deterministic model is used. To account for the uncertainties involved in reality, Li et al., 2022 conducted a stochastic analysis on CFRP-to-steel bonded joints, based on which a stochastic model was proposed to predict a range for bond interface behavior, as depicted in Figure 1.



(a) Fully developed shear stress profile (b) Load-displacement behavior

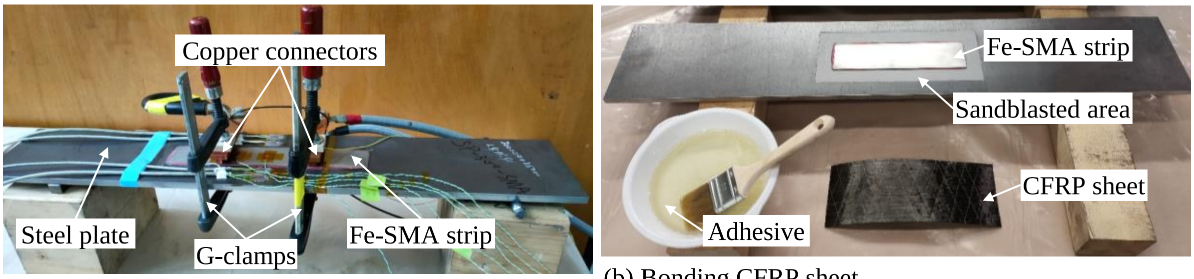
Figure 1. The predicted stochastic bond behavior (green dots) vs. experimental measurements, where red and blue curves represent two types of measurements using digital image correlation (DIC) and fiber optics (FO) (Li et al., 2022).

Effect of prestressing and stiffness of bonded CFRP plates at service loads

Ghafoori et al., 2015c employed bonded non-prestressed CFRP strips with different moduli for flexural strengthening of steel beams. It was found that the ultra-high modulus CFRP can effectively enhance the flexural stiffness of the steel beam and reduce the deflection, however, with a higher chance of debonding. Ghafoori et al., 2012b tested the fatigue life of notched steel beams, which were strengthened by bonded non-prestressed and prestressed CFRP plates, under high-cycle fatigue loading regimes. It was found that bonding prestressed CFRP plates can much more efficiently enhance the fatigue lives of cracked steel beams than non-prestressed CFRP plates. To better understand the behavior of the adhesive bond in the CFRP strengthening system, Ghafoori, 2013 derived an analytical model to compute the shear stress distribution of CFRP strengthened steel beams. The solution can be applied to both non-prestress and prestressed cases, with properly defined boundary conditions.

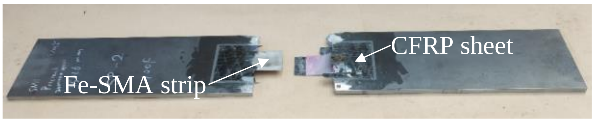
Fe-SMA/CFRP bonded patches for repair of fatigue cracks

The behavior shape memory alloy (SMA)-to-steel bonded joints has been experimentally and numerically investigated in previous studies (Li et al., 2023a; Li et al., 2023b; Wang et al., 2021a). As a new bonded system, an adhesively bonded patch composed of iron-based shape memory alloy (Fe-SMA) strips and CFRP sheets, i.e., Fe-SMA/CFRP bonded patch, was developed for repair of fatigue cracks in steel structures. An experimental study on cracked steel plates repaired with Fe-SMA/CFRP bonded patches was conducted. The repair solution consisted of following steps: (1) prestrained Fe-SMA strips were bonded on both sides of the steel plates over the cracks using SikaPower-1277 adhesive, (2) the Fe-SMA was activated using an electric resistant heating method, as shown in Figure 2a. The target activation temperature in the study was 180 ℃. By activation, i.e., a heating and subsequent cooling process, prestress was generated in the Fe-SMA strip. (3) CFRP sheets (S&P C-sheet 240) were then bonded using adhesive S&P Resin 55 HP, covering the Fe-SMA strips, as shown in Figure 2b.



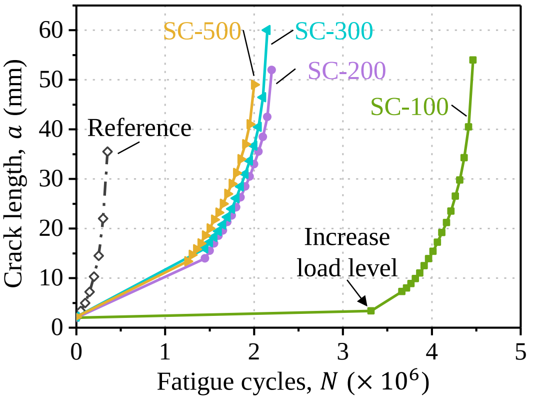
(a) Activation of bonded Fe-SMA strip

(b) Bonding CFRP sheet



(c) Failure mode of SC-100: Fe-SMA debonding + CFRP fracture +CFRP debonding

(d) Failure mode of SC-300: Fe-SMA and CFRP fracture + Fe-SMA and CFRP partial debonding



(e) $a - N$ curves of fatigue tests

Figure 2: Experimental study on cracked steel plates strengthened using Fe-SMA/CFRP bonded patches. (a) Activation of bonded Fe-SMA strip. (b) Bonding CFRP sheet. (c, d) Failure modes after fatigue tests. (e) Fatigue life of unstrengthened and strengthened specimens.

Fatigue tests were performed on an unstrengthened and four strengthened specimens (labelled as reference, SC-100, SC-200, SC-300, and SC-500, respectively). The dimensions of steel plates were 850 × 150 × 10 mm. The Fe-SMA strips had a width of 50 mm and thickness of 1.5 mm, whereas the length of the Fe-SMA strip was 100, 200, 300, and 500 mm, respectively. The middle half length of the Fe-SMA was activated while the two ends functioning as anchorage during activation. The CFRP sheets had a width of 90 mm and thickness of 0.113 mm, whereas the length varied with the Fe-SMA length with an additional 40 mm. The label “SC” means specimens strengthened with Fe-SMA/CFRP bonded patch and the subsequent number indicates the length of the Fe-SMA strip.

Failure modes of the strengthened specimens observed in the tests were Fe-SMA debonding, CFRP debonding, Fe-SMA fracture, and CFRP fracture, as shown in Figure 2c and d. Moreover, the failure mode was related to the patch length. Specimens strengthened with Fe-SMA/CFRP bonded patches exhibited fatigue life extensions of greater than 5.5 times, and even crack arrest could be achieved, as shown in Figure 2e. The study demonstrated the effectiveness of the Fe-SMA/CFRP bonded patches for repair of fatigue cracks.

PRESTRESSED UNBONDED REINFORCEMENT (PUR) SYSTEMS

Available research has raised some concerns about the influence of environmental exposure (e.g., elevated or subzero temperatures, water and moisture, and ultraviolet light) and dynamic loads (e.g., fatigue, impacts and earthquakes) on the long-term behavior and durability of CFRP composites bonded to steel substrate. Because of these concerns, which are mainly associated with the long-term performance of the CFRP-to-steel bond joints, a prestressed unbonded retrofit (PUR) system was introduced by Ghafoori and Motavalli, 2015a. Unlike the prestressed bonded reinforcement (PBR) solutions, the PUR system does not rely on adhesive bonding; instead, it utilizes a pair of friction clamps to secure the CFRP plates to the steel substrate. An independent reaction frame to pull the CFRP strip was developed, as shown in Figure 3. The prestressed CFRP strip was then clamped to the steel beam using mechanical fixtures. The force in the actuator was then released and the CFRP strip out of mechanical clamps was cut.

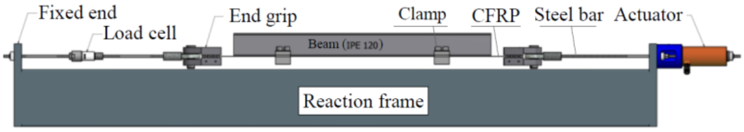


Figure 3. Various components of the prestressing setup, which uses an independent reaction frame to pull a CFRP plate (Ghafoori and Motavalli, 2015a).

The retrofitted beams were tested in a four-point bending static loading test set-up, as shown in Figure 4a. Figure 4b shows various components of the mechanical anchorage system. It has been shown that prestressed unbonded and bonded CFRP strip have almost identical effects on the behavior of CFRP-strengthened steel beams. Prestressed unbonded CFRP strips can prevent fatigue crack initiation (Ghafoori et al., 2015b) and propagation (Ghafoori et al., 2012a, Hosseini et al., 2017, Hosseini et al., 2019b) in steel members. In summary, extensive static and fatigue test results demonstrated that the behavior of steel beams are strongly governed by the prestress level in the CFRP strip, rather than the effect of the adhesive bond. Bonded and unbonded systems have shown relatively similar results, particularly in the linear-elastic domain (Ghafoori, 2015).

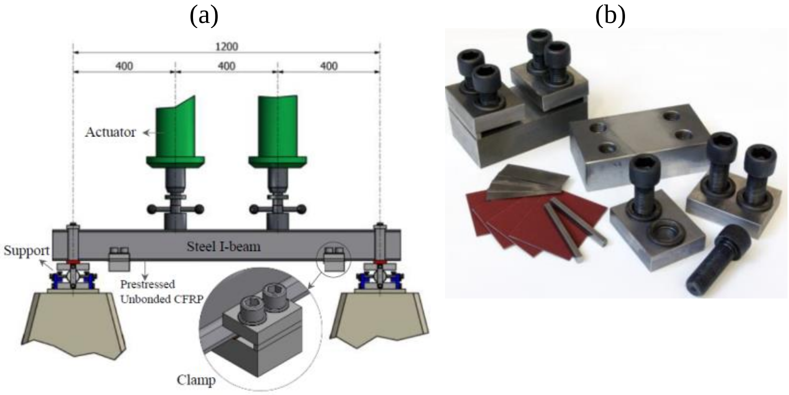


Figure 4. (a) Four-point bending test setup (all dimensions in mm); (b) various components of the mechanical anchorage system (Ghafoori and Motavalli, 2015a).

Trapezoidal PUR (TPUR) System

Figure 5a shows a PUR system with straight CFRP strips. Ghafoori and Motavalli, 2015a introduced a trapezoidal PUR (TPUR) system for strengthening a historical steel railway bridge in Switzerland (see Figure 5a). A summary of the prestressing procedure is explained as follows. Assume an I-girder as shown in Figure 3 (b). First, the mechanical clamps are placed near two extremities of the girder, and three parallel CFRP plates are placed and tightened inside the clamps. Each CFRP plate has dimensions of 50 mm by 1.2 mm (width × thickness). Each friction clamp consists 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 clamping force, which is applied by pre-tensioned bolts. The girder flange is also sandwiched 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 girder. After the desired pre-stress level is achieved, two plates are placed between the CFRP plates and the girder. Each plate is positioned between the saddle and a shoe. The two shoes are connected by two steel bars and four nuts, and then the pre-stressing chair is removed. Figure 5b shows the final configuration of the strengthened girder. More details can be found in Ghafoori and Motavalli, 2015a, Ghafoori et al., 2015a. The system has been then used for fatigue strengthening of a 125-year-old railway steel bridge in Switzerland (see Figure 5).

(a) (b)

Figure 5. (a) Münchenstein railway steel bridge (125-year-old) subjected to a passenger train; (b) TPUR system installed on the cross-girder (Ghafoori et al., 2015a).

Flat PUR (FPUR) system

Hosseini et al., 2018a developed a flat PUR (FPUR) system. As illustrated in Figure 6, the FPUR system relies on two sets of mechanical clamps i.e. a fixed clamp on one side, and a movable clamp on the other side of the beam. The two mechanical clamps are capable of transferring the prestressing force of the CFRP plates to the lower flange of a steel I-shaped girder via friction. Each set of 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 steps: (1) the unstressed CFRP plates are anchored on one side of the beam using the so called fixed clamp with the help of eight M20 high-strength (grade 12.9) bolts, which are tightened with a torque of 605 N·m, to generate a prestressing force of 223 kN per bolt; (2) On the other side, the unstressed CFRP plates are gripped in the so called movable clamp, while the clamp set is free to move horizontally along the beam axis; (3) Two 120-kN hollow plunger cylinders are then installed adjacent to the movable clamp using a cylinder housing; (4) With the help of two prestressing M16 rods, the movable clamp is pulled using the hollow plunger cylinders connected to a manual hydraulic pump, and, subsequently, the CFRP plates are prestressed; (5) Upon reaching the desired prestressing level in the CFRP plates, all the eight M20 bolts of the movable clamps are tightened; (6) Finally, the hydraulic pressure is released and the prestressing system consisting of the two hollow plunger cylinders and the housing are removed (Hosseini et al., 2018a).

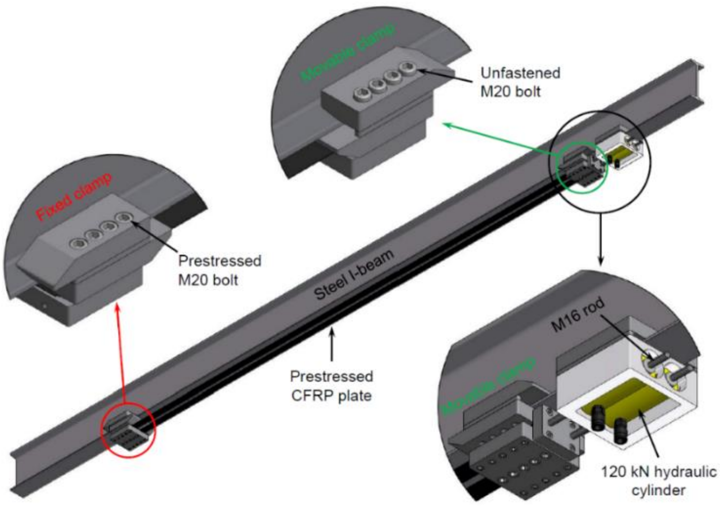


Figure 6. Various component of the flat prestressed unbonded reinforcement (FPUR) system (Hosseini et al., 2018a)

Various full-scale static and fatigue testing were conducted on the developed FPUR system at Empa using the test setup shown in Figure 7. Upon successful completion of those full-scale laboratory testing, the FPUR system was installed on two cross girders of a roadway steel bridge called SN6091 Bridge over Diamond-Creek along Heidelberg-Kinglake Road in Victoria, Australia (see Figure 8a). The steel I-shaped cross girders were strengthened with the proposed FPUR system having a prestressing level of approximately 38%. A wireless sensor network (WSN) was installed on the bridge for long-term monitoring of the strain levels in prestressed CFRP plates. Figure 8b shows the applied FPUR and the WSN systems on the cross girders of the so-called Diamond-Creek Bridge. Sets of truck loading (similar to Figure 8a) were conducted 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 (Hosseini et al., 2019a).

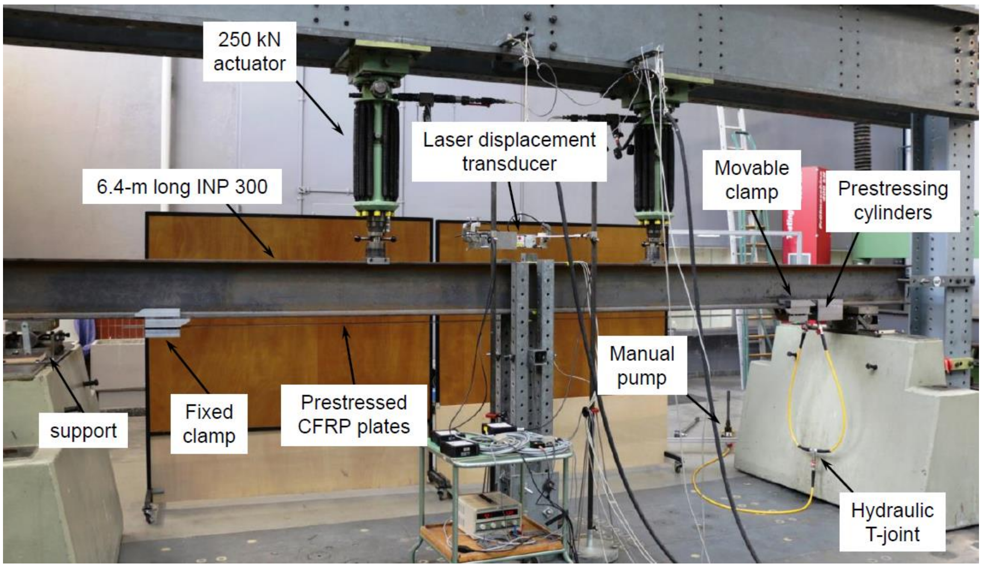


Figure 7. Four-point bending test setup used for the static and fatigue evaluation of the FPUR system (Hosseini et al., 2018a)

(a) (b)

Figure 8. Diamond-Creek Bridge: (a) 42.5-tonnes truck loading before and after strengthening; (b) application of FPUR system on two cross girders (Ghafoori et al., 2018).

Prestressed CFRP rods for strengthening of steel connections

Development of anchor system and laboratory tests

In steel bridges, stringer to floor-beam double-angle connections are among the most fatigue prone details (Haghani et al., 2012). In such connections, out-of-plane deformation of the angles results in distortion-induced stresses that can lead to fatigue cracks. To address this issue, a mechanical strengthening system using unbonded prestressed CFRP rods was developed (Heydarinouri et al., 2021b). The concept of the strengthening system is shown in Figure 9. The strengthening system consists of two main components: (a) a mechanical wedge-barrel anchorage that holds the prestressed CFRP rod, and (b) a clamping system that grabs the beam flange. Both components transmit the forces purely through friction.

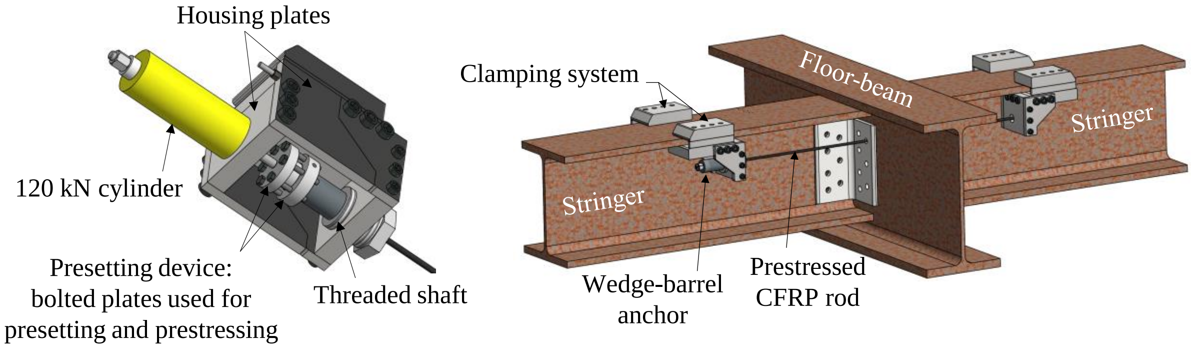
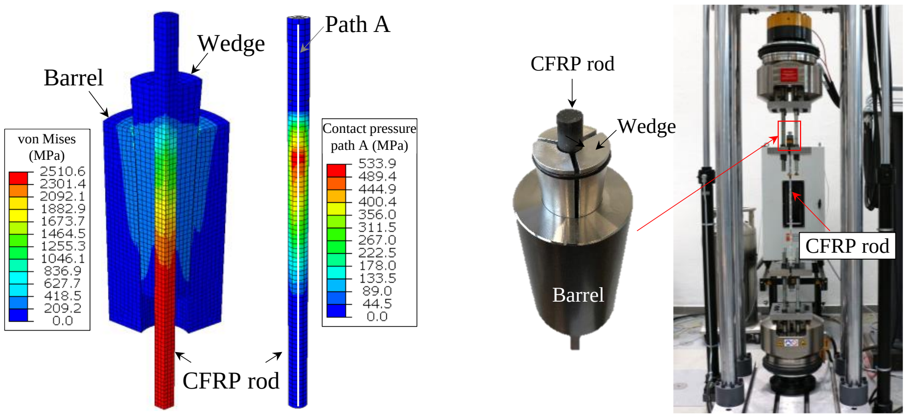


Figure 9: Concept of the mechanical strengthening system for stringer to floor-beam double-angle connections using prestressed CFRP rods

Installation of the strengthening system causes no interruption of traffic on the bridge and is implemented as follows (Heydarinouri et al., 2021b): The clamping systems on both sides of the floor beam are mounted by fastening the bolts. On one end of the CFRP rods, the wedge-barrel anchors are mounted, and the wedges are preset. Presetting of the wedges involves pushing the wedges into the barrel, before application of tensile load to the CFRP rods, which increases the contact pressure on the rod and ensures their friction resistance. The other ends of the rods are passed through the holes in the floor beam. On the other side of the floor beam, rods are anchored by wedges and barrels, and the wedges are preset using presetting device shown in Figure 9. In the last stage, two CFRP rods are simultaneously pulled using hydraulic cylinders. Once the desired value of the prestressing force is achieved, the hydraulic pressure actuating the cylinders is maintained, and the threaded shaft is fastened until it touches the back of the barrel. At this stage, the system becomes fixed, the hydraulic pressure in the cylinders is released, and the housing plates and presetting device are removed.

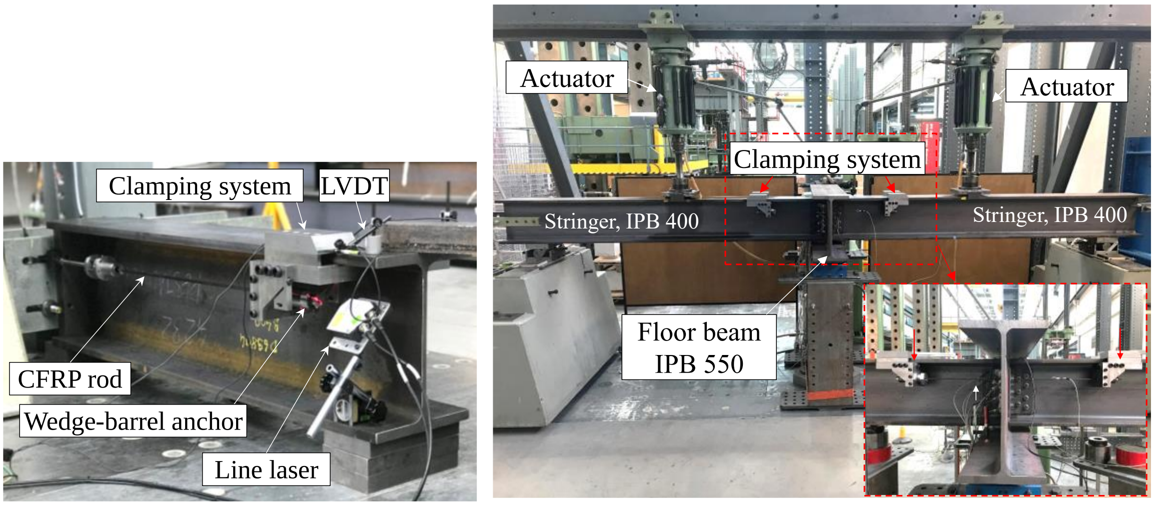
To develop the mechanical wedge-barrel anchors, finite element (FE) simulations were conducted to achieve the optimal stress distribution on CFRP rod aiming at minimizing the stress concentration at the loading end, so that the full tensile capacity of the CFRP rods are achieved (Heydarinouri et al., 2021d). Figure 10a shows the FE model and the stress distribution for the wedge-barrel anchors and CFRO rods. After achieving the optimal configuration, uniaxial static and fatigue tests were conducted on the wedge-barrel anchors to investigate their static and fatigue performance (Heydarinouri et al., 2021a). The test setup is shown in Figure 10b. Static test results showed that the average tensile strength of the CFRP rods was 2371.4 MPa, which was 16% greater than the guaranteed (nominal) tensile strength of rods being 2,047 MPa. Fatigue tests were performed according to ETAG 013 (EOTA, 2002) and results showed that no rupture occurred in the CFRP rods after minimum 2 million load cycles.



a) FE model of the wedge-barrel anchorage b) Test setup for static and fatigue test

Figure 10: Development of the wedge-barrel anchors

Static performance of the whole retrofitting system, including the clamping system was experimentally investigate in the pull-off tests shown in Figure 11a (Heydarinouri et al., 2021b). The results showed no slippage between the components during pulling of the CFRP rods. It was observed that the failure mode was CFRP rupture, with an average failure load of 110 kN, being equivalent to 2,188 MPa tensile stress in CFRP rods.



a) Static pull-off tests b) Real scale test setup for fatigue tests

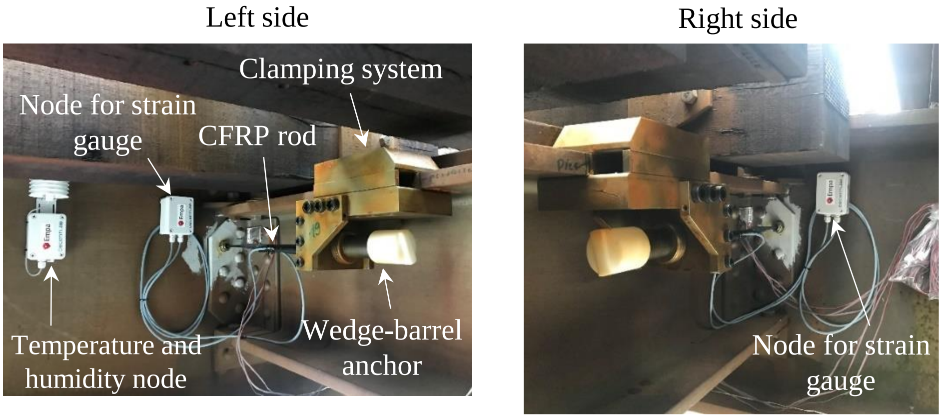
Figure 11: Development of the whole strengthening system including clamping system.

To investigate the applicability of the developed retrofitting system in complex practical applications, as well as its reliable performance under fatigue load, a real-scale test setup was built at Empa as shown in Figure 11b (Heydarinouri et al., 2021b). The dimensions of the beams and connections were similar to those of an old railway bridge in Switzerland, namely Aabach bridge, because the bridge connections were strengthened later using the developed strengthening system. In the fatigue tests, the load ratio was $R = 0.1$ and the maximum load per each actuator was 240 kN. The fatigue test results showed that after more than 11 million load cycles, neither any CFRP rupture nor any prestressing loss was observed in the CFRP rods.

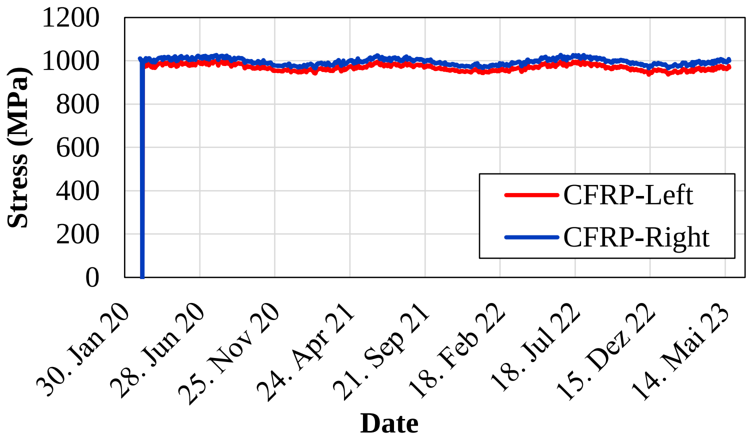
Bridge application

As a pilot project, the developed strengthening system was mounted on Aabach railway bridge in Switzerland (Heydarinouri et al., 2021c). Figure 12a shows the elements of the bridge structure, i.e., main truss and the deck elements. The installed strengthening system is shown in Figure 12b. As shown in the figure, wireless sensor nodes were also attached to the bridge for long-term monitoring of the retrofitting system performance. The sensors measure the strains in the CFRP rods, as well as air temperature and humidity. Typical results of the long-term monitoring measurements since the installation in February 2020 are depicted in Figure 12c. The figure shows no reduction in the prestressing level of CFRP rods, indicating that no slippage has occurred between the retrofitting system components.

(a) Elements of the bridge structure



(b) Installed strengthening system and wireless sensors for long-term monitoring



(c) Long-term measurements over more than 3 years after the installation

Figure 12. Strengthening of Aabach railway bridge in Switzerland (Heydarinouri et al., 2021c)

CONCLUSIONS

This study briefly discusses the two main differences between CFRP-concrete and CFRP-steel bonded members, which are related to the different failure modes and stiffness of retrofitted members. These differences led to the development of CFRP prestressing concepts for strengthening of steel members. Laboratory tests demonstrated that for both bonded and unbonded systems, CFRP prestressing force significantly improved the static and fatigue behavior of retrofitted steel beams. A new bonded system using Fe-SMA/CFRP bonded patches was introduced and its effectiveness in fatigue strengthening of tensile steel members was shown. To address the concerns regarding the impact of high ambient temperatures, moisture, freeze/thaw cycles, or fatigue loading on CFRP-to-steel bonded joints, different friction-based PUR systems for strengthening of steel members using CFRP composites were introduced. PUR systems transmitted the force purely through friction, without any damage to the parent structure. In addition, installation of the systems had no interruption with the traffic over the bridges. Numerical and experimental studies explored the effectiveness of PUR systems utilizing CFRP plates and rods for strengthening the steel girders and connections, respectively. The investigations demonstrated the effectiveness of PUR systems in improving the static and fatigue behavior of the beams and connections. The reliable performance of these diverse PUR systems was proved by their application in different steel bridges around the world.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.

CITATIONS

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