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Recent developments of strengthening techniques for metallic structures

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ABSTRACT: This paper introduces the most recent techniques that have been developed for pre-stressed strengthening of metallic members. Details of utilization of new advanced materials such as carbon-fibre reinforced polymer (CFRP), NiTiNb- and Fe-shape memory alloys (SMAs) and hybrid SMA/CFRP for pre-stressing existing metallic members are given. The paper begins with presenting the works on strengthening of metallic members using pre-stressed bonded CFRP material. Furthermore, a pre-stressed un-bonded retrofit system is described. The paper continues with explaining a new strengthening method using un-bonded pre-stressed Fe-SMA strips. Finally, an innovative prestressing system that uses a hybrid system of NiTiNb-SMA/CFRP material is presented. At the end, the paper provides some suggestions for future studies on this topic.

1 INTRODUCTION

The paper includes different pre-stressing techniques that have been recently developed for strengthening of metallic members (e.g., steel plates and beams). The paper starts with presenting the work on strengthening of metallic members using pre-stressed bonded carbon fiber-reinforced polymer (CFRP). Furthermore, pre-stressed unbonded retrofit systems will be presented. The paper continues with presenting a new strengthening technique using un-bonded pre-stressed iron-based shape memory alloy (SMA) strips. At the end, an innovative prestressing system that uses a hybrid system of CFRP and SMA material is described.

2 CFRP RETROFIT SYSTEMS

2.1 Pre-stressed bonded CFRP-strengthening system

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 CFRPs are effective in increasing the stiffness of the metallic girders and reducing the deformations. Metallic members have been traditionally strengthened using non-pre-stressed CFRP reinforcements. 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). Figure 1 shows the elements of the pre-stressing set-up, which uses an independent reaction frame to pull the CFRP strip. 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 strength. 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 utilizing pre-stressed CFRP reinforcements extended the fatigue life substantially, and in some cases, a complete fatigue crack arrest was achieved.

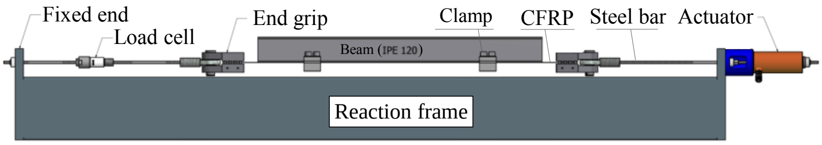
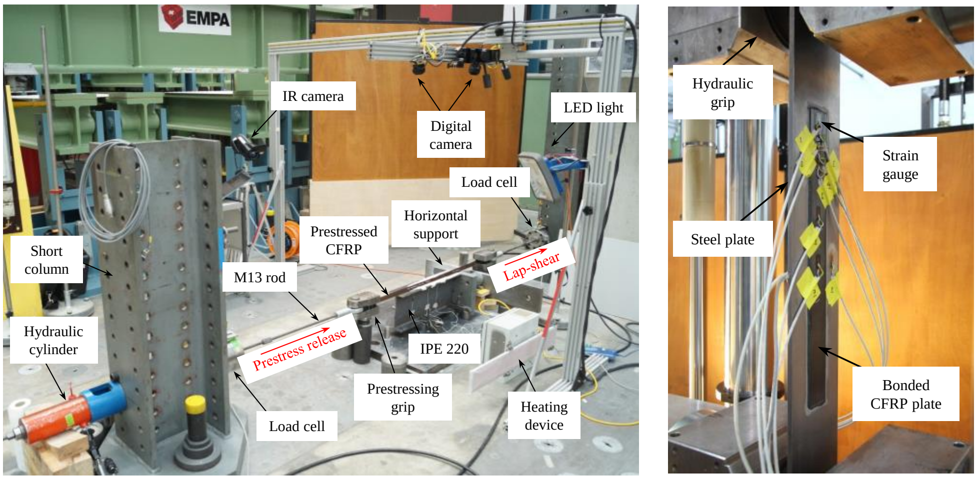


Figure 1. Elements of the pre-stressing set-up, which uses an independent reaction frame to pull the CFRP strip (Ghafoori and Motavalli 2015b).

Through another ongoing research topic at the Structural Engineering Research Laboratory of Empa, a special 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 design test setup allows lap-shear and prestress release tests to be systematically performed, while the test is 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. 2017a).



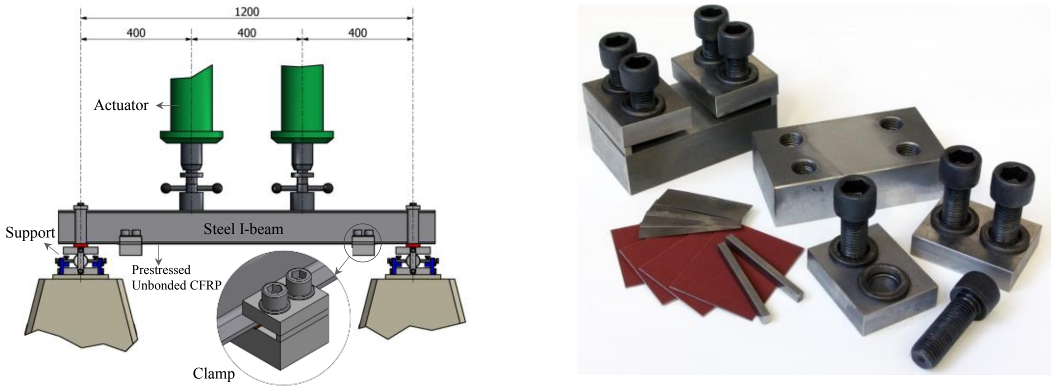
(a) (b)

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

It has been demonstrated by Hosseini et al. (2016) that although the existing knowledge on the bond behavior 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 behavior 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 modeling 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. 2017).

2.2 Pre-stressed un-bonded CFRP-strengthening system

The majority of the existing research on CFRP strengthening of metallic members has used CFRP material 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. 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 debonding.



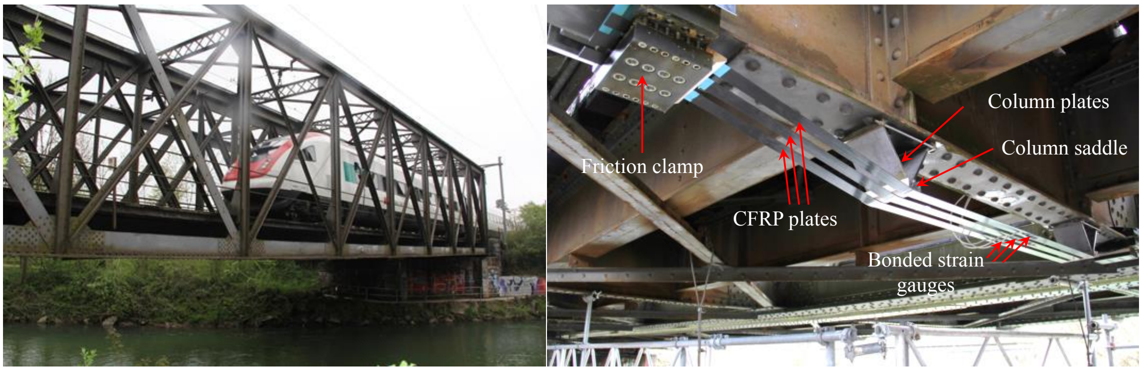
(a)

(b)

Figure 3. a) Test set-up (dimensions in mm), b) elements 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 long-term behavior and durability 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, Fernando et al. 2010). In contrast to the prestressed bonded reinforcement (PBR) solutions, the PUR system works without using any bond; instead, it uses a pair of friction clamps to connect the 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 CFRP strip out of 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 identical effect on the behavior of steel beams. Prestressed unbonded CFRP strips could prevent fatigue crack initiation (Ghafoori et al. 2015b) and propagation (Aljabar et al. 2016, Ghafoori et al. 2012a, Hosseini et al. 2016, Ghafoori and Motavalli 2016, Aljabar et al.) in steel members. 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 bond. Bonded and unbonded systems have shown relatively similar results, particularly in the linear-elastic domain (Ghafoori 2015).



(a) (b)

Figure 4. (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.

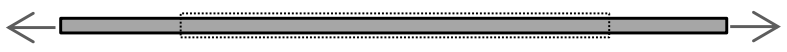
Trapezoidal PUR system: Figure 3a shows a PUR system with straight CFRP strips. Ghafoori and Motavalli 2015a have recently developed and patented a trapezoidal PUR system for strengthening of a historical metallic railway bridge in Switzerland (see Figure 4a). A summary of the prestressing procedure is explained as follows. Assume an I-beam as shown in Figure 4b. First, the mechanical clamps are placed near two ends of the beam, and three parallel CFRP plates are placed and tightened inside the clamps. 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 clamping 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. After the desired pre-stress level is achieved, two plates are placed between the CFRP plates and the beam. 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 4b shows the final configuration of the strengthened beam. 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 120-year-old railway metallic bridge in Switzerland (see Figure 4a). Figure 4b shows a riveted cross-girder of the bridge after strengthening.

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. 2017b.

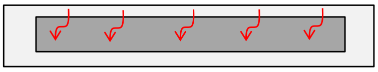
The behavior of each system has been examined using numerical, analytical and experimental investigations and, certain advantages and drawbacks of each system have been discussed.

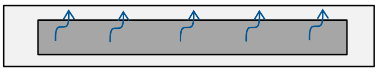
3 SMA RETROFIT SYSTEMS

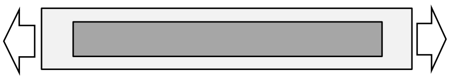
In some cases, application of prestressed CFRP laminates can be difficult or impossible. In such situations, the application of shape memory alloy (SMA) strips instead of CFRP laminates could ease the strengthening process as there is no need for large space, mechanical jacks and anchor heads for prestressing. SMAs are unique materials that have the ability to recover their shape after permanent deformation by heating and subsequent cooling (Cladera et al. 2014, Janke et al. 2005). A novel Fe-17Mn-5Si-10Cr-4Ni-1(V,C) SMA (hereafter called “Fe-SMA”) has been recently developed at Empa (Ghafoori et al. 2017). The alloy shows very promising mechanical, shape memory effect (SME) properties (e.g., a high recovered stress) and has been optimized for applications as pre-stressing elements in civil engineering domain. Different products of the Fe-SMA material (e.g., strips and bars) exist in the market (re-fer AG Company). When the deformation of Fe-SMA strips are constrained during heating and cooling procedure, the alloy produces prestressing forces in its attempt to revert back. Recently, the application of Fe-SMA strips instead of CFRP strips has been examined at Empa for strengthening of concrete structures (e.g., Czaderski et al. 2014, Janke et al. 2005). In this section, application of Fe-SMA strips for strengthening of steel plates will be briefly explained.

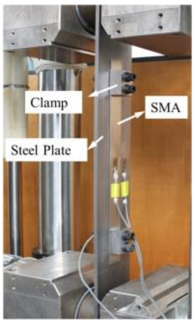

(a) Pre-straining of SMA strip


(b) Unloading of SMA strip


(c) Application on a steel plate and heating the SMA strip


(d) Cooling down the SMA strip


(e) Application of external loading to steel plate



(f)

Figure 5. Procedure of strengthening of steel plates with SMA strips: (a) pre-straining SMA strip; (b) unloading SMA strip; (c) attaching the SMA to the steel plate and heating up; (d) cooling down the SMA strip; (e-f) application of external load to the steel plate.

The SMA strip with 1.5-mm thickness and 46.7-mm width is pre-strained (see Figure 5a) and then unloaded (see Figure 5b). This process transforms the SMA strip from austenite phase to martensite phase (i.e., martensitic forward transformation). The SMA strip is then attached to the steel plate using a pair of mechanical clamps and then heated up to 260 °C using electrical resistive heating (ERH) technique (see Figure 5c). The heating process activates the shape memory effect (SME) through a martensite to austenite phase transformation process (i.e., revers transformation). The SMA strip is then cooled down to room temperature (see Figure 5d). A final recovery stress of about 380 MPa is achieved in the SMA strip. At this stage the SMA strip applies a compressive stress to the steel section. The SMA-strengthened steel plate will be then subjected to external quasi-static loading up to failure (see Figures 5(e),(f)). The results (which will be presented in another paper) show the effectiveness of the activated SMA strips to decrease the stresses along the steel plate. The advantage of the system is that it applies a beneficial compressive force to the critical steel detail with minimum effort.

4 SMA/CFRP RETROFIT SYSTEMS

A new approach to reinforcing cracked and crack-sensitive details in steel structures was recently developed at the University of Houston which employs a new type of SMA/CFRP patches (El-Tahan et al. 2015). The patching system employs a ternary nickel-titanium-niobium (NiTiNb) SMA with a wide thermal hysteresis which sustains recovery stresses upon cooling to freezing temperatures unlike many traditional Nitinol SMAs which generally lose their recovery stresses upon cooling to room temperature. The alloy used was a commercially available ternary alloy consisting of 38% titanium, 48% nickel and 14% niobium by weight. The wires were received from the manufacturer in a pre-strained and grit blasted configuration. The austenitic start and finish temperatures were 47ºC and 165ºC while the martensitic start and finish temperatures were -65ºC and -120ºC as reported by the manufacturer. Figure 6 illustrates the patching technique. The ends of the prestrained and grit-blasted NiTiNb wires are embedded in a carbon fiber fabric as shown in Figure 6a. The carbon fiber fabric is then saturated with a polymeric resin to form two CFRP tabs at the ends of the NiTiNb wires. After curing, the CFRP tabs are bonded to the steel surface near a crack sensitive detail such that the NiTiNb wires bridge the crack path as shown in Figure 6b. After the tabs are bonded to the steel surface, the NiTiNb wires are activated by heating to induce the shape recovery. Since the shape recovery is restrained by the CFRP tabs, the NiTiNb wires apply a compressive stress in the vicinity of the crack sensitive detail and ahead of the crack (if any). After activation, the NiTiNb wires and CFRP tabs are covered by a CFRP overly so that the carbon fibers also bridge the crack path as shown in Figure 6c.

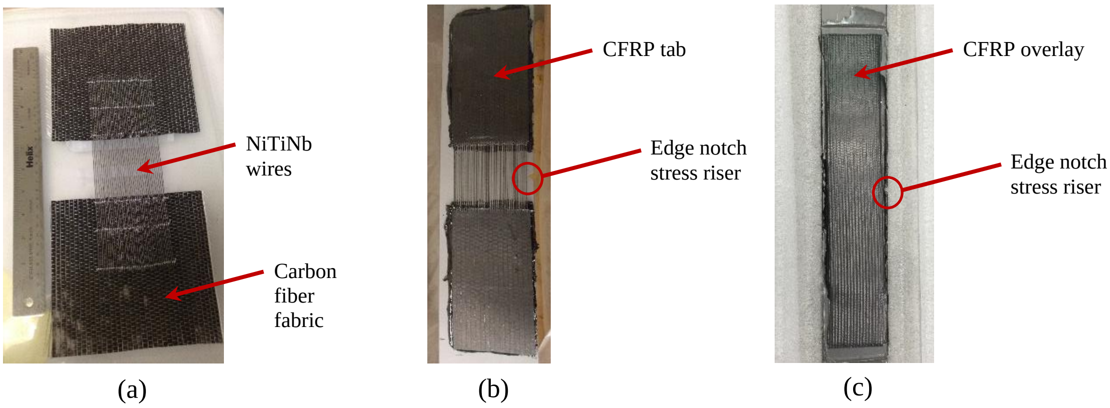


Figure 6. Fabrication of SMA/CFRP patches for retrofit of crack sensitive details in steel structures. (a) Preparation of SMA wires and carbon fiber fabric; (b) installation of the SMA wires embedded in CFRP tabs on a steel plate with edge notch stress riser; and (c) completed patch with CFRP overlay.

The SMA/CFRP patching technique provides several distinct benefits. Most notably, unlike most other prestressed repair techniques, this approach does not require the installation of any fixtures to anchor the system to the structure or to apply the prestressing. The prestress effect is induced by the unique thermomechanical properties of the SMA wires. These wires can be heated either directly, such as by forced air, or through electrical resistive heating which an electrical current is passed through the SMA wires thereby heating them. Both techniques have been applied successfully (El-Tahan et al., 2015, Zheng and Dawood, 2016). The integrity and effectiveness of the system does, however, rely on adequate bond between the SMA wires and the CFRP tabs and the CFRP tabs and the steel surface (El-Tahan and Dawood, 2015; El-Tahan and Dawood, 2017).

Debonding of the SMA wires from the CFRP tabs can result in a progressive loss of the prestressing effect with cyclic loading thereby undermining the effectiveness of the system. As such, two measures should be observed in the design and installation of the patches to preclude debonding. First, the patches should be designed such that the maximum stress level in the SMA wires, including the recovery stresses and any stresses induced by the application of load, should remain below the stress in the wire that would cause debonding from the patches. In typical applications, the stiffness of the SMA wires represents only 2% of the overall system including the steel element, the CFRP patch and the SMA. Consequently, the SMA wires generally attract very little of the applied stresses and it may generally be sufficient to prevent debonding during activation, with some acceptable margin of safety. Secondly, the anchorage region should be insulated during activation of the SMA wires. If the CFRP tabs are heated during the activation process, the adhesive may soften thereby providing insufficient anchorage to the SMA wires. As such, as the transformation of the SMA wires occurs they will be effectively unrestrained, or only partially restrained, thereby substantially reducing the magnitude of the prestressing force that is transferred to the underlying element. When heating by resistive heating, this isolation can be achieved by placing the electrodes on the bare portion of the SMA wires, away from the CFRP tabs. When activing the wires using forced air, care should be taken to place an insulating barrier, such as glass fiber batt insulation and reflective aluminum tape, over the CFRP tabs.

The effectiveness of the SMA/CFRP repair system has been demonstrated through a series of fatigue tests at various stress levels (Zheng and Dawood, 2016). Testing indicates that the presence of the SMA/CFRP patches can increase the average fatigue life of fatigue sensitive elements by up to 26 times from 45,000 cycles to over 1.2 million cycles for an applied stress range of 155 MPa. This improvement is achieved through two synergistic mechanisms. The presence of the CFRP overlay reduces the stress range near the crack tip thereby reducing the crack propagation rate. The presence of the prestress provided by the SMA wires reduces the maximum stress in the steel near the crack thereby increasing the critical crack length at which rupture of the steel plate occurs. The combination of the reduced crack growth rate and the increased critical crack length account for the significant increase of fatigue life that was observed using this system.

5 CONCLUSIONS

The paper summarized the most recent techniques that have been developed for strengthening of metallic members. The application of new materials such as CFRP composites as well as SMAs (such as NiTiNb- and Fe-SMAs) for prestressed strengthening of structural members was described. A new approach for strengthening of metallic critical details using a SMA/CFRP hybrid system was explained. It can be seen that the majority of the studies on CFRP-strengthening of metallic members have been conducted at room temperatures. However, the temperature of bridge metallic members under sunshine can rise up to more than 50 °C, which is in the range of glass transition temperature for most of the existing structural adhesives. Therefore, there is a need for future studies on fatigue behavior of CFRP-strengthened metallic members at elevated temperatures.

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