Flat Prestressed Unbonded Retrofit System for Strengthening of Existing Metallic I-Girders

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Abstract

In this study, a novel retrofitting system is developed to strengthen existing metallic I-girders using prestressed unbonded carbon fiber reinforced polymer (CFRP) plates. The system relies on a pair of mechanical clamps. Each clamp holds two CFRP plates (each having cross-sectional dimensions of 50 × 1.4 mm) and anchors their prestressing forces to a metallic I-girder via friction. A finite element (FE) model was established to optimize the design of the required mechanical components, and a set of pull-off tests was performed to evaluate the capacity of the optimized system. The proposed flat prestressed unbonded retrofit (FPUR) system was then applied on a 6.4-m-long steel I-beam, and the excellent performance of the system, in terms of stress reduction in the beam bottom flange, was confirmed based on the results of a set of static four-point bending tests. Moreover, a fatigue four-point bending test was conducted on the steel I-beam, strengthened using the proposed FPUR system with a prestressing level of 53% (i.e., approximately 1120 MPa prestress in the CFRPs). Experimental results of the high-cycle fatigue test confirmed the excellent fatigue performance of the proposed FPUR system, as no prestress loss was observed after 20 million fatigue cycles. An analytical model is proposed to accurately predict the stress state in an I-girder strengthened with the proposed FPUR system, while design recommendations are provided concerning the practical use of the system. Relying on the laboratory experimental test results, the proposed FPUR system was used to strengthen the metallic cross-girders of a 121-year-old bridge in Australia.

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Nomenclature

Latin symbols		Subscripts	
A	Cross-sectional area	bot	Bottom flange
d	Depth of girder section	f	FRP
E	Elastic modulus	$f-s$	FRP-to-steel
e	Eccentricity of prestressing force	M	Hogging moment
h	Lever arm	max	Maximum
I	Moment of inertia	min	Minimum
l	Length	n	Nominal
M	Hogging moment or resultants	P	External load
N	Number of fatigue cycles	p	Bolt preload
P	External load	pre	Prestressing
R	Fatigue load ratio	s	Steel
T	Tensile force or resultants	$s-s$	Steel-to-steel
ΔT	Temperature difference	T	Tensile force
Greek symbols		top	Top flange
α	Thermal expansion coefficient	ΔT	Temperature difference
δ	Horizontal deformation	u	Ultimate
ε	Strain	y	Yield
θ	Rotation angle		
μ	Friction coefficient		
σ	Stress/pressure		
τ	Tangential surface traction		

1. Introduction

The unique advantages of carbon fiber reinforced polymer (CFRP) composites have made CFRPs a suitable material for the strengthening of existing steel structures [1]. It has been demonstrated by many researchers that the strengthening of existing metallic members using CFRP reinforcement can enhance their ultimate and serviceability states [2–7]. More specifically, the fatigue life of critical/damaged metallic girders can be prolonged when they are strengthened with such advanced composite materials [8–17]. However, owing to the fact that the elastic modulus of steel is comparatively higher than that of normal modulus (NM) CFRPs, application of nonprestressed bonded NM CFRP reinforcement is often not so efficient. Therefore, researchers in the field have investigated the use of high modulus (HM) and ultra-high modulus (UHM) CFRP composites for the strengthening of steel structures [18–21]. Although the application of UHM CFRPs would be a more efficient alternative

1 compared to the use of the nonprestressed NM CFRPs, UHM CFRP composites are far more
2 expensive than NM CFRPs, while the brittle nature and the relatively low tensile strength of
3 UHM CFRP plates make their practical application for strengthening civil structures
4 challenging. On the other hand, it has been demonstrated that post tensioning or prestressing
5 of the reinforcing element has a more desirable effect on the strengthened steel member,
6 compared to what the elastic modulus of the reinforcement has [22]. In this regard, previous
7 experimental studies have shown that in certain configurations, crack prevention or crack
8 arrest is only possible when a prestressed CFRP reinforcement with a certain level of
9 prestressing is used [22–24].

10 Prestressed bonded reinforcement (PBR) systems exhibit certain limitations such as a
11 time-consuming and costly surface preparation, the inability to carry relatively high
12 prestressing forces, and premature debonding failure under service loads [25–27]. The
13 aforementioned drawbacks of the PBR systems have so far hampered the practical application
14 of such strengthening solutions. Furthermore, there are other open questions/concerns such as
15 the allowable service temperature, creep of the epoxy adhesive, and fatigue behavior of
16 adhesively bonded reinforcement, which still need to be further investigated prior to the wide-
17 spread safe application of PBR systems [22,28].

18 Owing to the limitations of the PBR systems, a novel trapezoidal prestressed unbonded
19 retrofit (TPUR) system was developed by Ghafoori and Motavalli [29]. This system was used
20 to strengthen a 121-year-old railway metallic bridge in Switzerland [30]. It was demonstrated
21 by the authors that the proposed TPUR system has certain advantages, including ease of
22 application, elimination of any surface preparation, and excellent performance of the system
23 in terms of prestressing levels [29]. Other possible configurations of prestressed unbonded
24 retrofit (PUR) systems for the strengthening of metallic I-beams have also been introduced
25 [31]. However, the development and testing of the PUR systems for the static and/or fatigue
26 strengthening of steel girders have so far been limited to the TPUR system. Nevertheless,

from a practical point of view, the post tensioning or prestressing of CFRP reinforcements in real-scale steel girders has always been a challenge.

In the present study, an alternative configuration of the PUR system, named the flat prestressed unbonded retrofit (FPUR) system, is introduced for an easy prestressed strengthening of real-scale metallic I-girders using CFRP plates. The main advantage of the proposed FPUR system compared with the existing TPUR system [29] is that the prestressed CFRP plates are kept adjacent to the strengthened metallic girder, and therefore, the system requires less space. Consequently, in the case of any traffic passage beneath the strengthened member, the risk of any accidental damage to the prestressed CFRPs can be significantly reduced. Furthermore, the prestressing procedure is performed using a pair of hydraulic cylinders, which makes the strengthening process much faster and easier.

In the current study, the design concept of different mechanical components is discussed, and a finite element (FE) simulation is established to optimize the system. Sets of pull-off tests, as well as static and fatigue four-point bending tests were conducted to confirm the excellent performance of the proposed system. An analytical model is developed to accurately determine the stress levels in a metallic I-girder strengthened with the proposed FPUR system, while design recommendations are provided for the practical use of the system. Finally, the field application of the proposed FPUR system on a 121-year-old metallic bridge is briefly addressed.

2. Concept and Overall View of the Proposed Strengthening System

As illustrated in Figure 1, 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 a metallic I-girder that needs to be strengthened. The two mechanical clamps are capable of transferring the total prestressing force of the CFRP plates to the lower flange of the member via friction. Each set of the mechanical clamps holds two prestressed NM CFRP plates with cross-sectional

1 dimensions of 50×1.4 mm (width $\times$ thickness). The strengthening procedure using the
2 proposed FPUR system consists of the following three steps:

3 1) Installation of the mechanical clamps and the CFRP plates (see Figure 1a). On both
4 sides of the girder, the nonstressed CFRP plates are sandwiched between 16-mm-thick
5 *toothed hard plates*, installed inside the *lower plate* and *upper plate*, with five M16 (grade
6 12.9) and ten M10 (grade 12.9) prestressed bolts (see Figure A1 in Appendix A for the
7 detailed sketches and dimensions of the different mechanical components of the system). The
8 bolts generate a total gripping force of approximately 1230 kN. On one side of the beam (the
9 left side in Figure 1a), the beam bottom flange is sandwiched between the upper plate and the
10 *over-flange plate* by fastening eight M20 (grade 12.9) bolts, each tightened to a torque of 605
11 Nm, to generate a prestressing force of 223 kN per bolt. This leads to the design gripping
12 force between the fixed clamp set and the beam bottom flange. On the other side of the beam,
13 the nonstressed CFRP plates are sandwiched in the movable clamp; however, this clamp set is
14 free to move horizontally along the beam axis for prestressing, as the M20 bolts are
15 unfastened.

16 2) Installation of the prestressing system, applying the required prestressing force, and
17 fastening the movable clamp. As illustrated in Figure 1b, a specially designed prestressing
18 system consisting of two 120-kN hollow plunger hydraulic cylinders, placed in a *cylinder*
19 *housing*, is installed adjacent to the movable clamp. Detailed sketches and dimensions of the
20 prestressing system are illustrated in Figure A2 in Appendix A. The cylinder housing is
21 anchored to the beam bottom flange in an almost similar way to that of the fixed clamp set.
22 However, in total, twelve M20 prestressed bolts are used to anchor the cylinder housing to the
23 beam bottom flange, instead of the eight M20 bolts, used for the clamping system. The reason
24 is attributed to the fact that any unexpected slippage of the cylinder housing during the
25 prestressing process needs to be avoided as a matter of safety. With the help of two M16
26 (Grade 8.8) threaded rods, the movable clamp can be pulled using the hollow plunger

hydraulic cylinders, actuated by a manual hydraulic pump. Consequently, the CFRP plates can be prestressed to the desired level. Note that, the prestressing force generated in the CFRP plates can be determined based on the hydraulic oil pressure and/or the readings of the strain gauges mounted on the CFRP plates (see Section 5.2). Upon reaching the desired prestressing level in the CFRP plates, all eight of the M20 bolts of the movable clamp can be tightened to a torque of 605 Nm, which leads to the design gripping force between the mechanical clamping system and the beam bottom flange.

3) Removing the prestressing system to realize the final configuration as depicted in Figure 1c. After reaching the desired prestressing force in the CFRP plates, the hydraulic pressure can be gently released, and the entire prestressing system consisting of the two hollow plunger cylinders and the cylinder housing can then be removed.

3. Finite Element Simulation

3.1. Model description

Due to the complexity of the proposed FPUR system, a finite element (FE) model was established in Abaqus [32] to optimize the geometry of the different mechanical components of the system, and to estimate the ultimate capacity of the optimized configuration before any slippage. FE analyses were conducted firstly to check the stresses in the upper, lower and over-flange plates, and subsequently, optimize their thicknesses; and secondly, to determine the number and diameter of the required prestressed bolts to provide enough friction force. The geometry and dimensions of the optimized configuration of the system are provided in Figure 2. Owing to the symmetry of the system, however, only half of the proposed mechanical clamping system, shown in Figure 2, was modeled. The FE model consisted of a NM CFRP plate with dimensions of $50 \times 1.4 \times 700$ mm (width $\times$ thickness $\times$ length) that was gripped between two hard plates inside the proposed mechanical clamping system. The mechanical clamping system was anchored to the INP300 bottom flange using the actions of M20 prestressed bolts, introduced to the upper plate and the over-flange plate. All the steel

components and the CFRP plate were modelled as isotropic linear-elastic materials with an elastic moduli of 210 and 160 GPa, respectively, and a Poisson's ratio of 0.3 for both materials.

A hard contact was considered between all the individual parts in the normal direction. However, using the penalty formulation, an isotropic tangential friction was introduced between the CFRP plate and the hard plates, as well as between the contact surfaces of the clamping system (i.e., both the over-flange plate and the upper plate) and the steel I-beam. Coefficients of friction equal to $\mu_{f-s} = 0.5$, and $\mu_{s-s} = 0.3$ were used in the case of the CFRP-to-hard plate and steel-to-steel interfaces, respectively (please see [29,33] for further details). The CFRP and the steel substrate were modelled using 8-node linear brick elements of type C3D8R with reduced integration and hourglass control, while the entire clamping system was modelled using 4-node linear tetrahedrons of type C3D4. The FE model consisted of approximately 365,000 elements (see Figure 3).

In addition to the symmetrical boundary condition (i.e., Y-Z plane), horizontal and vertical support boundaries were introduced into the model to stabilize the assembly (see Figure 3). The following four loading steps were incorporated in the FE simulation:

- 1) Activation of contact interactions. In the first loading step, a uniform pressure of 0.01 MPa was applied to the M20 bolt head locations of the over-flange plate, as well as on the M10 and M16 bolt head locations of the lower plate (see Figure 2), to assemble all the individual parts. Application of this loading step is required to activate the defined contact interactions between the components. It is important to note that avoiding this loading step might pose a convergency problem in such FE models [33].
- 2) Clamping the CFRP plate between the two hard plates. In this loading step, static uniform pressures (σ_p) of 394.9 and 539.6 MPa per bolt head location, as well as static tangential surface tractions (τ_p) of 41.5 and 70.8 MPa per thread location were introduced to the lower and upper plates, respectively (see Figure 3). This simulates

the prestressing forces of 52.1 and 142.4 kN per bolt, generated in the M10 and M16 high-strength bolts, respectively.

- 3) Gripping the beam bottom flange between the over-flange plate and the upper plate. In this loading step, $\sigma_p = 546.0$ MPa per M20 bolt head location and $\tau_p = 88.7$ MPa per M20 thread location were introduced to the over-flange plate and the upper plate, respectively, to simulate the prestressing force of 223 kN per M20 high-strength bolt, upon fastening to the allowable torque of 605 Nm.
- 4) Pulling the CFRP plate. In the final loading step, the ultimate load bearing capacity of the mechanical joint was evaluated. For this purpose, a uniform normal surface traction equal to 2800 MPa was applied to the free cross section of the CFRP plate in the Z direction (see Figure 3) in a linear ramp in twenty increments. This value was chosen as a typical upper bound of the nominal tensile strength ($\sigma_{f,n}$) of the NM CFRP plates.

3.2. FE results

Figure 3 illustrates the distribution of the von Mises stresses in the FE model when all four loading steps were applied to the model. It can be seen in Figure 3 that by using 40-mm-thick lower, upper, and over-flange plates, manufactured from M200 steel with a nominal yield strength (σ_y) of 1000 MPa, the maximum stress in the clamping system remained below $0.6\sigma_y$. This criterion was initially selected to design the thickness of the aforementioned mechanical components of the clamping system.

As it can be seen in Figure 2, longitudinal fillets of dimensions $43.8 \text{ mm} \times 31^\circ$ were cut on the front and back faces of the upper plate, and the over-flange plate (see Figure A1 for the detailed dimensions). The main intention of cutting these fillets was to increase the lever arm of the mechanical clamping system and therefore to enhance the capability of the system to better distribute the bending moment, caused by the eccentric prestressed force, to the beam bottom flange. It should be mentioned that avoiding such longitudinal fillets can cause very

high stress concentrations in the beam bottom flange at the edge lines of the upper and over-flange plates and, subsequently, damage the existing metallic structure, especially in the case of fatigue loading. The FE results confirmed that, by considering the aforementioned longitudinal fillets, the von Mises' stresses in the beam bottom flange remained below 200 MPa, even when the CFRP plate was pulled up to $\sigma_{f,n} = 2800$ MPa.

Figure 4 illustrates the load–deformation response of the mechanically anchored CFRP plate, obtained from the FE analysis during the final loading step. It can be seen in Figure 4 that the proposed mechanical clamping system is capable of transferring the entire nominal tensile capacity of the CFRP plate ($\sigma_{f,n} = 2800$ MPa) to the steel I-beam, before any slippage of the clamp occurs. Owing to the fact that pulling the CFRP plate was modeled in the FE simulation by applying a uniform normal surface traction (load step No. 4), any slippage of the clamping system could have caused a numerical instability in the FE analysis. However, such a numerical instability was not the case in the performed analyses, confirming no slippage of the mechanical clamping system.

It is worth mentioning here that obtaining an almost uniform contact pressure between the hard plates and the CFRP strip, more specifically in the transverse direction, is of utmost importance when designing such mechanical clamping systems that hold the prestressed CFRP plates [33]. This was achieved by cutting 9 mm transverse fillets with an inclination angle of 1.5° on the back surfaces of the hard plates that are in direct contact with the lower and upper plates (see Figure A1). Further discussion of the effect of the fillet dimensions on the distribution of the contact pressure in the transverse direction can be found in [25].

4. Experimental Program

4.1. Pull-off test

To evaluate the ultimate capacity and the failure mode of the proposed mechanical clamping system when subjected to prestressing forces, a pull-off test setup was designed and

assembled in the Structural Engineering Research Laboratory of Empa (Figure 5). As can be seen in this figure, the proposed mechanical clamping system was installed on an INP300 steel profile, while the I-profile was properly anchored to the strong floor with the help of prestressed M32 rods. Mechanical grips were used to pull the CFRP plates using two 200-kN hollow plunger hydraulic cylinders. A manual hydraulic pump, connected to a hydraulic T-joint, was used to simultaneously actuate the hydraulic cylinders. A 300-kN load cell was used to monitor the applied load during the pull-off test. Detailed sketches of the test setup, including all the necessary dimensions, are provided in Figure A3 in Appendix A.

Foil strain gauges of type 1–LY66–6/120 with an electrical resistance of $120\ \Omega \pm 0.30\%$ (HBM AG, Germany) were mounted at the mid-length and mid-width locations of the CFRP plates. A digital data acquisition system of type QuantumX (HBM AG, Germany) was used to simultaneously record the output signal of the utilized load cell and the strain gauges during the test with a data measuring frequency of 10 Hz.

4.2. Static and fatigue four-point bending tests

To evaluate the performance of the proposed FPUR system for the strengthening of metallic I-girders, sets of static and fatigue tests were conducted at the Structural Engineering Research Laboratory of Empa on a 6.4-m-long INP300 steel beam under four-point bending. The test setup is shown in Figure 6, while the detailed sketches of the four-point bending test setup are provided in Figure A4 in Appendix A. Four-point bending tests were conducted using two 250-kN Amsler hydraulic actuators with a center-to-center distance of 1.8 m, which were actuated by an Amsler pulsator machine of type P131 (Maschinenfabrik Alfred J. Amsler & Co., Switzerland). Static tests were performed at a displacement speed of approximately 2 mm/min, while the fatigue test was performed under load-control conditions with a load ratio ($R = \frac{P_{\min}}{P_{\max}}$) of 0.2 and a constant loading frequency of 4.35 Hz. Load levels

were monitored using two dynamic 500-bar pressure transducers of type P8AP (HBM AG, Germany).

Foil strain gauges of type 1–LY66–6/120 as mentioned before were mounted at the mid-length and mid-width locations of the CFRP plates. Moreover, strain gauges of type 1–LY61–6/120 with an electrical resistance of $120\ \Omega \pm 0.30\%$ (HBM AG, Germany) were mounted at the mid-width location of the top and bottom flanges of the steel I-beam at the mid-span. A non-contact laser displacement transducer of type OptoNCDT–ILD 2200 with a measuring range of 100 mm (Micro-Epsilon Messtechnik GmbH & Co. KG, Germany) was installed on the top flange of the beam at the mid-span to measure the deflection of the beam during the static and fatigue tests.

A digital data acquisition system of type MGCplus (HBM AG, Germany) was used to simultaneously record the output signal of all the sensors. A data measuring frequency of 5 Hz was utilized in all the static tests. During the high-cycle fatigue test, however, a so-called periodic measurement with a frequency of 2400 Hz and an interval of 60 s was incorporated, during which only the Min. and Max. values of all the channels were recorded. During the fatigue test, the air temperature was monitored using a type K thermocouple connected to the same data acquisition system.

4.3. Material properties

All the required components of the mechanical clamping systems were manufactured from M200 high-strength steel with a nominal yield strength of 1000 MPa. Toothed plates were hardened after manufacturing to assure a hardness of HRC 58(–60) on the Rockwell scale. The steel I-profiles (INP300) utilized in the pull-off tests and the four-point bending tests were of type S275JR. The average elastic modulus (E_s), yield strength (σ_y), and ultimate strength ($\sigma_{s,u}$) of the steel were determined using two standard dog-bone samples with a length of 350 mm, extracted from the same batch of material in the rolling direction, and were tested

according to ISO 6892–1:2009 [34]. The mechanical properties of the steel utilized were determined as $E_s = 203.3$ GPa, $\sigma_y = 328$ MPa, and $\sigma_{s,u} = 465$ MPa.

Unidirectional NM CFRP plates of type S&P 150/2000–50/1.4 (S&P Clever Reinforcement Company AG, Switzerland) were used in all the tests with nominal elastic modulus ($E_{f,n}$) and tensile strength ($\sigma_{f,n}$) values of 145 GPa and 2100 MPa, respectively. The elastic modulus (E_f) and tensile strength ($\sigma_{f,u}$) values of the utilized CFRP composite were determined using coupon tests prepared and performed by the manufacturer in accordance with EN 2561:1995 [35]. These mechanical properties were reported to be $E_f = 161.0$ GPa and $\sigma_{f,u} = 2595$ MPa for the CFRP composite utilized.

5. Experimental Results and Discussion

5.1. Pull-off tests

Two pull-off tests, having identical configurations, were conducted on the proposed mechanical clamping system to evaluate its ultimate load bearing capacity. Figure 7a shows the history of the applied load during the pull-off tests up to the tensile rupture of the CFRP plates. As mentioned earlier in Section 4.1, a manual hydraulic pump was used to actuate the pull-off tests. Therefore, as the tests were performed under load-control conditions, any slippage of the clamp would have caused a sudden drop in the load level, which was not the case during the loading procedure until the tensile rupture of the CFRP plates.

The strain levels generated in the two CFRP plates (see Figure A3), hereafter called CFRP 1 (length = 650 mm) and CFRP 2 (length = 1035 mm), vs. the applied load per hydraulic cylinder are provided in Figure 7b. To better distinguish the test results in this figure, the strain–load responses obtained in pull-off test 2 were plotted with a load offset of 25 kN. It can be seen in the figure that the strain response of the CFRP plates was almost linear with respect to the applied load up to the tensile rupture of CFRP and CFRP 1 that occurred in the first and second pull-off tests, respectively. Figure 7c shows the tensile rupture

of CFRP 2 in the first pull-off test. It is obvious that upon reaching the tensile rupture in one of the two CFRP plates, the hydraulic pressure was suddenly released. Therefore, the other CFRP plate remained almost intact.

Table 1 summarizes the experimental results of the two pull-off tests, including the average values. It can be seen in this table that the obtained elastic moduli of the utilized CFRP plates correlate very well with the values obtained from the coupon tests (see Section 4.3). On the other hand, comparing the average ultimate tensile strength value of the CFRP plates achieved in the pull-off tests (i.e., $\sigma_u = 1933$ MPa) with that of the coupon tests (i.e., $\sigma_{f,u} = 2595$ MPa) reveals that a lower tensile strength was achieved in the pull-off tests. The reason is attributed to the fact that the clamping force can cause undesired stress concentrations at the anchored extremities of the CFRP plates, either in the proposed mechanical clamping system, or in the mechanical grips that were used to apply the pull-off force. This leads to a bi-directional stress state at the CFRP extremities and, eventually, to a decreased rupture load of the CFRP composite, compared to that of the coupon test. However, it can be seen that the obtained σ_u in the pull-off tests is approximately equal to 92% of the $\sigma_{f,n}$, which is the nominal tensile strength of the CFRP plate utilized. Therefore, the experimental results confirmed the excellent performance of the proposed mechanical clamping system in terms of carrying high prestressing forces, as the system experienced no slippage until the tensile rupture of CFRP plates occurred.

5.2. Static tests

Table 2 provides the layout of the six static four-point bending tests performed on one INP300 steel beam. First the bare steel I-beam was loaded as a reference unstrengthened case up to a load level of $P = 75$ kN per cylinder, which corresponded to a maximum bending stress of approximately $0.6\sigma_y$ in the beam. Afterwards, the proposed strengthening system was applied to the beam as a flat unbonded reinforcement (FUR), without any prestressing force, and the beam was reloaded up to $P = 75$ kN. The intention of using the FUR configuration

was to comparatively evaluate the efficiency of using nonprestressed CFRP reinforcements for the strengthening of steel I-beams. A total preload of 2.4 kN was applied in this case to ensure that the CFRPs are straight, and consequently, they can contribute in load bearing when the strengthened beam is subjected to external loading. Finally, the CFRP plates were prestressed up to 14, 27, 40, and 53% of the nominal tensile strength of the CFRP material ($\sigma_{f,n} = 2100$ MPa), and each time, the beam was subjected to the four-point bending up to the same load level of $P = 75$ kN. It is worth mentioning here that the prestressing levels ($\frac{\sigma_{pre}}{\sigma_{f,n}}$) were initially considered with a nominal CFRP strength of $\sigma_{f,n} = 2800$ MPa as the upper bound for NM CFRP plates (see Section 3.1). Therefore, the corresponding utilized prestressing levels in the tests, considering $\sigma_{f,n} = 2800$ MPa, are also reported in Table 2.

Figure 8 illustrates the strain history of the CFRP plates and the top and bottom flanges of the INP300 during the prestressing process for the case of FPUR with a prestressing level of 53% (see Section 2 for the details of the prestressing procedure). It can be seen in this figure that providing a prestressing level of 53% in the unbonded CFRP plates, corresponded to a total prestressing force of $T_{pre} = 155.7$ kN, a compressive strain of $346 \mu\text{m/m}$ was generated in the bottom flange of the beam at the mid-span, which corresponded to $\sigma_{bot} = -70.3$ MPa. Furthermore, this prestressing level resulted in a tensile strain level of $116 \mu\text{m/m}$ generated in the top flange of the beam at the mid-span, which corresponded to $\sigma_{top} = 23.6$ MPa.

The experimental results provided in Figure 8 indicate that the application of the proposed FPUR system with relatively high prestressing forces can generate significant compression stresses in the bottom flange of the INP300 steel I-beam while introducing tensile stresses into its top flange. Furthermore, careful inspection of Figure 8 reveals that the application of the proposed FPUR system is very quick, as the entire procedure of prestressing took less than 15 min. This is in contrast to the bonded solutions, as no additional curing time

1 is needed for the proposed FPUR system after fastening the movable clamp and releasing the
2 prestressing cylinders.

3 Figure 9 illustrates the experimental results of all the performed static four-point
4 bending tests in terms of the load–deflection of the beam, as well as the load–strain responses
5 of the bottom flange and the CFRP plates. It can be seen in Figure 9a that the application of
6 the nonprestressed FUR system (i.e., test label FUR (0%)) slightly increased the stiffness of
7 the member. This elastic stiffness improvement, however, is not remarkable, owing to the fact
8 that the utilization of NM CFRP composites cannot considerably enhance the stiffness of a
9 real-scale steel member. Figure 9a illustrates that the load–deflection responses of FPUR
10 cases were parallel to that of the FUR (0%) case. This means that by using the proposed
11 FPUR system with different prestressing levels, the same effect as that of the nonprestressed
12 FUR system was obtained on the stiffness improvement of the strengthened beam. The reason
13 is attributed to the fact that the stiffness of the CFRP strengthening system is constant for the
14 cases of FUR and FPUR systems. However, the maximum deflection of the strengthened steel
15 I-beam under service loads can be significantly reduced provided that higher prestressing
16 levels in the FPUR system are introduced. This is the desired effect of prestressed
17 strengthening, achieved by using the proposed FPUR system.

18 Figure 9b shows the load–strain responses of the steel beam bottom flange for all the
19 performed static four-point bending tests, while σ_{bot} at $P = 75$ kN is also reported for each test
20 in Table 2 for comparison purposes. Figure 9b demonstrates that the strengthening of the steel
21 I-beam with the nonprestressed FUR system was not capable of substantially reducing the
22 bending strains. The stress reduction in this case compared to the reference unstrengthen
23 beam is only 4.6% (see Table 2). On the other hand, applying higher prestressing levels in the
24 proposed FPUR system can considerably reduce the strain/stress level in the beam bottom
25 flange up to 38.5%, in the case of FPUR (53%). Therefore, it can be concluded that the
26 proposed FPUR system can be a very efficient strengthening solution to decrease the bending

stresses in an existing steel I-girder and subsequently increase its static and/or fatigue performance.

Figure 9c demonstrates the average strain response of the two CFRP plates in the cases of using the nonprestressed FUR system and the FPUR system with different prestressing levels. It can be seen in Figure 9c that all of the load–strain responses of FPUR cases are parallel to that of the nonprestressed FUR case, regardless of the prestressing level. The reason is attributed to the fact that the contribution of the unbonded CFRP plates in carrying the external loading is identical for both the FUR and FPUR systems. This contribution is, however, independent of the initial prestressing force. Nevertheless, providing higher prestressing levels in the CFRP plates leads to a significant stress reduction in the strengthened member (see the test results provided in Figure 9b and Table 2), while a more efficient utilization of the tensile capacity of the composite reinforcement can be achieved (see Figure 9c).

5.3. Fatigue test

In addition to the static four-point bending tests, the performance of the proposed FPUR system was also evaluated under fatigue loading for 20 million fatigue cycles while the CFRP plates were prestressed up to 53% of their ultimate strength. The maximum load level during the fatigue test was equal to $P_{\max} = 40.2$ kN per cylinder, corresponding to a bending stress level of approximately $0.33\sigma_y$ in the top and bottom flanges of the unstrengthened INP300 beam. The loading ratio ($\frac{P_{\min}}{P_{\max}}$) was chosen to be $R = 0.2$. Note that the aforementioned fatigue loading was selected based on a numerical simulation of a practical case, i.e., metallic cross-girders of a roadway bridge in Australia, subjected to the allowable service load (see Section 7).

Figure 10a illustrates the evolution of the maximum and minimum stress levels in the FPUR system and the bottom flange of the INP300 with respect to the elapsed fatigue cycles.

The stress values, provided in Figure 10a, are calculated by multiplying the elastic modulus of CFRP and steel by the corresponding strain values, obtained from the mounted electrical strain gauges on the prestressed CFRP plates and the steel bottom flange, which were being monitored during the fatigue test (see Section 4.2). It can be seen in Figure 10a that during the fatigue test, the maximum and minimum stress levels in the prestressed CFRP plates remained almost constant for 20 million loading cycles. This strongly proves that the proposed FPUR system experienced no slippage during 20 million fatigue cycles, as no prestress loss was observed. Moreover, Figure 10a shows that the bottom flange of the INP300 beam remained in compression for more than half of the loading range, as the beam was strengthened using the proposed FPUR system with a prestressing level of 53%. Consequently, these measurements during the fatigue test reveals that the fatigue performance of a real-scale metallic I-girder can be substantially enhanced by reducing the stress ratio and alternating stress range in its tension flange, when strengthened with the proposed FPUR system with a relatively high prestressing level.

Careful inspection of Figure 10a demonstrates that the maximum and minimum stress levels in the CFRP plates slightly increased over the first 1 million fatigue cycles and then decreased over the following 3 million fatigue cycles (up to $N = 4$ million). This fluctuation of the maximum and minimum stress levels in the prestressed CFRP plates corresponded to an opposite response of the stress levels in the beam bottom flange, experiencing a very slight reduction up to $N = 1$ million, followed by a gradual increase up to $N = 4$ million. This was due to the temperature changes that occurred during the fatigue test, which caused thermal stresses in the CFRP-strengthened I-beam as a result of the thermal expansion coefficient mismatch between CFRP and steel. The evolution of the air temperature with respect to the elapsed test time is plotted in Figure 10b. Although the graph shows significant fluctuations that corresponded to day-night temperature differences, the general trend of the temperature history shows that the air temperature firstly increased to almost 21 °C for the first 2-3 days

and later decreased to approximately 19 °C on the eleventh day. Consequently, owing to the negligible thermal expansion coefficient of CFRP in the direction of fibers, the stress level in the CFRP plates followed the general trend of the temperature evolution due to the generated thermal strains in the steel I-beam (see Figure 10). It is obvious that such small thermal stress fluctuations are deemed to be acceptable, while unavoidable, during a 55-day-long fatigue test.

6. Determination of the Stress State in a Metallic I-girder Strengthened with the Proposed FPUR System

6.1. Analytical modeling

The schematic of a metallic girder, strengthened using the proposed FPUR system, is presented in Figure 11a. During the prestressing process, with no external loading on the girder, the prestrain level in the CFRP composites (ε_{pre}) and/or the total prestressing force (T_{pre}) applied to the CFRP plates using the hollow plunger hydraulic cylinders are known. Therefore, considering the actions of the prestressing force on the metallic girder during the prestressing procedure (see Figure 11b), and by assuming the Euler–Bernoulli beam theory, the maximum bending stresses in the bottom and top fibers of the girder, σ_{bot} , and σ_{top} , respectively, can be formulated as follows:

$$\sigma_{bot} = -\frac{T_{pre}}{A_s} - \frac{M_{pre}d}{2I_s} \quad (1)$$

$$\sigma_{top} = -\frac{T_{pre}}{A_s} + \frac{M_{pre}d}{2I_s} \quad (2)$$

where A_s , I_s , and d , are the cross-sectional area, moment of inertia, and depth of the metallic girder section, respectively; M_{pre} is the hogging moment, caused by the prestressing force, which can be written as:

$$M_{pre} = T_{pre}h = T_{pre}\left(\frac{d}{2} + e\right) \quad (3)$$

where h is the lever arm of the prestressing force and e is the eccentricity of the FPUR system with respect to the girder bottom flange (see Figure 11a). It is worth mentioning that the CFRP reinforcements and the metallic girder are assumed to behave as linear-elastic materials, while no slippage occurs between the FPUR system and the metallic girder. It is obvious that both of the aforementioned assumptions are valid for the strengthening of metallic girders using the proposed FPUR system.

When a metallic girder, strengthened with an unbonded CFRP strengthening solution, is subjected to the external loading, the strengthened member should be treated as a statically indeterminate system. Thus, the total generated force in the unbonded CFRP plates needs to be calculated by solving the equilibrium and compatibility equations. It is important to note that, in the case of using the FPUR system, the strengthened girder shall not be treated as a steel-CFRP composite member. The reason is attributed to the fact that no interfacial shear stress can be transferred between the CFRP reinforcements and the bottom flange of the girder. The FPUR system, however, acts as a truss element, which only exhibits stiffness along its longitudinal axis.

Owing to the force equilibrium condition, the strengthened girder is subjected to the external loading, P , as well as the reactions of the tensile force, T , generated in the nonprestressed CFRP plates due to the effect of the external loading on the strengthened member (see Figure 11c). As the unbonded CFRP plates act as truss members, the axial deformation of the CFRP plates (δ_f) can be written as a function of T as follows:

$$\delta_f = \frac{Tl_f}{2E_f A_f} + \frac{\alpha_f \Delta T l_f}{2} \quad (4)$$

where δ_f is the total elongation of the CFRP plates with respect to the centerline of the girder and l_f is the initial length of the CFRP plates, to be measured as the center-to-center distance of the mechanical clamping systems (see Figure 11a); A_f and E_f are the total cross-sectional area and elastic modulus of the CFRP reinforcements, respectively; α_f is the thermal

expansion coefficient of the CFRP composite, and ΔT is the probable temperature difference, which the strengthened girder might be subjected to, after the strengthening.

Assuming the Euler–Bernoulli beam theory, and given that no slippage occurs between the clamping system and the beam bottom flange, the deformation compatibility condition leads to the following equation:

$$\delta_f = \delta_{bot} + e\theta \quad (5)$$

where θ is the rotation angle of the beam at the clamp location and can be formulated as:

$$\theta = \frac{\delta_{bot} - \delta_{top}}{d} \quad (6)$$

where δ_{bot} and δ_{top} are the horizontal deformation of the bottom and top fibers, respectively, of the girder at the clamp location (see Figure 11c). Considering the free-body diagram of the strengthened girder, depicted in dash lines in Figure 11c, δ_{bot} and δ_{top} can be determined as follows:

$$\left\{ \begin{array}{l} \delta_{bot} = \int_b^{b+\frac{l_f}{2}} \varepsilon(x, y) dx; y = \frac{d}{2} \\ \delta_{top} = \int_b^{b+\frac{l_f}{2}} \varepsilon(x, y) dx; y = -\frac{d}{2} \end{array} \right. \quad (7)$$

where $\varepsilon(x, y)$ is the axial strain function in the girder and can be written as:

$$\varepsilon(x, y) = \varepsilon_T + \varepsilon_M + \varepsilon_P + \varepsilon_{\Delta T} \quad (8)$$

where

$$\varepsilon_T = -\frac{T}{E_s A_s} \quad (9)$$

$$\varepsilon_M = -\frac{My}{E_s I_s} \quad (10)$$

$$\varepsilon_p = \begin{cases} \frac{Pxd}{2E_s I_s}; b \leq x \leq a \\ \frac{Pad}{2E_s I_s}; a \leq x \leq b + \frac{l_f}{2} \end{cases} \quad (11)$$

$$\varepsilon_{\Delta T} = \alpha_s \Delta T \quad (12)$$

1 where M is the hogging moment caused by T ; P is the concentric external loading applied at x
2 $= a$ (see Figure 11); and α_s is the thermal expansion coefficient of steel. Substituting Eqs. (9)–
3 (12) into Eq. (8), δ_{bot} and δ_{top} can be determined by solving Eq. (7), and subsequently, θ can
4 be evaluated using Eq. (6). Substituting Eq. (6) into Eq. (5), and applying the compatibility
5 condition (i.e., substituting Eq. (4) into Eq. (5)), T can be explicitly expressed as:

$$T = \frac{\frac{Ph}{E_s I_s l_f} [al_f - (a-b)^2] + (\alpha_s - \alpha_f) \Delta T}{\frac{1}{E_f A_f} + \frac{1}{E_s A_s} + \frac{h^2}{E_s I_s}} \quad (13)$$

6 Finally, by superposing the actions of prestressing with that of the external loading, σ_{bot}
7 and σ_{top} can be formulated as follows:

$$\sigma_{bot} = -\frac{T_f}{A_s} - \frac{(M_f - Pa)d}{2I_s} \quad (14)$$

$$\sigma_{top} = -\frac{T_f}{A_s} + \frac{(M_f - Pa)d}{2I_s} \quad (15)$$

8 where T_f is the total force in the CFRP plates when they are prestressed and the beam is
9 subjected to the external loading,

$$T_f = T_{pre} + T \quad (16)$$

10 and M_f is the hogging moment caused by T_f ,

$$M_f = T_f h \quad (17)$$

11 6.2. Verification of the proposed model with the experimental test results

Figure 12 illustrates the experimental stress response of the beam bottom flange and the CFRP plates as a function of the applied load, P , on the INP300 steel I-beam in the performed static four-point bending tests. The generated stress in the beam bottom flange as well as the CFRP reinforcements were predicted by the proposed analytical model (see Section 6.1), and the predictions are also plotted in black lines in Figure 12 for comparison purposes. It can be concluded from Figure 12 that the proposed analytical model is capable of accurately predicting the stress state in a CFRP-strengthened I-girder, both in the strengthened member and in the CFRP reinforcements, for different prestressing levels. A quantitative evaluation of the proposed analytical model is provided in Table 2. It can be seen in the last two columns of Table 2 that the proposed analytical model predicts the stress levels in the CFRP plates and the beam bottom flange with discrepancies of not more than 0.6 and 2.2%, respectively, based on the corresponding experimental results. This certainly reveals the excellent performance of the proposed analytical model.

As mentioned earlier, the linear-elastic behavior of the strengthened metallic girder and the reinforcements as well as no slippage of the mechanical clamps are the main assumptions of the developed analytical model. These assumptions indeed apply when the CFRP-strengthening of existing metallic members using the proposed FPUR system is of interest.

7. Field Application of the Proposed FPUR System

After the successful laboratory tests were conducted on the proposed FPUR system, this system was used to strengthen the cross-girders of a roadway metallic bridge named the *SN6091 Bridge* over Diamond Creek on the Heidelberg–Kinglake Road in Victoria, Australia. The metallic I-shaped cross-girders were strengthened with the proposed FPUR system with a prestressing level of approximately 38%. A wireless sensor network (WSN) system was used for the long-term monitoring of the strain levels in the prestressed CFRP plates. Figure 13 shows the FPUR systems applied on the cross-girders of the Diamond Creek Bridge, together with the WSN nodes, magnetically installed on the girders for long-term measurements of

prestrain level in the CFRP plates. Sets of truck loading were performed using a 42.5-tonne semi-trailer before and after the strengthening, which confirmed the excellent performance of the FPUR system. The maximum bending stresses in the bottom flanges of the girders were reduced by almost half, after the girders were strengthened using the FPUR system. The long-term performance of the system will be monitored for at least one year using the installed WSN system. As a detailed explanation of the field application of the FPUR system on the Diamond Creek Bridge is beyond the scope of the current paper, readers are referred to [36] for a comprehensive discussion on this topic.

8. Design Recommendations

8.1. Static/fatigue strengthening of existing metallic girders using the proposed FPUR system

When the static and/or fatigue strengthening of an existing metallic member is of interest, the required stress reduction in the member, which needs to be provided by the strengthening system, can be determined using an appropriate model (see the literature for examples [22,24,30]). In other words, the desired stress reduction in the member to reach a target level of stress, which is deemed to be the allowable/safe stress level under the ultimate/service loading, is known to the designer. Consequently, by applying the analytical model that is proposed in Section 6.1, the required prestressing force in the FPUR system can easily be determined to ensure that the maximum stress level in the metallic member of interest, subjected to the combined actions of external loading and temperature change, will not exceed the allowable value.

It is worth mentioning that four-point bending is likely to be the external loading configuration of many existing metallic I-girders in practical cases. A well-known example is cross-girders of metallic railway bridges, which are often loaded in a four-point bending configuration by the secondary longitudinal girders supporting the rail track. However, in the case of other external loading configurations, the proposed analytical model presented in

Section 6.1 can still be used by easily adapting Eqs. (11), (14), and (15) for the specific configuration of external loading.

8.2. Maximum prestressing level in the CFRP reinforcements

Although the proposed FPUR system is capable of transferring the entire tensile capacity of CFRP plates to the bottom flange of a metallic I-girder, it is clear that a maximum limit should be considered for the prestressing levels used in practical cases. However, none of the few available guidelines dealing with the strengthening of steel structures (see [1]) address such a limitation. The reason might be attributed to the fact that proper practical prestressed strengthening solutions for metallic members have not yet been sufficiently developed. According to ACI 440.4R-04 [37], in prestressed concrete applications, the prestressing level in the CFRP tendons should not exceed 65% of the maximum stress that can be developed when tested using an anchorage device. This stress limitation is based on the creep-rupture characteristics of CFRP tendons [38]. Therefore, it is recommended here to limit the prestressing level in the CFRP plates of the proposed FPUR system to $0.65\sigma_{f,n}$ (or 65% of the pull-off strength, if available). Further research on this topic is needed to provide adequate design guidelines for the strengthening of existing metallic structures using prestressed CFRP reinforcements.

It is worth mentioning that the stress level in the prestressed CFRP plates should always be calculated using the proposed analytical model (Section 6.1), to ensure that the CFRP tensile rupture will not occur at the ultimate state, considering adequate environmental reduction factors (for examples, see [39,40]).

9. Summary and Conclusions

In the current study, a novel friction-based unbonded strengthening solution, named the flat prestressed unbonded retrofit (FPUR) system, was developed to strengthen metallic I-girders using prestressed CFRP plates. For this purpose, an FE simulation was carried out to

1 optimize the dimensions of the required mechanical components of the system. A set of pull-
2 off tests was performed on the optimized system, which showed that the proposed mechanical
3 clamping system is capable of transferring the entire tensile capacity of two NM CFRP plates,
4 each having cross-sectional dimensions of 50×1.4 mm (width $\times$ thickness), to the steel
5 substrate via friction. A set of static four-point bending tests was then performed to show the
6 capability of the proposed FPUR system to reduce the bending stresses in a large-scale
7 INP300 steel beam. Furthermore, a fatigue four-point bending test was conducted on the steel
8 I-beam strengthened using the proposed FPUR system with a prestressing level of 53%.
9 Experimental results of the high-cycle fatigue test confirmed that the performance of the
10 proposed system is not affected by fatigue loading, as neither slippage of the mechanical
11 clamping system nor any CFRP prestress loss was observed over 20 million fatigue cycles.

12 The advantages of the proposed FPUR system can be summarized as follows: (1) ease
13 of installation and straightforward prestressing procedure, (2) active control over the
14 prestressing effect on the strengthened member during the prestressing process, (3)
15 elimination of surface preparation, which is required for bonded retrofit solutions, (4)
16 prevention of any installation damage to the existing member, (5) avoiding traffic interruption
17 during the strengthening, (6) capability of modifying (decreasing or increasing) the
18 prestressing level at any time, (7) capability of easy removal of the entire system without any
19 damage to the strengthened member, (8) insensitivity of the system to cyclic thermal stresses
20 and high service temperatures, which might be problematic issues for adhesively bonded
21 reinforcements, and (9) excellent performance of the system in terms of prestressing levels
22 and fatigue behavior.

23 In addition to the experimental tests, an analytical model was proposed in this study to
24 predict the stress state in a steel girder strengthened with the proposed FPUR system. The
25 comparisons between the experimental results and the corresponding predictions of the
26 proposed analytical model revealed that the analytical model is capable of accurately

1 predicting the stress levels in the prestressed CFRP reinforcements and the steel I-girder when
2 the strengthened member is subjected to external loading.

3 Based on the laboratory test results and the clear advantages of the proposed FPUR
4 system, it is concluded that the system can be an efficient strengthening solution to increase
5 the static and/or fatigue performance of existing metallic I-girders. The proposed FPUR
6 system has been applied to the cross-girders of the Diamond Creek Bridge in Victoria,
7 Australia, and its long-term performance will be monitored using a wireless sensor network
8 (WSN) system.

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Appendix A. Detailed Dimensions of the Mechanical Components and Test Setups

Detailed dimensions of the mechanical components of the FPUR system, as well as the pull-off and four-point bending test setups are provided in this appendix. Detailed sketches and 3D view of the proposed mechanical clamping system are depicted in Figure A1, while Figure A2 illustrates the detailed sketches and 3D view of the proposed prestressing system. Figures A3 and A4 depict the detailed dimensions of the pull-off, and the static and fatigue four-point bending test setups, respectively.

References

1. Zhao XL. FRP-strengthened metallic structures. CRC Press, 2013.
2. Zhao XL, Zhang L. State-of-the-art review on FRP strengthened steel structures. *Engineering Structures*. 2007;29(8):1808-23.
3. Deng J., Lee M.M.K., Moy S.S.J. Stress analysis of steel beams reinforced with a bonded CFRP plate. *Composite Structures*. 2004;65(2):205-15.
4. Deng J., Lee M.M.K. Behaviour under static loading of metallic beams reinforced with a bonded CFRP plate. *Composite Structures*. 2007;78(2):232-42.
5. Schnerch D., Dawood M., Rizkalla S., Sumner E. Proposed design guidelines for strengthening of steel bridges with FRP materials. *Construction and Building Materials*. 2007;21(5):1001-10.
6. Rizkalla S., Dawood M., Schnerch D. Development of a carbon fiber reinforced polymer system for strengthening steel structures. *Composites - Part A*. 2008;39(2):388-97.
7. Mustafa S.A.A., Moy S.S.J. Strengthening cast iron struts using carbon fibre reinforced polymers - Finite element modelling. *Composites Part B: Engineering*. 2011;42(5):1048-56.
8. Bassetti A. *Lamelles précontraintes en fibres carbone pour le renforcement de ponts rivetés endommagés fatigue* (Ph.D. thesis) EPFL no 2440. Lausanne: Ecole Polytechnique Fédérale de Lausanne; 2001 [in French].
9. Tavakkolizadeh M, Saadatmanesh H. Fatigue Strength of Steel Girders Strengthened with Carbon Fiber Reinforced Polymer Patch. *Journal of structural engineering*. 2003;129(2):186-96.
10. Deng J., Lee M.M.K. Fatigue performance of metallic beam strengthened with a bonded CFRP plate. *Composite Structures*. 2007;78(2):222-31.
11. Täljsten B, Hansen CS, Schmidt JW. Strengthening of old metallic structures in fatigue with prestressed and non-prestressed CFRP laminates. *Construction and Building Materials*. 2009;23(4):1665-77.
12. Ghafoori E, Motavalli M, Botsis J, Herwig A, Galli M. Fatigue strengthening of damaged metallic beams using prestressed unbonded and bonded CFRP plates. *International Journal of Fatigue*. 2012;44:303-15.
13. Colombi P., Fava G., Sonzogno L. Fatigue crack growth in CFRP-strengthened steel plates. *Composites Part B: Engineering*. 2015;72:87-96.
14. Ghafoori E, Motavalli M, Zhao XL, Nussbaumer A, Fontana M. Fatigue design criteria for strengthening metallic beams with bonded CFRP plates. *Engineering Structures*. 2015;101:542-57.
15. Colombi P., Fava G. Fatigue crack growth in steel beams strengthened by CFRP strips. *Theoretical and Applied Fracture Mechanics*. 2016;85:173-82.
16. Yu Q-Q, Wu Y-F. Fatigue strengthening of cracked steel beams with different configurations and materials. *Journal of Composites for Construction*. 2016;21(2):04016093.
17. Yu Q-Q, Wu Y-F. Fatigue retrofitting of cracked steel beams with CFRP laminates. *Composite Structures*. 2018.
18. Wu C, Zhao X, Duan WH, Al-Mahaidi R. Bond characteristics between ultra high modulus CFRP laminates and steel. *Thin-Walled Structures*. 2012;51:147-57.
19. Wu C, Zhao X-L, Al-Mahaidi R, Emdad MR, Duan W. Fatigue tests of cracked steel plates strengthened with UHM CFRP plates. *Advances in Structural Engineering*. 2012;15(10):1801-15.
20. Ghafoori E, Motavalli M. Normal, high and ultra-high modulus CFRP laminates for bonded and un-bonded strengthening of steel beams. *Materials and Design*. 2015;67:232-43.
21. Wu C, Zhao XL, Al-Mahaidi R, Emdad MR, Duan WH. Fatigue tests on steel plates with longitudinal weld attachment strengthened by ultra high modulus carbon fibre reinforced polymer plate. *Fatigue and Fracture of Engineering Materials and Structures*. 2013;36(10):1027-38.

22. Hosseini A, Ghafoori E, Motavalli M, Nussbaumer A, Zhao X-L. Mode I fatigue crack arrest in tensile steel members using prestressed CFRP plates. *Composite Structures*. 2017;178:119-34.
23. Ghafoori E, Schumacher A, Motavalli M. Fatigue behavior of notched steel beams reinforced with bonded CFRP plates: Determination of prestressing level for crack arrest. *Engineering Structures*. 2012;45:270-83.
24. Ghafoori E, Motavalli M, Nussbaumer A, Herwig A, Prinz G, Fontana M. Determination of minimum CFRP pre-stress levels for fatigue crack prevention in retrofitted metallic beams. *Engineering Structures*. 2015;84:29-41.
25. Hosseini A, Ghafoori E, Motavalli M, Nussbaumer A, Al-Mahaidi R, Terrasi G. A novel mechanical clamp for strengthening of steel members using prestressed CFRP plates. In *Fourth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures (SMAR 2017)*, Zurich, 13-15 September 2017.
26. Hosseini A, Ghafoori E, Motavalli M, Nussbaumer A, Zhao X-L. Stress analysis of unbonded and bonded prestressed CFRP-strengthened steel plates. In: *Proceedings of 8th International Conference on Fiber Reinforced Polymer (FRP) Composites in Civil Engineering (CICE2016)*. Hong Kong, 14-16 December 2016, p. 1179-86.
27. Hosseini A, Wellauer M, Ghafoori E, Sadeghi Marzaleh A, Motavalli M. An experimental investigation into bond behavior of prestressed CFRP to steel substrate. In *Fourth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures (SMAR 2017)*, Zurich, 13-15 September 2017.
28. Hosseini A, Barbezat M, Michels J, Ghafoori E, Motavalli M, Terrasi G. Glass transition evaluation of commercially available epoxy adhesives for strengthening of steel structures with bonded CFRP plates. In: *Proceedings of 9th International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE2018)*. Paris, France, 17-19 July 2018.
29. Ghafoori E, Motavalli M. Innovative CFRP-Prestressing System for Strengthening Metallic Structures. *Journal of Composites for Construction*. 2015;19(6):04015006.
30. Ghafoori E, Motavalli M, Nussbaumer A, Herwig A, Prinz GS, Fontana M. Design criterion for fatigue strengthening of riveted beams in a 120-year-old railway metallic bridge using pre-stressed CFRP plates. *Composites Part B: Engineering*. 2015;68:1-13.
31. Kianmofrad F, Ghafoori E, Elyasi MM, Motavalli M, Rahimian M. Strengthening of metallic beams with different types of pre-stressed un-bonded retrofit systems. *Composite Structures*. 2017;159:81-95.
32. ABAQUS U. Version 6.14-1. Providence, RI: Dassault Systèmes Simulia Corp.; 2014.
33. Hosseini A, Ghafoori E, Motavalli M, Nussbaumer A, Zhao X-L, Koller R. Prestressed Unbonded Reinforcement System with Multiple CFRP Plates for Fatigue Strengthening of Steel Members. *Polymers*. 2018;10(3):264.
34. ISO E. 6892-1. Metallic materials-Tensile testing-Part 1: Method of test at room temperature. International Organization for Standardization; 2009.
35. EN 2561. Carbon fibre reinforced plastics: unidirectional laminates—tensile test parallel to the fibre direction. European Committee for Standardization; 1995.
36. Ghafoori E, Hosseini A, Al-Mahaidi R, Zhao XL, Motavalli M, Koay YC. Strengthening steel girders of an Australian bridge with CFRP laminates. *9th International Conference on Bridge Maintenance, Safety and Management (IABMAS2018)*, Melbourne, 9-3 July 2018.
37. ACI 440.4R-04. Prestressing concrete structures with FRP tendons. American Concrete Institute. Farmington Hills, MI, 2004.
38. Dolan, C.W., 2001. Design recommendations for concrete structures prestressed with FRP tendons: FHWA contract; final report August 1, 2001. Federal Highway Administration.

- 1 39. CNR-DT 202. Guidelines for the design and construction of externally bonded FRP systems for
2 strengthening existing structures–Metallic structures (Preliminary study). National Research
3 Council Advisory Committee on Technical Recommendations for Construction. 2005.
- 4 40. ACI 440.2R-17. Guide for the design and construction of externally bonded FRP systems for
5 strengthening concrete structures. American Concrete Institute. Farmington Hills, MI, 2017.

Tables

Table 1. Pull-off test results.

Test	Ultimate load per CFRP plate, T_u (kN)	σ_u (MPa)	ε_u^* (%)	$E_f^\dagger$ (GPa)	Failure mode
Pull-off test 1	140.5	2007	1.267	155.5	tensile rupture of CFRP 2
Pull-off test 2	130.1	1859	1.189	154.2	tensile rupture of CFRP 1
Average value	135.3	1933	1.228	154.9	–

* Average of the strain readings of both CFRP plates at failure

† Determined between 0.1 and 0.5 T_u

1

Table 2. Static four-point bending test results and comparisons with the analytical predictions.

Test label	Prestressing level,			Experimental results			Analytical prediction		Discrepancy	
	$\frac{\sigma_{pre}}{\sigma_{f,n}}$ (%)			(at $P = 75$ kN)			(at $P = 75$ kN)		(%)	
	$\sigma_{f,n} = 2800$ MPa	$\sigma_{f,n} = 2100$ MPa	T_{pre}^* (kN)	σ_f (MPa)	σ_{bot} (MPa)	Stress reduction in bottom flange [†] (%)	$\sigma_{f,model}$ (MPa)	$\sigma_{bot,model}$ (MPa)	σ_f	σ_{bot}
Reference	–	–	–	–	201.7	N.A.	–	200.6	N.A.	0.5
FUR (0%)	≈ 0	≈ 0	2.4	179.7	192.5	4.6	178.7	189.7	0.6	1.5
FPUR (14%)	10	14	39.7	447.7	175.6	12.9	444.9	173.0	0.6	1.5
FPUR (27%)	20	27	78.5	724.1	158.1	21.6	722.3	155.8	0.2	1.5
FPUR (40%)	30	40	117.8	1006.9	140.2	30.5	1003.1	138.3	0.4	1.4
FPUR (53%)	40	53	155.7	1281.5	124.1	38.5	1273.8	121.4	0.6	2.2

* Total prestressing force applied to the CFRP plates

† Compared to the reference unstrengthened beam

FUR = flat unbonded reinforcement

FPUR = flat prestressed unbonded retrofit

2

1
2 **Figures**
3

4 Figure 1. Strengthening of a metallic I-girder using the flat prestressed unbonded retrofit (FPUR)
5 system: (a) step 1–installation of different components; (b) step 2–prestressing; (c) step 3–final
6 configuration after fastening the movable clamp and removing the prestressing system.

1

(c)

2 Figure 1. (*Continued*).

Figure 2. Dimensions used in the finite element simulation (all dimensions are in mm).

Figure 3. Finite element (FE) model created in Abaqus and the distribution of the von Mises' stresses at the nominal tensile strength of the CFRP plate (deformation scale factor = 5).

1

2 Figure 4. FE results: load–deformation response of the mechanically anchored CFRP plate.

Figure 5. Pull-off test setup.

Figure 6. Static and fatigue four-point bending test setup.

(a)

(b)

(c)

1 Figure 7. Pull-off test results: (a) loading history; (b) strain in CFRP plates vs. applied load; (c) tensile
2 rupture of the CFRP plate in pull-off test 1.

1
2 Figure 8. Strain history in unbonded CFRP plates and top and bottom flanges of the steel I-beam (at
3 mid-span) during the prestressing process.

(a)

(b)

(c)

1 Figure 9. Static test results: (a) load–deflection response; (b) load–strain response of the bottom
2 flange; (c) load–strain response of the CFRP plates.

(a)

(b)

1 Figure 10. Fatigue test results: (a) evolution of the maximum and minimum stresses in the bottom
2 flange and CFRP plates in response to the elapsed fatigue cycles; (b) evolution of the air temperature
3 with respect to the elapsed time.

1 Figure 11. (a) An assumed metallic girder strengthened with the proposed FPUR system; (b) effect of
2 prestressing; (c) effect of external loading.

1 Figure 12. Comparison of the static test results with the predictions of the proposed analytical
2 modeling: (a) stress in the bottom flange vs. applied load; (b) stress in the CFRP plates vs. applied
3 load.

Figure 13. Application of the proposed flat prestressed unbonded retrofit (FPUR) system and wireless sensor nodes on the cross girders of the Diamond-Creek Bridge, Victoria, Australia.

Appendix A Figures

Figure A1. Detailed sketches and 3D view of the proposed mechanical clamping system (all dimensions are in mm).

1

2 Figure A2. Detailed sketches and 3D view of the proposed prestressing system (all dimensions are in
3 mm).