Behavior of prestressed CFRP plates bonded to steel substrate: numerical modeling and experimental validation

Enzo Martinelli ^{a*}, Ardalan Hosseini ^{b,c}, Elyas Ghafoori ^b, and Masoud Motavalli ^b

^a *Department of Civil Engineering, University of Salerno, Fisciano, SA, Italy*

^b *Structural Engineering Research Laboratory, Swiss Federal Laboratories for Materials Science and Technology (Empa), Dübendorf, Switzerland*

^c *Resilient Steel Structures Laboratory, Swiss Federal Institute of Technology Lausanne (EPFL), Lausanne, Switzerland*

Abstract

In recent years, retrofitting of steel structures has emerged as a major issue in structural engineering and construction management. As the adhesive bond is often the critical aspect controlling the actual performance of steel profiles externally strengthened by composite plates, this paper investigates the bond behavior of fiber reinforced polymer (FRP) composites glued to steel substrate; the effect of prestress, being relevant in practical applications, is also covered herein. A simplified mechanical model, based on assuming mode II fracture for FRP-to-steel debonding is formulated at first, and then, a numerical solution is implemented. The proposed solution is validated by experimental tests. Finally, a parametric study highlights the role of several relevant parameters on the response of carbon FRP plates under prestress-release tests; it paves the way for further developments of the present study aimed to predict the prestress force release and lap-shear behavior of FRP-to-steel bonded joints based on the mechanical properties of the materials and the bond-slip relationship assumed for the adhesive interface.

Keywords: FRP, steel, debonding, prestress release, lap-shear test, numerical modeling

* Corresponding author. Tel.: +39 089 96 4098; Email address: e.martinelli@unisa.it
Martinelli, E., Hosseini, A., Ghafoori, E., & Motavalli, M. (2018). Behavior of prestressed CFRP plates bonded to steel substrate: numerical modeling and experimental validation. Composite Structures. <https://doi.org/10.1016/j.compstruct.2018.09.023>

1 Introduction

Existing structures are often in need for retrofitting due to the possibly combined effect of several factors such as degradation phenomena, new and more severe loading scenarios, fatigue loading, and enhancing in structural safety standards [1].

Fiber-Reinforced Polymer (FRP) composites are widely employed in strengthening and repair interventions of structural members in existing constructions [2]. Although their use is much more common for strengthening either reinforced concrete (RC) [3] or masonry [4] members, FRP composites are gaining consensus across the scientific and technical community as a generally viable and often competitive solution for strengthening existing structural metallic elements, both in buildings and in bridges [5]–[7].

FRP strips are generally Externally Bonded (EB) to steel profiles with the twofold aim to reduce stresses under service loads with the final aim to enhance the fatigue life under cyclic actions (e.g., [8]) and enhance ultimate bearing capacity of profiles (e.g., [9]). Therefore, the interaction between the existing steel member and the FRP reinforcement is controlled by the actual behavior of an adhesive interface, which is the “weakest link” of the strengthened structural system [10]. Therefore, extensive experimental programs have been carried out by several research groups worldwide [5],[11]–[15], with the aim to observe the bond behavior and debonding capacity of different kinds of FRP composites bonded to steel characterized by different geometric and mechanical properties [16],[17].

As the self-weight and sustained loads are always present in civil structures and infrastructures and, moreover, they generally represent a significant fraction of the applied loads, “passive” EB FRP strips cannot give any mechanical contributions to reduce their effect on existing structures. Therefore, the use of “prestressed” FRP strips is getting increasingly of interest in those applications in which designers wish to reduce the effect of these actions (both in terms of stresses and strains) [18]. It has been shown in previous studies that the application of

1 prestressed FRP strips can substantially enhance the flexural capacity [19],[20], buckling
2 strength [21], and fatigue behavior [22] of metallic members.

3 Structural metallic members are often subjected to cyclic loading, which might result in
4 initiation and propagation of fatigue cracks in the metallic substrate. Results of the extensive
5 laboratory tests have revealed that prestressed carbon FRP (CFRP) can prevent fatigue crack
6 initiation (e.g., [23],[24]) or even can arrest existing fatigue cracks (e.g., [25],[26]) in critical
7 hot-spots of metallic structures. A prestressed unbonded retrofit (PUR) system has been
8 developed and tested at Empa for strengthening of metallic plates [27] and beams [28]–[31].
9 Although the PUR systems are capable to be actively used for the strengthening of metallic
10 members with relatively high prestress levels (e.g., 40% of CFRP ultimate strength), they are
11 mostly suitable for strengthening of large structural members such as bridge girders. Despite
12 of this background, fatigue cracks often initiates from small complex details such as bridge
13 riveted or welded connections, where the application of the developed PUR systems can be
14 difficult or even impossible due to limited available space. On the other hand, applications of
15 passive (i.e., nonprestressed) CFRP composites, even ultra-high modulus CFRPs, often
16 cannot arrest the fatigue crack growth (FCG) in the metallic details [25]. Therefore,
17 development of prestressed bonded retrofit (PBR) systems, particularly for the strengthening
18 of small cracked metallic details, is of high interest.

19 The actual capacity of FRP composites bonded to concrete/steel substrate to sustain the
20 interface stresses induced by the release of the prestressing force can be scrutinized by means
21 of the so-called prestress release test [32],[33]. The test consists in bonding a prestressed FRP
22 strip to a concrete/steel substrate and, after the adhesive curing (either at room- or higher-
23 temperatures using accelerated techniques), letting the prestressing action be released on one
24 of the two ends of the strip up to either (i) total release of the aforementioned prestressing
25 action, or (ii) debonding of the FRP strip during the prestress force release procedure. If
26 debonding does not occur during the prestress release stage, the FRP strip can be pulled from

the opposite side, i.e., a subsequent lap-shear test can be performed. Hence, an interaction relationship between the initial level of prestressing and the maximum lap-shear strength can be determined [32]. This interaction obviously depends on various relevant properties, such as the bond length, the interface bond–slip relationship and the FRP properties.

Although some research studies can be found in the literature in which the bond behavior and debonding capacity of prestressed FRP-to-concrete were investigated [32],[34],[35], to the best knowledge of the authors, much less attention has been focused on the bond behavior of prestressed FRP-to-steel joints [36]–[39]. On the other hand, owing to the certain advantages of using prestressed FRP reinforcement for static/fatigue strengthening of steel members, it is of great importance and interest to investigate the aforementioned topic. Consequently, the current study aims to contribute to a better understanding about the bond behavior of prestressed FRP to steel substrate. More specifically, it proposes a simplified, yet mechanically consistent, numerical model that can be employed for understanding the response of prestressed FRP plates glued to steel substrate, and to scrutinize the role of the relevant parameters controlling the behavior observed in prestress release tests. In the Authors' opinion, this is a significant advance in the research about this subject, as numerical simulations can be employed for a more targeted design of tests, which can be utilized to either confirm or confute – in the spirit of the well-established “scientific method” – the hypotheses formulated by researchers on the mechanical system under consideration.

This paper is structured as follows. Section 2 proposes a simplified theoretical formulation intended at simulating the response of prestressed FRP strips in force release and subsequent lap-shear tests, considering the fact that no well-established model is available in the literature with this aim. Specifically, the FRP strip is modeled as an elastic rod glued to a perfectly stiff steel substrate, whereas FRP-to-steel debonding is simulated as a “mode II” fracture phenomenon described by a multilinear bond–slip relationship uniformly defined throughout the adhesive interface. Section 3 describes a simple numerical procedure implementing a

1 Finite Difference (FD) solution for the nonlinear differential equations derived in Section 2.
2 Moreover, the procedure formulated in Section 2 and numerically implemented in Section 3,
3 is firstly validated in Section 4 with respect to some experimental results obtained in previous
4 studies by some of the authors [33]. Then, the proposed procedure is employed in Section 5
5 for a parametric study intended at pointing out the role of the bond–slip relationship,
6 incorporated in the numerical modeling, as well as the main geometric and mechanical
7 parameters of relevance in the problem under consideration. Finally, Section 6 summarizes
8 the main findings of the present study and figure out the main directions toward which it will
9 be developed in the near future.

2 Model formulation

The theoretical model proposed in this paper is based upon the following main assumptions:

- debonding is described by a fracture process developing in pure mode II (shear mode);
- the FRP-to-steel interface is described by an invariant bond–slip relationship;
- the aforementioned bond–slip relationship can be either bi- or tri-linear in shape;
- the FRP strip behaves elastically;
- the FRP strip is prestressed at $\sigma_{\text{pre}} = E_f \epsilon_{\text{pre}}$ before gluing it to the steel substrate.

It is worth mentioning here that the out-of-plane deformation caused by mode I (tensile mode) fracture during prestress force release of a CFRP plate bonded to concrete substrate is quite significant [32]. It has been experimentally shown that for the case of CFRP-to-concrete bonded joints often the value of the separation (i.e., the relative CFRP-to-concrete out-of-plane deformation) at debonding failure is much more than that of the slip (i.e., the relative CFRP-to-concrete in-plane deformation) in a prestress release test [32]. Therefore, the available experimental test results show that mode I fracture of concrete more likely governs the failure mechanism in a prestress release test [32], and consequently, assuming a pure mode II fracture to model the prestress release behavior of CFRP-to-concrete might be misleading.

On the other hand, the only available test results, performed by the authors [33], demonstrated that the prestressed CFRP strip undergoes certain separation values (in the same order as the slip values) during the prestress force release procedure. However, the bond behavior and debonding load of the CFRP strips bonded to steel substrate are almost the same for the case of prestress release and lap-shear tests (see also Section 4). This might be attributed to the fact that in the case of FRP-to-steel bonded joints, unlike in concrete, the fracture occurs in the adhesive layer (and not in the substrate). Consequently, relying on the available lap-shear and prestress release test results, it is believed that as the first step towards a better understanding

of the prestress release behavior of CFRP plates bonded to steel substrate, pure mode II fracture process can be assumed in the proposed numerical modeling. It is obvious that a more realistic modeling of the prestress force release procedure of CFRP-to-steel bonded joints needs to take into account the mixed-mode I/II fracture state, developed in the adhesive layer (see Section 6).

2.1 Field equations

The field equilibrium, compatibility and (generalized) stress-strain relationships for the FRP strip glued to the concrete substrate are reported in the following subsections.

2.1.1 Equilibrium equation

Figure 1 depicts a segmental element of the FRP strips and highlights the relevant stress components. The equilibrium in the direction of the FRP longitudinal axis can be easily written as follows:

$$t_f \cdot d\sigma_f + \tau \cdot dx = 0 \quad (1)$$

and, hence, the following differential equation can be derived:

$$\frac{d\sigma_f}{dx} + \frac{\tau(s)}{t_f} = 0 \quad (2)$$

2.1.2 Generalized stress-strain relationship and bond-slip law

The axial strain ε_f is related to the corresponding stress σ_f by the following elastic relationship:

$$\sigma_f = E_f \varepsilon_f \quad (3)$$

where E_f being the Young's modulus of FRP in the axial direction (the only relevant properties in a 1D model).

- 1 A general bond–slip relationship can be introduced with the aim to connect interface slips s
 2 and the corresponding interfacial shear stress $\tau(s)$:

$$\tau = \tau(s) . \quad (4)$$

- 3 A multi-linear relationship defined below is assumed in the present paper:

$$\tau = - \begin{cases} \frac{\tau_{\max}}{s_e} \cdot s & \text{if } |s| \leq s_e \\ \frac{s}{|s|} \cdot \tau_{\max} & \text{if } s_e \leq |s| \leq s_p \\ \frac{s}{|s|} \cdot \frac{s_u - |s|}{s_u - s_p} \cdot \tau_{\max} & \text{if } s_p \leq |s| \leq s_u \\ 0 & \text{if } |s| > s_u \end{cases} \quad (5)$$

- 4 Figure 2 shows the mechanical meaning of the parameters $\tau_{\max}$, s_e , s_p and s_u that define the
 5 analytical expression of Eq. (5): it is self-evident that, as $s_e = s_p$, this relationship reduces to the
 6 widely adopted bi-linear elastic-softening (i.e., triangular) relationship.

7 2.1.3 Compatibility equation

- 8 Figure 3 represents the axial displacement components and the corresponding axial strain
 9 measures. Since the relative slip s is only relevant after gluing FRP to concrete, the following
 10 relationship can be stated between the constitutive part (namely, the part related to forces
 11 active after gluing) ε_f of the axial strain developed by FRP and the first derivative of the
 12 interface slip s :

$$\varepsilon_f = \varepsilon_{\text{pre}} + \frac{ds}{dx} , \quad (6)$$

- 13 where ε_{pre} corresponding to the prestressing action σ_{pre} before gluing. Right after gluing, the
 14 interface slip is uniformly equal to zero and, hence, ε_f is initially equal to ε_{pre} . On the other
 15 hand, the (generally negative) values of the first derivative of s developing at the release stage
 16 lead to reducing the axial ε_f and, hence, the corresponding elastic stress σ_f .

2.1.4 General differential equation

Substituting Eq. (3) into Eq. (2), and further deriving once with respect to x , and finally, introducing Eq. (6) the following differential equation can be derived:

$$\frac{d^2 s}{dx^2} + \frac{\tau(s)}{E_f t_f} = 0 \quad (7)$$

It is worth highlighting that, since ε_{pre} is assumed being uniform throughout the bonding length (as it represents the axial strain imposed at the prestressing stage) its first derivative is zero and, hence, it does not appear in Eq. (7).

2.2 Boundary conditions

Proper boundary conditions have to be introduced with the aim to describe the behavior of the mechanical system during the release stage and the eventual lap-shear stage (see Figure 4).

2.2.1 Release stage

Release stage consist in a progressive reduction of the axial stress ε_f at one hand (schematically, the left hand side, as depicted in Figure 4a). Mathematically, the two boundary conditions need to be imposed at the two ends by requesting that, on the one hand, ε_f is equal to $\varepsilon_{pre} - \varepsilon_{rel}$ (with $\varepsilon_{rel} \leq \varepsilon_{pre}$) at $x=0$ (left hand side) and, on the other hand, it is kept constantly equal to the initial value ε_{pre} on the other side ($x=L$):

$$\begin{cases} \sigma_f|_{x=0} = E_f \cdot \varepsilon_f = E_f \cdot (\varepsilon_{pre} - \varepsilon_{rel}) \\ \sigma_f|_{x=L} = E_f \cdot \varepsilon_{pre} \end{cases} \quad (8)$$

with

$$\varepsilon_{rel} \leq \varepsilon_{pre} \quad (9)$$

It is worth highlighting that assuming $\varepsilon_f(L) = \varepsilon_{pre}$ during the entire releasing process means that releasing axial stresses on one side does not affect the same stress on the other end, which is

reasonably accurate for “long” bonding lengths. As an alternative, the problem could be described by assigning both slip s and axial stresses for $x=0$ and the differential structure of the problem would change (from a “boundary value” problem to “an initial value” problem) with no special complications on the solving technique that will be described in Sections 2.3 and 3.

2.2.2 Lap-shear stage

The release process would terminate as $\varepsilon_f=0$ at $x=0$, which would imply that a certain interface slip $s_{0,rel}$ develops at the releasing end of the FRP-to-steel interface. If no debonding occurs (namely, if $s_{0,rel} < s_u$), a subsequent lap-shear test can be initiated by applying a force F at the opposite side of the FRP strip. It is worth mentioning that such a subsequent lap-shear can fairly simulate the effect of service/external loading on a steel member (an I-beam for example), which its bottom flange is strengthened with prestressed FRP reinforcement.

Although, experimentally, this process is often run in force control [33], the analysis process can be either simulated in force control:

$$\begin{cases} \sigma_f|_{x=0} = 0 \\ \sigma_f|_{x=L} = E_f \cdot \varepsilon_{pre} + \frac{F}{b_f t_f} \end{cases} \quad (10)$$

where F is the applied force at the current increment of the pull-out stage, or in displacement control:

$$\begin{cases} \sigma_f|_{x=0} = 0 \\ s|_{x=L} = s_L \end{cases} \quad (11)$$

where s_L is the slip imposed at the loaded end.

Eqs. (10) and (11) describe the two processes in the case of force or displacement control for the theoretical analyses.

1 A proper termination condition (e.g. $s_L=s_u$ or $s_0=s_e$) needs to be incorporated with the aim to
2 detect the eventual occurrence of debonding during the lap-shear process.

3 **2.3 Incremental formulation of equations**

4 The field equations and the various boundary conditions for the “integral” solution in terms of
5 interface slip distribution $s(x)$ throughout the FRP-to-steel (Sections 2.1 and 2.2.), can be
6 turned into incremental force with the aim to approach a numerical solution process (which
7 will be described in Section 3) capable of implementing a progressive prestress release and
8 lap-shear processes.

9 Therefore, if Eq. (7) leads to the integral solution $s(x)$, it should be met also by each
10 increment $\Delta s(x)$ and $\Delta \tau(x)$:

$$\frac{d^2 \Delta s_i}{dx^2} + \frac{\Delta \tau_i(s)}{E_f t_f} = 0 \quad (12)$$

11 In fact, these incremental solutions are induced by either a given imposed release strain $\Delta \epsilon_{rel}$:

$$\begin{cases} \Delta \sigma_f|_{x=0} = E_f \cdot \Delta \epsilon_{rel} \\ \Delta \sigma_f|_{x=L} = 0 \end{cases} \quad (13)$$

12 or an imposed force ΔF :

$$\begin{cases} \Delta \sigma_f|_{x=0} = 0 \\ \Delta \sigma_f|_{x=L} = \frac{\Delta F}{b_f t_f} \end{cases} \quad (14)$$

13 or displacement Δs_L increment during the eventual lap-shear process:

$$\begin{cases} \Delta \sigma_f|_{x=0} = 0 \\ \Delta s|_{x=L} = \Delta s_L \end{cases} \quad (15)$$

1 If the latter is the case (as it is assumed in the present study), the increment ΔF in the global
 2 force during the lap-shear process can be determined as a function of the corresponding
 3 increment of the axial strain $\Delta \varepsilon|_{x=L}$ determined at the loaded end of the FRP strip:

$$\Delta F|_{x=L} = E_f t_f b_f \cdot \Delta \varepsilon|_{x=L} \quad (16)$$

4 or, alternatively, as an integral of the interface shear stress incremental distribution $\Delta \tau$
 5 throughout the FRP-to-steel interface:

$$\Delta F|_{x=L} = \int_0^L b_f \Delta \tau dx \quad (17)$$

6

3 Finite difference solution scheme

The model formulated in Sections 2 leads to differential equations that, because of the non-linear analytical expression of the assumed bond-slip law described by Eq. (5), need to be solved numerically. This section proposes a Finite Difference (FD) solution scheme based on discretizing the bond length L into a sequence of points spaced at distance Δx :

$$\Delta x = \frac{L}{n} \quad (18)$$

n being the numbers of spaces between the grid points (Figure 5).

Based on a Central Difference (CD) approximation scheme, Eq. (12) can be turned to the following analytical expression:

$$\frac{\Delta s_{i,k+1} - 2 \cdot \Delta s_{i,k} + \Delta s_{i,k-1}}{\Delta x^2} + \frac{\Delta \tau_{i,k}(s)}{E_f t_f} = 0 \quad \text{for} \quad k=0, n \quad (19)$$

involving the slip Δs_i and stress $\Delta \tau_i$ increments at the i -th loading step at the k -th point and at the two neighbor points.

The values of the stress increment $\Delta \tau_{i,k}$ can be determined as follows:

$$\Delta \tau_{i,k} = -K_{T,i,k} \Delta s_{i,k} \quad \text{for} \quad k=0, n \quad (20)$$

where Δs_i is the corresponding slip increment and $K_{T,i,k}$ is the tangential stiffness that can be easily defined for each one of the four branches of the bond-slip relationship described by Eq. (5).

Moreover, the boundary conditions that are given in Eq. (13) in the release stage can be converted to the following analytical expressions:

$$\begin{cases} \Delta s_{i,1} - \Delta s_{i,-1} = 2\Delta x \cdot \Delta \varepsilon_{rel} \\ \Delta s_{i,n+1} - \Delta s_{i,n-1} = 0 \end{cases} \quad (21)$$

1 where $\Delta\epsilon_{rel}$ is the increment (actually a decrement) of the axial strain imposed at the left end
2 of the strip.

3 If debonding does not occur at the prestress release stage, the FRP strip can be pulled by
4 imposing given displacement (or axial stress/strain) increments Δs_L at the right end of the FRP
5 strip:

$$\begin{cases} \Delta s_{i,1} - \Delta s_{i,-1} = 0 \\ \Delta s_{i,n} = \Delta s_L \end{cases} \quad (22)$$

6 The occurrence of debonding can be detected by monitoring slips throughout both release and
7 lap-shear stages.

8 **3.1 Iterative solution procedure**

9 An iterative solution can be implemented to solve the (n+1) Eqs. (20) coupled with the
10 appropriate boundary conditions, either dictated by Eqs. (21) or (22), respectively at the
11 prestress release or lap-shear stages. Hence, at each iteration, a set of (n+3) equations in (n+3)
12 unknown has to be solved.

13 Starting from the distribution of interface slips at the iteration step (j-1), the corresponding
14 tangent stress increments can be determined by considering the expression of the bond-slip
15 relationship (Eq. (5)):

$$\Delta\tau_{i,k}^{(j-1)} = -K_{T,i,k}^{(j-1)} \Delta s_{i,k}^{(j-1)} \quad (23)$$

16 Therefore, the (n+1) equations can be solved with respect to $\Delta s_{i,k}^{(j)}$, also taking into account
17 the two more equations deriving from the relevant boundary conditions:

$$\Delta s_{i,k}^{(j)} = \frac{\Delta s_{i,k+1}^{(j)} + \Delta s_{i,k-1}^{(j)}}{2 + \frac{K_{T,i,k}^{(j-1)}}{E_f t_f} \cdot \Delta x^2} \quad \text{for} \quad k=0,n \quad (24)$$

1 Therefore, the trial displacement at the j -th iteration j of the i -th “increment” can be defined as
 2 follows:

$$s_{i,k}^{(j)} = s_{i-1,k} + \Delta s_{i,k}^{(j)} \quad (25)$$

3 and the corresponding tangential stiffness of the bond–slip relationship can be duly updated:

$$K_{T,i,k}^{(j)} = K_T \left[s_{i,k}^{(j)} \right] \quad (26)$$

4 and, subsequently, the trial bond stress can be written:

$$\tau_{i,k}^{(j)} = \tau_{i-1,k} + \Delta \tau_{i,k}^{(j)} = \tau_{i-1,k} - K_{T,i,k}^{(j)} \Delta s_{i,k}^{(j)} \quad (27)$$

5 Iterations proceeds from Eq. (23) as long as the variations in the interfacial shear stresses
 6 (collected in a vector $\Delta \tau$) at iteration j are sufficiently close to the ones obtained at iteration (j -
 7 1):

$$\left| \Delta \tau^{(j)} - \Delta \tau^{(j-1)} \right| \leq \delta \quad (28)$$

8 where δ is a predefined tolerance value.

9 Finally, the resulting global force increment ΔF can be easily evaluated by either integrating
 10 the interface bond stresses upon convergence or by means of the FD version of Eq. (16) as
 11 follows:

$$\Delta F_i = E_f t_f b_f \cdot \frac{\Delta s_{n+1} - \Delta s_{n-1}}{2 \cdot \Delta x} . \quad (29)$$

4 Experimental validation

4.1 Test setup, material properties, and experimental results

In order to validate the proposed numerical model, the performance of the model was evaluated using a set of single lap-shear and prestress release tests, carried out at the Swiss Federal Laboratories for Materials Science and Technology (Empa). A special test setup was designed and assembled at the Structural Engineering Research Laboratory of Empa (see Figure 6), which allows the execution of lap-shear and prestress release tests in a systematic manner [33]. As it is shown in Figure 7, all the tests were monitored using a noncontact 3D digital image correlation (DIC) system, known as ARAMIS [40] (GOM GmbH, Braunschweig, Germany).

IPE 220 steel I-profiles with a strength grade of S355J2+M, and CFRP plates of type S&P 150/2000 (S&P Clever Reinforcement Company AG) with a cross-sectional dimensions of 50×1.4 mm (width $\times$ thickness) were used in the experiments. The nominal ultimate strength of the CFRP composite was 2800 MPa according to the manufacturer; the elastic modulus of the CFRP plates, E_f , was determined to be 160.0 GPa [33]. A two-component epoxy adhesive of type S&P Resin 220 (S&P Clever Reinforcement Company AG) with a linear stress–strain behavior was used to bond the CFRP plates to the sand blasted surfaces of IPE 220 steel profiles. The mechanical properties of the utilized epoxy adhesive were determined in accordance to ISO 527 [41][42] and the results are provided in Table 1.

Table 2 presents the experimental results of the two lap-shear (designated as L–SP–RTC–1(2)), and the two prestress release (designated as P90–SP–RTC–1(2)) tests, which are considered for validating the proposed numerical model. A detailed discussion on the experimental program is beyond the scope of the current paper, and thus, readers are referred to [33] for further information about the test setup, experimental procedure, and experimental test results.

4.2 Different bond–slip relationships

As it can be seen in Figure 8, four different bond–slip relationships having identical fracture energy (G_f) were considered to be incorporated in the proposed numerical model, as they all can be reproduced by employing special values of the relevant parameters involved in Eq.(5). In all the bond–slip relationships, the ultimate slip value was considered to be $s_u = 0.17$ mm, which is the average of s_u values, obtained in the experimental tests (see Table 2). The maximum interfacial shear stress ($\tau_{\max}$) was determined as follows [13]:

$$\tau_{\max} = 0.9f_{a,u} \quad (30)$$

where $f_{a,u}$ is the tensile strength of the epoxy adhesive (see Table 1). In case of the constant bond–slip relationship, τ_{cte} was considered to be half of $\tau_{\max}$, thus an identical G_f could be obtained also in this case (see Figure 8). It is worth mentioning that for the case of bi-linear bond–slip relationship, the elastic slip was considered to be $s_e = 0.02$ mm. This value was obtained using a parametric study to find the best fitted load–slip response of the proposed model to that of the experimental tests (see Sections 4.3 and 5.1). It should be mentioned that, in all the numerical analyses reported hereafter, $n=300$ was considered for defining Δx according to Eq. (18).

4.3 Comparison of experimental and numerical results

Figure 9 shows the load vs. the slip at the loaded end (hereafter called load–slip) responses of the tested CFRP-to-steel joints under single lap-shear and prestress release loading. As it can be seen in the figure, by using a bi-linear bond–slip relationship, the proposed numerical model can fairly predict the load–slip response of the tested CFRP-to-steel joints. Careful inspection of Figure 9 reveals that the experimental load–slip response of specimen P90–SP–RTC–1 slightly diverges from those of the other three specimens. The reason is attributed to the fact that due to a technical problem, the test was executed with certain delays, and therefore, the adhesive curing time was almost doubled in this specimen [33]. It is evident that

a longer curing time results in a stiffer behavior of the epoxy adhesive [43][44], and thus, a shorter effective bond length and a lower bond capacity can be expected (see [33] for further details). It is obvious that the performance of the proposed model in accurately predicting the load-slip behavior of CFRP-to-steel joints is a strong function of the input parameters such as the bond-slip relationship. Consequently, the performance of the proposed model can be certainly improved by having more prestress release test data available in the future to calibrate the input parameters.

Figure 10 shows the comparison between the experimental and numerical results in case of a simple lap-shear test (without any initial prestressing force). Figures 10a and b illustrate the experimental and numerical slip and strain profiles at different load levels, respectively. It can be seen in the figure that by using a bi-linear bond-slip relationship, the proposed numerical model is capable of accurately predicting the slip and strain distributions along the CFRP plate at different load levels up to the debonding failure. Moreover, the experimentally obtained interfacial shear stress distribution at the maximum load stage before debonding failure ($F_{\max}$) is plotted together with the numerical prediction in Figure 10c. It can be concluded from Figure 10c that the numerical prediction of the interfacial shear stress profile very well correlates with that of the experimental measurements.

In general, the comparisons provided in Figure 10 reveals that the proposed numerical model can accurately predict the bond behavior of CFRP-to-steel joints at different levels of lap-shear loading. It should be mentioned here that, $F_{\max}$ is the maximum load level, in which the last pair of the digital images were captured by the 3D DIC system, and therefore, $F_{\max}$ can be slightly less than the ultimate load bearing capacity of the joint, measured by either of the load cells and provided in Table 2. It is also worth mentioning that the experimental interfacial shear stress profiles were calculated based on the DIC measurements of the longitudinal strain profiles by using an artificial gauge length of approximately 25 mm (see Hosseini and Mostofinejad [45] for the calculation method).

Figure 11 illustrates similar experimental to numerical comparisons, as those provide in Figure 10, but for the case of a pure prestress release test. Figure 11a reveals that there is a good correlation between the experimental slip profiles and those of the numerical predictions at different prestress release levels. It can be seen in Figure 11b that in a prestress release test, by gradually releasing the prestress force, compression strains are generated in the CFRP plate in the effective bond zone. Figure 11b demonstrates that, this phenomenon can be fairly captured by the proposed numerical model, while the strain profiles predicted by the numerical model very well fit to those of the experimental measurements. Figure 11c illustrates the distribution of interfacial shear stress along the CFRP plate at $F_{\max}$. It can be seen in the figure that the shape of the τ profile as well as the value of $\tau_{\max}$, predicted by the proposed numerical model correlate well with those of the experimental measurements.

It should be noted here that, in a prestress release test, DIC technique exhibits more parasitic measurements (Figure 11) compared to a single lap-shear test (Figure 10). The reason is attributed to the out-of-plane deformation of the CFRP plate in a prestress release test (see [33] for further details). Regardless of the parasitic DIC measurements, the comparisons provided in Figure 11 clearly prove that the proposed numerical model is capable of predicting the prestress release behavior of CFRP plates bonded to the steel substrate using a bi-linear bond–slip relationship.

5 Parametric study

This section aims to provide a brief overview on the influence of important parameters on the bond behavior of prestressed CFRP plates to steel substrate. In Section 5.1 the influence of different bond–slip relationships used in the numerical model, on the obtained bond behavior of the CFRP-to-steel is discussed. Section 5.2 provides a parametric study to demonstrate the influence of the elastic modulus and thickness of the CFRP reinforcement on the debonding load of prestressed CFRP plates bonded to steel substrate.

5.1 Effect of bond–slip relationship on bond behavior of CFRP-to-steel joints

Figure 12 illustrates the influence of using different bond–slip relationships in the proposed numerical model on the obtained load–slip response of a CFRP-to-steel bonded joint under prestress release test. Note that the exact definition of each bond–slip relationship can be found in Figure 8. It can be seen from Figure 12 that neither the debonding load, nor the ultimate slip of the joint depends on the utilized bond–slip relationship in the numerical model. This is obviously due to the fact that the ultimate slip (s_u) and the fracture energy (G_f) of the joint were considered to be identical for all the different bond–slip relationships (see Figure 8). However, careful inspection of Figure 12 reveals that the stiffness of the joint (defined as the tangential or secant slope of the load–slip response) is a great function of the utilized bond–slip relationship in the numerical model. Consequently, incorporating a realistic bond–slip relationship into the numerical model is crucial in order to capture an accurate load–slip response of the joint. This is certainly of great significance for the serviceability limit state evaluation of prestressed CFRP-strengthening of steel structures, where for example a constant or descending bond–slip relationship leads to an unsafe overestimation of the initial stiffness of the joint (see Figure 12).

Figure 13 shows the effect of using different bond–slip relationships in the proposed numerical model on the distributions of slip, strain, and interfacial shear stress along a

1 prestressed CFRP plate at the initiation of debonding during prestress release. From the
2 numerical results, shown in Figure 13, it can be concluded that the utilized bond–slip
3 relationship obviously affects the shape of the slip, strain, and interfacial shear stress profiles.
4 Although this influence may be considered negligible in case of slip and strain profiles
5 (Figures 11a and b), it is quite significant in case of the interfacial shear stresses. Therefore,
6 utilizing a nonrealistic bond–slip relationship can underestimate the interfacial shear stresses,
7 and subsequently, lead to an unsafe design of a prestress CFRP reinforcement for
8 strengthening of a steel member.

9 Figure 14 shows the plots of numerically obtained debonding load vs. the bond length for the
10 different bond–slip relationships utilized in the proposed numerical model. It can be seen in
11 Figure 14 that, regardless of the utilized bond–slip relationships, similar to CFRP/concrete
12 bonded joints, there exists an *effective bond length* beyond which any increase in the bond
13 length does not provide an increase in the debonding load [46]. Numerical results presented in
14 Figure 14 demonstrate that the influence of the utilized bond–slip relationship is not so
15 significant on the effective bond length of the CFRP-to-steel joint, as from a practical point of
16 view, all the four different bond–slip relationships result in almost the same effective bond
17 lengths in the range of 80 to 120 mm. Moreover, Figure 14 reveals that all the four different
18 bond–slip relationships give identical debonding load, provided the bond length is larger than
19 the effective bond length. However, careful scrutiny of Figure 14 shows that in case of having
20 bond lengths smaller than the effective bond length, utilizing the constant bond–slip
21 relationships results in a very conservative evaluation of the debonding load. Consequently,
22 using a nonrealistic bond–slip relationship might hamper the design of relatively small CFRP
23 patch reinforcements for strengthening of fatigue prone/damaged steel details.

5.2 Effect of elastic modulus and thickness of CFRP reinforcement

In practical cases dealing with the static/fatigue strengthening of an existing steel member, the required stress reduction in the member, which needs to be provided by the strengthening system, can be determined using a proper model (see for example [18],[25],[30]). Therefore, a suitable strengthening system has to be designed in a way that provides the required stress reduction in the strengthened member to ensure the target allowable/safe stress level under service/ultimate loads. In a prestressed bonded CFRP reinforcement system, however, the allowable prestressing force is limited [33],[47]. Consequently, except the width of the CFRP reinforcement, which is proportional to the obtained bond capacity, the designer has only the elastic modulus and the thickness of the CFRP reinforcement in hand to satisfy the demand. Thus, it is of great interest to investigate the effect of the two aforementioned parameters on the bond capacity of CFRP-to-steel joints during prestress release by using the proposed numerical model.

Effects of elastic modulus and CFRP plate thickness on the debonding load of prestress CFRP to steel joints, as a function of the bond length, are illustrated in Figures 15 and 16, respectively. As expected, using CFRP composites with higher elastic modulus can significantly increase the debonding load of the joint (Figure 15). Moreover, Figure 16 demonstrates that increasing the CFRP thickness can slightly increase the bond capacity, provided that the bond length is enough. However, careful inspection of Figures 15 and 16 reveals that, in case of having relatively short bond lengths (less than the effective bond length), the bond capacity of CFRP-to-steel is almost independent of the elastic modulus and thickness of the CFRP reinforcement. This important aspect has to be considered in the design of relatively small bonded CFRP patches for the strengthening of metallic details, given the fact that high modulus (HM) and ultra-high modulus (UHM) CFRP reinforcements are typically much more expensive than normal modulus (NM) CFRPs.

1 The numerical results provided in Figures 15 and 16 reveal that utilizing higher elastic moduli
2 or thicker CFRP plates can increase the bond capacity, provided that there exists enough bond
3 length. However, in such cases, a longer effective bond length is also required in order to
4 reach the increased bond capacity. Moreover, it is worth mentioning that in practical cases,
5 the application of UHM CFRP composites as a prestressed reinforcement is not feasible,
6 owing to the brittle nature and relatively low tensile strength of the UHM CFRP composites
7 [16].

6 Conclusions and future research works

This paper proposed a simplified theoretical model intended at simulating the release response of initially prestressed FRP strips glued to a steel substrate. In cases in which no debonding occurs during the release stage, the model can be employed also to simulate a subsequent lap-shear process. The model is based on the fundamental assumption of fracture response in pure mode II (shear mode). Although the formulation is completely general, the proposed model and the implemented numerical procedure has been validated with respect to experimental results of sets of lap-shear and prestress release tests performed on CFRP plates bonded to steel substrate. The following main observations can be drawn out from the validation procedure and the subsequent parametric analysis:

- The proposed model is capable of accurately estimating the load–slip response of CFRP-to-steel joints both at the lap-shear and prestress release stages, when incorporating a realistic bi-linear bond–slip relationship for the utilized so called linear epoxy adhesive used in the experiments. It is clear that the performance of the proposed model can be certainly improved by having more prestress release and lap-shear test results available in the future to incorporate a realistic bond–slip relationship.
- It has been demonstrated that by using a bi-linear bond–slip relationship, the proposed model can accurately predict the bond behavior of CFRP-to-steel joints, in terms of slip and strain of the CFRP strip, as well as the interfacial shear stress distributions along the bond length at different levels of prestress force release or lap-shear loading.
- It has been shown that the incorporated bond–slip relationship in the proposed numerical model can significantly influence the numerical results. Therefore, identification of realistic bond–slip relationships for different adhesive types and curing conditions (through conducting experimental tests) is of crucial importance.

The reason is attributed to the fact that using nonrealistic simplified bond–slip relationships such as a constant τ can lead to an unsafe overestimation of the initial stiffness of the CFRP-to-steel joint, while underestimate the interfacial shear stresses upon prestress release, and consequently, it can lead to an unsafe design of prestress CFRP strengthening systems for metallic structures.

- The performed parametric study has implied that using FRP composites with higher elastic moduli or application of thicker FRP reinforcement results in an increased prestress release/ lap-shear capacity of the FRP-to-steel bonded joints, provided that there is enough bond length.
- Numerical results revealed that in case of relatively short FRP patch reinforcements, the bond capacity of the FRP-to-steel is almost independent of the elastic modulus and thickness of the FRP reinforcement. This finding is certainly important to consider, particularly for selecting the most efficient strengthening solution for small metallic details where there is often not enough space to apply relatively long FRP reinforcements.

It should be noted that several developments of the proposed model are already in progress and will be proposed soon:

- Determination of prestress release–lap-shear interaction curves for FRP strips on steel substrate, depending on the main geometric and mechanical parameters, such as bond length, bond–slip relationship and FRP mechanical properties;
- Extension of the model kinematics with the aim to simulate a mixed-mode I/II (tensile and shear modes) fracture process at the FRP-to-steel interface;
- Formulation of a consistent indirect identification procedure [49] capable of identifying the bond–slip relationship of FRP-to-steel interfaces based on the results of few experimental prestress release–lap-shear tests;

- Extension of the model to other mechanically relevant situations, such as the exposure to elevated environmental temperature and the use of non-linear adhesives.

1 **Acknowledgements**

2 The authors gratefully acknowledge the financial support provided by the Swiss National
3 Science Foundation (SNSF Project No. 200021–153609). The authors would like to thank the
4 technicians of the Structural Engineering Research Laboratory of Empa for their outstanding
5 cooperation in performing the experimental tests. Furthermore, supports from S&P Clever
6 Reinforcement Company AG, Switzerland through the provision of the materials used in the
7 current study is acknowledged.

References

- [1] Costa A, Arêde A, Varum H (Eds.), *Strengthening and Retrofitting of Existing Structures*, 2018, Springer Singapore.
- [2] Hollaway LC, Teng JG, *Strengthening and Rehabilitation of Civil Infrastructures Using Fibre-Reinforced Polymer (FRP) Composites*, 2008, Woodhead Publishing.
- [3] fib, *Externally bonded FRP reinforcement for RC structures*, 2001, federation international du béton, bulletin 14, Lausanne (CH).
- [4] Babatunde SA, Review of strengthening techniques for masonry using fiber reinforced polymers, *Composite Structures*, 2017, 161, 246-255.
- [5] Zhao XL, Zhang L. State-of-the-art review on FRP strengthened steel structures. *Engineering Structures*, 2007;29(8):1808-23.
- [6] Zhao XL. *FRP-Strengthened Metallic Structures*. Boca Raton, FL: Taylor and Francis; 2013.
- [7] Teng JG, Yu T, Fernando D., Strengthening of steel structures with fiber-reinforced polymer composites, *Journal of Constructional Steel Research*, 2012, 78, 131-143.
- [8] Kamruzzaman M, Jumaat MZ, Ramli Sulong NH, Saiful Islam ABM, A Review on Strengthening Steel Beams Using FRP under Fatigue, *The Scientific World Journal*, 2014, Article ID 702537 (<http://dx.doi.org/10.1155/2014/702537>).
- [9] Pellegrino C, Maiorana E, Modena C, FRP strengthening of steel and steel-concrete composite structures: an analytical approach, *Materials and Structures*, 2009, 42, 3, 353–363.
- [10] Haghani R, Analysis of adhesive joints used to bond FRP laminates to steel members – A numerical and experimental study, *Construction and Building Materials*, 2010, 24(11), 2243-2251.

- [11] Özes C, Neşer N, Experimental Study on Steel to FRP Bonded Lap Joints in Marine Applications, *Advances in Materials Science and Engineering*, 2015, Article ID 164208, 6 pages (<http://dx.doi.org/10.1155/2015/164208>).
- [12] Fawzia S, Al-Mahaidi R, Zhao X-L. Experimental and finite element analysis of a double strap joint between steel plates and normal modulus CFRP. *Composite structures*, 2006;75(1-4):156-62.
- [13] Fernando ND. Bond behaviour and debonding failures in CFRP-strengthened steel members. Kowloon, Hong Kong: The Hong Kong Polytechnic University; 2010.
- [14] Yu T, Fernando D, Teng J, Zhao X. Experimental study on CFRP-to-steel bonded interfaces. *Composites Part B: Engineering*, 2012;43(5):2279-89.
- [15] Fernando D, Teng J-G, Yu T, Zhao X-L. Preparation and characterization of steel surfaces for adhesive bonding. *Journal of Composites for Construction*. 2013;17(6):04013012.
- [16] 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.
- [17] Fernando D, Yu T, Teng J-G. Behavior of CFRP laminates bonded to a steel substrate using a ductile adhesive. *Journal of Composites for Construction*. 2013;18(2):04013040.
- [18] 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.
- [19] Ghafoori, E., 2013. Interfacial stresses in beams strengthened with bonded prestressed plates. *Engineering Structures*, 46, pp.508-510.
- [20] Ghafoori, E. and Motavalli, M., 2013. Flexural and interfacial behavior of metallic beams strengthened by prestressed bonded plates. *Composite Structures*, 101, pp.22-34.

- 1 [21] Ghafoori, E. and Motavalli, M., 2015. Lateral-torsional buckling of steel I-beams
2 retrofitted by bonded and un-bonded CFRP laminates with different pre-stress levels:
3 experimental and numerical study. *Construction and Building Materials*, 76, pp.194-
4 206.
- 5 [22] Ghafoori E., Motavalli M., Botsis J., Herwig A., Galli M. Fatigue strengthening of
6 damaged metallic beams using prestressed unbonded and bonded CFRP plates.
7 *International Journal of Fatigue*, 2012. 44: p. 303-315.
- 8 [23] Ghafoori, E. and Motavalli, M., 2016. A retrofit theory to prevent fatigue crack
9 initiation in aging riveted bridges using carbon fiber-reinforced polymer materials.
10 *Polymers*, 8(8), p.308.
- 11 [24] Ghafoori, E., Motavalli, M., Zhao, X.L., Nussbaumer, A. and Fontana, M., 2015.
12 Fatigue design criteria for strengthening metallic beams with bonded CFRP plates.
13 *Engineering Structures*, 101, pp.542-557.
- 14 [25] Hosseini, A., Ghafoori, E., Motavalli, M., Nussbaumer, A. and Zhao, X.L., 2017. Mode
15 I fatigue crack arrest in tensile steel members using prestressed CFRP plates. *Composite*
16 *Structures*, 178, pp.119-134.
- 17 [26] Ghafoori, E., Schumacher, A. and Motavalli, M., 2012. Fatigue behavior of notched
18 steel beams reinforced with bonded CFRP plates: Determination of prestressing level
19 for crack arrest. *Engineering Structures*, 45, pp.270-283.
- 20 [27] Hosseini, A., Ghafoori, E., Motavalli, M., Nussbaumer, A., Zhao, X.L. and Koller, R.,
21 2018. Prestressed Unbonded Reinforcement System with Multiple CFRP Plates for
22 Fatigue Strengthening of Steel Members. *Polymers*, 10(3), p.264.
- 23 [28] Hosseini A., Ghafoori E., Motavalli M., Nussbaumer A., Zhao X.L., Al-Mahaidi R. Flat
24 Prestressed Unbonded Retrofit System for Strengthening of Existing Metallic I-Girders.
25 *Composites Part B: Engineering*, 2018, (under review).

- 1 [29] Kianmofrad, F., Ghafoori, E., Elyasi, M.M., Motavalli, M. and Rahimian, M., 2017.
2 Strengthening of metallic beams with different types of pre-stressed un-bonded retrofit
3 systems. *Composite Structures*, 159, pp.81-95.
- 4 [30] Ghafoori, E., Motavalli, M., Nussbaumer, A., Herwig, A., Prinz, G.S. and Fontana, M.,
5 2015. Design criterion for fatigue strengthening of riveted beams in a 120-year-old
6 railway metallic bridge using pre-stressed CFRP plates. *Composites Part B:
7 Engineering*, 68, pp.1-13.
- 8 [31] Ghafoori, E. and Motavalli, M., 2015. Innovative CFRP-prestressing system for
9 strengthening metallic structures. *Journal of Composites for Construction*, 19(6),
10 p.04015006.
- 11 [32] Czaderski-Forchmann, C., 2012. Strengthening of reinforced concrete members by
12 prestressed, externally bonded reinforcement with gradient anchorage (Doctoral
13 dissertation, ETH Zurich).
- 14 [33] Hosseini A, Wellauer M, Ghafoori E, Sadeghi Marzaleh A, Motavalli M. An
15 experimental investigation into bond behavior of prestressed CFRP to steel substrate.
16 Fourth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil
17 Structures (SMAR 2017). ETH Zurich, Switzerland, 2017.
- 18 [34] Motavalli, M., Czaderski, C. and Pfyl-Lang, K., 2010. Prestressed CFRP for
19 strengthening of reinforced concrete structures: Recent developments at Empa,
20 Switzerland. *Journal of Composites for construction*, 15(2), pp.194-205.
- 21 [35] Michels, J., Zile, E., Czaderski, C. and Motavalli, M., 2014. Debonding failure
22 mechanisms in prestressed CFRP/epoxy/concrete connections. *Engineering Fracture
23 Mechanics*, 132, pp.16-37.
- 24 [36] Colombi, P., Bassetti, A. and Nussbaumer, A., 2003. Analysis of cracked steel members
25 reinforced by pre-stress composite patch. *Fatigue & Fracture of Engineering Materials
26 & Structures*, 26(1), pp.59-66.

- [37] Täljsten, B., Hansen, C.S. and Schmidt, J.W., 2009. Strengthening of old metallic structures in fatigue with prestressed and non-prestressed CFRP laminates. *Construction and Building Materials*, 23(4), pp.1665-1677.
- [38] Koller, R.E., Stoecklin, I., Weisse, B. and Terrasi, G.P., 2012. Strengthening of fatigue critical welds of a steel box girder. *Engineering Failure Analysis*, 25, pp.329-345.
- [39] Nakamura, H., Yamamura, Y., Ito, H., Lin, F. and Maeda, K., 2014. Development of pre-tensioning device for CFRP strips and applicability to repair of cracked steel members. *Advances in Structural Engineering*, 17(12), pp.1705-1717.
- [40] ARAMIS - User Manual Software v. 6.3. GOM GmbH Braunschweig Germany, 2008.
- [41] ISO-527-1 (2012). Plastics – Determination of tensile properties – Part 1: General principles.
- [42] ISO-527-2 (2012). Plastics – Determination of tensile properties – Part 2: Test conditions for moulding and extrusion plastics.
- [43] Michels J, Cruz JS, Christen R, Czaderski C, Motavalli M. Mechanical performance of cold-curing epoxy adhesives after different mixing and curing procedures. *Composites Part B: Engineering*. 2016;98:434-43.
- [44] Moussa O, Vassilopoulos AP, de Castro J, Keller T. Early-age tensile properties of structural epoxy adhesives subjected to low-temperature curing. *International Journal of Adhesion and Adhesives*, 2012;35:9-16.
- [45] Hosseini A, Mostofinejad D. Effect of groove characteristics on CFRP-to-concrete bond behavior of EBROG joints: experimental study using particle image velocimetry (PIV). *Construction and Building Materials*. 2013;49:364-73.
- [46] Hosseini A, Mostofinejad D. Effective bond length of FRP-to-concrete adhesively-bonded joints: experimental evaluation of existing models. *International Journal of Adhesion and Adhesives*. 2014;48:150-8.

- [47] 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.
- [48] 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. Fourth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures (SMAR2017). ETH Zurich, Switzerland, 2017.
- [49] Ferreira SR, Martinelli E, Pepe M, de Andrade Silva F, Toledo Filho RD, Inverse identification of the bond behavior for jute fibers in cementitious matrix, 2016, *Composites Part B: Engineering*, 95, 440-452.

Table 1. Nominal average tensile strength, $f_{a,u}$, strain at rupture, $\varepsilon_{a,u}$, and elastic modulus, E_a for the utilized epoxy adhesive.

Type of adhesive	Number of tested samples	$f_{a,u}$ (MPa)	CV* (%)	$\varepsilon_{a,u}$ (%)	CV* (%)	E_a (GPa)	CV* (%)
S&P Resin 220	5	18.9	12.4	0.24	20.5	9.32	3.8

* CV = Coefficient of variation.

Table 2. Experimental test results (F_{pre} = initial prestressing force; t_a = adhesive thickness; F_u = debonding load; s_u = ultimate slip of the joint at the loaded end).

No.	Specimen label [33]	Type of test	F_{pre} (kN)	t_a (mm)	F_u (kN)	s_u (mm)
1	L-SP-RTC-1	Lap-shear	-	2.0	40.9	0.10
2	L-SP-RTC-2	Lap-shear	-	2.7	40.6	0.13
3	P90-SP-RTC-1	Prestress release	90.3	2.9	35.3	0.24
4	P90-SP-RTC-2	Prestress release	92.1	2.7	40.9	0.20

Figure 1: Stress components acting on a differential element of FRP strip.

Figure 2: Multilinear bond-slip relationship.

Figure 3: Displacement components and corresponding strain measures on a segmental element of the FRP strip.

Figure 4: Schematic of (a) release, and (b) subsequent lap-shear stages.

Figure 5: Finite-difference discretization of the FRP strip throughout the bond length.

2 *Figure 6. Lap-shear and prestress release test setup (all dimensions in mm).*

Figure 7. 3D digital image correlation (DIC) system used to monitor the bond behavior of CFRP-to-steel during lap-shear and prestress release tests.

Figure 8. Different bond–slip relationships considered in the numerical modeling ($G_f = 1.42 \text{ N/mm}$ and $s_u = 0.17 \text{ mm}$ for all cases; $s_e = 0.02 \text{ mm}$).

Figure 9. Comparison of experimental and numerical results in terms of load-slip response of the CFRP-to-steel joints under single lap-shear and prestress release loading (bond-slip relationship = bi-linear; $F_{pre} \approx 90$ kN).

(a)

(b)

(c)

1 Figure 10. Comparison of experimental and numerical results in case of a lap-shear test in terms of
 2 distribution of: (a) slip; (b) CFRP strain; (c) interfacial shear stress (bond-slip relationship = bi-
 3 linear; test specimen = L-SP-RTC-2; last stage load $F_{max} = 39.7$ kN).

1 Figure 11. Comparison of experimental and numerical results in case of a prestress release test in
2 terms of distribution of: (a) slip; (b) CFRP strain; (c) interfacial shear stress (bond-slip relationship
3 = bi-linear; test specimen = P90-SP-RTC-2; prestressing load $F_{pre} = 92.1$ kN; last stage load $F_{max} =$
4 40.4 kN).

1

2 *Figure 12. Influence of bond-slip relationship on load-slip response of CFRP-to-steel joint ($b_f = 50$*

3 *mm; $t_f = 1.4$ mm; $E_f = 160$ GPa).*

(a)

(b)

(c)

1 Figure 13. Effect of different bond–slip relationships on the obtained numerical results at initiation of
 2 debonding during prestress release: (a) slip profile; (b) CFRP strain profile; (c) interfacial shear
 3 stress profile ($b_f = 50$ mm; $t_f = 1.4$ mm; $E_f = 160$ GPa).

Figure 14. Effect of different bond-slip relationships on the obtained numerical results in terms of debonding load vs. bond length ($b_f = 50$ mm; $t_f = 1.4$ mm; $E_f = 160$ GPa).

Figure 15. Effect of CFRP elastic modulus on the obtained numerical results in terms of debonding load vs. bond length ($b_f = 50$ mm; $t_f = 1.4$ mm; bond-slip relationship = bi-linear).

1
2 Figure 16. Effect of CFRP plate thickness on the obtained numerical results in terms of debonding
3 load vs. bond length ($b_f = 50$ mm; $E_f = 160$ GPa; bond-slip relationship = bi-linear).