Short-term bond behavior and debonding capacity of prestressed CFRP composites to steel substrate

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Abstract

In this study, the short-term bonding behaviors of prestressed CFRP plates to steel substrates and their debonding capacities have been investigated. For this purpose, single lap-shear and prestress release tests were performed on adhesively bonded CFRP-to-steel joints. The feasibility of accelerated curing (AC) of the adhesive by heating was also investigated based on the conducted tests. Moreover, bond tests with partial prestress release and subsequent lap-shear loading were conducted to examine the feasibility of prestressed strengthening of steel members using AC. A three-dimensional (3D) digital image correlation (DIC) technique was utilized to monitor the bond behavior of CFRP-to-steel joints. Experimental results demonstrated that a mixed-mode I/II (tensile/shear) fracture governs the debonding failure of CFRP-to-steel joints during the prestress release. However, given that the steel substrate cannot undergo tensile failure, a relatively high prestressing force can be transferred to the steel substrate prior to debonding. The experimental results also revealed that the AC of the epoxy adhesive can be an advantageous alternative to the conventional room temperature curing (RTC) for strengthening steel members with prestressed bonded CFRP plates.

Keywords: Strengthening of steel structures, Carbon fiber reinforced polymer composite, Prestressing, Short-term bond behavior of CFRP-to-steel, Lap-shear test, Accelerated curing, Digital image correlation.

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1. Introduction

Strengthening of existing steel structures using carbon fiber reinforced polymer (CFRP) composites has become a commonly used technique owing to the unique advantages of the material, such as its light weight, corrosion resistance, increased strength, and fatigue endurance [1]. It has been shown that applications of CFRP composites can enhance the ultimate and serviceability states of steel members [2–7]. Externally bonded reinforcement (EBR) is the most commonly used strengthening technique through which CFRP laminates are applied on the surface of a steel or concrete member using proper epoxy adhesive. The technique has attracted increased interest as a fast and relatively easy solution for static and fatigue strengthening of existing structural elements. However, the efficiency of the EBR method is hampered by premature debonding of the composite reinforcement from the substrate [8,9]. Such an undesirable debonding failure significantly reduces the efficiency of the EBR solution, as the tensile capacity of the CFRP reinforcement cannot be utilized in its entirety [10].

Owing to the importance and complexity of the issue, a number of studies have been conducted to investigate the bond behavior and debonding capacity of CFRP-to-steel joints [10–14]. Moreover, it is well-known that the application of nonprestressed EBR can only partially contribute in supporting the additional service loads on the structure, while the application of prestressed CFRPs can reduce the existing stresses in a member. The latter solution, that is, the application of prestressed CFRPs, is of significant interest in cases of fatigue strengthening of steel structures [15–17] as it reduces the mean stress levels, thereby resulting in an enhanced fatigue life [5–7]. Despite the advantages, fewer attempts have been expended to utilize prestressed bonded CFRP reinforcements to strengthen steel elements [18–24]. The reason is attributed to the fact that adhesively bonded CFRP composites exhibit a low bond capacity prior to the debonding failure from the steel/concrete substrate, as mentioned above. However, this limited capacity can be severely affected by the prestressing of the CFRP reinforcement [16,23,25]. Therefore, in almost all the aforementioned studies that deal with the

strengthening of steel members with prestressed bonded CFRP reinforcements, mechanical end-anchorage were used to avoid undesirable premature debonding of the prestressed reinforcement. Using such mechanical end-anchorage in the previous research studies, to prevent debonding of prestressed CFRPs from the steel substrate, certainly indicates the lack of knowledge on the bond behavior and debonding capacity of prestressed CFRP composites to the steel substrate. Consequently, the current study is dedicated to address the aforementioned knowledge gap. The main intention of the present study is therefore to investigate the bond behavior of prestressed CFRP plates to steel substrate during prestress force release procedure.

In this study, a special lap-shear and prestress release test setup has been designed and assembled at the Structural Engineering Research Laboratory of Empa in order to systematically investigate and compare the bond behavior of nonprestressed and prestressed CFRP plates to steel substrates. Sets of experiments were conducted, while a 3D digital image correlation (DIC) system was used for full-field deformation measurements to better interpret the bond behavior of the tested CFRP-to-steel joints. Furthermore, in the current study, the feasibility of accelerated curing (AC) of epoxy adhesive layer based on heating—to be used as an alternative for the conventional cold curing in adhesively bonded CFRP-to-steel joints—has also been investigated. It is worth mentioning that, the current paper is an extended version of the authors' paper presented in the Fourth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures (SMAR 2017) [26].

2. Prestressed Partially Bonded Reinforcement Technique

The concept of a practical solution for strengthening of steel beams using prestressed CFRP reinforcement is proposed in this section. A CFRP plate is placed on the bottom flange of a steel beam with the epoxy resin applied to both ends (Figure 1a). The bonded length, on each end, should be at least two times the effective bond length (see Section 4.3.4). After the prestressing of the CFRP reinforcement to the desired level (considering an adequate safety fac-

tor) the adhesive in the two ending zones is cured using the AC procedure (see Section 3.2 for further details). After the AC of the epoxy adhesive in both of the prestressed reinforcement ends, a waiting period of approximately two hours is required to reach the ambient temperature. The prestress load can be then released to be carried by the end-zones of the formed bond (Figure 1b). This allows the permanent loads on the steel member to be partly carried by the prestressed partially bonded CFRP reinforcement, and subsequently lead to a reduction of the existing stress level in the member. For this purpose, approximately half of the bond length is required, while the other half is reserved for the additional external forces that are transferred to the CFRP reinforcement owing to the service loads (Figure 1c). In order to investigate the short-term response of the proposed prestressed partially bonded CFRP reinforcement at the bonded end zones, different bond tests have been designed and performed in this study, which are comprehensively explained in the following section.

3. Experimental Program

3.1. Test setup

Sets of lap-shear, prestress release, and mixed bond tests, were conducted to investigate and compare the bond behavior of nonprestressed and prestressed CFRP plates to the steel substrate. In a lap-shear test (Figure 2a), curing of the epoxy adhesive layer is the first step that occurs in an unloaded (nonprestressed) state, while at the second step the load is increased on one side until the joint begins to fail. In a prestress release test (Figure 2b), however, the first step is to increase the tensile load in the CFRP plate to a desired prestressing level. The adhesive layer is then cured, and the prestress force is then gradually released from one side, while being kept constant on the other side.

Figure 3 shows the procedure of a mixed bond test, i.e., prestress release followed by a subsequent lap-shear test. The first step of the mixed bond test (see step 1 in Figure 3) is very similar to a prestress release test except from the fact that the CFRP plate should be prestressed to a level that is lower than the bond strength (see Section 4.1.2). This avoids any

1 debonding failure during the prestress release process. In the second step, AC of epoxy is
2 conducted to reduce the curing time of the adhesive layer. Once the prestressing force is re-
3 leased to zero on one side, in the final step, the force in the CFRP plate is increased on the
4 opposite side until occurrence of the failure of the bond (see Figure 3). The main aim of per-
5 forming a mixed bond test is to simulate the stress state in the end zones of a prestressed par-
6 tially bonded CFRP reinforcement, when the prestress force is released and the strengthened
7 member is subjected to external service loading (see Figure 1).

8 Figure 4 depicts the test setup, which has been developed at the Structural Engineering
9 Research Laboratory of Empa to perform the different bond tests. A steel I-profile (IPE 220)
10 was vertically anchored to the strong floor with the help of four prestressed forks, while a hor-
11 izontal constraint was provided to avoid any rigid-body movement of the specimen during the
12 lap-shear or prestress release tests. Two mechanical grips, which were connected to the high-
13 strength (Grade 12.9) M13 threaded steel rods, were used to clamp the CFRP plate. MTS load
14 cells, with a capacity of 150 kN were installed on either side of the grips to monitor the pre-
15 stressing and/or lap-shear forces. M13 steel rods were kept in the center axis of hollow plung-
16 er hydraulic cylinders, which were installed on the outer flanges of short columns on both
17 sides of the test setup (see Figure 4).

18 **3.2. Adhesive curing conditions**

19 Two different curing conditions were used for the epoxy adhesive layer between the
20 CFRP plate and the flange of the IPE 220 steel profile: (a) room temperature curing (RTC),
21 which is straightforward but demands a longer waiting time (i.e., a period of three days was
22 used in the current study), and (b) accelerated curing (AC), which can be advantageous in a
23 practical applications by reducing the required time. The AC would especially improve the in-
24 stallation progress in a practical strengthening project dealing with prestressed reinforce-
25 ments, where the prestressing setup needs to stay in place to keep the prestressing force con-
26 stant over the curing period of the epoxy adhesive. In addition, the AC of epoxy adhesive can

1 slightly improve its glass transition temperature (T_g), which is of great interest for outdoor
2 strengthening of steel structures, subjected to moderately high service temperatures [27]. In
3 the current study, the AC was carried out by using a special heating device, as shown in Fig-
4 ure 5.

5 The heating device was originally developed at Empa for application of prestressed
6 CFRP plates on concrete using the gradient anchorage method (see [28] for further details).
7 The entire procedure of the AC takes 35 min during which the maximal temperature in the
8 heating element (and not in the adhesive layer) reaches 160 °C for approximately 15 min. An
9 infrared (IR) camera was used to capture the heat distribution in the specimen during the AC
10 procedure. It can be seen in Figure 6a that almost the entire steel substrate (i.e., IPE 220 steel
11 profile) was heated up during the AC of epoxy adhesive. Furthermore, the temperature within
12 the adhesive layer was measured at three different positions using thermocouples, and the re-
13 sults are plotted in Figure 6b. The measured temperature history shows that the maximal cur-
14 ing temperature was approximately 80 °C. This temperature is slightly lower than the curing
15 temperature in the AC of the adhesive layer in concrete strengthening applications [29]. This
16 observation could be attributed to the higher thermal conductivity coefficient of the steel sub-
17 strate compared to that of concrete.

18 3.3. Test layout

19 Ten tests were conducted in three main experimental series, i.e., lap-shear (L), prestress
20 release (Px), and mixed bond tests (PxL). The notation used for the test specimens in the lap-
21 shear series is L-SP-C- n , where L refers to the lap-shear test; SP refers to the type of adhe-
22 sive which is S&P Resin 220, C identifies the curing condition (i.e., RTC or AC), and n dis-
23 tinguishes the ordinal number of each test (1 or 2). For the prestress release series, the nota-
24 tion used for the test specimens was similar to the lap-shear series (Px-SP-C- n) with the
25 exception of P that referred to the prestress release test, and x , which is the initial prestressing

force in the CFRP plate in kN. Similarly, in the case of the mixed bond test series, the specimens were designated as $PxL-SP-C-n$, in which L referred to the subsequent lap-shear test.

3.4. Material properties

Steel I-profiles of type IPE 220 were used in the experiments with a grade of S355J2+M and a nominal yield strength and elastic modulus of 355 MPa and 210 GPa, respectively. In all the tests, CFRP plates of type S&P 150/2000–50/1.4 were used (S&P Clever Reinforcement Company AG) with a width of 50 mm and a thickness of 1.4 mm. The nominal ultimate strength of the utilized CFRP, $f_{f,u}$, was 2800 MPa according to the manufacturer's catalogue. The elastic modulus of the CFRP material was measured to be $E_f = 160$ GPa.

A two-component epoxy adhesive of type S&P Resin 220 (S&P Clever Reinforcement Company AG) was used to bond the CFRP plates to the steel substrate. In order to characterize the mechanical properties of the utilized epoxy adhesive, sets of tensile tests were conducted on dogbone samples of the epoxy adhesive prepared at RTC and AC conditions. In the case of the RTC, the dogbone samples were cured in a climate room under a constant temperature of 20°C and a relative humidity of 50% for 7 d. In the case of the AC, however, the samples were placed inside a Vötsch climate chamber (model VC 4100) for 60 min under a constant temperature of approximately 95°C. The samples were then placed in a climate room under a constant temperature of 20°C and a relative humidity of 50% for 2 h to allow them to cool down. Finally, the specimens were demolded and tested according to ISO 527 [30,31]. Further details regarding the performed tensile tests, as well as the determination of the glass transition temperature T_g of the utilized epoxy resin can be found in [27]. The obtained stress–strain (σ_a – ε_a) curves for all the tensile tests are plotted in Figure 7, while the average ultimate tensile strength, $f_{a,u}$, rupture strain, $\varepsilon_{a,u}$, and elastic modulus, E_a for the tested samples are provided in Table 1. Note that the reported tensile stress, σ_a , as well as the ultimate tensile strength, $f_{a,u}$, are nominal values, as they are obtained by dividing the applied maximum tensile force by the average cross-sectional area of the samples. Therefore, the stress values do

not account for the existence of any pores that may reside inside the failure plane, as sometimes observed in hand-mixed resin batches under ambient temperature and/or accelerated curing (see [32] for more details).

3.5. Specimen preparation

In order to ensure the bond quality, adequate surface preparation was performed on the steel substrate prior to the application of the epoxy adhesive. Thus, the surface on the upper flange of steel I-profiles used for the adhesive bonding was sandblasted and carefully cleaned with acetone. The IPE 220 steel profile was then placed into the right position in the test setup and was tightened to the strong floor (see Figure 5). The S&P Resin 220 was then used to glue the CFRP plate to the sand blasted area of the IPE 220 steel profile. It is noted that a foil of Teflon was used to prevent adhesive bonding outside the considered bond zone, i.e., the 50×300 mm middle area of the IPE 220 steel profile.

3.6. Digital image correlation (DIC)

A noncontact, full-field, 3D digital image correlation (DIC) system, known as ARAMIS [33] (GOM GmbH, Braunschweig, Germany), was used to monitor the deformations in all the tests. The system consisted of two digital cameras with four-megapixel resolutions that were installed on an aluminum frame (see Figure 8). Using ARAMIS [33] software, the entire 3D deformation/strain fields of the object were obtained by comparing the reference (unloaded) stage with the successive images taken during the loading process. It is worth mentioning that in order to ensure successful image processing, it was necessary for the images to have a suitable texture to create random features [34]. Thus, because neither the steel nor the CFRP surfaces originally contained a suitable texture, a black and white speckle pattern was applied on to the specimen's surface using an airbrush just before the execution of the experiments (see Figure 8). Further discussions regarding the accuracy and validation of the DIC system utilized, are provided in Section 4.3.1.

4. Results and Discussions

4.1. Bond strength

4.1.1. *Lap-shear and prestress release tests*

Table 2 presents an overview of all the performed tests, including the average adhesive thickness t_a , and the ultimate bond strength F_u , as obtained in each test. The obtained results from the bond strength tests of the CFRP-to-steel joints under the RTC condition revealed that the capacity of the joint was more or less the same for the lap-shear and prestress release tests, provided that the adhesive was cured at room temperature. Unlike all other specimens cured at room temperature, specimen P90–SP–RTC–1 was cured for 6 d rather than 3 d owing to some technical problems encountered in the execution of the test. Assuming that no other factor such as probable defects in the adhesive layer, influenced the obtained bond capacity in the aforementioned specimen, it may be concluded that by curing the adhesive for 6 d, the bond strength was reduced by 15% owing to the longer curing time. It has been demonstrated in [32,35] that a longer curing time resulted in a stiffer adhesive behavior. Therefore, in the case of a CFRP-to-steel joint, shorter effective bond lengths and lower bond strengths can be expected. Further research, however, is needed to confirm this hypothesis.

The tests in which the AC was implemented, exhibited a significant difference in the obtained bond strength based on the type of loading, i.e., lap-shear or prestress release. In the lap-shear tests under the AC, the average bond strength was in the same range as those test specimens cured at room temperature. However, the bond strength of prestress release series, in which the AC was used, was significantly higher than that of the RTC specimens. This result is attributed to an indirect influence of the adhesive layer thickness, which is comprehensively explained in the following paragraphs.

Figure 9a illustrates the bond strength of all the performed lap-shear and prestress release tests versus the thickness of the adhesive layer. As discussed earlier, all the RTC specimens had bond capacities in the same range, regardless of loading type (lap-shear or prestress

release). This indicates that although the values of the adhesive layer thickness ranged from 2.0 to 2.9 mm, there was no significant influence of t_a on the obtained bond capacities. In the tests with AC, however, the bond strength increased with the increase of t_a . The former results (i.e., RTC specimens) revealed no direct influence of the thickness, while the latter suggested an indirect influence of the adhesive layer thickness associated with the AC procedure. This indirect influence can be found when examining the temperature measurements, as presented in Figure 9b for two of the tested specimens that were used as examples.

In Figure 9b, both curves show the temperatures measured at the center of the bond length. In specimen L-SP-AC-1, the adhesive layer was considerably thinner ($t_a = 0.9$ mm) than specimen P90-SP-AC-1 ($t_a = 1.7$ mm). The reason is that by putting the heating device on the prestressed CFRP plates in specimens P90-SP-AC-1(2), the weight of the heating device could be partially carried by the prestressed CFRP plate, unlike the case of the nonprestressed CFRP plates used in specimens L-SP-AC-1(2). Additionally, the viscosity of the adhesive was reduced by heating, while the epoxy adhesive was squeezed out of the specimens L-SP-AC-1(2) during the AC procedure. Thus, the adhesive layer was significantly thicker in specimens P90-SP-AC-1(2), which means that less energy was available to cure the adhesive. Consequently, the epoxy adhesive reached lower temperature levels during the AC period (see Figure 9b). This resulted in a partly cured adhesive in specimens P90-SP-AC-1(2) with a more ductile behavior as previously observed [32]. A more ductile epoxy adhesive, however, allows the bond to achieve higher load levels before debonding failure occurs [13].

It is worth mentioning here that, experimental results of some existing research studies on bond strength of CFRP-to-steel joints, cured at room temperature, showed that an increase in the adhesive layer thickness might lead to an increased bond capacity [12,36]. However, some other experimental investigations revealed that no general correlation can be found between the adhesive layer thickness and the bond capacity of such joints, due to the scatter of

the test results [37]. Therefore, it is believed that further research studies are needed to investigate the role of adhesive layer thickness on bond behavior and debonding capacity of CFRP-to-steel joints, specifically when using the AC.

4.1.2. Mixed bond tests

In the case of prestress release tests, the CFRP plates were prestressed up to a target tensile force of approximately 90 kN, which was higher than the CFRP-to-steel bond capacity during prestress release. As it can be observed in Table 2, an average bond capacity of 74.1 kN is obtained in the prestress release tests in which the AC was incorporated.

By assuming an approximately 50% of the prestress release bond capacity as the design prestressing level for practical strengthening applications (utilizing the same configuration of CFRP, adhesive, and AC), an initial prestressing force of 40 kN (approximately 20% of the CFRP tensile strength) was used for the mixed bond tests (test numbers 9 and 10 in Table 2). As previously mentioned, the main intention of performing such mixed bond tests was to investigate the residual lap-shear capacity of a bonded CFRP reinforcement after release of the design prestressing force. The subsequent lap-shear test simulates the effect of external loading on the member after strengthening (see Section 2). The experimental results presented in Table 1 shows that the bonded CFRP-to-steel joints can still carry a significant lap-shear force after the prestress force is released. This short-term residual lap-shear capacity is almost the same as the bond capacity obtained in prestress release tests in which the AC was used, i.e., P90-SP-AC-1(2). Further explanations regarding this interesting result are provided in Section 4.3.4.

4.2. Failure mode

Figure 10 illustrates typical failure modes observed in the performed tests. Cohesive failure was observed in all ten experiments, regardless of the implemented curing condition (see Figure 10). In the lap-shear tests, the debonding crack propagated in close proximity to the CFRP-adhesive interface (Figure 10a,b). In prestress release tests, however, debonding

crack propagation was closer to the steel-adhesive interface. Careful inspection of Figure 10 reveals that the debonding crack propagated in close proximity to the steel-adhesive interface in the case of mixed bond tests (Figure 10e,f). It is worth mentioning that in this case, failure occurred owing to the subsequent lap-shear loading, and not during prestress release. Consequently, the failure that occurred in the bonded zone subjected to the subsequent lap-shear should be considered as the dominant mode of failure, and the rest is believed to be the secondary effect of the brittle debonding failure (see Figure 10e,f). In all of the performed tests, the adhesive was attached in one of the adherends. On the other hand, as only a thin layer of adhesive remained on one of the adherends (on the CFRP in the case of the lap-shear, and on the steel surface in the case of the prestress release), the failure mode can be better referred to as “*cohesive near interface*” failure.

4.3. Investigation of bond behavior using 3D DIC

4.3.1. Validation of the DIC measurements

According to the user manual of the DIC system utilized [33], the accuracy of the measurements is 0.01–0.1 pixels for the in-plane, and 0.1–1.0 pixels for the out-of-plane deformations, respectively. This can be translated to accuracy ranges of 0.002–0.018 mm, and 0.018–0.175 mm, for the in-plane and out-of-plane deformation measurements, respectively, considering that in the test setup utilized the field of interest was 350×350 mm, monitored by 2000×2000 pixel cameras.

Although there is no doubt regarding the guaranteed accuracy of the DIC system used, a comparison between conventional strain gauge readings and DIC measurements, in terms of strain and in-plane deformation of the CFRP plate, is indicatively provided in this section. For that purpose, several electrical strain gauges of type 1–LY–66–6/120 with an electrical resistance of $120 \, \Omega \pm 0.30\%$ (HBM AG, Germany) were mounted on the prestressed CFRP plate in test specimen P90–SP–RTC–2 (Figure 11a). Afterwards, a black and white speckle pattern was applied onto the entire specimen’s surface. Figure 11b shows the DIC field of in-

terest and the section which was considered for comparing the DIC measurements with the strain gauge readings.

Figure 12a illustrates the evolution of the longitudinal strain profiles during the prestress force release, which were obtained from both the DIC measurements and strain gauge readings. As it can be seen in Figure 12a, the agreement between the strain values, measured by the DIC and strain gauges, is quite satisfying. Careful inspection of Figure 12a reveals that the strain profiles obtained by the DIC system exhibit certain fluctuations; however, the strain values obtained by the DIC system at the locations of the strain gauges (illustrated by black dots) are almost the same as those measured by the strain gauges. It is worth mentioning that the strain values obtained from the DIC and strain gauges are not supposed to be identical, owing to the following reasons: (1) as illustrated in Figure 11b the location of the strain gauges (in the transverse direction of the CFRP plate) is not identical to that of the considered DIC section, because the DIC measurements on the strain gauges could be biased, and (2) the strain gauges in fact provide an average strain value for the entire grid length (6 mm for the strain gauge utilized), while the strains provided by the DIC system are based on the displacement values measured on a fine grid of points with an interval of 13 pixels (2.275 mm). The latter also explains why the DIC results exhibit more fluctuations, compared to the strain gauge readings.

Similar DIC-to-strain gauge comparisons, but in terms of in-plane CFRP deformation, are provided in Figure 12b. Note that the strain gauge readings can be used to calculate the longitudinal deformation of the CFRP, assuming that the substrate is rigid (please refer to [12] for the detailed formulation). Figure 12b shows that a very good correlation exists between the in-plane deformation profiles obtained from the DIC measurement and those calculated based on the strain gauge readings. Once again, the DIC results are not supposed to be in complete agreement with those of the strain gauges due to the previously mentioned reasons.

However, careful scrutiny of Figure 12b reveals that the accuracy of the DIC system is indeed within the range, guaranteed by the manufacturer.

4.3.2. Global behavior of the bond in lap-shear and prestress release tests

In all the lap-shear and prestress release tests, the relative in-plane displacement between the CFRP plate and the steel substrate (hereafter referred to as slip s_f) at the loaded end of the CFRP plate was determined for the captured stages of loading using the DIC system. The results were used to plot the load–slip curves, as shown in Figure 13. It can be observed in Figure 13 that all the lap-shear tests yielded similar behaviors, regardless of the curing condition. However, in the case of prestress release tests, the load–slip response of the RTC specimens exhibited a nonlinear behavior at lower load levels compared to the exhibited behavior of the lap-shear tests. This might be explained by the mixed-mode I/II (shear/tensile) state of loading in a prestress release case, which expedited the debonding failure (see Section 4.3.3). Moreover, the load–slip behavior of specimens P90–SP–AC–1(2) confirmed the previous statement regarding the increased ductile behavior of the partly cured adhesive (see Section 4.1.1). From the very first stages of loading, these joints were much softer and experienced larger slip values compared to fully cured specimens (see Figure 13b). This ductile behavior of the partly cured adhesive allowed the joint to withstand a considerably higher load level before debonding failure occurred. It is also evident that specimen P90–SP–AC–2 ($t_a = 1.7$ mm) exhibited a slightly stiffer behavior compared to specimen P90–SP–AC–1 ($t_a = 2.0$ mm) owing to the increased energy available for curing during the AC procedure, and owing to the thinner layer of adhesive in the former specimen (see the discussions in Section 4.1.1).

4.3.3. Evolution of the in-plane and out-of-plane deformation profiles in the lap-shear and prestress release tests

In order to further investigate and compare the bond behavior of nonprestressed and prestressed CFRP plates to the steel substrate, and to better realize the effect of accelerated curing, full-field 3D deformations obtained from the DIC measurements were used to plot the

in-plane and out-of-plane deformation profiles in Figure 14. Figure 14a,b shows that in a lap-shear test, the shear deformation (i.e., mode II) governs the behavior regardless of the curing condition as the relative out-of-plane deformation of the CFRP plates (hereafter referred to as separation r_f) is almost negligible.

In the prestress release tests, a significant separation of the CFRP plate from the steel substrate was observed (see Figure 14c,d). This separation occurred because of the eccentricity of the prestress release load with respect to the steel surface, which generated considerable tensile (peeling) stresses in the adhesive layer. Consequently, the assumption of pure mode II behavior is no longer valid for the prestress release case, as the mixed-mode I/II behavior governed. Furthermore, it can be observed in Figure 14c that the effective bond length in specimen P90–SP–RTC–2 is approximately equal to 70 mm, and approximately equal to 120 mm in specimen P90–SP–AC–2 (Figure 14d). Therefore, it can be concluded that the partly cured condition of adhesive achieved in the AC process resulted in a more ductile adhesive, and subsequently, in a larger effective bond length, and in increased bond strength.

4.3.4. Mixed bond tests

Figure 15 shows the longitudinal deformation field obtained by ARAMIS [33] for specimen P40L–SP–AC–1 after the prestress release and just before the debonding failure owing to the subsequent lap-shear. It can be observed in this figure that the deformation field owing to the prestress release on the left side of the bonded zone did not interfere with that of the subsequent lap-shear on the other side of the CFRP plate. This observation correlates well with the previously presented test results regarding the subsequent lap-shear capacity of the joint (see Section 4.1.2).

In order to further investigate the bond behavior of the prestress CFRP to steel during the mixed bond test of specimen P40L–SP–AC–1, the obtained full-field deformation measurements were used to plot the slip, separation, longitudinal strain, and interfacial shear stress profiles in Figure 16. Note that the interfacial shear stress profiles were calculated using the

longitudinal strain profiles using a virtual gauge length of approximately 25 mm (see Hosseini and Mostofinejad 2013 [38] for the calculation method). As it can be seen from Figure 16, by releasing the prestress force in specimen P40L-SP-AC-1, the strain and the interfacial shear stresses gradually increased over the effective bond length, while the CFRP plate exhibited no significant separation owing to the fact that the released force was designed to be approximately half of the prestress release capacity of the bonded joint. The effective bond length in this case was approximately 120 mm, while the rest of the bonded length was absolutely intact, and this nonstressed intact bond length (on the right side) was capable of carrying the full lap-shear capacity. Figure 16g illustrates that the peak interfacial shear stress, τ_a , during prestress release was maintained at approximately 10 MPa, while the critical value that corresponded to the debonding failure was approximately 20 MPa (see Figure 16h).

The full-field deformation measurements in the mixed bond tests suggest that by providing enough bond length (at least two times the effective bond length), an adhesively bonded CFRP-to-steel joint can safely hold the design prestressing force, while concurrently possessing the full lap-shear capacity to withstand the external (service) loading on the joint.

5. Summary and Concluding Remarks

In the current study, sets of single lap-shear and prestress release tests were conducted on CFRP-to-steel bonded joints to investigate the short-term bond behavior and capacity of prestress CFRP plates to the steel substrate. The feasibility of the accelerated curing (AC) of epoxy adhesive based on heating was also studied. Moreover, a set of mixed bond tests with partial prestress release and a subsequent lap-shear was conducted to examine the short-term response and stress state in a prestressed partially bonded CFRP reinforcement, which can be used for strengthening of existing steel beams. A DIC system was used in all the tests in order to monitor the 3D full-field behavior of CFRP plates bonded to the steel substrate, during the lap-shear and/or prestress release test. Based on the experimental results and the 3D DIC measurements, the following concluding remarks can be drawn:

- The AC of the epoxy adhesive layer based on heating led to almost the same lap-shear strength as the cured CFRP-to-steel joints at room temperature. However, the debonding loads of the prestress release tests performed on the accelerated-cured CFRP-to-steel bonded joints were much higher than those developed in the corresponding joints cured at room temperature. The reason for such behavior can be attributed to the partly cured state of the epoxy adhesive, which resulted in a more ductile behavior, a longer effective bond length, and consequently, to a higher bond strength.
- In the case of CFRP-to-steel bonded joints cured at room temperature, the debonding loads of prestress release tests were slightly lower than the corresponding loads in lap-shear tests. It was observed that in the prestress release tests, the slip and separation of the CFRP plate with respect to the steel substrate had the same order of magnitude. Consequently, the lower debonding load obtained in prestress release tests compared to the lap-shear tests, was attributed to the mixed-mode I/II state of the fracture in the adhesive layer in the prestress release test. However, more research is needed to further investigate the bond behavior of prestressed CFRPs to the steel substrate, and to better clarify the influence of a partly cured epoxy adhesive as well as the role of adhesive layer thickness in the mixed-mode I/II stress state.
- The AC of the epoxy adhesive based on heating can be a promising alternative to the conventional room temperature curing (RTC) for strengthening of steel members with prestressed bonded CFRP plates. It is clear that the AC can be certainly advantageous in practical applications in reducing the overall strengthening time. The AC would especially improve the installation progress in a practical strengthening project dealing with prestressed CFRP reinforcements, where the prestressing system needs to stay in place to maintain the prestressing force constant during the curing period.
- A new strengthening approach was proposed, which employs a prestressed partially bonded reinforcement. In order to simulate the stress state in the anchorage zones of

1 the proposed technique, a set of mixed bond tests with a partial prestress force release
2 and a subsequent lap-shear loading was conducted. Experimental results revealed that
3 by providing enough bond length (at least two times the effective bond length), an ad-
4 hesively bonded CFRP-to-steel joint can hold the design prestressing force, while con-
5 currently possessing the full lap-shear capacity to withstand the external (service)
6 loading on the joint. Future laboratory studies, as well as pilot field applications are
7 indeed required to extend the existing knowledge on the long-term behavior of pre-
8 stressed bonded CFRP reinforcements for the strengthening of steel members.

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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 (RTC=room temperature curing, AC=accelerated curing).

Curing condition	Age of sample at the day of test	Number of tested samples	$f_{a,u}$ (MPa)	CV* (%)	$\varepsilon_{a,u}$ (%)	CV* (%)	E_a (GPa)	CV* (%)
RTC	7 d	5	18.9	12.4	0.24	20.5	9.32	3.8
AC	2 h (cooling time)	4	16.4	20.8	0.21	19.9	8.15	7.2

* CV = Coefficient of variation.

Table 2. Test results (RTC=room temperature curing; AC=accelerated curing).

No.	Specimen label	Type of test	Type of curing	Initial prestress force, F_0 (kN)	Adhesive thickness, t_a (mm)	Bond strength, F_u (kN)
1	L-SP-RTC-1	Lap-shear	RTC	-	2.0	40.9
2	L-SP-RTC-2	Lap-shear	RTC	-	2.7	40.6
3	L-SP-AC-1	Lap-shear	AC	-	0.9	43.7
4	L-SP-AC-2	Lap-shear	AC	-	0.5	39.2
5	P90-SP-RTC-1*	Prestress release	RTC	90.3	2.9	35.3
6	P90-SP-RTC-2	Prestress release	RTC	92.1	2.7	40.9
7	P90-SP-AC-1	Prestress release	AC	87.6	2.0	78.5
8	P90-SP-AC-2	Prestress release	AC	88.3	1.7	69.7
9	P40L-SP-AC-1	Mixed	AC	39.8	1.8	67.1
10	P40L-SP-AC-2	Mixed	AC	40.5	1.5	67.2

* Cured at room-temperature for 6 d.

Figure 1. Principle of the proposed technique for strengthening steel beams using prestressed partially bonded CFRP plates: (a) prestressing and accelerated curing of the epoxy adhesive, (b) releasing the prestressing force after cooling, and (c) effect of additional (service) load on the strengthened member.

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Figure 2. Procedure of (a) lap-shear and (b) prestress release test (F_{LS} = lap-shear capacity; F_{pre} = pre-stressing force; F_{PR} = prestress release capacity).

Figure 3. Procedure of mixed bond test depicting the prestress release, and subsequent lap-shear test (F_{PR} = prestressing force; F_{LS} = lap-shear capacity).

Figure 4. Test setup (all dimensions in mm).

Figure 5. Accelerated curing of epoxy adhesive using a special heating device.

Figure 6. (a) Infrared thermal image showing the heat distribution in IPE 220 during AC of epoxy adhesive, (b) temperature history in the adhesive layer in specimen P90–SP–AC–1 ($T_i = i^{th}$ thermocouple in the adhesive layer).

Figure 7. (a) Effect of curing condition on the stress–strain behavior of the utilized epoxy adhesive (RTC=room temperature curing (5 samples), AC=accelerated curing (4 samples)).

Figure 8. 3D digital image correlation (DIC) system used for full-field deformation measurements during tests.

Figure 9. (a) Effect of the adhesive thickness and curing condition on bond strength of CFRP-to-steel joints, and (b) influence of adhesive thickness on the temperature history of the adhesive during the AC procedure.

Figure 10. Typical failure modes of tested specimens.

(a)

(b)

Figure 11. (a) Arrangement of the strain gauges mounted on CFRP plate, and (b) DIC field of interest and position of the considered DIC section in specimen P90-SP-RTC-2 (all dimensions are in mm).

(a)

(b)

Figure 12. Comparison of 3D DIC measurements (full lines) with strain gauge readings (dash lines) in specimen P90–SP–RTC–2: (a) longitudinal strain profiles, and (b) in-plane deformation profiles along the CFRP plate ($F_{pre} = 92.1$ kN, last stage load $F_{max} = 40.4$ kN).

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Figure 13. Load vs. slip at the loaded end of the CFRP plate for lap-shear and prestress release tests: (a) full range, (b) initial stiffness (* note that the specimen was cured at room temperature for 6 d before the test execution).

(a) L-SP-RTC-1 (last stage load $F_{max} = 38.6$ kN)

(b) L-SP-AC-1 (last stage load $F_{max} = 40.0$ kN)

(c) P90-SP-RTC-2 (last stage load $F_{max} = 40.4$ kN)

(d) P90-SP-AC-2 (last stage load $F_{max} = 69.2$ kN)

Figure 14. Evolution of in-plane and out-of-plane deformation profiles during lap-shear and prestress release tests.

Figure 15. Longitudinal deformation field in specimen P40L-SP-AC-1 after prestress force release just before failure owing to the subsequent lap-shear measured using the 3D DIC system.

Figure 16. Evolution of (a), (b) slip, (c), (d) separation, (e), (f) longitudinal strain, and (g), (h) interfacial shear stress profiles during prestress release and subsequent lap-shear test in specimen P40L-SP-AC-1 ($F_{pre} = 39.8$ kN, $F_{LS} = 65.2$ kN).