An experimental investigation into bond behavior of prestressed CFRP to steel substrate

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ABSTRACT: Nowadays, strengthening of existing steel structures using advanced carbon fiber reinforced polymer (CFRP) composites is becoming a common technique due to the unique advantages of the material such as light weight, high strength and fatigue endurance, as well as their relatively easy installation. Recently, the tendency to strengthen steel structures with prestressed CFRP plates is growing, especially in case of fatigue strengthening, where a reduction in acting stresses on the structures would be possible using prestressed reinforcements. However, the efficiency of using prestressed bonded CFRP reinforcements is severely affected by the undesirable premature debonding of CFRP from the steel substrate, before reaching the ultimate tensile capacity of the strengthening material. Consequently, it is of great importance to investigate the anchorage resistance and bond behavior of prestressed CFRP plates bonded to steel substrate. In the current study, a set of single lap-shear and prestress release tests was performed on CFRP-to-steel joints. All the tests were monitored using a 3D digital image correlation (DIC) system to understand the bond behavior of CFRP plates during lap-shear and prestress release tests. Moreover, the effect of accelerated curing on bond anchorage of the prestressed CFRP plates was investigated. Prestress release test results of the current study showed that the governing phenomenon in CFRP-to-steel joints is completely different than that in CFRP-to-concrete joints. The reason is that, despite in concrete, no tensile failure can occur in steel; consequently, relatively high prestressing forces can be transferred to the steel substrate before reaching debonding.

1 INTRODUCTION

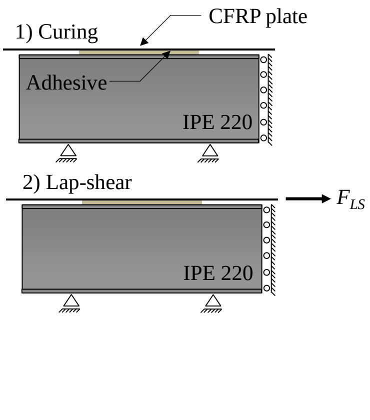
Owing to the certain advantages of carbon fiber reinforced polymers (CFRPs) such as light weight, high elastic modulus and strength, excellent fatigue performance, and ease of application, these advanced composite materials have attracted lots of interest for static and/or fatigue strengthening of existing steel structures (Zhao, 2013). Externally bonded reinforcement (EBR) method is the most common technique for strengthening existing steel members through which the CFRP laminates are applied on the surface of the member using an epoxy adhesive. However, the efficiency of the EBR method is hampered by premature debonding of the CFRP laminate from the steel substrate. Thus, due to the importance of the issue, a number of studies have been conducted in the literature to investigate the bond strength and bond behavior of CFRP-to-steel joints (for example see Fernando 2012; Yu et al. 2012). On the other hand, externally applied reinforcements only contribute in carrying the additional service loads on the structure, while applying prestressed CFRP reinforcements can reduce the existing stresses in a member, which is of great interest in case of fatigue strengthening of steel structures. However, very limited investigations have been focused on bond behavior of prestressed CFRP plates to the steel substrate (Ghafoori, 2015; Hosseini et al. 2016). Consequently, the main intention of the current ongoing research study at the Structural Research Laboratory of Empa is to further investigate the bond behavior of prestressed CFRP plates to the steel substrate using a single lap-shear test setup. Furthermore, the feasibility of accelerated curing of the adhesive by heating, to be used as an alternative for conventional cold curing in externally bonded CFRP-to-steel joints, is studied as a part of the current study.

2 EXPERIMENTAL PROGRAM

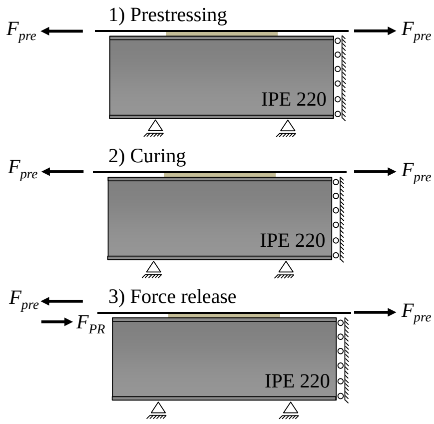
2.1 Test setup

In order to investigate the bond behavior of nonprestressed and prestressed CFRP plates to the steel substrate, a set of lap-shear and prestress release tests was planned. In a lap-shear test (Figure 1a), curing of the adhesive takes place in an unloaded (non-prestressed) state, while as the second step, the load is increased on one side until the failure of the joint occurs. In a prestress release test (Figure 1b), however, the first step is to increase the tensile load in the CFRP plate to the desired prestressing level. In that state, the adhesive layer is cured, and subsequently, as the final step, the prestress force is gradually released on one side, while it is kept constant on the other side.

The test setup developed in this research to study the bond behavior of nonprestressed and prestressed CFRPs to the steel substrate is demonstrated in Figure 2. The steel profile (IPE 220) is vertically anchored to the strong floor with the help of four prestressed forks, while a horizontal constraint is provided to avoid any rigid-body movement of the specimen during a lap-shear or a prestress release test. Two special prestressing grips, which are connected to high strength (Grade 12.9) M13 threaded steel rods, hold the CFRP plate. Load cells are installed on either side of these grips and the rods are kept in place with hydraulic cylinders installed on the outer flanges of the short columns on both sides (see Figure 2).



(a)



(b)

Figure 1. Procedure of: (a) lap-shear test; (b) prestress release test.

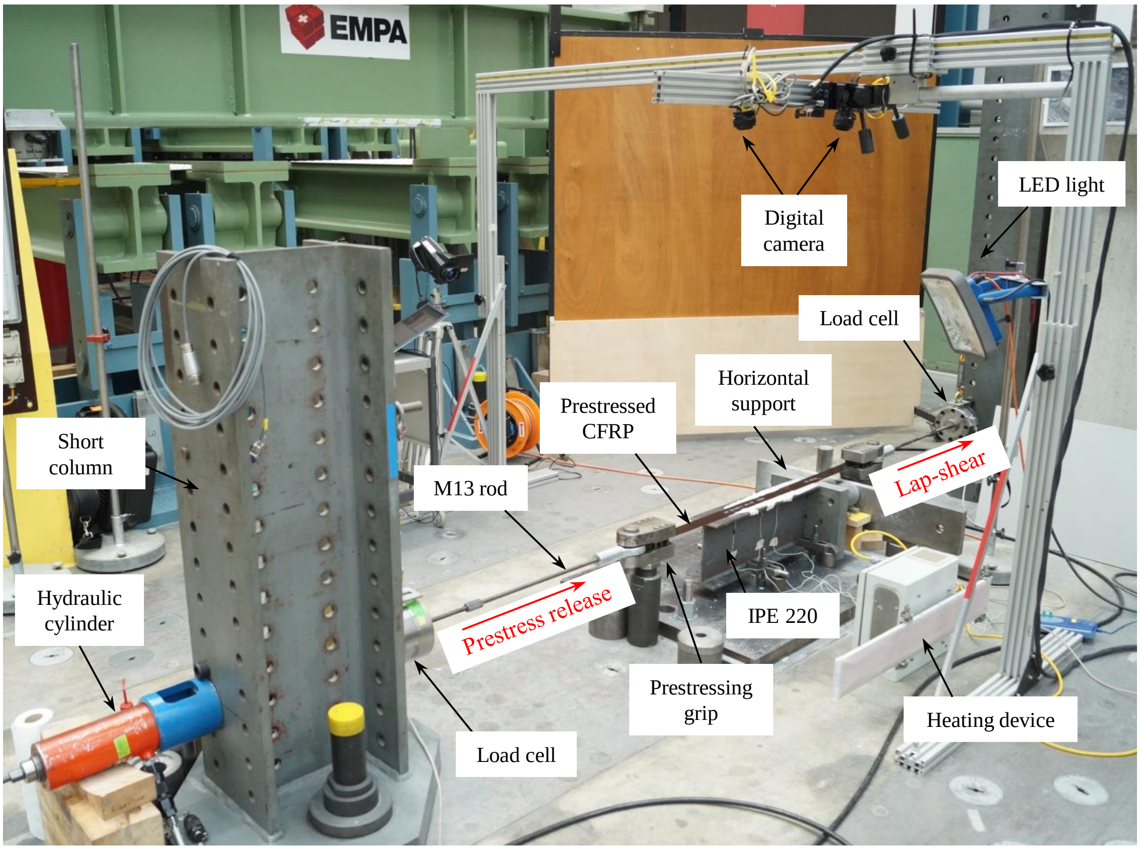


Figure 2. Lap-shear and prestress release test setup.

2.2 *Type of curing*

Two different methods were used to cure the epoxy resin in between the CFRP plate and the IPE 220: (a) room-temperature curing (RTC), which is straightforward but demands a longer waiting time (a waiting time of three days was used in the current study); (b) accelerated curing (AC), which in a practical application can be advantageous to reduce the time demand. AC would especially improve the installation progress in a practical strengthening project dealing with prestressed reinforcements, where prestressing grips need to stay in place to keep the prestressing force during the curing of the adhesive. To do AC, the heating device shown in Figure 2 was used. The device was originally developed at Empa for application of gradient anchorage method on concrete (see Michels et al. 2012 for further details). Note that the entire procedure of AC takes 35 minutes during which the maximal temperature in the heating element (and not in the adhesive layer) reaches 160 °C for approximately 15 minutes.

2.3 *Test layout*

In total eight tests were conducted in two main series, i.e., lap-shear (L) and prestress release (P) series. The notation of test specimens in the lap-shear series is L-SP-*C*-*n*, where L refers to the lap-shear test; SP refers to the type of adhesive which is S&P 220 resin; *C* identifies the type of curing (i.e., RTC or AC), and *n* distinguishes the ordinal number of each test (1 or 2). For the prestress release series, the notation of test specimens is similar to the lap-shear series as P*x*-SP-*C*-*n* with the exception of P referring to the prestress release test, accompanying with *x* which is the initial prestressing force in the CFRP plate in kN.

2.4 Material properties

IPE 220 steel profiles used in the experiments were made from steel grade S355J2+M with a nominal yield strength and elastic modulus of 355 MPa and 210 GPa, respectively. In all the tests, CFRP plate of type S&P 150/2000-50/1.4 (S&P Clever Reinforcement Company), having a width of 50 mm and a thickness of 1.4 mm, was used. The nominal ultimate strength of the CFRP, $f_{p,u}$ = 2800 MPa according to the manufacturers catalogue. The elastic modulus of the CFRP was determined in one of the tests, prior to applying the epoxy adhesive, and found to be E_p = 160 GPa. A two-component epoxy adhesive of type S&P 220 resin (S&P Clever Reinforcement Company) was used to bond the CFRP plates to the steel substrate. No auxiliary test was performed on the adhesive as part of the current study; however, a comprehensive experimental study has been done by Michels et al. (2016) to characterize the material properties of the S&P 220 resin under different curing and aging conditions.

2.5 Specimen preparation

In order to ensure the quality of the bond, adequate surface preparation is required for the steel prior to applying the epoxy adhesive. Thus, the area on the upper flange of steel I-profiles, used for the adhesive bonding, was sandblasted and carefully cleaned with acetone. The IPE 220 was then brought into the position in the test setup (Figure 2), and S&P 220 resin was used to glue the CFRP plate to the sand blasted area of the IPE 220. It should be noted that a foil of Teflon was used to prevent adhesive bonding outside the 50 × 300 mm area of the bond.

2.6 3D digital image correlation (DIC)

A non-contact full field 3D digital image correlation (DIC) system, called ARAMIS (2008) (GOM GmbH, Braunschweig, Germany), was used to monitor the tests. The system consists of two 4-megapixel digital cameras, installed on an aluminum frame (Figure 2). Using ARAMIS software, the entire 3D deformation/strain fields of the object can be obtained by comparing the reference (unloaded) stage with the successive images taken during the loading process.

3 RESULTS AND DISCUSSIONS

3.1 Ultimate bond strength

Table 1 presents an overview of all the performed lap-shear and prestress release tests, including the adhesive thickness t_a, and the ultimate bond strength F_R obtained in each test. Considering the bond strength of CFRP-to-steel joints under the RTC condition reveals that the capacity of the joint is more or less the same for the lap-shear and prestress-release tests when the adhesive is cured at room temperature. Unlike all other room-temperature cured specimens, specimen P90-SP-RTC-1 was cured for 6 days rather than 3 days owing to some technical problems for performing the test. It can be seen that by curing the adhesive for 6 days, the bond strength reduced by 15% due to the fact that a longer curing time results in a stiffer behavior of the adhesive (see Michels et al. 2016) and a shorter effective bond length, which leads to a lower bond strength. On the other hand, the tests in which AC was incorporated, exhibited a significant difference in bond strength based on the type of loading, i.e. lap-shear or prestress release. In the lap-shear tests under accelerated curing (L-AC), the average bond strength was in the same range as in the L-RTC tests. However, the bond strength of prestress release series (P90-AC) was significantly higher. This result is attributed to the curing state of the adhesive in the accelerated cured prestress release tests. It can be seen in Table 1 that the adhesive layer in specimens P90-SP-AC-1(2) is significantly thicker than the layer in specimens L-SP-AC-1(2) owing to the fact that by putting the heating device on the prestressed CFRP plates of specimens P90-SP-AC-1(2), the weight of the heating device could be carried by the prestressed CFRP plate. Thus, due to the thicker adhesive layer compared to the L-AC specimens, less energy was available for the accelerated curing of the adhesive. This resulted in a partly-cured adhesive in specimens P90-SP-AC-1(2) with a more ductile behavior, which allowed the bond to carry higher load levels before the ultimate debonding occurred.

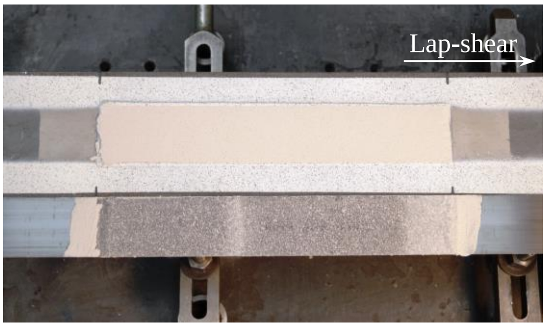
Table 1. Test results.

No.	Specimen label	Type of test	Type of curing	Initial prestress force, F_0 (kN)	Adhesive thickness, t_a (mm)	Bond strength, F_R (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	90.1	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

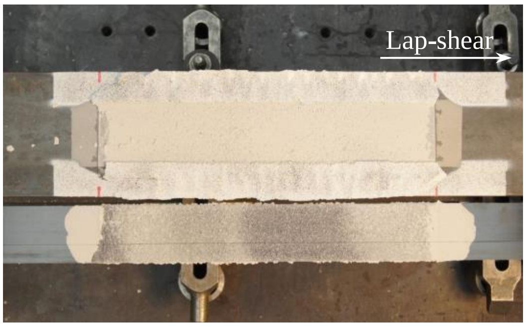
* Cured at room temperature for 6 days.

3.2 Failure mode

Similar cohesive failures were observed in all the eight tests (lap-shear or prestress release), regardless of the curing type (see Figure 3).



(a) Specimen L-SP-RTC-1



(b) Specimen L-SP-AC-1

(c) Specimen P90-SP-RTC-1

(d) Specimen P90-SP-AC-1

Figure 3. Failure modes observed in the tested specimens.

In the lap-shear tests, the debonding crack propagated in close proximity of the CFRP- adhesive interface (Figure 3a,b). In prestress release tests, however, crack propagation was closer to the steel-adhesive interface. Neither in lap-shear nor in prestress release tests was the adhesive fully removed from one of the adherends. On the other hand, as only a thin layer of adhesive was remained on one of the adherends (on CFRP in case of lap-shear, and on steel in case of prestress release) the failure mode can be better called as *cohesive near interface* failure.

3.3 Global behavior of bond

In all specimens, the relative displacement between the CFRP plate and the steel substrate (called slip, s_f) was determined for the captured stages of loading using ARAMIS, and the load-slip curves are plotted in Figure 4. It can be seen from Figure 4 that all the lap-shear tests behaved similarly, regardless of the curing type. However, in case of prestress release tests, the load-slip response of the room-temperature cured specimens exhibited a non-linear behavior in lower load levels compared to the lap-shear tests. This might be explained by the mixed-mode state of loading in a prestress release case, which expedites the debonding failure (see Section 3.4). On the other hand, the load-slip behavior of the specimens P90-SP-AC-1 and P90-SP-AC-2 confirms the previously made statement regarding the more ductile behavior of the partly-cured adhesive (see Section 3.1). From the very first stages of loading, the joint behaved much softer with experiencing larger slip values compared to a fully cured specimen. This ductile behavior of the partly-cured adhesive allows the joint to carry a considerably higher load level before deboning failure occurred. It is also evident that specimen P90-SP-AC-2 (t_a = 1.7 mm) exhibited a stiffer bond compared to specimen P90-SP-AC-1 (t_a = 2.0 mm) owing to the more energy available for curing during the AC process, because of the thinner layer of adhesive in the former specimen (see Section 3.1).

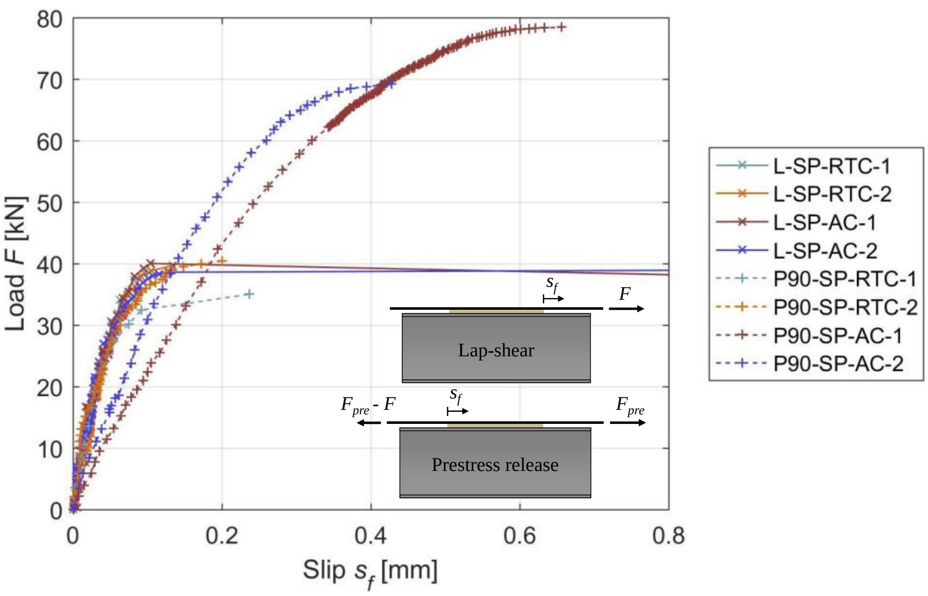
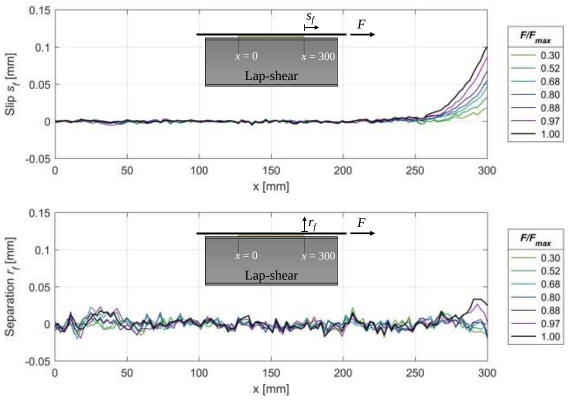


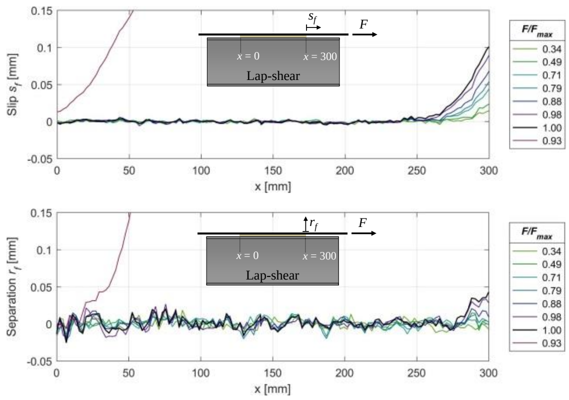
Figure 4. Load versus slip at the loaded end of tested specimens.

3.4 *Evolution of in-plane and out-of-plane deformation profiles*

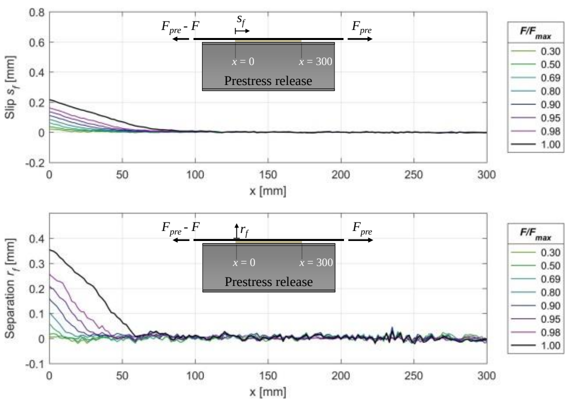
To further investigate the bond behavior of nonprestressed and prestressed CFRPs to the steel substrate, and to better realize the effect of accelerated curing, full filed 3D deformations obtained from ARAMIS were used to plot the slip and separation profiles in Figure 5. It can be seen in Figure 5a,b that in a lap-shear test, regardless of curing type, the shear deformation (mode II) in the adhesive is governing, since the relative vertical deformation of the CFRP plates (separation) is negligible compared to the in-plane slip values. In contrast, in the prestress release tests, a significant separation of the CFRP plate from the steel substrate was observed (see Figure 5c,d). This separation occurs because of the eccentricity of the prestress release load with respect to the steel surface, which generates considerable tensile mode I stresses in the adhesive bond. Consequently, the assumption of pure mode II behavior is no longer valid for prestress release tests, while a mixed-mode (I/II) behavior is governing. Furthermore, it can be seen in Figure 5c that the effective bond length in specimen P90-SP-RTC-2 is approximately equal to 60 mm, while it is around 120 mm in specimen P90-SP-AC-2 (Figure 5d). Thus, it can be concluded that providing a partly-cured adhesive through the AC procedure, resulted in a more ductile adhesive, and subsequently, in a larger effective bond length and a higher debonding load.



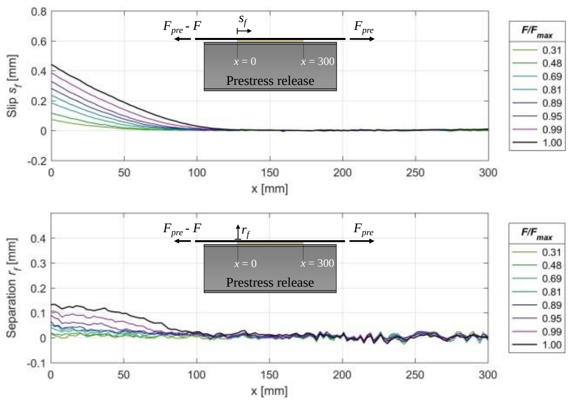
(a) L-SP-RTC-1 (Last stage load F_{max} = 38.6 kN)



(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 5. Evolution of in-plane and out-of-plane deformation profiles during loading (s_f = slip; r_f = separation).

4 CONCLUSIONS

A set of single lap-shear and prestress release tests was conducted in the current study to investigate the bond behavior of prestress CFRP plates to the steel substrate. Based on the experimental results and 3D DIC measurements, performed in the current study, the following concluding remarks can be drawn:

- Accelerated curing of the epoxy adhesive by heating, as an alternative to the conventional cold curing, leads to the same lap-shear strength as room-temperature cured CFRP-to-steel joints.
- For room-temperature cured joints, the debonding load of prestress release tests is slightly lower than that of lap-shear tests. The reason is attributed to the mixed-mode (I/II) state of the stresses within the bond in a prestress release test.
- Debonding load of prestress release tests, performed on accelerated cured CFRP-to-steel joints, is much higher than that of room-temperature cured joints, owing to the partly-cured state of the epoxy adhesive. This state of curing results in a more ductile behavior and a longer effective bond length, which leads to a higher debonding strength.
- It is observed that in the prestress release test on CFRP-to-steel joints, the slip and separation of the joint are in the same order of magnitude, which proves the mixed-mode (I/II) state of fracture in the adhesive layer. However, further research is needed to better understand the bond behavior of prestressed CFRPs to steel substrate, and the influence of a partly-cured epoxy adhesive.

5 ACKNOWLEDGMENTS

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