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

Ardalan Hosseini[a,b,*], Elyas Ghafoori[a], Matthias Wellauer[a], Abdollah Sadeghi Marzaleh[a], Masoud Motavalli[a,c]

[a] Structural Engineering Research Laboratory, Swiss Federal Laboratories for Materials Science and Technology (Empa), Switzerland
[b] Resilient Steel Structures Laboratory, Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland
[c] School of Civil Engineering, University of Tehran, Iran

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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.

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 using prestressed bonded CFRP reinforcements, mechanical end-anchorages were utilized to avoid undesirable premature debonding of the

* Corresponding author at: Structural Engineering Research Laboratory, Swiss Federal Laboratories for Materials Science and Technology (Empa), Überlandstrasse 129, CH-8600 Dübendorf, Switzerland.
E-mail addresses: ardalan.hosseini@empa.ch, ardalan.hosseini@epfl.ch (A. Hosseini).

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prestressed reinforcement. Using such mechanical end-anchorages 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 (Fig. 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 factor) 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 (Fig. 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 (Fig. 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 (Fig. 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 fails. In a prestress release test (Fig. 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.

Fig. 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 Fig. 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 debonding failure during the prestress release process. In the second step, AC of epoxy is conducted to reduce the curing time of the adhesive layer. Once the prestressing force is released to zero on one side, in the final step, the force in the CFRP plate is increased on the opposite side until occurrence of the failure of the bond (see Fig. 3). The main aim of

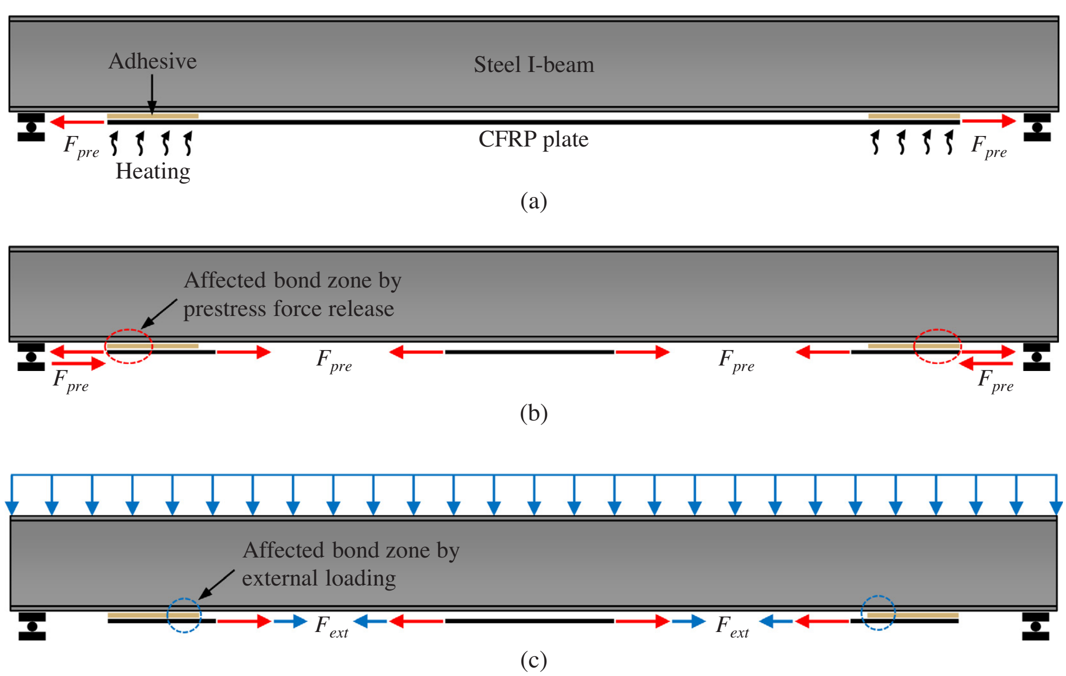

Fig. 1. Principle of the proposed technique for strengthening steel beams using prestressed partially bonded CFRP plates: (a) prestressing and accelerated curing of the epoxy adhesive, (b) prestress force release and state of the tensile force in the CFRP plate (assuming a relatively stiff substrate), and (c) effect of external (service) load on the strengthened member.