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Flexural strengthening of reinforced concrete beams using externally bonded FRP laminates prestressed with a new method

Jincheng Yang[1], Reza Haghani[1], Mohammad Al-Emrani[1]

[1] Chalmers University of Technology, Gothenburg, Sweden

ABSTRACT:

This paper presents a new method and a device for applying prestressed carbon fiber reinforced polymer (CFRP) laminates to flexural structural members without the need for mechanical anchorage of the laminates. An experimental test was conducted aiming to verify the feasibility of the stepwise prestressing method and investigate the flexural behavior of beams strengthened with passive (non-prestressed) CFRP and prestressed CFRP, respectively. Three RC beams with 4.2-meter-span were tested under four-point bending--one beam not strengthened as the control group, one with EB passive (non-prestressed) CFRP, and one with EB prestressed CFRP using the new prestressing technique. The strain values monitored during prestressing process demonstrated that a gradually decreasing prestressing force profile towards the CFRP ends was achieved by using this new prestressing method which eliminated the need for mechanical anchorage at laminate ends. The test results from four-point bending also revealed that using prestressed CFRP led to higher flexural stiffness, postponed yielding load, increased ultimate load bearing capacity, higher utilization of CFRP material tensile strength and reduced crack width.

1 INTRODUCTION

Using externally bonded (EB) carbon fiber reinforced polymer (CFRP) laminates is nowadays a common technique to improve the flexural capacity of reinforced concrete (RC) members. The first application of bonded CFRP composites for flexural strengthening of reinforced concrete bridges took place in late 1980s (Bakis et al., 2002). Although the externally bonded (EB) CFRP enhances the ultimate load-bearing capacity of RC beams, tests have proven limitations in the extent of obtainable increase in capacity due to premature debonding of the bonded laminate initiated at intermediate cracks (Kotynia et al., 2010). In order to fully utilize the strength of CFRP laminates, it is suggested to prestress the CFRP reinforcement before bonding to concrete members. This will not only increase the ultimate flexural capacity but also improves the serviceability performance by delaying the cracking load (in un-cracked sections) and reduction of crack width (in cracked sections) and thus enhanced durability. The research on EB prestressed CFRP started in the 1990s (Triantafillou and Deskovic, 1991; Triantafillou et al., 1992; Meier, 1995; Bryan and Green, 1996; Garden and Hollaway, 1998; Quantrill and Hollaway, 1998).

The primary issue in application of bonded prestressed CFRP laminates is the concentration of high shear stress at the ends of the laminate and thus anchorage of the laminate at these locations. In un-anchored laminates, upon the release of pretension, very high shear stress develops in the interface between the CFRP laminate and the concrete substrate at the end regions (Haghani et

al., 2009), which leads to immediate failure of concrete substrate and thus debonding of the CFRP laminate. Without end anchors, the CFRP laminates may debond from the concrete substrate already at prestressing levels as low as of 5% of the ultimate strength of CFRP (Meier, 1995). However, to observe considerable effect of prestressing on the behavior of the strengthened member, researchers have suggested to apply a prestressing level of approximately 50% of the ultimate strength of the composite laminate (Garden and Hollaway, 1998). To overcome the anchorage problem, metallic end anchorages were required to prevent laminate debonding from RC members (Kim et al., 2008). The most commonly used mechanical anchor system is composed of two steel plates that installed on the concrete with help of bolt fasteners which clamp the CFRP laminate before the prestressing force is released. Since the anchors are made of steel material, it would introduce corrosion risk during the service life of the system, especially regarding galvanic corrosion. To resolve the problem, non-metallic anchors could be used. Such anchors have been studied by, for example, (Kim et al., 2008). However, non-metallic anchors have not yet been commercialized and are not available on market.

The idea of gradient prestressing was first introduced by (Stöcklin and Meier, 2001; Meier and Stöcklin, 2006). Gradient prestressing is based on gradual releasing of the prestressing force in the strengthening FRP laminate in several steps aided by a fast curing device. Reducing the gradient of the axial prestressing force in the FRP laminate would result in reduction of interfacial stresses. In this manner, the magnitude of the interfacial stresses could be manipulated so that they could be tolerated by the concrete substrate. Even though this method eliminates the need for mechanical anchors and therefore many complications related to using such anchors, it is very complicated itself and involves use of sophisticated computer controlled systems to make the curing and gradual force release possible.

To overcome the problem, a stepwise prestressing method and a device based on it was introduced by (Haghani et al., 2015). The device was composed of a simple mechanism including several aluminum tabs interconnected with series of springs (steel bars). The tabs would be connected to the strengthening FRP laminates through a medium (a GFRP plate) as illustrated in Figure 3. The novel prestressing device would introduce a varying pretension levels in the laminate in one go with a reducing trend towards the ends of the laminate. Using this method, it is easily possible to manipulate the gradient of the prestressing force in the composite laminate by changing the number of steps. After curing of the adhesive and removal of the prestressing device (aluminum tabs and steel bars), the prestressing force in CFRP would be transferred to concrete through cued adhesive layer. Since the application of this prestressing method eliminates the concentration of shear stress near the CFRP laminate ends, the conventional anchorage would no longer be required.

This paper aims to investigate the feasibility and efficiency of the newly developed stepwise prestressing method used for EB CFRP strengthening. Experimental tests on concrete beams strengthened with prestressed and passive CFRP laminates were performed and the results were compared.

2 EXPERIMENTAL TESTS

2.1 Test specimens and set-up

Three identical reinforced concrete (RC) beams were tested under four-pointed bending. The dimensions of RC beams were 4500 × 200 × 300 (Length × Width × Height, unit: mm). Two steel bars of 16-mm-diameter were placed in compression and tension sides. The transversal stirrups had diameter of 10 mm and were placed at spacing of 75 mm. The average yielding strength of

internal reinforcement was 560 MPa. Concrete of strength class C30/37 was used to cast the beams. The specimens' geometry and test set-up is shown in Figure 1.

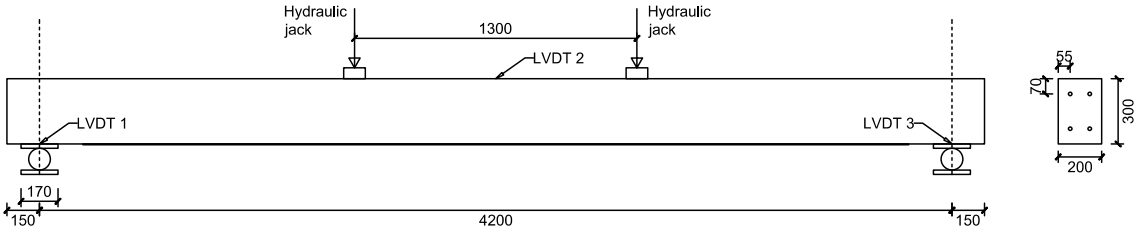

Figure 1. Beam specimens under four-point bending test

The first beam—B1—was not strengthened and used as control specimen. The second beam—B2—was strengthened with one externally bonded passive (non-prestressed) CFRP laminate. The CFRP laminate was 3.8-meter-long with cross-section of 80 × 1.4 (Width × Thickness, unit: mm). In the third beam, B3, the CFRP laminate was prestressed using the new stepwise prestressing method. The same CFRP plate (StoFRP IM 80 C) was used in specimen B2 and B3. The average modulus of elasticity in tension and ultimate tensile strength were 210 GPa and 3300 MPa, respectively. The prestressing force in CFRP laminate in specimen B3 was 80 kN, equivalent to 22 percent of ultimate tensile strength of CFRP laminate. The specimens were tested under four-point bending in displacement-control manner. The monotonic load was applied at speed of 1 mm per minute. The distance between two hydraulic cylinders was 1300 mm. The beam specimens were equipped with measurement devices and monitored during the test. Monitoring devices included strain gauges and linear variable differential transducers (LVDT). Three LVDTs were located at the midspan and the center of each support in order to get the net midspan deflection during loading (see Figure 1). Two strain gauges were installed on two internal reinforcement bars on the tension side of all the specimens. On the CFRP laminate bonded to specimen B2, seven strain gauges were used at distances of 5 mm, 55 mm, 155 mm, 1900 mm, 3645 mm, 3745 mm, and 3795 mm away from one end. On the CFRP laminate in specimen B3, nineteen strain gauges were installed as illustrated in Figure 2. This arrangement was used to capture the axial force distribution in the CFRP laminate.

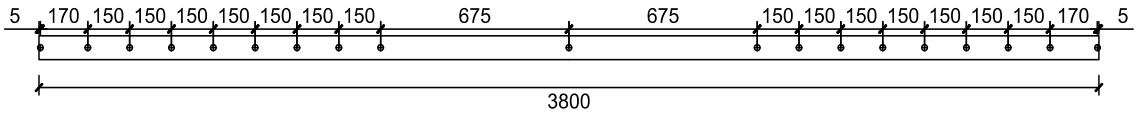

Figure 2. Placement of strain gauges installed on CFRP laminate in Specimen B3

2.2 Prestressing technique

As mentioned before, the laminate in beam B3 was prestressed using a new technique described in (Haghani et al., 2015). Different from the conventional method that results in constant axial force in CFRP along the full length, in the stepwise prestressing method a prestressing device (Figure 3) was used to apply the pretension force. The total prestressing force in the stepwise prestressing device is distributed to CFRP laminate with the help of a sequence of aluminum tabs connected by a series of springs (steel bars with varying diameters). The tabs are connected to CFRP laminate via a GFRP plate as medium. When the prestressing force is applied, the force transferred from the prestressing device to the CFRP plate is dependent on the ratio of cross-sectional stiffness between the CFRP and springs (steel bars). Considering the increasing diameter

of steel bars towards the CFRP ends, the prestressing force transferred to the CFRP exhibits a gradually decreasing profile of prestressing force towards the CFRP ends.

The device used in this study consisted of eight aluminum tabs (nodes), which were inter-connected by steel bars (springs) with certain diameters. To connect the prestressing device to CFRP, a 10-mm-thick GFRP plate was used as a medium. The GFRP plate was manufactured with embedded nuts enabling a simple connection to tabs via using standard M6 bolts. The GFRP plate was firstly bonded to CFRP laminate using an epoxy adhesive.

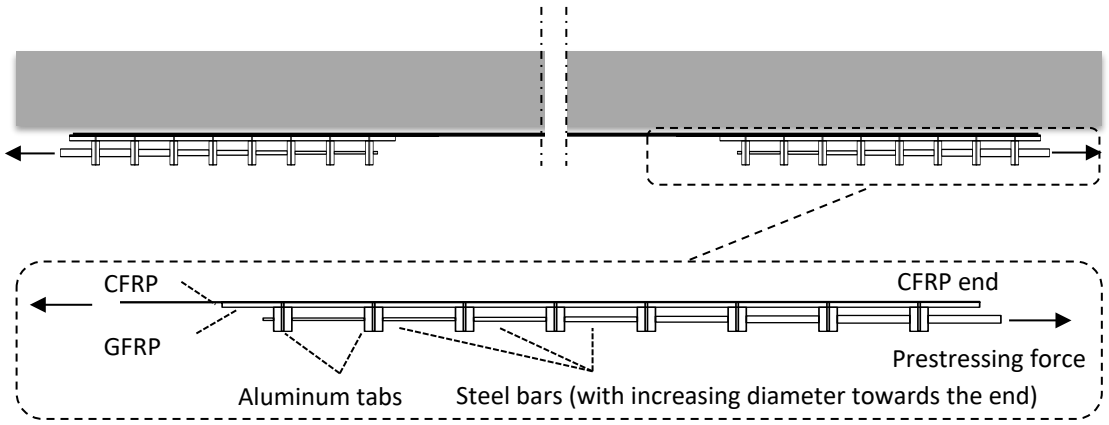

Figure 3. Applying prestressing force to CFRP laminate using the new technique

The bottom surface of the strengthened concrete beams was grinded to obtain a coarse surface and cleaned from dust before CFRP bonding. After applying the structural epoxy adhesive between the CFRP laminate and concrete substrate, the prestressing force was introduced to the device using a hydraulic jack. The prestressing device was maintained for 24 hours to assure that the epoxy reaches enough strength to transfer the interfacial stresses to concrete beam. The prestressing force was then released and the prestressing device was removed. Upon the release of the prestressing force, shear stress was developed along the bond line, of the magnitude of which is directly related to the gradient of the axial pretension force in CFRP (Al-Emrani and Kliger, 2006; Haghani et al., 2009). Previous numerical and experimental studies proved that it was possible to reduce the shear and peeling stresses in the bond line below 1.0 and 0.2 MPa, respectively, given a prestressing force of 80 kN distributed over eight steps and hence eliminating the need for mechanical anchorage systems at CFRP ends.

3 TEST RESULTS AND ANALYSIS

3.1 Strain distribution in the CFRP during prestressing

As discussed before the level of prestressing force in the CFRP laminate within the “anchorage length” is expected to gradually reduce towards the ends of the CFRP laminate. To verify this, the strains in CFRP between sequent tabs were monitored versus the total prestressing force. This was done through readings from 19 strain gauges placed along the CFRP laminate (Figure 2). Figure 4 shows the measured strain values in the CFRP laminate under different prestressing forces up to 80 kN. Given a certain prestressing force, it was clear to identify that in the middle section of CFRP the strain reached the highest level, while the strain started decreasing gradually towards the CFRP laminate ends within the “anchorage length”. The results prove that a gradual force profile along the anchorage length can be achieved using stepwise prestressing device.

Figure 5 showed the evaluated interfacial shear stress that could developed between CFRP laminate and concrete beam once upon the removal of prestressing force after the adhesive bond was cured. Contributing to the gradually decreasing prestressing force in CFRP within the anchorage length, the maximum shear stress developed along the bond line was less than 1.5 MPa when the prestressing force of 80 kN is released

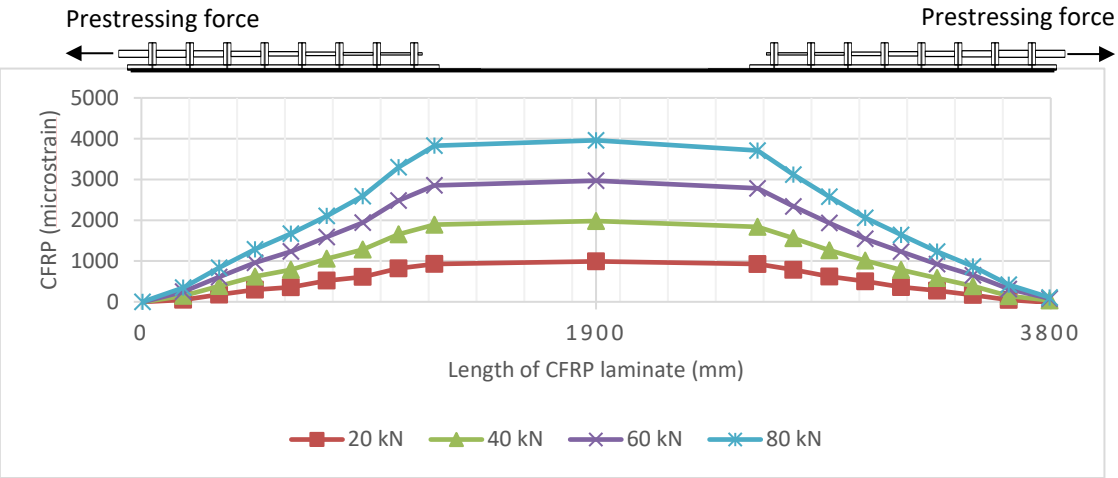

Figure 4. Tensile strain in CFRP laminate under prestressing force up to 80 kN in specimen B3

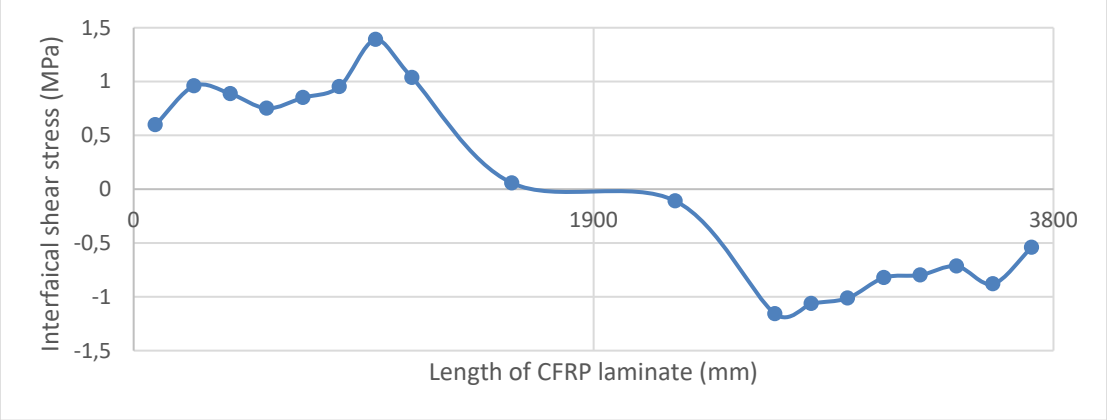

Figure 5. Interfacial shear stress between CFRP laminate and concrete beam under prestressing force of 80 kN in specimen B3

3.2 Load bearing capacity

The load bearing capacities of tested beams specimens under four-point bending test are summarized in Table 1. It shows clearly that both the yielding capacity and ultimate capacity were increased in beam specimens B2 and B3 strengthened with EB CFRP laminates. For instance, compared with B1 the EB CFRP enhanced the ultimate load bearing capacity of B2 and B3 from 65.0 kN to 105.8 kN and 146.9 kN, which were equivalent to 93% and 167% increase, respectively.

Figure 6 shows the midspan deflection of three specimens with respect to load under four-point bending. The load-deflection curve B1 showed that the steel reinforcement in reference beam (B1) started yielding at a load (P) of 55 kN, approximately. According to the theoretical

calculations, the yielding load was predicted to be 53.4 kN, which matched well with the experimental result.

Table 1. load bearing capacity of beam specimens under four-point bending test

Specimen	Strengthening method	Yielding load[1] (kN)	Ultimate load[2] (kN)
B1	Control beam with no strengthening	55	65
B2	EB passive CFRP	79	106
B3	EB prestressed CFRP	104	147

[1] Total vertical loads when the monitored average strain of steel reinforcement bars reaches 2.67 millistrain (yielding strength 560 MPa; Young's modulus 210 GPa)
[2] Maximum vertical load when specimens reached failure.

The comparison between the load-deflection curves also reveals that the application of prestressed CFRP further improves the flexural stiffness compared to the beam with bonded passive CFRP. This observation can be attributed to narrower cracks in beam B3 compared to beam B2, where mechanical engagement of aggregates due to smaller crack size is more pronounced.

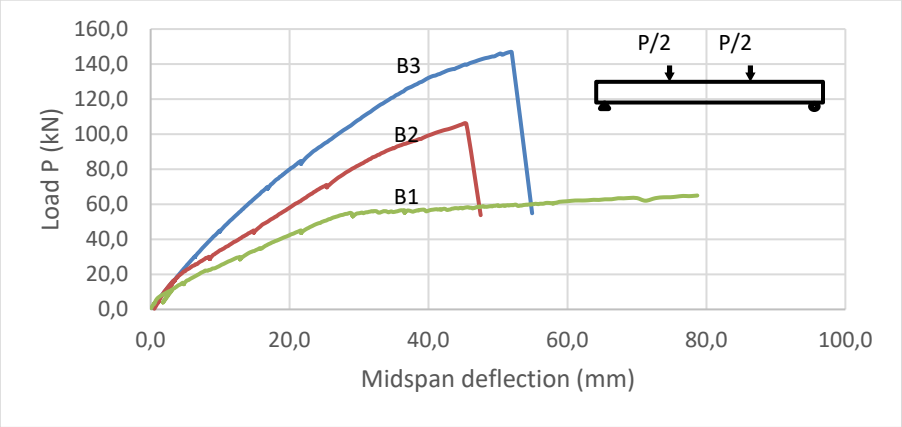

Figure 6. Load-deflection curves of beam specimens under four-point bending test

(a) (b) (c)

Figure 7. (a) Intermediate cracks; (b) Debonding of the laminate due to intermediate cracks in B2; (c) Rupture of the laminate in beam B3

The failure of specimen B2 was associated with the separation of the CFRP laminate due to intermediate crack introduced debonding (Figure 7). The maximum longitudinal strain built up in

CFRP laminate at mid-span was 4.97 millistrain, corresponding to the utilization ratio 32 % with respect to tensile strength. In specimen B3 the failure mode was characterized by the rupture of CFRP laminate (Figure 7). The initial strain of CFRP at mid-span due to prestressing was 3.50 millistrain before bending test, and the maximum strain at failure was measured to be 10.29 millistrain.

3.3 Crack width

The crack widths of each specimen were evaluated at load (P) levels of 15 kN, 45 kN and 70 kN, respectively. An optical microscope was used to take magnified photos of cracks occurred at certain load levels. The magnitude of cracks' width was obtained from the embedded software, which multiplies the pixels' number of a crack on picture by the current magnification factor (mm/pixel). Figure 8 shows the average width of cracks that occurred within the 1.3-meter-long section in the middle part of the RC beams—the region with constant bending moment under four-point bending. In specimen B3 the average crack width at 70 kN was 0.145 mm, which was even less than the average crack width in B1 and B2 loaded at 15 kN.

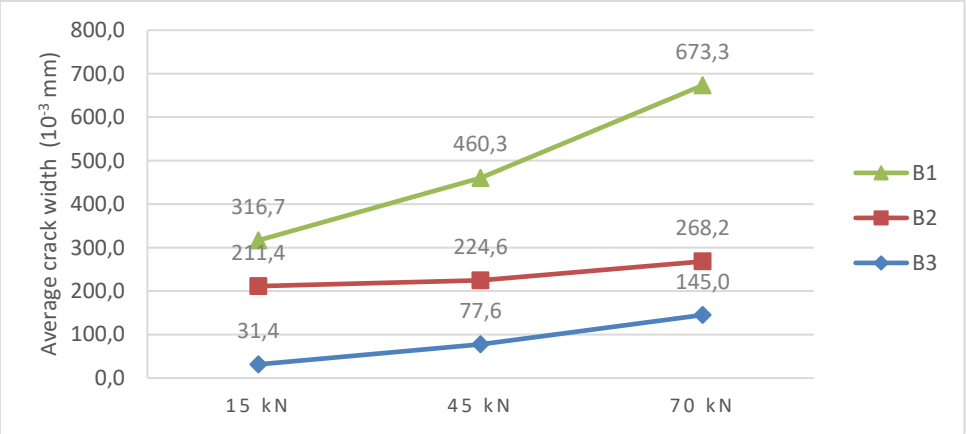

Figure 8. Average value of crack width in the 1.3-meter-long middle section (under constant bending moment) of beams at total vertical load of 15 kN, 45 kN and 70 kN

4 CONCLUSION

This paper aimed to investigate the feasibility and efficiency of a new stepwise prestressing method. Based on the observations from experimental study, the following conclusions could be highlighted:

- The new stepwise prestressing method and device are practical to be applied for flexural strengthening of RC beams using externally bonded (EB) CFRP laminates. A gradually decreasing prestressing force profile towards the CFRP ends was achieved in the beam specimen B3 as expected. Meanwhile, the average interfacial shear stress between CFRP and concrete was controlled below 1.5 MPa upon releasing the prestressing force equivalent to 22% of the tensile capacity of CFRP.
- Results from four-point bending test showed that externally bonded (EB) CFRP could enhance the flexural performance of RC beams in terms of yielding capacity, ultimate capacity, flexural stiffness, and crack width under bending test. Using stepwise prestressed CFRP laminate (specimen B3) could further improve the bending

performance and utilize full tensile strength of CFRP material compared with using passive CFRP (specimen B2).

Further study could focus on —aided by finite element (FE) analysis--the effect of prestressing level on failure models and optimization of prestressing level considering ultimate load capacity, ductility and crack width control.

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