Proceedings of International Structural Engineering and Construction
Holistic Overview of Structural Design and Construction
Edited by Vacanas, Y., Danezis, C., Singh, A., and Yazdani, S.

ISSN: 2644-108X

EFFECT OF CFRP STRIPS BONDING LOCATION ON FLEXURAL CAPACITY AND DUCTILITY OF REINFORCED CONCRETE BEAMS

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Strengthening reinforced concrete beams using laminate of advanced composite materials has gained ground recently due to its lower cost and simplicity compared to traditional methods. These traditional methods are usually done by either increasing the reinforcement or the beam's dimensions, which naturally requires formwork, and hinder the structural usage. One of the most impediments of using bonded laminate in strengthening beams is debonding. In flexural strengthening of beams, this debonding occurs via mid-span debonding or end-delamination of the laminate. Herein, ten RC beams were experimentally tested in flexure under three-point loading. The reinforced concrete beams have rectangular cross sections and were strengthened by bonded CFRP strips. Flexural strength and ductility were investigated in order to reveal the impact of changing the CFRP strips' locations with respect to the beams' cross section. The CFRP strips were attached to the reinforced concrete beams sides of bottoms. The first configuration is thought to reduce the effect of flexure cracks in the mid-span of the beams, which may delay the deboning of these laminates. In order to anchor the strips, close to the support and eliminate end delamination, CFRP sheets were wrapped at these locations. Based on the proposed configurations, the flexure strength of the beams increased by an average of 40%.

Keywords: CFRP laminate, Debonding, Flexure strengthening, RC beams.

1 INTRODUCTION

Reinforced concrete (RC) beams retrofitting is a persistent issue for structural engineers nowadays. Several strengthening options are available to designers, whether to increase the concrete cross-sectional area or adding another material to the cross-section to increase its strength. One of the most appropriate and currently available options is the externally bonding fiber reinforce polymers (FRP) laminate to the regions that have low tensile strength (e.g. bottom of simply supported reinforced concrete beams subject to gravity loads). There are several FRP products that can be used in such applications; Carbon Fiber Reinforced Polymers (CFRP) present the most attractive options for designers due to its high tensile strength-to-weight ratio and its high elastic modulus (e.g. Chen and Teng 2001, Hosny *et al.* 2006, Bakay *et al.* 2009, Sayed-Ahmed *et al.* 2009).

CSA S806-12 (2012) classifies the possible failure modes of RC beams strengthened with bonded FRPs in two categories. The first category is a flexural failure mode (concrete crushing in compression prior to FRP failure by rupture or steel yielding, or steel yielding and/or failure of the FRP in tension followed by crushing of the concrete). The second category is a debonding failure mode (Chen and Teng 2001, Ueda *et al.* 2003, Yuan *et al.* 2004, Lu *et al.* 2005) that is characterized by separation in the adhesive layer due to vertical section translations caused by cracking, or anchorage failure.

Regarding the debonding failure modes, the mid-span flexural-crack induced debonding failure mode governs the failure model in case of using thin CFRP laminate combined with long-span beams compared to end delamination of the laminate (Sebastian 2001, Sayed-Ahmed *et al.* 2004, Bakay *et al.* 2009, Sayed-Ahmed *et al.* 2009). In many cases, flexural cracks initiate the mid-span debonding and it is self-propagating with increasing the magnitude of the applied load. It is suggested that bonding the FRP strips to the beam's side for strengthening these RC beams in flexure (Figure 1) may reduce the effect of flexural cracks on debonding. This configuration delays the mid span flexure crack beginning, and this pauses this mid span debonding. In addition, the side bonded FRP strips configuration has another advantage over bottom bonded one where in many practical cases the bottom of the beam is both fully accessible, particularly when this beam supports partitions or walls.

In order to prevent or delay the premature end delamination failure, several researchers recommended using end anchorage to support the end strip zone, which is subjected to high stress concentration, and thus, delay the premature end delamination (Grelle and Sneed 2013, Al-Amery and Al-Mahaidi 2006, Ceroni *et al.* 2008).

Herein, the effect of boding CFRP strips to the beams sides or bottom as shown in Figure 1 is experimentally investigated. A comparative study between the effect of both configurations on the strengthened beams' strength and ductility is presented. The paper also presents the effect of anchoring the strips at their ends by using CFRP sheets on delaying the deboning failure.

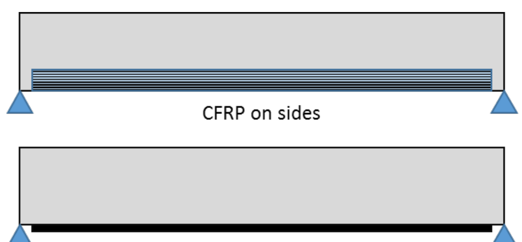

Figure 1. Side bonded CFRP strips versus bottom bonded beams.

2 THE EXPERIMENTAL PROGRAMME

Ten reinforced concrete beams were flexurally tested by subjecting them to three-point loading with a concentrated load at their mid-span. All the tested beams had a 150×400 mm cross-section and length of 3000 mm. The beams were reinforced with 3no.16 in tension side and 2no.12 in the compression side. Stirrups hangers adopted for the beams were no.10@150 mm spacing near the supports to avoid any shear failure; the spacing of the stirrups increased to 200 mm in the central 1.0 m span of each beam. High modulus CFRP strips with a nominal width of 50 mm and a nominal thickness of 1.4 mm were bonded to bottom or the sides of the beams. Furthermore, U-wrapped CFRP sheets with a nominal width of 500 mm and a nominal thickness of 0.165 mm were used as an end anchorage for the CFRP strips.

2.1 Material Properties

The concrete was mixed, casted and cured in the laboratory. The concrete strength was determined using standard 150×150×150 mm cube strength. The average 28-days strength of concrete was 34.7 MPa with standard deviation of 2.3 MPa. The properties of main steel reinforcement were not tested but the reported yield strength and ultimate strength by the manufacturer were 400 MPa and 600 MPa, respectively. The stirrups were made of mild steel with reported yield strength and ultimate strength of 280 MPa and 400 MPa, respectively. Shear and flexural reinforcement used were all of the same batch in order to maintain same material properties for all beams. Two types of CFRP laminate were used: high modulus CFRP strips were used for flexural strengthening and CFRP sheets were used as end anchorage. The reported properties of the CFRP strips and sheets were 2687 MPa and 3500 MPa, respectively. Two-component epoxy-based resin recommended by the CFRP laminate manufacturer was used and a professional trained team of high experience in FRP laminate applications conducted the application of strips and sheets to the beams.

2.2 Test Set-up and Instrumentation

The beams were tested to failure under three-point loading with a central concentrated load. In order to maintain a steady load application rate, a displacement-controlled hydraulic jack applied the load to the beams. A load cell was used to measure the applied load and all data were collected simultaneously by a computerized data acquisition system. One linear variable displacement transducer (LVDT) was mounted at the bottom point of the beams at the mid-span to measure the vertical displacement at this location. Two strain gauges were provided at the mid-span section on the two outer lower bars. Steel cylinders were used under the beams at the support location in order to allow free rotation at the ends of the beam; they were 2900 mm apart, as shown in Figure 2.

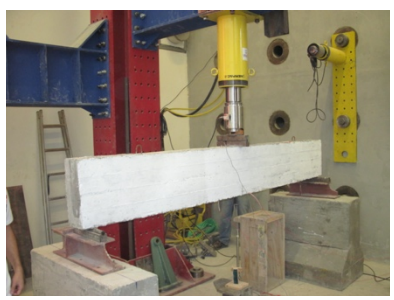

Figure 2. Test set-up for a control beam.

2.3 Configuration of Test Specimens

The ten test beams were divided into five pairs, each test is repeated once to confirm the results. A special designation system (Type–CFRP Strip Location–Beam Number) is adopted to identify each specimen. The first letter identifies the type of the specimen (C for control specimens and S for strengthened specimens). The type is followed by the location of the bonded CFRP strips (0 for control specimens, S for side CFRP strips, and B for bottom CFRP strips). Another letter (E) is added beside the location letter to indicate if the beam has a CFRP sheets as end anchorage. Finally, the number of specimens is specified as each group is composed of two beams. For example, S-BE-1 designates the first strengthened specimen with CFRP strip bonded to the bottom of the beam with CFRP sheets adopted as end anchorage for the strips, while C-0-2 designates the second control specimen. The first pair of beams presents the control specimens (without any CFRP) to which the strength enhancement that was achieved for the other strengthened beams can be compared. The second pair of beams present strengthened specimens with bottom bonded CFRP strips; two strips were used beside each other so the total width of CFRP applied was 100 mm. The third pair presents strengthened specimens with side bonded CFRP strips; one laminate with 50 mm width was applied on each side of the beam. The fourth pair of beams is similar to the second pair with additional end anchorage of one-ply CFRP sheets U-wrapped at the end of the beam with a nominal width of 500 mm. The fifth pair of beams is similar to the third pair with an additional end anchorage similar to the one adopted for the fourth pair.

3 TEST RESULTS

3.1 Failure Load and Strength Enhancement

Table 1 provides a summary of the test results presented as the maximum reached loads for the tested beams and the corresponding mid-span vertical displacement. In addition, the corresponding gain in strength is calculated as the ratio between the average ultimate capacities of the strengthened beams and the control ones minus unity. The strain gauges' readings revealed that the main reinforcement yielded before the ultimate capacity was reached for all the strengthened specimens. The minimum recorded strength enhancement was 28% in case of using side CFRP strips with no end anchors (S-S-1 and S-S-2). The maximum recorded strength enhancement was 37% for bottom bonded CFRP strips with end anchors (S-BE-1 and S-BE-2). It is evident from Table 1 that all the strengthened beams had a lower mid-span deflection compared to the control ones, which indicates a lower ductility for CFRP strengthened beams in flexure due to the low ultimate strain of the CFRP strips.

Table 1. Test results and strength enhancement.

Specimen	Specimen ID	Ultimate Ld (kN)	Deflection (mm)	Average Ld (kN)	Strength gain
Control	C-0-1	162.7	57.3	156.7	N/A
	C-0-2	150.7	42.3		
Strengthened	S-B-1	205.9	16.6	207.3	32 %
	S-B-2	208.7	17.9		
	S-S-1	192.8	15.4	199.9	28 %
	S-S-2	207	16.2		
	S-BE-1	217.9	20.5	214.5	37 %
	S-BE-2	211.1	18.4		
	S-SE-1	209.4	17.9	205.1	31 %
	S-SE-2	200.7	16.3		

3.2 Load-Displacement Behaviour and Ductility

In Figure 3, plots the load versus the vertical displacements are presented for all the tested beams. Figure 3-a shows this behaviour for beams strengthened with bottom-bonded CFRP strips with and without end anchorage compared to behaviour of control beams. On the other hand, Figure 3-b shows the same behaviour for beams with side-bonded CFRP strips with and without end anchorage compared to the control beams as well. Ductility of the strengthened and unstrengthened beams may be presented by the area under the load displacement curve. It is evident from Figure 3 that all the CFRP strengthened beams have a lower ductility than the control ones.

As shown in Figure 3, for bottom-bonded CFRP strips, the effect of adding end anchorage affected the load-displacement plots: beams with end anchorage had several drops in the load curve compared to those without end anchorage. On the other hand, the average load of both tests in each group has almost the same ductility level. For side-bonded CFRP strips (Figure 3b), adding end anchorage obviously affected the ductility: both beams with end anchorage had about 10 mm of vertical displacement without a notable drop in the strength.

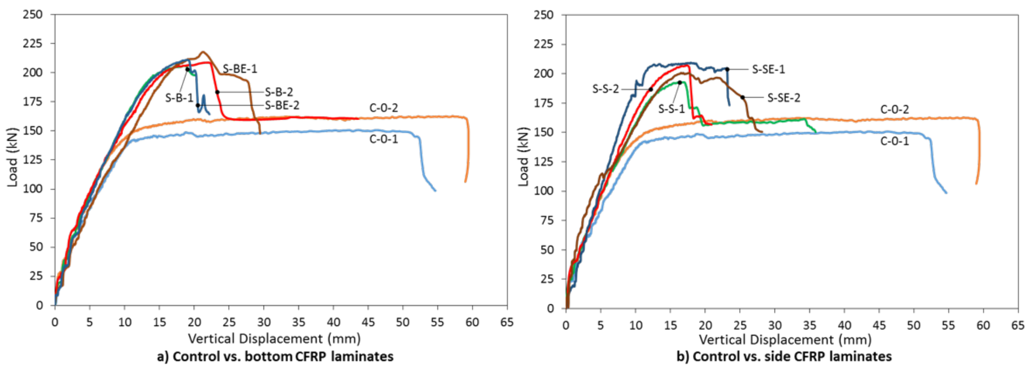

Figure 3. Load versus vertical displacement for all the tested beams.

3.3 Failure Modes

Figure 4 shows the failure modes for the tested beams; one photo is presented for each group with Figure 4-a presenting the common flexural failure of the control beam.

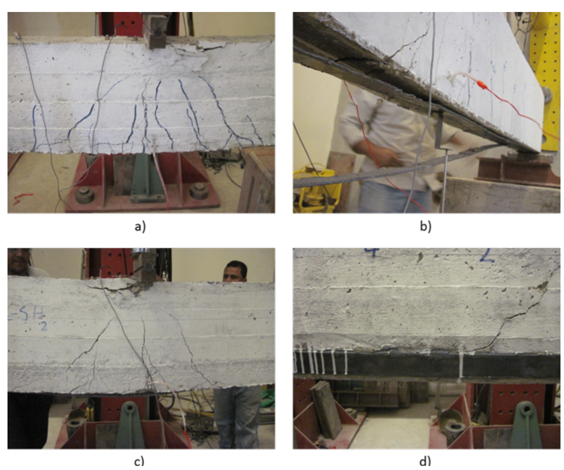

Figure 4. Failure modes.

For the CFRP strips bonded to the bottom or the side of the beams without end anchorages, the failure mode was end delamination of the CFRP strips after steel yielding, as shown in Figure 4-b. For the beams strengthened by bottom-bonded CFRP strips with end anchorages, failure occurred by mid-span flexural crack-induced debonding where debonding of the strips started in the vicinity of the mid span flexural cracks and propagated towards the end of the strips tearing the CFPR sheets of the end anchor (Figure 4-c). For beams strengthened by side-bonded CFRP strips with end anchorages, the failure mode started as mid-span flexural crack-induced debonding followed by sudden debonding of the strip (Figure 4-d). The latter failure mode is different from that of the bottom-bonded CFRP strip and needs further discussion. In case of bottom-bonded strip, the difference in vertical displacements between the two sides of a flexural crack causes high stress on the strip, which is resisted by the strip thickness, so it gradually delaminates. On the other hand, in case of the side-bonded strip, the same deferential vertical displacements on the two sides of the crack is resisted by the strip's full depth. Thus, stress builds-up till it can overcome this high resistance and at this moment sudden and total debonding occurs as compared to the gradual debonding of the bottom-bonded strips.

4 CONCLUSIONS

Externally bonded CFRP laminates is an effective method of strengthening reinforced concrete structures. Side-bonded CFRP strips is also proven to be equally effective to bottom bonded ones and it can be adopted for flexural strengthening of RC beams when the bottom of the beam is unreachable. Providing end anchorages can increase the overall capacity as it delays the premature end delamination. However, using side-bonded CFRP strips affects the ductility of the strengthened beams. Ductility of RC beams with externally bonded CFRP laminates is generally lower than that of the original beam and this fact should be considered in design.

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