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Flexural Behavior of RC Beams Strengthened with CFRP Strips

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ABSTRACT: In this research, the results of an experimental investigation on reinforced concrete (RC) beams strengthened in flexural with near surface mounted (NSM) laminate strips made of carbon fiber-reinforced polymer (CFRP) are presented and discussed. Ten tests are carried out. One specimen without laminate strips are used as reference specimen, while nine specimens are strengthened with laminate CFRP strips. The influence of the ratio between the CFRP strips cross section Area (A_{CFRP}) and steel area (A_{Steel}), the distance between the strips, and pre-loading on the stress redistribution is studied.

1 INTRODUCTION

The NSM technique is attractive solution for flexural strengthening of slabs and girders, as it has a greater bending capacity compared to externally bonded CFRP laminates (Nanni et al. 2000). The groove depth, location and CFRP laminates area (A_{FRP}) have a significant effect on the strengthening efficiency of NSM as well as on the durability and cost (Rizkalla et al. 2000). This technique is often able to mobilize a greater proportion of the strength of the CFRP because of superior bond characteristics that help to prevent debonding failures. The influence of the reinforcing ratio [A_{CFRP}/A_{Steel}], the distance between strips and pre-loading on the cracking behavior of reinforced concrete members strengthened with near-surface mounted has not been sufficiently investigated. In the case of confined construction areas as concrete beams, which present narrow width and restrained concrete cover, one, should be able to determine the optimal amount of CFRP laminates area A_{FRP} and optimal location of embedment that produce sufficient strengthening efficiency (Ibrahim et al. 2011). Ten tests are carried out. One specimen without CFRP strips is used as reference specimen, and nine specimens are strengthened with CFRP strips. The influence of the reinforcement ratio [A_{CFRP}/A_{Steel}], the distance between strips and pre-loading on the crack width, crack spacing of RC members strengthened with near-surface mounted CFRP strips is studied.

2 RESEARCH SIGNIFICANCE

This paper discusses the flexural behavior of reinforced concrete beams that are strengthened using CFRP laminates. The test results add to the existing database of reinforced concrete beams that are strengthened using CFRP laminates, provide information about the influence of the reinforcement ratio [A_{CFRP}/A_{Steel}], the distance between strips and pre-loading on the crack width, crack spacing of concrete beam strengthened with near-surface mounted CFRP strips. These data are particularly important for the design guidelines for strengthened existing reinforced concrete structures with CFRP strips.

3 LITERATURE REVIEW

A large amount of tests for reinforced concrete beams that strengthened using CFRP laminates under flexural have been carried out in the past. Several studies on experimental and analytical models of RC members strengthened with NSM laminate CFRP strips have been conducted. However, the influence of strengthening with NSM laminate CFRP strips on the tension stiffening and cracking of reinforced concrete members has not been sufficiently studied. This paper will address these deficiencies.

4 EXPERIMENTAL PROGRAM

A total of ten RC-beams, 200 cm. long and 40 cm. deep 20 cm. width, are fabricated for this experimental program. Table 1 presents reinforcement details of the ten test specimens. One of the specimens is tested without CFRP reinforcement, and is identified as beam B1. Each strengthened specimen is prepared by first saw cutting grooves perpendicular to the concrete surface of the depth and width given in Table 1. A FRP strip is then embedded into each groove using Epoxy adhesive. In the strengthened specimens, the objective is to observe the flexure behavior; therefore, a potential shear failure needed to be avoided. So, the stirrups are provided every 10 cm.

Table 1 – Test matrix of the experimental program.

Group	Beam labels	Steel bars	CFRP Strips (Thick x Width)mm	Groove Dim. (Thick x Width) mm	Number of Strips	A_{CFRP} / A_{Steel}
Control	B1	2 ϕ 10	--------	--------	-------	-----
Group 1	B2	2 ϕ 10	1.2 x 25	3 x 40	2	0.38
	B3	2 ϕ 10	1.2 x 37.5	3 x 50	2	0.57
	B4	2 ϕ 10	1.2 x 50	3 x 50	2	0.76
Group 2	B5	2 ϕ 10	1.2 x 50	3 x 50	2	0.76
	B6	2 ϕ 10	1.2 x 3.3	3 x 50	3	0.76
	B7	2 ϕ 10	1.2 x 25	3 x 40	4	0.76
Group 3	B8	2 ϕ 10	1.2 x 25	3 x 40	2	0.38
	B9	2 ϕ 10	1.2 x 25	3 x 40	2	0.38
	B10	2 ϕ 10	1.2 x 25	3 x 40	2	0.38

4.1 Specimen Fabrications and Strengthening using the NSM technique

To measure the strain in the Steel/CFRP reinforcement during loading, up to four strain gauges are mounted at the mid-length of the reinforcements. Then, the steel reinforcement is placed into wooden forms that are previously prepared and lubricated with oil for easy stripping. A normal concrete is poured into the forms. During curing, the specimens are covered with wet burlap and plastic sheets for at least 7 days. For the strengthened specimens, the CFRP strips are placed into grooves pre-cut into the concrete. The grooves made by a diamond concrete saw. After cleaning the grooves, they are half filled with epoxy and the CFRP strips are placed and pressed into the grooves. Then the grooves are completely filled with epoxy.

4.2 Concrete, steel reinforcement, CFRP strips and epoxy

The average compressive strength of concrete based on (DIN EN 12390-3) is 25MPa and the average tensile strength is 2.50 MPa based on (DIN EN 12390-6). The average yield strength of steel reinforcement (BSt 500S) is 560 MPa with a modulus of elasticity of 200 GPa based on (DIN 50145) and the ultimate strength is 600 MPa. The manufacturer (BASF) provides the mechanical properties of the CFRP strips. Based on the data sheet provided, the average ultimate strain is 0.014 (1.40%), and the modulus of elasticity is 165 GPa. MBRACE epoxy is used for bonding.

4.3 Test Setup

For a detailed flexural analysis, all specimens are tested as simply supported members with a span length of 180 cm, and loaded in a four –point arrangement with a constant moment region of 60 cm. The test setup is shown in Fig. 1.

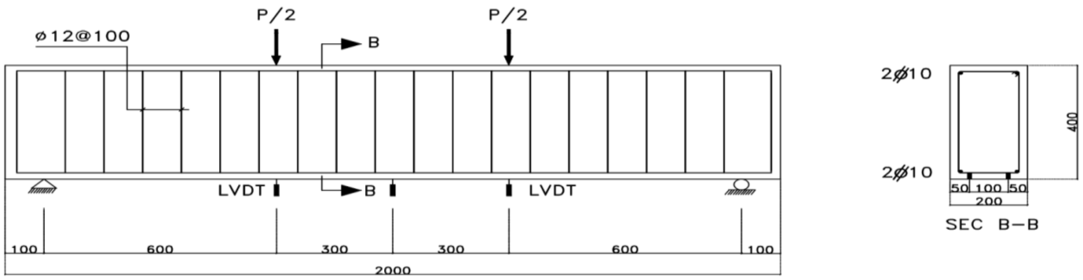

Figure 1. Test Specimen and Setup (dimensions in mm).

4.4 Instrumentation

Three linear variable differential transducers [LVDT’s] and strain gauges are used to measure the deflection and strains in steel and CFRP strips. Four strain gauges with sizes of 5 mm are placed on the Steel reinforcement and CFRP strips at mid-length to measure the maximum tensile Steel reinforcement and CFRP strips strains. All data is recorded by a data acquisition system at a scan rate of 3 Hz.

5 RESULTS AND DISCUSSIONS

All beams are tested under load control up to failure. A summary of test is given in Table 2.

Table 2 – Results of Tests.

Group	Beam labels	Ultimate load (kN)	Failure mode
Control	B1	110	concrete crushing after yielding
Group 1	B2	260	CFRP debonding
	B3	310	CFRP debonding & Cover separation
	B4	290	CFRP debonding & Cover separation
Group 2	B5	310	CFRP debonding & Cover separation
	B6	280	CFRP debonding
	B7	250	CFRP debonding
Group 3	B8	250	CFRP debonding & Cover separation
	B9	230	CFRP debonding & Cover separation
	B10	200	CFRP debonding & Cover separation

5.1 Failure Process

In general, the failure process can be divided into four stages as detailed next. (1) The elastic stage: this stage refers to the short stage during which only elastic deformation was measured and no cracking development was observed. (2) Crack initiation and development stage: with the increase of load, new cracks were observed in the mid-span zone where the tensile stresses at the bottom surface of beam are usually maximal. (3) Yielding stage: with the further increase of load, tension bars were yielded which was associated with a significant decrease of the beam stiffness. It is worthy of noting that debonding initiation can be observed at the ends of cracks during this stage, which can be attributed to the stress concentration at these cracks. (4) Failure stage: all the test beam specimens fail by FRP debonding or a combination of FRP debonding and concrete cover separation.

A comparison between the failure processes of beams (group 1&2) and the rest beams (group 3) with pre-loading reveals that pre-loading has nearly no effect on the failure mechanism of the strengthened beams. However, existence of pre-loading decreases the stiffness of the strengthened beams, and leads to the early debonding of FRP at the ends of cracks and thus may decrease the ultimate load of the strengthened beams.

Figure 2. Failure modes.

5.2 *Effect of Reinforcement Ratio*

The specimens with high [A_{CFRP} + A_{Steel}] values have significantly lower crack widths compared to specimens with lower reinforcement area [A_{CFRP} + A_{Steel}] values due to the increased stiffness. Table 3 includes all the major crack width and spacing results related to the study.

Table 3 – The Crack Width for First Crack and Stabilized Crack.

Specimen	First crack width (mm)	Stabilized crack	
		avg. crack width [mm]	avg. crack spacing [mm]
B1	0.10	0.40	200
B2	0.08	0.25	150
B3	0.06	0.20	120
B4	0.05	0.16	100
B5	0.06	0.15	100
B6	0.06	0.20	100
B7	0.05	0.15	80
B8	0.08	0.25	150
B9	0.10	0.25	150
B10	0.10	0.25	150

5.3 Effect of Pre-loading level before strengthening

Two levels of beams pre-loading were considered: The pre-loading level corresponded to 25%, 50% and 75% of the yield strength of non-strengthened beam (B1), respectively. The ultimate load-carrying capacities of the test specimens (Group-3) are reported in Table 2. From table 2, it can be seen that: (1) the load-carrying of beam B8 is the largest among all the test specimens (Group-3), the load-carrying capacities of beam B9 and beam B10 are reduced by 12% and 20% respectively compared with that of beam B2. From the above observation, it can be concluded that, the existence of pre-loading leads to a decrease of the load-carrying capacity.

5.4 Effect of the distance between strips

Based on the beams B5, B6 and B7, the distance between strips was also studied. The distance between strips was varied from (40 mm to 66 mm). Also the edge distance was from (40 mm to 66 mm). The beam B7, with the minimum edge distance (40 mm), the failure was edge splitting. With beam B7 having the smaller distance, compared to beam B5, the concrete between the strips was spilled off completely. It was found that the distance between strips has a significant effect on the load-carrying capacities of the beams.

6 CONCLUSIONS

Based on the test results the following conclusions can be deducted:

1. The specimens with high [A_{CFRP} + A_{Steel}] values have significantly lower crack widths compared to specimens with lower reinforcement area [A_{CFRP} + A_{Steel}] values due to the increased stiffness.
2. The flexural tests showed that large increases in the ultimate load and significant increases in the post cracking stiffness could be achieved with NSM CFRP reinforcement.
3. The failure mode of strengthened beams is observed during the experimental tests, cracking of the concrete surrounding the groove close to the maximum moment region.
4. Debonding of the NSM CFRP strips occurred at a tensile strain ranged from 37% to 43% of the ultimate strain. Full composite action between the NSM CFRP reinforcement is achieved.
5. The existence of pre-loading decreases the stiffness of the strengthened beams, and leads to the early debonding of FRP at the ends of cracks and thus may decrease the ultimate load of the strengthened beams.
6. The closer crack spacing leads to a larger bending stiffness and a higher debonding strength as well.
7. The distance between strips has a significant effect on the load-carrying capacities of the beams.

Finally, a wider experimental base is needed to confirm and more precisely quantify the trends indicated by the present study.

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