Role of U-shaped anchorages on behaviour of RC beams strengthened by CFRP plates

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ABSTRACT: Deterioration of civil engineering infrastructure may be attributed to the aging, environmentally induced degradation, poor initial design and/or construction, lack of maintenance, change of use, more stringent design criteria and natural events such as earthquakes. Non-corrosive fiber reinforced polymer (FRP) reinforcement have recently made major breakthroughs in civil engineering applications. FRP rehabilitation is a cost-effective, state-of-the-art technology in the repair and strengthening of structures. Use of Carbon Fiber Reinforced Polymer (CFRP) Plates, as externally bonded reinforcement, is a practically efficient and technically sound method of strengthening and upgrading structurally inadequate or otherwise damaged or deteriorating reinforced concrete (RC) members. Externally bonded plates help in improving the structure performance by reducing deflections or cracking and increasing ultimate strength. The ultimate capacity of the strengthened beam is controlled by either compression crushing of concrete, rupture of the composite plate, local failure of concrete at the plate end due to stress concentrations and flexural shear crack-induced debonding of Concrete-CFRP interface. Another factor that could affect the ultimate strength and mode of failure is the shear span. These failure modes along with the variation of shear span were considered in this study to investigate the ultimate load carrying capacity and failure modes of strengthened beams. Beams with U-shaped anchorages were tested in four point bending to determine the ultimate load carrying capacities of the beams. Properly placed U-shaped anchorages at plate cut-off points and along the span were shown to be effective in optimizing the deformability and strength characteristics of CFRP strengthened RC beams in flexure and shear.

1 INTRODUCTION

Deterioration of civil engineering infrastructure may be attributed to the aging, environmentally induced degradation, poor initial design and/or construction, lack of maintenance, change of use, more stringent design criteria and natural events such as earthquakes. Use of conventional materials and methodologies to upgrade and replace existing structures has often led to repair of the repairs. Development FRPs have changed the perception of concrete, concrete repair and strengthening and understanding of materials and methods. FRPs have recently made major breakthroughs in civil engineering applications. FRP rehabilitation is a cost-effective, state-of-the-art technology in the repair and strengthening of structures.

Reinforced concrete members strengthened in bending by bonding of FRP may present several failure modes: failure of material (reinforcing steel, concrete and composite material) or failure of the interface between concrete adhesive or adhesive-FRP. Nevertheless, experience gained from testing confirms that in most cases delamination prevails over the other possible rupture modes (Casas & Pascual 2007). Different delamination failure modes can be classified into two main types: due to high interfacial stresses near plate ends and due to flexural or flexural-shear crack (intermediate crack) away from the plate ends (Teng et al. 2003).

Extensive theoretical and experimental research have been undertaken to study the flexural behaviour of Reinforced Concrete (RC) beams externally strengthened bonded by Fibre Reinforced Polymer (FRP) laminates. Less attention has, however, been paid to the structural behaviour of RC beams with FRP laminates bonded to the tensile face and subject to shear dominant loading regimes. It has been observed in the beams reinforced by externally bonded plates that the failure mechanism is governed primarily by the bond and anchorage efficiency rather than by the tensile strength of the shear strengthening plate material (Bencardino et al. 2007). U-shaped external anchorage have been used to enhance the shear resistance of eternal plate bonding but the reported results are not adequate yet to draw rational conclusions. This is due to the complex relationship between strengthening parameters, such as shear span-to-depth ratio (a/d), the bond–slip relationship, and the inclination of FRP (Al-Sulaimani et al. 1994, Chajes et al. 1995, Traintafillou 1998, Khallifa & Nanni 2000).

This paper focuses on investigating the role of U-shaped anchorages on ultimate load carrying capacities and failure modes of normal and strengthened RC beams in predominant flexure and shear loadings by varying shear span-to-depth ratio (a/d).

2 EXPERIMENTAL PROGRAM

This section describes the experimental setup and testing of the normal and strengthened RC beams. Overall six beams, three control and strengthened and three pre-cracked and strengthened, rectangular in cross-section, 150 mm × 200 mm, 1600 mm long, with two 12 mm dia. bars as tension reinforcement, were tested under static loading to determine the ultimate load carrying capacity and failure modes of the beams. Beams were divided in three pairs. Each pair was tested as simply supported beams under four point bending with a span of 1400 mm and shear spans of 550 mm, 475 mm and 400 mm respectively. Midspan deflections were recorded at load increments using displacement gauges. All the measurements were continuously monitored and recorded. Experimental program is summarized in Table 1.

Details of control and strengthened RC beams are shown in Figures 1-3. All the beams were designed to fail in flexure. Casting and curing of the beams and bonding of the CFRP strips and wraps were carried out in Material Testing Laboratory of Civil Engineering Department, NED University of Engineering and Technology.

Compressive strength of concrete used was 20.7 MPa. Steel reinforcement used had yield stress of 415 MPa and elastic modulus of 200 GPa. The unidirectional CFRP strips of 50 mm width and 1.4 mm thick had ultimate tensile strength of 2500 MPa and Young's modulus of 150 GPa. Flexible carbon fiber fabric had a thickness of 0.117 mm, tensile strength of 3800 MPa and Young's modulus of 240 GPa.

Table 1. Experimental Program

Beam	Description
CB1	Control beam with shear span a = 550 mm (a/d = 3.08)
CB1S	Beam CB1 strengthened after failure with CFRP strip and full depth anchors with shear span a = 550 mm (a/d = 3.08)
PB1S	Pre-cracked by loading up to 70% of ultimate load from CB1 and strengthened with CFRP strip and full depth anchors with shear span a = 550 mm (a/d = 3.08)
CB2	Control beam with shear span a = 475 mm (a/d = 2.92)
CB2S	Beam CB2 strengthened after failure with CFRP strip and full depth anchors with shear span a = 475mm (a/d = 2.92)
PB2S	Pre-cracked by loading up to 70% of ultimate load from CB2 and strengthened with CFRP strip and full depth anchors with shear span a = 475mm (a/d = 2.92)
CB3	Control beam with shear span a = 400 mm (a/d = 2.46)
CB3S	Beam CB3 strengthened after failure with CFRP strip and full depth and anchors with shear span a = 400 mm (a/d = 2.46)
PB3S	Pre-cracked by loading up to 70% of ultimate load from CB3 and strengthened with CFRP strip and full depth anchors with shear span a = 400 mm (a/d = 2.46)

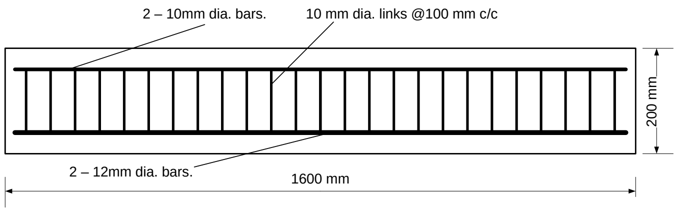

Figure 1. Details of control unstrengthened beams.

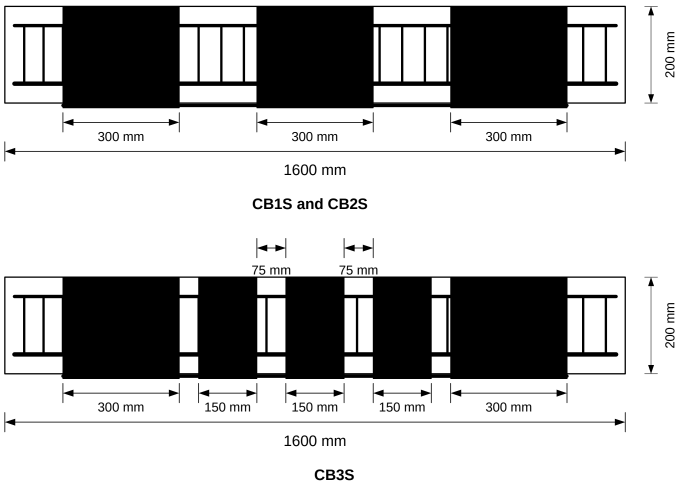

Figure 2. Details of control strengthened beams.

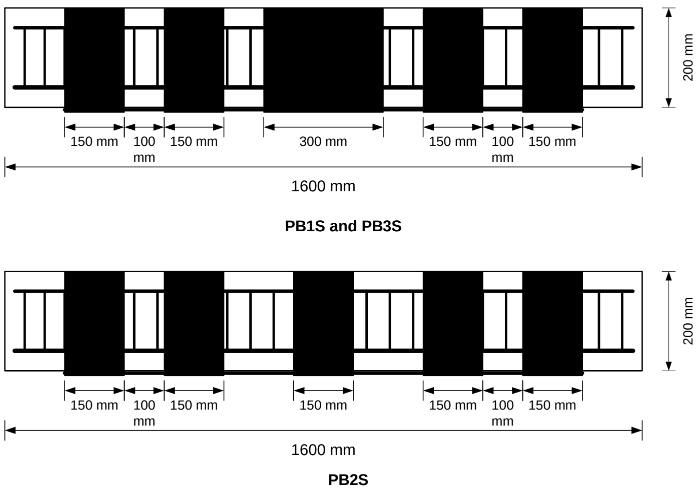

Figure 3. Details of precracked strengthened beams.

3 RESULTS AND DISCUSSIONS

3.1 *Ultimate loads and failure modes*

The ultimate loads and failure modes of control and strengthened beams are summarized in Table 2. Beam CB1 failed at an ultimate load of 68 kN in conventional ductile flexure mode with yielding of the main reinforcing steel. Beam CB1 was repaired and strengthened by using CFRP strip and full depth anchors of 300 mm width at the ends and at midspan. The strengthened beam (CB1S) failed at ultimate load of 90 kN carrying an additional 22 kN prior to failure (24.5% increase in load carrying capacity). It failed in desirable flexure mode by crushing of concrete as the steel has already yielded. Concrete in the compression zone was allowed to reach its ultimate strain capacity. Beam PB1S was first pre-cracked by loading the beam up to 70% of the ultimate load from CB1 and was then strengthened by externally bonded CFRP strips with full depth anchors of 150 mm and of 300 mm width at the ends and at midspan respectively. It failed in desirable flexure mode by yielding of steel followed by crushing of concrete and carried an additional 33 kN prior to failure (32% increase in load carrying capacity). It was observed in the case of beams CB1S and PB1S that cracks developed during initial loading of the beams started to open up and extend towards the compression zone ultimately leading to failure. PB1S was able to carry a higher load than CB1S due to the fact that anchorages at the end were spread over larger span that prevented premature debonding of CFRP strip between the anchorages.

Beam CB2 failed at an ultimate load of 95 kN in mixed flexure and shear mode. Beam CB2 was repaired and strengthened by using CFRP strip and full depth anchors of 300 mm width at the ends and at midspan. The strengthened beam (CB2S) failed at ultimate load of 96 kN carrying an additional 1 kN prior to failure (marginal increase in load carrying capacity). It failed in mixed flexure and shear mode. Beam PB2S was first pre-cracked by loading the beam up to 70% of the ultimate load from CB2 and was then strengthened by externally bonded CFRP strips with full depth anchors of 150 mm width at the end and at midspan. It carried an additional 33 kN prior to failure (35% increase in load carrying capacity). It failed in mixed flexure and shear mode but new flexural cracks were observed in pure flexural zone when the load exceeded 96 kN. The failure was transforming to flexure mode but excessive shear cracking in the shear span led to the shear failure of concrete at end anchorages.

Beam CB3 failed at an ultimate load of 92.3 kN in pure shear mode with a prominent diagonal tension crack starting from the support and moving towards the load. Beam CB3 was repaired and strengthened by using CFRP strip and full depth anchors of 300 mm and of 150 mm width at the ends and at midspan respectively. The strengthened beam (CB3S) failed at ultimate load of 96 kN carrying an additional 3.7 kN prior to failure (marginal increase in load carrying capacity). It failed in shear mode. Beam PB3S was first pre-cracked by loading the beam up to 70% of the ultimate load from CB3 and was then strengthened by externally bonded CFRP strips with full depth anchors of 150 mm and of 300 mm width at the ends and at midspan respectively. It carried an additional 24.7 kN prior to failure (27% increase in load carrying capacity). It failed in mixed flexure and shear mode. New flexural cracks were observed in pure flexural zone when the load exceeded 92.3 kN but the failure was due to excessive shear cracking in the shear span that led to the failure of concrete at end anchorages.

Table 2. Ultimate loads and failure modes

Beam	Ultimate Load (kN)	Failure Mode
CB1	68	Tension steel yielding
CB1S	90	Crushing of concrete
PB1S	101	Tension steel yielding followed by crushing of concrete
CB2	95	Flexure-shear Failure.
CB2S	96	Shear-flexure failure with shear cracks domination due to debonding of CFRP strip in shear zone
PB2S	128	Flexure-shear failure, flexure cracks domination due to be bonding of CFRP strip in flexure zone, shear failure of concrete in shear span
CB3	92.3	Shear failure
CB3S	96	Debonding of end anchorage due to shear failure of concrete
PB3S	117	Debonding of end anchorage due to shear failure of concrete

3.2 *Load-deflection curves*

Figures 4-6 shows the comparison of load-deflection curves for all the tested beams, i.e., control and strengthened with CFRP strips and anchorages at ends and midspan. It can be noticed that load-deflection curves for all the strengthened beams are stiff as compared to the respective control beams. All the precracked strengthened beams carried additional load as compared to the respective control beams with the increase in load carrying capacity varying from 27% to 35%.

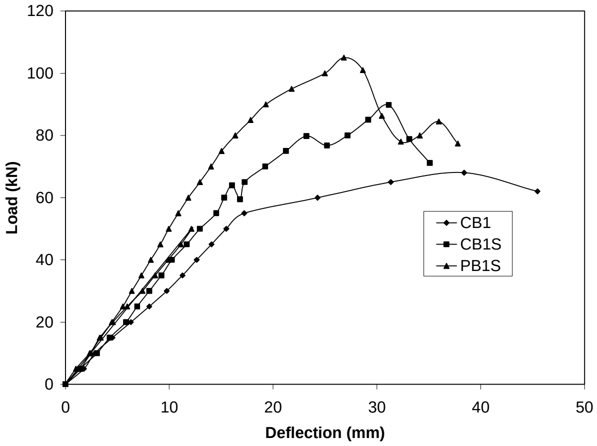

Figure 4. Load-deflection curves for beams CB1, CB1S and PB1S.

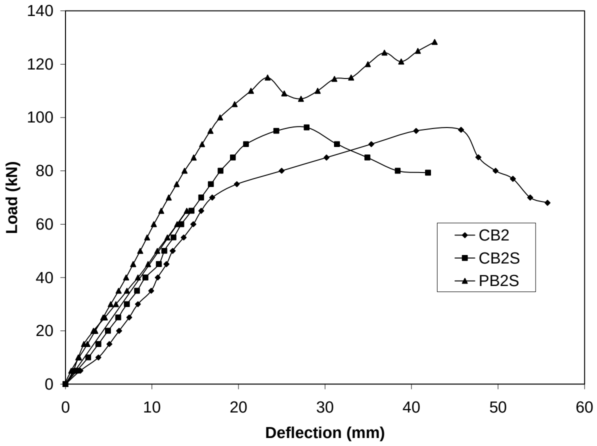

Figure 5. Load-deflection curves for beams CB2, CB2S and PB2S.

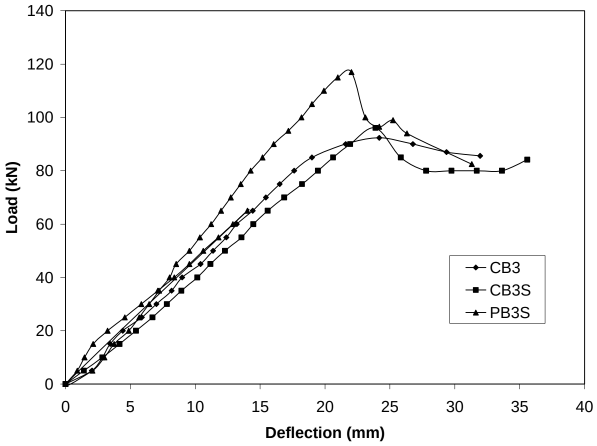

Figure 6. Load-deflection curves for beams CB3, CB3S and PB3S.

All the control strengthened beams carried at least the load which the control beams initially carried with the beam having the largest shear span showing the maximum increase. The U-shaped anchorages provided at ends and at midspan helped in increasing the ductility of the strengthened beams as in their absence failure would have been sudden and brittle. They in fact not only contributed towards increasing the ductility but they also increased the shear capacity of the section by adding an additional shear component due to end anchorages to the shear resistance provided by concrete and shear reinforcement. They also prevented the premature failure of the beams that would have taken place due to the debonding of the CFRP strips as can be noticed in Figures 4-6 thereby minimizing the loss of ductility as compared to the respective control beams.

4 CONCLUSIONS

The main conclusions drawn from this study are summarized as follows:

1. U-shaped anchorages provided at ends and at midspan improved the structural performance of the RC beams strengthened with externally bonded CFRP strips through enhanced strength and greater ductility as can be seen in the case of all the beams.
2. Properly placed U-shaped anchorages allowed the concrete in the compression zone to reach its ultimate strain capacity leading to crushing of concrete in compression in the case of beams CB1S and PB1S, while in other beams they increased the shear capacity of the beams thereby transforming the brittle mode of failure to ductile mode.
3. Ultimate load carrying capacities of the strengthened beams increased by as much as 35 % over respective control beam.
4. Observed mode of failure varied from flexure to flexure-shear and pure shear in the case of control and control-strengthened beams depending on the shear span while it varied from flexure to flexure-shear in the case of precracked-strengthened beams.

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