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Evaluation of the contribution of flexural CFRP plates in shear strengthening RC beams

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ABSTRACT: Strengthening of RC beams for shear has been typically done by externally attaching strips of steel plates or carbon-fiber reinforced polymer (CFRP) sheets or plates on the sides of the beams. However, sides of beams deficient in shear may not be always accessible for such a strengthening technique. The objective of this pilot study is to investigate the effectiveness of externally bonded CFRP flexural reinforcement to improve the shear strength of beams and to quantify their contributions. A pilot test was conducted which included three beam specimens. All beams were reinforced with 2ϕ12 steel bars (approximately 1% reinforcement ratio) and were casted without transverse reinforcement in their shear span. Two beams were strengthened with one and two layers of CFRP plates as external flexural reinforcement while the third beam was left as the control specimen. The beams were tested under four-point loading. Load and mid-span deflection readings were recorded until failure. All specimens failed in shear as a result of a diagonal-tension crack. The strengthened specimens with one and two layers of CFRP plates showed an increase in their shear capacity of 32% and 39%, respectively, over the control specimen. It was concluded that CFRP plates, when externally bonded to the soffit of simply supported beams, enhance both flexural and shear capacity of such beams. As a result, a comprehensive testing program is now underway. Specimens will be tested by varying the steel reinforcement ratio, the CFRP reinforcement ratio, and CFRP plates vs. sheets, in an effort to quantify the contribution of flexural CFRP reinforcement in shear strengthening of RC beams.

1 INTRODUCTION

In the past two decades a large number of research studies have been conducted on the use of fiber reinforced polymers (FRP) sheets and plates in repairing and strengthening reinforced concrete (RC) members and structures. Various studies have been conducted on increasing the flexural, shear, and axial strengths of RC members and on enhancing their stiffness and ductility (Challal et al (1998), Ashour et al (2004), Barros and Dias (2006), Monti and Liotta (2007), Jayaprakash et al (2008), Tamimi et al (2011), Rahal and Rumaih (2011), Hawileh et al (2014), Hawileh et al (2015)). Experimental and numerical investigations have been conducted on RC beams deficient in flexure and the results showed an increase of up to 100% in the load carrying capacity of specimens strengthened with externally bonded carbon fiber reinforced polymer (CFRP) laminates as compared to the control unstrengthened specimen (Barros et al. 2007).

Similarly, CFRP laminates have been used to increase the shear strength of RC beams (Taljsten 2003). Conventionally, CFRP strips have been bonded to the sides of the beams either vertically or inclined to capture diagonal shear cracks and ultimately to strengthen shear-deficient beams. For instance, Taljsten (2003) tested seven shear-deficient RC beams to investigate the effect of CFRP laminates on the beam's shear strength when attached to the vertical sides of the beam at 0, 90 and 45 degrees (Taljsten 2003). Test results showed an increase in the shear capacity of the strengthened specimens in the range of 98 to 169% over the control specimen.

Design codes have always taken into consideration the effect of internal flexural steel reinforcement (ρ) on the shear strength provided by concrete (V_c) of reinforced concrete members (ACI318 (2011), CSA (2004)). Therefore, it is hypothesized that external flexural CFRP reinforcement will increase V_c of beams, similar to the effect of ρ, due to the expected increase in the depth of the compression zone and the subsequent decrease in the width of the flexural-shear cracks. However, the literature is lacking adequate information on the effect of the external flexural CFRP plates on V_c. Since the sides of the beams might not be always accessible for strengthening, or beam depth is too short to develop the full strength of the FRP system, or simply to save on FRP cost if CFRP plates are already used to strengthen the beam for flexure, it is reasonable to study the effect of flexural CFRP plates on V_c. Since this method of strengthening shear-deficient beams has not received enough attention by researchers, it is the aim of this research investigation to study the effect of longitudinal CFRP plates on V_c.

2 EXPERIMENTS CONDUCTED

2.1 Beam Specimens and testing setup

To test the hypothesis that longitudinal CFRP plates can increase the shear strength of shear-deficient RC beams, three beams were built reinforced with 2ϕ12 bars as tension reinforcement and 2ϕ8 bars as compression reinforcement. The size and the reinforcement details of the tested beams are shown in Fig. 1. The flexural reinforcement provided is approximately 1% reinforcement ratio which is a typical value in practical designs. The effect of the CFRP flexural plates on the shear strength of RC beams for various internal steel reinforcement ratios is the subject of a future study. All beams had a shear span to depth ratio *a/d* of approximately 3 to ensure a shear failure. No shear reinforcement in the form of stirrups was provided in the shear span. One beam was externally reinforced with one plate of CFRP having a thickness of 1.4 mm and a width of 100 mm and was designated as B1P1. Another beam was strengthened with two plates of CFRP and designated as B1P2 while the third beam was not strengthened to serve as the control beam and was designated as B1. All beams were tested under four point bending as shown in Fig. 1 using a Universal Testing Machine (UTM).

2.2 Properties of Materials Used

2.2.1 Concrete

Concrete used was supplied by a local ready mix company and had a water/cement ratio of 0.38. In addition to the beam specimens eight concrete cylinders (100 by 200 mm) were casted at the same time. All beams and cylinders were from one batch and they were all cured under the same conditions. The average compressive strength of concrete at 28 days was 19 MPa. The control beam was tested at 38 days and concrete had a compressive strength of 19 MPa.

Specimens B1P1 and B1P2 were tested at 93 days and the concrete had a compressive strength of 23 MPa.

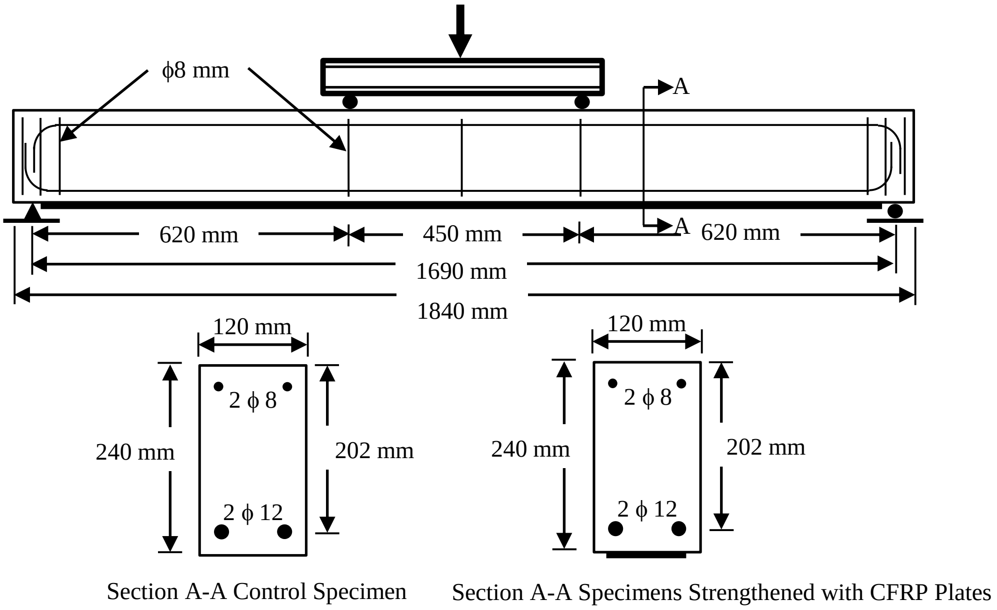

Figure 1. Specimens details and test setup

2.2.2 Steel

A standard tension test was performed on four ASTM A615 steel reinforcement bars to determine their mechanical properties. The average yield stress, ultimate stress, and modulus of elasticity was 593 MPa, 689 MPa, and 199.6 GPa, respectively.

2.2.3 CFRP Plates

The CFRP plates used had a nominal thickness of 1.4 mm and width of 100 mm, ultimate tensile strength of 3100 MPa, and modulus of elasticity of 170 GPa, as provided by the manufacturer. The epoxy adhesive used had a tensile strength of 30 MPa and an elastic modulus of 10 GPa as given by the manufacturer.

3 EXPERIMENTAL RESULTS

All specimens were tested under four point bending at a rate of 2 mm/min. During the test the applied load and the midspan deflection were continuously recorded and cracks were inspected. Figure 2 shows the load vs. midspan deflection for all three specimens.

All specimens failed in a brittle manner due to a diagonal tension crack. The control specimen as well as the other two strengthened specimens had almost the same behavior prior to cracking. After cracking the strengthened specimens exhibited higher stiffness than the control specimen.

Specimen B1P2 showed higher stiffness than specimen B1P1 due to the increase in the number of CFRP plates provided which increased the moment of inertia of the beam after cracking. Table 1 shows the percent increase of the shear strength of the strengthened specimens to that of the control specimen after normalizing with respect to concrete strength and *bd*. Specimens B1P1 and B1P2 had 32% and 39% increase in their shear strength, respectively. The data clearly suggest that using CFRP plates externally bonded to the soffit of RC beams increase the shear capacity provided by concrete as well as the beam's stiffness.

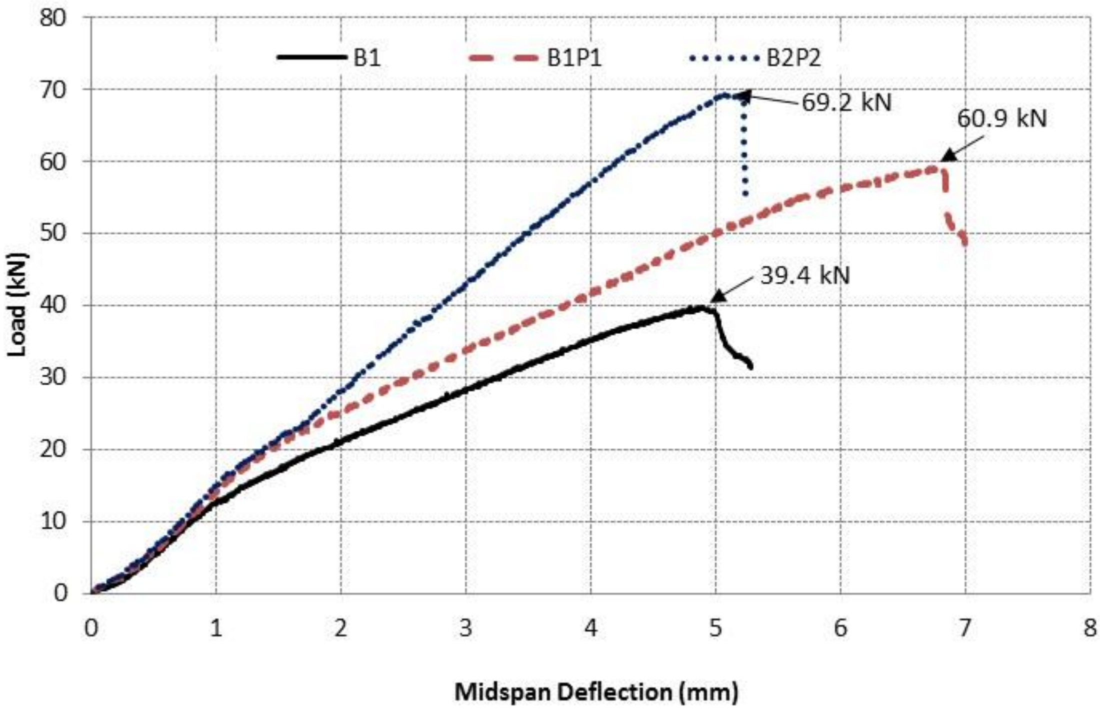

Figure 2. Load vs. midspan deflection for all tested specimens

Table 1. Experimental results

Specimen	Load P_{exp} (kN)	Midspan Deflection (mm)	% Increase in Shear Strength*
B1	39.4	4.84	-
B1P1	60.9	6.78	32
B1P2	69.2	5.08	39

* After normalizing with respect to concrete strength and *bd*

4 CONCLUSIONS

The results of this pilot study indicate that it is viable to enhance the shear strength of RC shear-deficient beams by only adding external longitudinal flexural reinforcement. Both strengthened specimens showed a considerable increase in the shear strength provided by concrete when flexural CFRP reinforcement was bonded to the soffit of the RC beams. However, the rate of increase in the shear strength was decreasing as the area of CFRP was increasing. Based on the obtained results a larger experimental program is currently underway to investigate the influence of various factors on increasing the shear strength of reinforced concrete beams using this proposed method. The results will be compared with analytical shear strength equations such as the ACI318 and Canadian Standards as well as other shear strength models available in the literature. The objective is to propose an equation that will take into consideration the effect of both internal steel flexural reinforcement as well as external CFRP flexural reinforcement on the shear strength provided by concrete of reinforced concrete beams.

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