External Strengthening of Shear Deficient Reinforced Concrete Beams with Flexural CFRP Laminates

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ABSTRACT

This paper presents an experimental investigation of reinforced concrete (RC) beams strengthened in shear with externally bonded flexural carbon-fiber reinforced polymer (CFRP) sheets attached to the soffit of the beam via epoxy adhesives. The current state-of-the-art technology of shear strengthening of RC beams is by externally bonding CFRP sheets or plates to the vertical sides of the beam's web with different orientations and configurations using epoxy adhesives. However, in certain applications, the sides of the beam might not be accessible for shear strengthening or might be too shallow to develop the strength of the CFRP laminates without anchors. Therefore, the objective of this study is to investigate the contribution of external flexural longitudinal CFRP laminates on the shear strength of RC beams casted without internal stirrups. The beam specimens were simply supported and tested under four point bending and the load versus mid-span displacement responses were recorded until failure. As expected, all beams failed in shear as a result of a diagonal-tension crack. The strengthened specimens showed an increase in the load-carrying capacity of 49%-61% over the control unstrengthened specimen. It could be concluded that external flexural CFRP reinforcement has a significant effect on the concrete shear strength of beams and could be used as a valid alternative when the vertical sides of RC beams are not accessible.

1. INTRODUCTION

Many structures around the world are in immediate need for strengthening and rehabilitation due to ageing and deterioration of structural members. Severe environmental conditions, structural design errors, and corrosion of steel reinforcement are some of the factors affecting the strength of these structures [1-7]. Strengthening and retrofitting of existing reinforced concrete (RC) structures has given a lot of attention to the use of externally bonded fiber reinforced polymer

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(FRP) systems [5]. In the conventional method of flexure and shear strengthening of RC beams, carbon-fiber reinforced polymer (CFRP) sheets and laminates are bonded externally to the deteriorated surface via epoxy adhesives in order to increase their load carrying capacity. Extensive experimental and numerical investigations had been conducted on RC beams deficient in flexure and the results showed an increase of up to 100% in load carrying capacity of specimens strengthened with externally bonded CFRP laminates as compared to the control unstrengthened specimen [1]. Thus, external CFRP reinforcement (sheets or laminates) played the same role as that of the internal steel reinforcement. Researches [8-9] have also shown that flexural reinforcement ratio has significant effect on the concrete shear strength (V_c) of RC beams. Thus, it could be expected that external flexural CFRP reinforcement would have the same role as that of the internal steel reinforcement in enhancing V_c of RC beams. Typical shear strengthening is done by bonding CFRP sheets or laminates on the vertical sides of the beam web using epoxy adhesive. A conventional shear strengthening study was conducted by Taljsten [10]. Seven shear deficient RC beams were tested to investigate the effect of CFRP laminates on the shear strength of RC beams when attached to the sides of the beam at 0, 90 and 45 degrees [11, 12]. Test results showed an increase in the shear capacity of the strengthened specimens in the range of 98 to 169% over the control specimen. Strengthening RC beams for shear using longitudinal external CFRP reinforcement has not received to date enough attention by researchers, unlike the use of external vertical/inclined side bonded CFRP reinforcement. Therefore, the literature is lacking information about the contribution of flexural CFRP composite plates or sheets on the shear strength of RC beams [11,12] .The main aim of this study is to investigate the effect of flexural CFRP sheets on the concrete shear strength V_c when bonded externally to the soffit of shear deficient RC beams.

2. EXPERIMENTAL PROCEDURE

2.1 Specimen Detailing

An experimental investigation was conducted on three shear deficient RC beams reinforced in flexure with 2Φ12 (No.12, total area = 219.6 mm^2) bars on the tension side located at a depth of 202 mm from the top of the beam, and 2Φ8 (No.8, total area = 49.8 mm^2) bars on the compression side as shown in Figure 1. All specimens were casted without internal stirrups in the shear span, however, stirrups of Φ8 were only used near the supports and in zero shear zone to avoid any stress concentration. The beams had a nominal width of 120 mm, nominal height of 240 mm and length of 1840 mm with shear span to depth ratio of 3.06. All beams were designed to ensure shear failure.

Table I provides a summary of the test matrix including the configuration of external CFRP sheets. Beam “B1” was used as the control specimen while the other two remaining beams were strengthened with two and three layers of CFRP sheets bonded externally to the soffit of the beam via epoxy adhesives. CFRP sheets, 0.17 mm thick, were attached to the full width (120 mm) of the beam. Four point

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bending test was conducted using Universal Testing Machine (UTM) and the load was applied on the beam using a hydraulic actuator with a capacity of 2000 kN. All beams were simply supported and tested over a total span of 1690 mm with a loading rate of 2 mm/min.

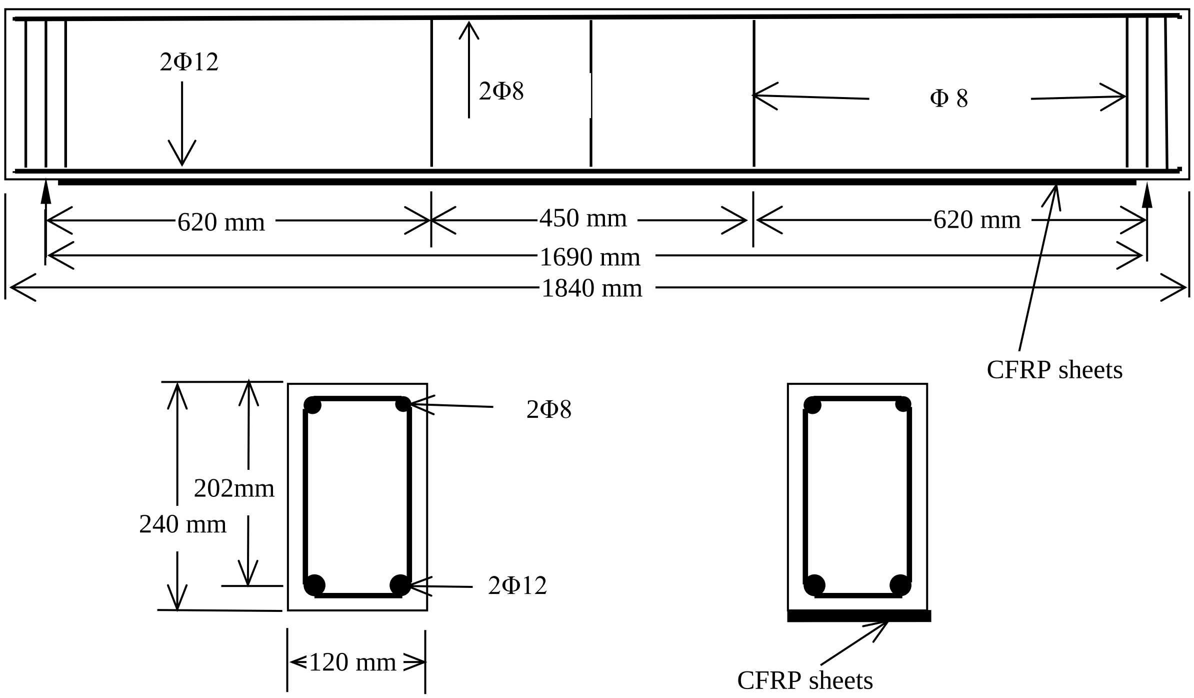

Figure 1. Tested beams details

TABLE I. Test Matrix

Specimen Designation	Layers of CFRP	Strengthening type	Compressive strength at day of test (MPa)
B1(control)	-	No strengthening	18.6
B1S2	2	Two layers of CFRP	21.0
B1S3	3	Three layers of CFRP	21.0

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2.2 Material

Ready mix concrete was provided by a local supplier and all specimens were casted in a single batch of concrete. Eight concrete cylinders (100 by 200 mm) were casted on site simultaneously with beam specimens. All beams and cylinders were casted and cured under the same conditions. The average compressive strength of concrete at 28 days was 19.4 MPa. Compressive strength of each specimen at the day of the test is shown in Table I.

Three steel bars were tested to determine the mechanical properties of the steel used in this study. The average obtained elastic modulus, yield stress, tensile strength, and percent elongation at failure was 199.6 GPa, 594 MPa, 690 MPa, and 12.2%, respectively.

The bond behavior between CFRP and reinforced concrete beam is greatly affected by the strengthening technique, which depends upon the performance of epoxy resin used [12]. In this research Sikadur-330 was used as an epoxy adhesive to bond the Sikawrap 300C CFRP sheets to the soffit of the RC beams. Sikawrap 300C has a thickness of 0.17 mm and a modulus of elasticity of 230 GPa. Sikadur epoxy has a modulus of elasticity of 4.5 GPa and an ultimate tensile strength of 30 MPa.

More details about the specimens and the materials used can be found in reference [12].

3. RESULTS AND DISCUSSIONS

Figure 2 shows the load versus midspan deflection response of the tested specimens. Prior to cracking the stiffness and load-midspan deflection curves were similar, however, after cracking specimens had different stiffness depending upon the number of layers of CFRP sheets used. Experimental results show that increasing the number of layers of CFRP sheets enhances the stiffness of the beam and reduces the midspan deflection. Table II shows the load at the first major shear crack which corresponded to the ultimate load attained during the test. Table II and Figure 2 also show that the beams strengthened with two and three layers of CFRP sheets attained an increase in their shear capacity over the control beam of 49% and 61%, respectively. It could be concluded from Figure 2 that the stiffness and the shear capacity of the strengthened specimens increased due to the externally bonded flexural CFRP laminates [11, 12].

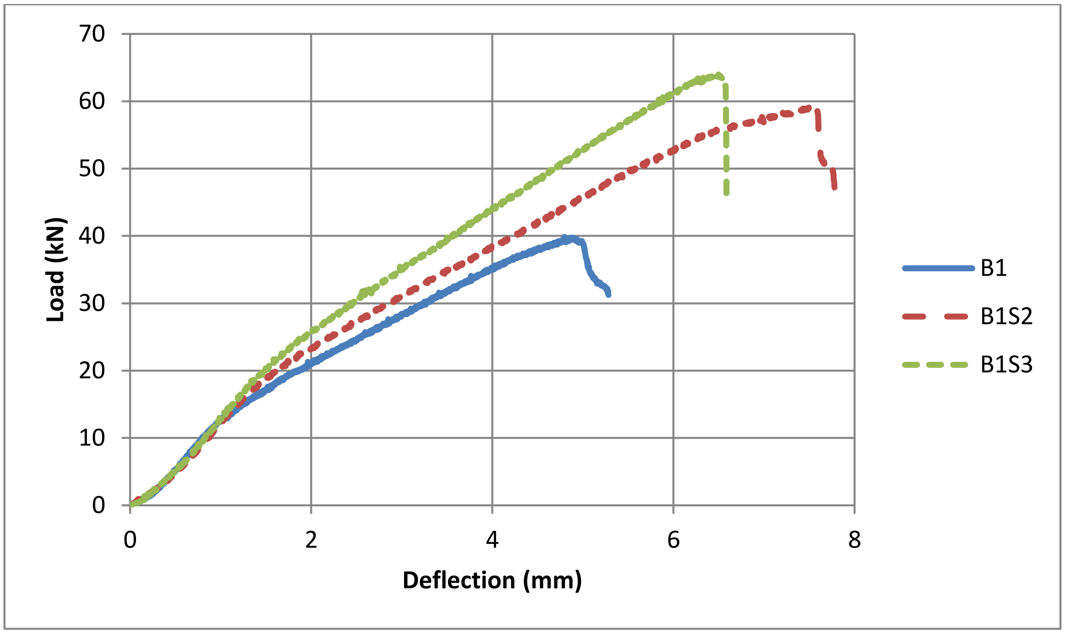
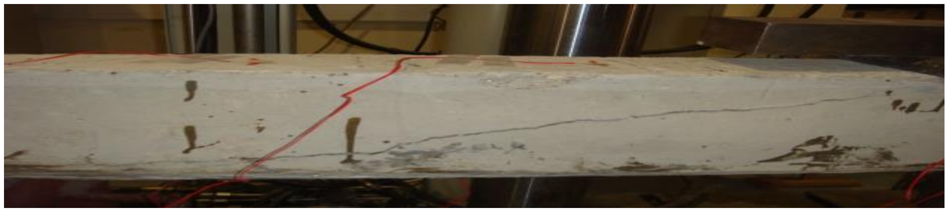


Figure 2. Load versus midspan deflection response

TABLE II. Summary of experimental results

Specimen Designation	Shear Strength V_c (kN)	Load P_{exp} (kN)	Midspan Deflection (mm)	P_{exp}/P_{exp} of B1
B1(Control)	19.70	39.39	4.84	1
B1S2	29.39	58.78	7.45	1.49
B1S3	31.71	63.42	6.43	1.61

In all specimens a typical "diagonal tension" failure was observed as shown in Figure 3. Flexural cracks developed first in the moment span where the moment is the highest. As the load further increased more flexural cracks started to develop in the shear span and then with further increase in load these cracks changed from flexural cracks to flexural-shear cracks. These flexural-shear cracks were inclined and they propagated towards the loading point [12]. The formation of these cracks resulted in a diagonal tension failure which caused a sudden drop in the load as shown in Figure 3. All specimens failed in a sudden brittle shear failure.



(a) Control beam B1 shear failure

(b) Strengthened specimen B1S3 shear failure

Figure 3. Failure modes of tested specimens

4. CONCLUSION

The results of an experimental program to investigate the effect of flexural CFRP sheets on the concrete shear strength of RC beams were presented. Two beams were strengthened with two and three layers of CFRP sheets and one beam was unstrengthened to serve as the control specimen. All beams were tested under four-point bending. All beams failed suddenly due to a diagonal tension crack. When compared to the control unstrengthened beam, the beams strengthened with two and three layers of CFRP sheets attained an increase in shear strength of 49% and 61%, respectively. The beam stiffness increased and the midspan deflection decreased as the number of CFRP sheets increased. From this initial study it can be concluded that flexural CFRP reinforcement has a significant effect on the shear strength provided by concrete, V_c, of RC beams. Further research is needed to quantify the contribution of the CFRP flexural reinforcement on V_c.

5. REFERENCES

[1] Barros, J.A.O., Dias, S.J.E, and Lima, J.L.T. (2007). " Efficacy of CFRP-based techniques for the flexural and shear strengthening of concrete beams," *Cement and Concrete Composites*; 29: 203-217.

[2] Jayaprakash, J., Abdul Samad, A.A., Anvar, A., and Abang, A. (2008). " Shear capacity of precracked and non-precracked reinforced concrete shear beams with externally bonded bi-directional CFRP strips," *Construction and Building Materials*; 22: 1148-1165.

[3] Dias, S.J.E., and Barros, J.A.O. (2011). “ Shear strengthening of RC T-section beams with low strength concrete using NSM CFRP laminates,” *Cement and Concrete Composites;* 33: 334-345.

[4] Monti, G., and Liotta, M.A. (2007). “ Tests and design equations for FRP-strengthening in Shear,” *Construction and Building Materials*; *21:* 799-809.

[5] Hawileh, R.A., Rasheed, H.A., Abdalla, J.A., and Al-Tamimi, A.K. (2014). “Behavior of reinforced concrete beams strengthened with externally bonded hybrid fiber reinforced polymer systems,” *Material and Design;* 53:972-982.

[6] Hawileh, R.A., Abdalla, J.A., and Al-Tamimi, A.K.. (2011). “Flexural performance of strengthened RC beams with CFRP laminates subjected to cyclic loading,” *Key Engineering Materials;* 471-472:697-702.

[7] Al-Tamimi, A.K., Hawileh, R.A., Abdalla, J.A., and Rasheed, H.A. (2011). “Effect of ratio of CFRP plate length to shear span and end anchorage on flexural behavior of SCC R/C beams ,” *Composite Construction;*15(6):875-1002.

[8] Frosch, R.J. (2002). “Contribution of concrete to shear resistance,” *ACI Structural Journal*; 99(4): 427-433.

[9] Tureyen , A.K., and Frosch, R.J. (2003). “Concrete shear strength: another perspective,” *ACI Structural Journal*; 100(5): 609-615.

[10] Taljsten, B. (2003). “Strengthening concrete beams for shear with CFRP sheets,” *Construction and Building Material*; 15-26.

[11] Hawileh, R.A., Nawaz, W., Abdalla, J.A., and Saqan, E.I. (2015). “Effect of flexural CFRP sheets on shear resistance of reinforced concrete beams ,” *Composite Structures;*122:468-476.

[12] Nawaz, W. (2014). “Effect of flexural CFRP sheets and plates on shear resistance of reinforced concrete beams,” Master Thesis, Department of Civil Engineering, American University of Sharjah.