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RESEARCH ARTICLE Open Access

Shear Strengthening of Reinforced Concrete Beams Using CFRP Strips

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Abstract:
In this study, the shear strengthening of reinforced concrete (RC) beams by externally web-side bonded carbon fiber-reinforced polymer (CFRP) strips is investigated experimentally. The current study regards the problems associated with shear strengthening of RC beams without stirrups by using externally bonded CFRP strips on two opposing web sides of the beam and four ratios of longitudinal reinforcements were used as the test variables. To investigate the shear capacity of RC beams, a total of eight 130 mm x 250 mm x 2,400 mm RC beams without shear reinforcement were used. Parameters varied in the tests and included a ratio of longitudinal reinforcement (1.24%, 1.86%, 2.47%, and 3.09%) and vertical application of CFRP strips. Considering the experiment's findings, the capacity of RC beams strengthened in shear with externally bonded web-sided CFRP strips is 1.88-1.95 times greater than that of control beams. It was revealed that the longitudinal reinforcement ratio significantly influences the failure type and crack patterns in the shear span zone. With an increasing longitudinal reinforcement ratio, the shear capacity of the beam increased slightly.

Keywords: *Reinforced Concrete Beam; Carbon Fiber-Reinforced Polymer; Shear Strengthening; Shear Capacity; Diagonal Cracking.*

1. Introduction

Fiber-reinforced polymer (FRP) composites are commonly used for strengthening and retrofitting reinforced concrete structures owing to their corrosion resistance, flexibility, and durability [1]. The performance of concrete beams strengthened in shear applying externally bonded FRP composites has been the subject of extensive research over the past decade [2]. It has been shown that many kinds of structures can be amplified using CFRP strips that are externally connected. Various structural elements such as columns, beams, walls, slabs, etc., have been strengthened using this kind of method. The application of an external CFRP strip may be defined as shear strengthening, flexural strengthening and improving the ductility of compression members [3].

The shear strength of the RC beams can be strengthened by externally bonding CFRP strips to the beam's cross-sectional sides. Similar to steel stirrups, the CFRP transfers loads across diagonal tension cracks in the concrete [4].

On the basis of previous research findings, codes and design standards for FRP strip applications has been developed as well. ACI 440.2R-17 is the current code that the American Concrete Institute has published using FRP materials in strengthening concrete structures. Several typical wrapping techniques and fiber orientations are utilized for shear strengthening by FRP strips, as indicated in ACI 440.2R-17 [5], as shown in Figure 1 and Figure 2.

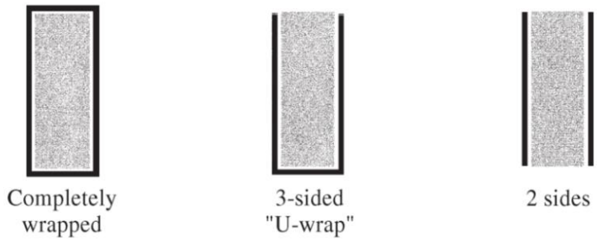
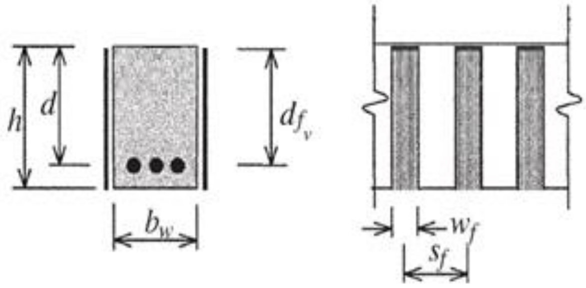


Figure 1: Common shear strengthening wrapping methods using FRP sheets



(a) (b)

Figure 2: Dimensional variables used in calculations for shear-strengthening using FRP strips [5]

Several important variables affect the FRP contribution, and various parameters cause differences between the predicted and the experimental shear capacity. Examples of affecting parameters are: shear span-to-depth ratio, type of wrapping, FRP thickness, effective height of the beam, the angle between the fiber orientation and the longitudinal axis of the beam, FRP effective strain, longitudinal steel bar ratios, etc.

Therefore, it is vital to conduct experimental study to better understand the shear capacity of CFRP strips used in RC beams without stirrups. The four longitudinal reinforcements ratio and vertical (90^o) application of CFRP strips were the test variables employed in this investigation. The stripping was externally connected to the two opposite web sides of the RC beam.

2. Literature Review

Three traditional and practical FRP strengthening configurations [6,5,7], on which most of the strengthening methods and models have been developed are extensively used for externally bonded FRP supporting schemes. However, in the most practical scenario, it may be necessary to gain access and repair the beams top surface, such as slabs on building beams or deck pavement on bridge beams. Drilling an opening through the slab and bonding FRP sheets all the way around the portion would be the ideal solution, if it were possible. However, this is a difficult and expensive process. Therefore, in the following database and models, complete wrapping arrangement is not taken into consideration.

The ratio of longitudinal reinforcement is one of the key factors affecting the growth of diagonal shear cracking load [8]. The transverse force, or "dowel force," produced in longitudinal reinforcements when diagonal cracks appear helps the reinforced concrete beams resist shear. The impact of the ratio of longitudinal reinforcement on the slope of a diagonal fracture in the shear span zone has, however, only been the subject of a small number of investigations.

Externally bonded FRP reinforcement for RC beams in shear strengthening could be simply assigned by using continuous or strip jacketing. Side bonding, U-jacketing to the soffit and faces, and fully wrapping around the beam cross section are the three most common configurations that are employed as strengthening schemes with externally bonded FRP reinforcement [9]. Although researches have been done to explain the shear contribution of the externally bonded FRP composites, it is still not palpable. Currently, the broad variety of potential FRP configurations used for shear strengthening has been one of the difficulties, and has made the exact computation of FRPs' shear contribution to the strengthened RC member complex. In addition, the experimental data are rather controversial, and there is no general agreement about the design guidelines [10].

FRP composites have become an attractive method and have been approved among researchers and practitioners during recent years. FRP composites offer an outstanding solution for strengthening the capacity of existing structures, particularly concrete buildings. The superiority of the FRP materials over traditional techniques is attributed to the high mechanical strength, lower weight, easier applicability or simplicity in installation and corrosion resistance of the former [11].

This literature review has given an account of and the reasons for the widespread use of FRPs in the field of application. It has been shown that the contribution of FRPs to shear capacity relies on many parameters as mentioned earlier. Effect of vertically applied of thin CFRP strips and longitudinal rebar ratio on shear which is a parameter that has been added to ACI 318M-19. With CFRP strips externally attached to the beam's two opposing web sides and four longitudinal reinforcement ratios serving as the test variables, the current study addresses the issues with shear strengthening of RC beams without stirrups. The aim of the current research is to investigate the contribution of vertically applied CFRP strips and various longitudinal rebar ratios to shear capacity of RC beams with no stirrups with the objective to enhance shear strength of the RC beams.

3. Experimental work

3.1 Materials Properties

The properties of the steel rebars, concrete, and CFRP strips materials utilized to construct the specimens are displayed in Table 1. In response to a request from 4Bridges Company for one batch of ready-mix concrete, the RC beams were cast following the necessary specifications and qualities. The concrete compressive strength was evaluated using the ASTM C39/C39M-14 standard test for the cylindrical compressive strength of specimens [12]. A concrete cylinder test 28 days after casting revealed an average concrete compressive strength of 31.72 MPa.

The longitudinal rebar is comprised of two-five 16 mm diameter rebars at the bottom and two 10 mm diameter rebars at the top of the beam. Testing was performed according to ASTM A615/A615M-22. Table 1 shows the properties and results of the steel bars [13]. A carbon fiber cloth CFRP type (SikaWrap®-300 C) and an epoxy-based impregnated resin type (Sikadur -330) were applied to the reinforced concrete beams outside the shear span. The material properties of the CFRP strip (SikaWrap®-300 C) are also shown in Table 1. A two-point loading was used in the experiment.

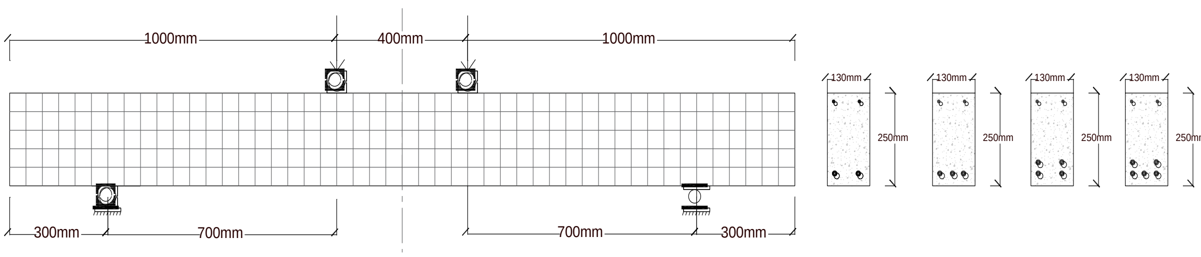
Table 1: Properties of CFRP strip and steel rebar materials

Materials	Dimensions (mm)	f_y (MPa)	f_u (MPa)	E (GPa)	Elongation (%)
Steel reinforcing	D10 D16	420.5 448.7	610.4 687.6	200 200	17.1 16.4
CFRP strips (SikaWrap®-300 C)	t_f = 0.167	-	3500	220	1.7

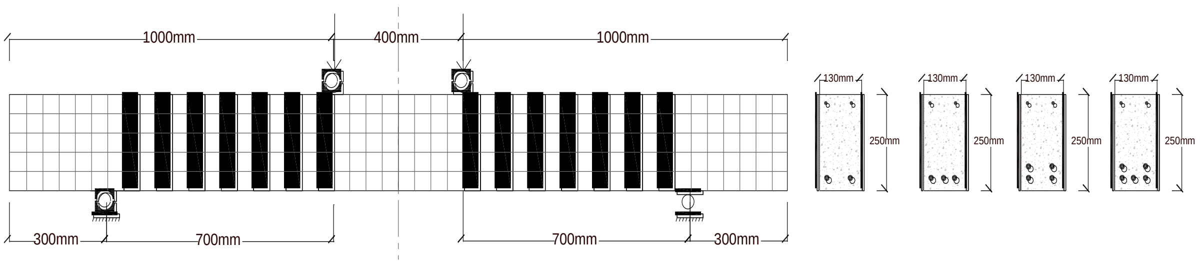
3.2 Sample Preparation

Eight reinforced concrete beams without stirrups were prepared and tested for this experimental study, four of which served as control beams while the other four were strengthened with CFRP strips. The chosen rectangular cross-section had dimensions of 250 mm in depth and 130 mm in width, with a 2300 mm overall span length. The shear span measured 700 mm in length, and the distance between the two-point loads was 400 mm, as shown in Figure 3. The test variables were the ratios of longitudinal reinforcements (1.24%, 1.86%, 2.47%, and 3.09%) and the vertical (90^o) application of CFRP strips, as shown in Table 2.

The installation process of CFRP strips, for the required shear span, was scuffed and ground using mechanical abrasion techniques to achieve a sound bond between the concrete substrate and the epoxy resin. After preparing the beam surfaces to the required standards, the CFRP is measured and pre-cut according to the required sizes. The matrix was mixed, regarding the manufacturer's guidance, a two-part epoxy resin. The layer of the epoxy resin was applied on the prepared surface for the required shear span, as shown in Figure 4. The CFRP strips were then put on top of the epoxy resin and gently pressed into the epoxy resin. The CFRP strips were then rolled in the fiber direction to simplify the impregnation.



(a) Control beams (Group G1)



(b) Vertical (90^o) application of CFRP strips (Group G2)

Figure 3: Test beams dimensions, loading position, and CFRP strip schemes

Table 2: Beam details and capacities

Group	Specimens	Shear strengthening (CFRP) strips							Longitudinal reinforcement bar (Tension)			ACI 318-19		ACI 440.2R-17		Experimental shear strength	Failure modes
		S_f (mm)	t_f (mm)	W_f (mm)	n	A_f (mm^2)	d_f (mm)	α	N	d_b (mm)	ρ (%)	V_c (kN)	V_s (kN)	V_f (kN)	ΦV_n (kN)	$V_{u,\,exp.}$ (kN)	
G1	BSC-01	-							2	16	1.24	25.17	0.0	-	18.88	32.35	SF
	BSC-02								3		1.86	28.81			21.61	35.60	SF
	BSC-03								4		2.47	31.67			23.75	39.65	SF
	BSC-04								5		3.09	34.12			25.59	48.75	SF
G2	BSV-01	100	0.167	50	1	16.7	225	90°	2	16	1.24	25.17	0.0	21.66	32.69	60.86	SF+ DF
	BSV-02								3		1.86	28.81			35.42	68.95	SF+ DF
	BSV-03								4		2.47	31.67			37.56	77.22	SF+ DF
	BSV-04								5		3.09	34.12			39.40	92.90	SF+ DF

Note: SF = Shear failure, DF = Debonding failure

Figure 4: Preparation of concrete beam surface and applying CFRP strips

3.3 Test Procedure

A hydraulic jack testing machine with 2500 kN capacity and 2 kN/min load rate was used to test the eight simply supporting RC beams until the beams failed. This study adopted a four-point static bending test method, as illustrated in Figure 5. Two concentrated loads, spaced 400mm apart, were applied to the beams at mid-span. An LVDT dial gauge was used to measure the mid-span deflection. Additionally, the electrical strain gauges fixed to the top surface of the beam and the reinforcement steel bars were recorded for strain using the data logger.

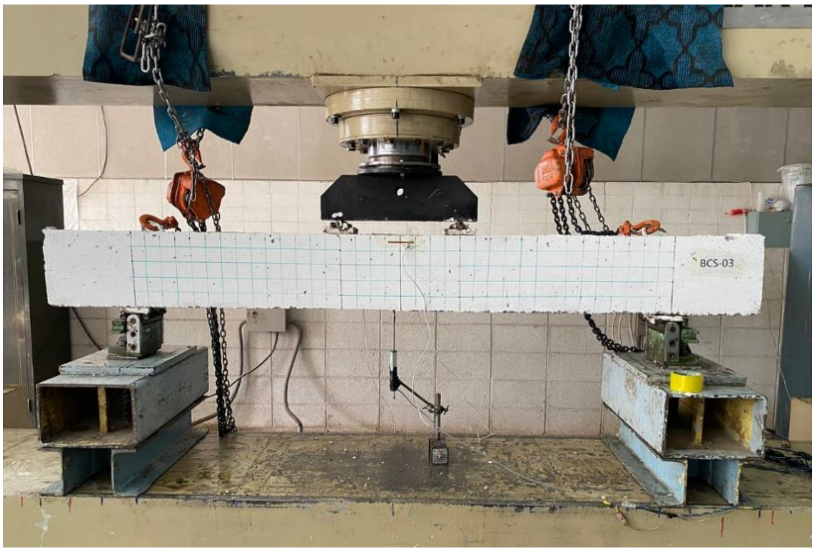


Figure 5: Test setup

4. ACI Code Format for Shear Design of RC Strengthened Beams

4.1 ACI Code Provision for Shear

The nominal shear strength (V_n) of a RC beam can be determined by adding the nominal shear strength of the concrete (V_c) and the shear strength of steel reinforcement (V_s). This is presented in ACI 318M-19 as follows [14]:

(1) $$V_n = V_c + V_s \quad ; \quad V_s=0$$

The ACI 318M-19 permits the use of the following equation for computing the nominal shear strength obtained by concrete and tension reinforcement bars for each of the specimens:

(2) $$Vc = [\, 8\ \lambda_s\ \lambda\ (\rho_w)^{\frac{1}{3}}\ \sqrt{f'_c} + \frac{N_u}{6\,A_g}]\ b_w\, d$$

(3) $$\lambda_s = \sqrt{\frac{2}{1+0.004d}} \leq 1$$

Where λ_s is the factor for considering the component height; λ is the standard light weight concrete factor; ρ_w is the tension longitudinal bar ratio; f'_c is the cylindrical concrete compressive strength; A_g is the area of cross section; N_u is the design axial force; b_w is the beam width and d is the beam effective depth.

4.2 Capacity of a CFRP Strengthened Section in Shear

The capacity of strengthened beam in shear by externally bonded FRP strips, may be computed by simply adding the third term to take into consideration the contribution from FRP composites to shear capacity (V_f) an adopted from ACI 440.2R-17 [5]:

(4) $$\Phi V_n = \Phi\ (V_c + V_s + \Psi_f\, V_f)$$

(5) $$V_f = \frac{A_{fv}\, f_{fe}\ (\sin\alpha + \cos\alpha\ )\ d_{fv}}{s_f}$$

(6) $$A_{fv} = 2\, n\, t_f\ w_f$$

(7) $$f_{fe} = \epsilon_{fe}\, E_f$$

For two –side strips:

(8) $$\epsilon_{fe} = k_v\ \epsilon_{fu} \leq 0.004$$

(9) $$k_v = \frac{k_1\, k_2\, L_e}{11900\ \ \epsilon_{fu}} \leq 0.75$$

(10) $$k_1 = (\frac{f'_c}{27})^{2/3}$$

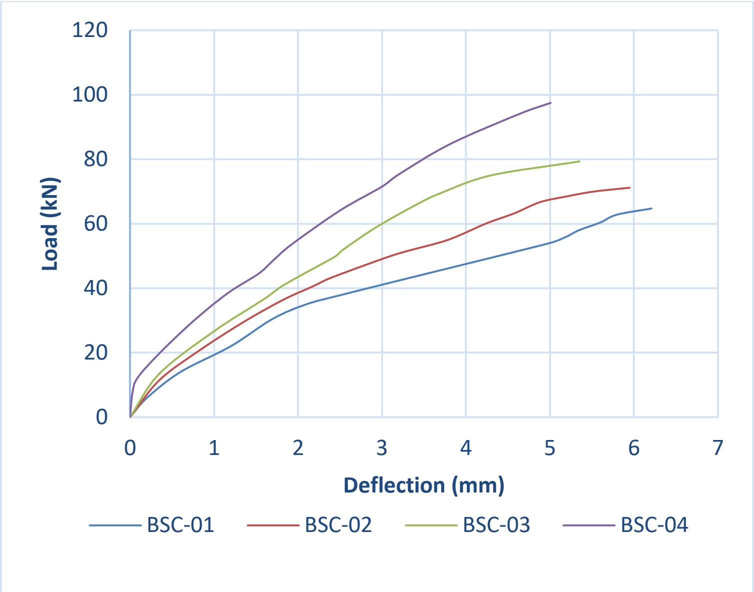
(11) $$k_2 = \frac{d_{fv} - 2\, L_e}{d_{fv}}$$

(12) $$L_e = \frac{23300}{(\mathrm{n}\ \ t_f\ \ E_f)^{0.58}}$$

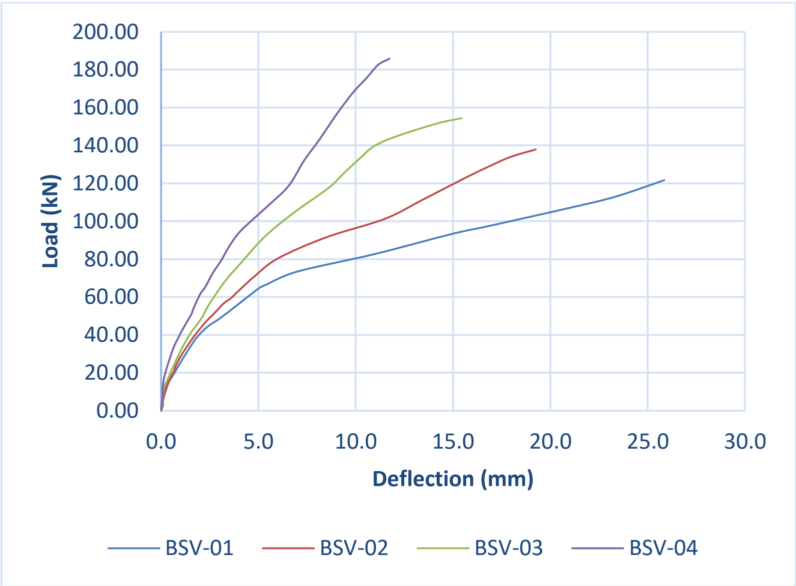
Where Φ is the shear strength reduction factor; Ψ_f is a reduction factor, a value of 0.85 for two-opposite side schemes; A_{fv} is the FRP shear reinforcement area; s_f is the spacing of FRP strips center-to-center; f_{fe} is FRP effective stress; d_{fv} is the effective depth of FRPs; α is the orientation of FRP reinforcement application; n is the number of plies in the FRP strips; t_f is the FRP strip thickness ; w_f is the width of FRP strip; ϵ_{fe} is the effective strain level in FRPs achieved at failure; E_f is the tensile modulus of elasticity of FRP; k_v is the coefficient bond-reduction; k_1 & k_2 are the modification factors and L_e is the active bond length. ACI adopts 45^o as truss angle regardless differences of the shear crack angle.

5. Results and Discussion

The load-deflection curves obtained from the experimental study are shown in Figure 6 for all control beams (Group G1) and strengthened beams by CFRP strips (Group G2) with various longitudinal reinforcement ratio. Diagonal shear cracks that formed in the shear span zone caused the complete set of control beams to fail in shear. Equation (2) is used to compute the nominal shear strength determined to be provided by tension steel bars and concrete. This equation's estimation of shear strength is conservative. The shear strength contribution of CFRP strips is computed by equation (4), as shown in Table 2.



(a)



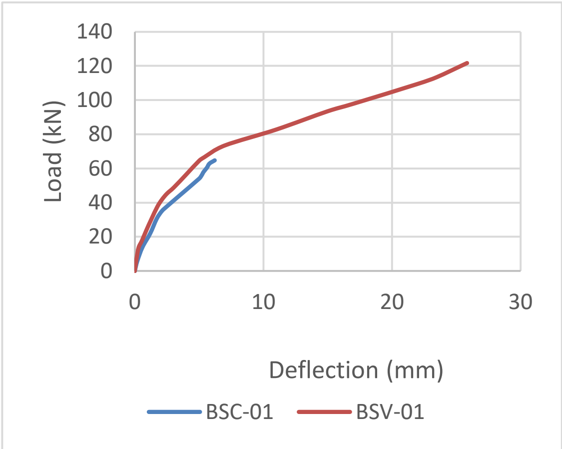
(b)

Figure 6: Load-deflection curves comparison for beams with different ratios of longitudinal reinforcement: (a) control beams , and (b) strengthened beams with CFRP strips

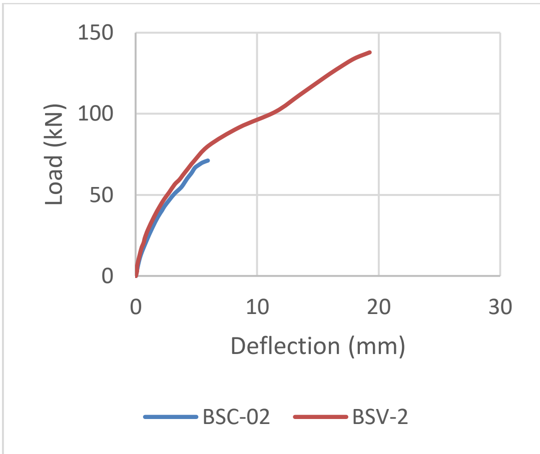
Load deflection curves of the tested beams are shown in Figure 7. The capacity of the RC beams increases as the ratio of longitudinal reinforcement increases. Also, the application of CFRP strips increased the ultimate shear, and these strips arrested the formation of cracks.

The longitudinal bars had considerable influence on the ultimate load, as shown in Fig. 8. For all groups of RC beams the average increase in the ultimate load for specimens with three, four and five longitudinal bars compared to specimen with two longitudinal bars were 12%, 23% and 50%, respectively.

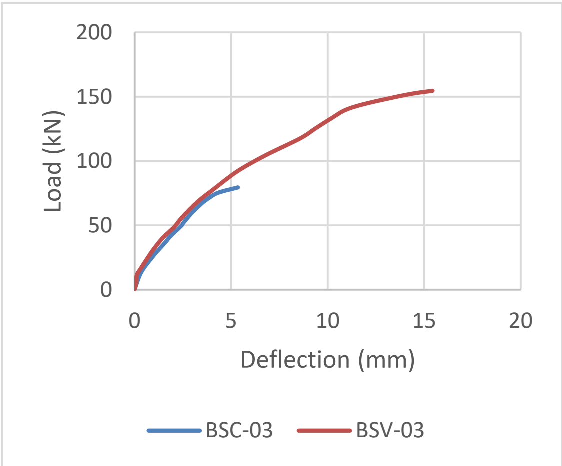
The load carrying capacity for strengthened beams G2 has increased 1.88-1.95 times as compared to control specimen G1. This shows the significance of strengthened beams by externally bonded CFRP strips applied vertically (90°), as shown in Fig. 8.



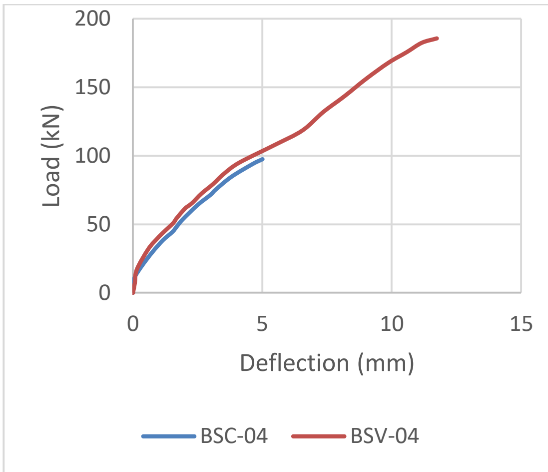
(a) Reinforcement ratio 1.24%



(b) Reinforcement ratio 1.86%



(c) Reinforcement ratio 2.47%



(d) Reinforcement ratio 3.09%

Figure 7: Load-deflection curves comparison for strengthened beams and control beams

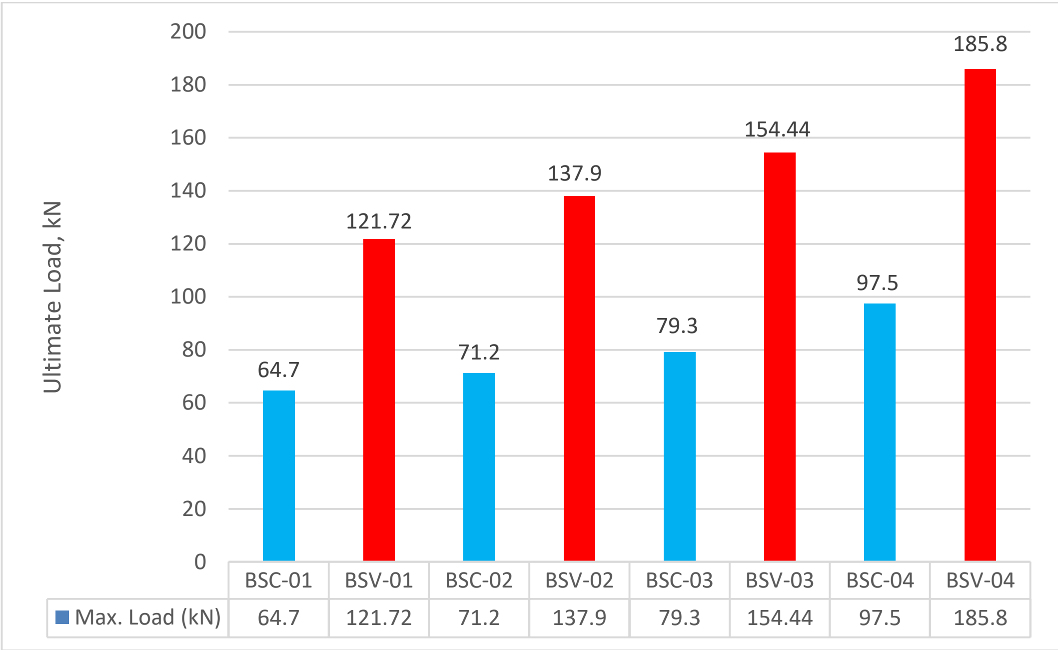
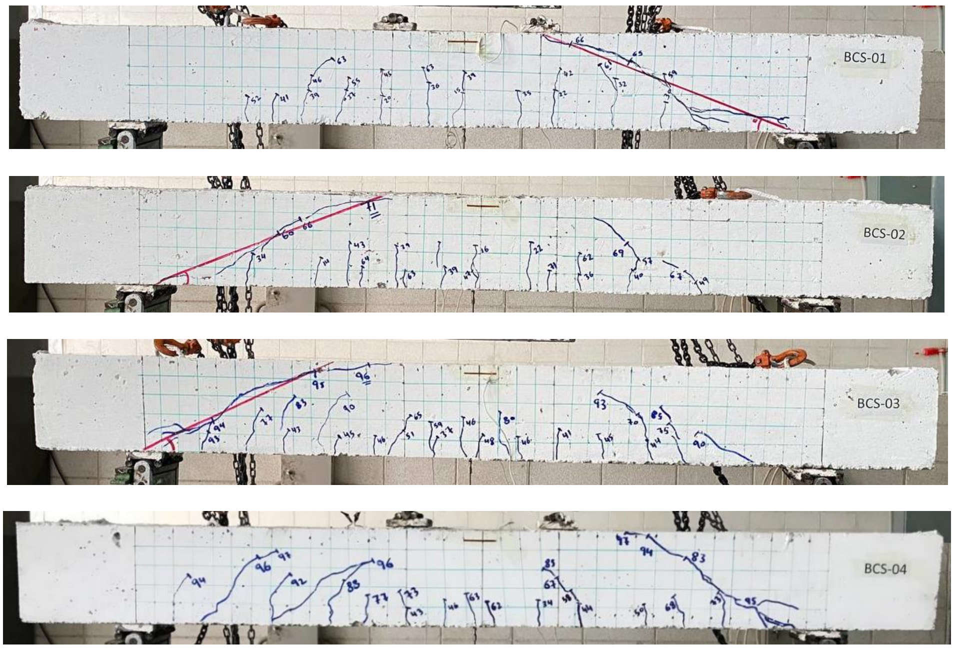


Figure 8: Ultimate loads for RC beams

5.1 Crack Patterns

The crack patterns of the tested RC beams are shown in Fig. 9. Generally, the primary flexural crack dependably happened in the constant moment region near the mid-span. Diagonal shear cracks in the shear span zone triggered the control beam shear failure. Meanwhile, the installation of CFRP strips in the shear span zone significantly affects the cracking patterns, making the zone of the maximum moment to have cracks. The mode of the shear failure was diagonal shear failure for tested beams. Debonding failure for the tested strengthened beams occurred in the shear span zone at the loading support, accompanied by concrete cover separation. However, the application of the CFRP strip led to beams with more cracks, as seen in Fig. 9.



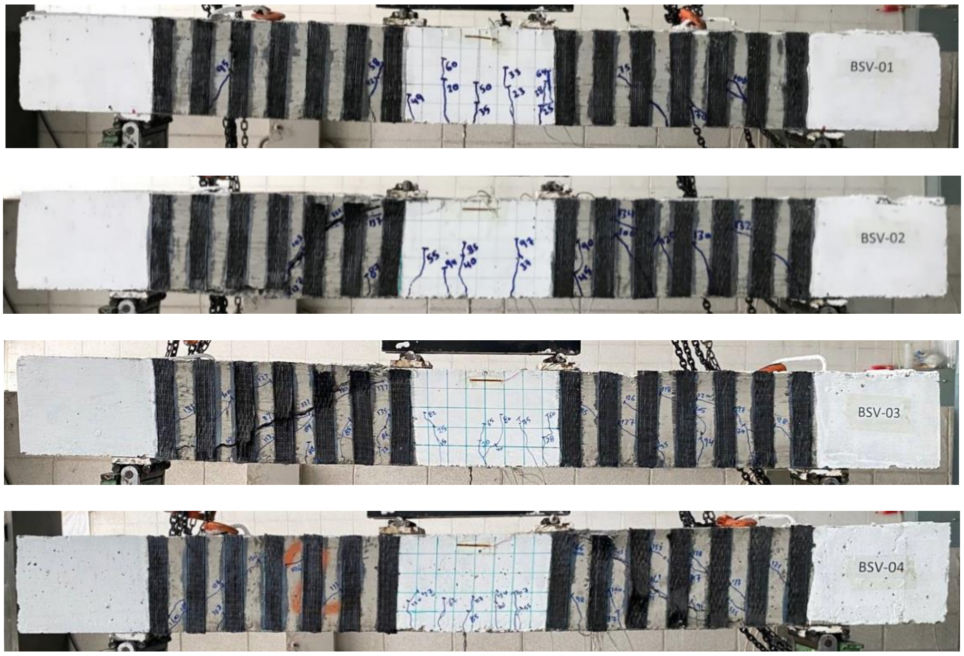


Figure 9: RC beam failure modes and cracking patterns

6. Conclusion

This study used vertical CFRP strips at the shear span zone to strengthen RC beams.
The following conclusions were drawn:

- In comparison to control beams with the same ratio of longitudinal reinforcement, the capacity of RC beams strengthened with CFRP strips increased 1.88-1.95 times in shear strength.
- The longitudinal reinforcement ratio influenced the capacity of the beam specimens in shear strength, which was noticeable in their load-deflection behavior. Consequently, the RC beams by increasing the reinforcement ratio from (1.24% to 3.09%), the ultimate load enhancement was (12% to 50%).
- Debonding failure occurred in the shear span zone at the loading support for all tested strengthened beams, accompanied by concrete cover separation.
- The ACI 440.2R-17 equation's theoretical shear strength contribution to CFRP strips reveals that the equation is conservative.

7. Conflict of Interest

In relation to this paper, there is no conflict of interest.

8. Acknowledgement

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9. Authors' contributions

The authors certify that all identified authors have read and approved the manuscript. The authors affirm that each made the same contribution to the work and that they both agreed on the order in which their names are listed in the manuscript.

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