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Experimental Non-linear Shear Behavior and Failure Mechanism of Low-Strength Reinforced Concrete Beams Strengthened with CFRP Sheets

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ABSTRACT

In this experimental study, 10 RC beams with 2000 mm in length, 150 mm in width, and 300 mm in height were tested for shear under three-point loading test. Eight specimens had varied concrete strength were strengthened by attaching CFRP sheets, while the other two were kept unwrapped for comparison purposes. The parameters considered in the current study included concrete strength, reinforcement ratio, and amount and configuration of FRP strips. The RC beams strengthened by using inclined strips of CFRP showed significant increase in failure load. As the amount of main reinforcements and concrete compression strength increased, the effect of using CFRP in strengthening of targeted RC beams became more efficient. The experimental shear capacities of RC beams showed a good agreement with calculated values according to Egyptian code of practice, ECP 208-05 (1).

1. Introduction

Shear failure of low strength RC beams due to poor quality control in construction sites is possible and strengthening mechanism of RC elements using CFRP is widely applied (Al-Tersawy, 2013) (2). The main concern in this research is to elaborate brittle failure mechanism of beams with low strength concrete in shear and to find out the most efficient CFRP configuration to increase the shear capacity and provide a flexural ductile failure.

Advanced composite materials have been considered by engineers and researchers as a promising repair technique (Triantafillou et al, 2000 (3); Bousselham et al, 2004 (4)). CFRP is a composite material typically consists of high tensile integrated carbon fibers in a multifunctional system, where the fibers are considered as main load carrying component. CFRP can be easily attached on outer clean surface of RC structural element by using special bond material which makes it an effective way of strengthening.

According to design codes and past research work, there are two possible mechanisms of CFRP sheets failure as debonding or fracture (Feng et al., 2020 (5); Mohammed et al., 2021 (6)). The ultimate carrying capacity in shear of retrofitted concrete beams is mainly affected by several factors such as the type of CFRP, bonding material, inclination of CFRP strips with shear crack, concrete compression strength, shear reinforcement ratio, and flexural reinforcement ratio (Hamed et al., 2019 (7); El Battawy et al., 2019 (8)).

Several experimental research works have been conducted and clearly illustrated the dominant improvement in shear and flexural capacities of beams strengthening with strips of CFRP, (Hawileh and Nawaz, 2018 (9); Osman and Abdulhameed, 2018 (10); Mosallam and Banerjee, 2007 (11)). A number of FEM numerical models could successfully simulate the nonlinear performance of such beams strengthened with CFRP (Rangan,

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1998 (12); Zhang and Hsu, 2005 (13); Al-Tersawy, 2013 (2); Hamed et al., 2019 (7)). Recently, design codes, specifications, and guidelines have considered design equations for strengthening of RC elements (JSCE, 2001 (14); CSA-S806-02, 2002 (15); ACI Committee 440, 2008 (16)).

Although the past research work clearly illustrated the significant effect of using CFRP technique in strengthening and retrofitting of RC elements, its effect on beams with low strength concrete is not well studied specially for shear failure mechanism (Bousselham and Chaallal, 2004 (4); Al-Tersawy, 2013 (2)). Therefore, the current research work is mainly focusing on enhanced mechanism of shear failure of reinforced concrete beams with low-strength concrete strengthened with strips of CFRP.

In this experimental study, ten RC beams (150 mm * 300 mm * 2000 mm) were cast and tested for shear. The concrete compression strength were considered as 15 MPa (low strength), and 25 MPa (common design value) to check its effect on rate of improvement due to the use of CFRP strips vertically (90°) or inclined (45°). The web reinforcement amount was kept constant (5 Ø 8/m), and main bottom reinforcement was considered as 3Ø12 or 5Ø12. For few specimens, bottom longitudinal layers (one or two layers) of CFRP were placed in addition to vertical strips to check its effect on failure mode. Finally, the experimental shear test results were compared to the values estimated according to the provision of the Egyptian code for fiber reinforced polymers (ECP208) (1).

2. Experimental Procedure

Ten RC beams considered in this current study were cast with constant length as 2000 mm and same cross-section dimensions of 150 mm and 300 mm in width and in height respectively as shown in Figure 1 and Figure 2. CFRP strips (U-shape) with 100 mm in width, and clear spacing of 100 mm were bonded to the outer side and bottom faces of beams, vertically at (90-degree) and inclined at (45-degree). All beams were experimentally tested by three-point loading considering shear span of 900 mm and beam depth of 250 mm (a/d= 3.6).

3. Construction Materials

3.1. Concrete

Two mix proportions of concrete were designed to get low-strength concrete of 15 MPa and normal one of 25 MPa. The experiments were carried out, 28 days after casting day. The proportions of used concrete mix are shown in Table 1.

3.2. Steel reinforcement

Domestic steel bars were used for flexural and shear reinforcements. High grade deformed bars (36/52) with 12 mm in diameter was considered for flexural top and bottom longitudinal reinforcement, while mild smooth steel bars (24/36) were considered for shear reinforcement as stirrups.

3.3. CFRP

In this research, the CFRP sheets produced by BASF Company called Master Brace FIB 300/50 (Technical of Data of Basf Wrap sheets) were used for RC beams strengthening. The CFRP sheet is 0.166 mm in thickness. The mechanical and physical properties of used products are shown in Table 2.

The epoxy resin used to bond CRFP to RC surface in this experiment was Master Brace FIB 300/50 (Technical of Data of Basf DUR-300). The manufacturer stated the minimum compressive strength, shear strength, tensile strength and bond strength to steel after ten days are 85, 16, 26 and 21 MPa. The bond strength to the concrete surface was equal to the concrete failure strength.

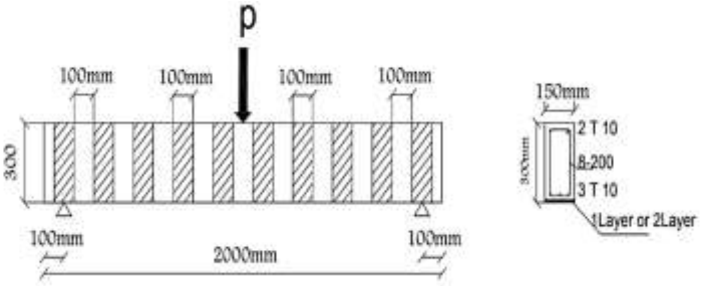

Figure 1: Strengthened RC beams with vertical strips and bottom layers of CFRP

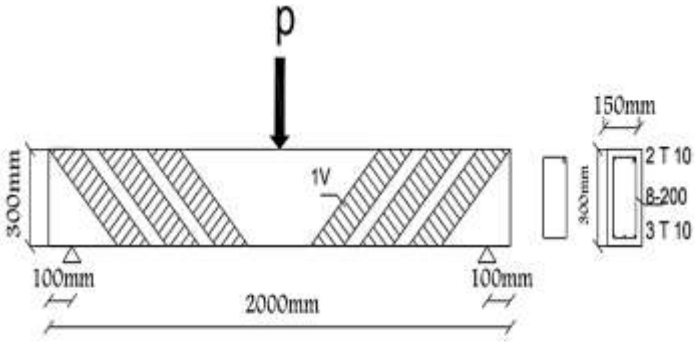

Figure 2: Strengthened RC beams with inclined strips of CFRP

Table 1: Sample Table

Material	25 MPa strength	15 MPa strength
Cement	300 kg	200 kg
Water	200 liter	200 liter
Fine Aggregate (Sand)	670 kg	720 kg
Coarse Aggregate (Dolomite Size No 1)	565 kg	565 kg
Coarse Aggregate (Dolomite Size No 2)	565 kg	565 kg
Super-Plasticizer	3 liter	2 liter

Table 2: CFRP Mechanical and Physical properties

Master Brace® FIB 300/50 CFS	
Density	1.82 g/cm^3
Thickness	166 µm (According to content of fiber)
Area-density	300 g/m^2 ±10 g/m^2 (carbon fibers only)
Tensile strength	4900 N/mm^2
Modulus of Elasticity in Tension	230 kN/mm^2
Elongation at Break	2.1%

4. Shear specimens classifications

Two specimens were considered as control beams without CFRP, (B1-control-15, and B7-control-25) by changing only the concrete compression strength (15 MPa, and 25 MPa), and bottom longitudinal reinforcement (3Ø12, and 5Ø12) respectively.

The remaining eight specimens have been strengthened by using vertical or inclined strips of CFRP. To make the performance comparison judgmental, the ten specimens were classified into 6 groups as mentioned in Table 3.

Table 3: CFRP Mechanical and Physical properties

Groups	Beam code	Fcu (MPa)	As	Stirrups	Wrapping scheme	FRP angle
1	B1-control-15	15	3 Ø12	8–200 mm	---	---
	B2-1V-15	15	3 Ø12	8–200 mm	partial	90º
	B3-1V-1L-15	15	3 Ø12	8–200 mm	partial	90º
	B4-1V-2L-15	15	3 Ø12	8–200 mm	partial	90º
	B5-1I-15	15	3 Ø12	8–200 mm	partial	45º
2	B7-control-25	25	5 Ø12	8–200 mm	---	---
	B8-1V-25	25	5 Ø12	8–200 mm	partial	90º
	B9-1I-25	25	5 Ø12	8–200 mm	partial	45º
3	B6-1V-15	15	5 Ø12	8–200 mm	partial	90º
	B8-1V-25	25	5 Ø12	8–200 mm	partial	90º
4	B5-1I-15	15	3 Ø12	8–200 mm	partial	45º
	B10-1I-25	25	3 Ø12	8–200 mm	partial	45º
5	B2-1V-15	15	3 Ø12	8–200 mm	partial	90º
	B6-1V-15	15	5 Ø12	8–200 mm	partial	90º
6	B9-1I-25	25	5 Ø12	8–200 mm	partial	45º
	B10-1I-25	25	3 Ø12	8–200 mm	partial	45º

1V: Vertical CFRP U- strips (one layer).
1L: longitudinal bottom CFRP strip (One Layer)
1I: Inclined CFRP U- strips (45o one layer)
2L: longitudinal bottom CFRP strip (Two Layer)

The main target for this research is to elaborate the enhanced performance of low strength concrete beams strengthened by using CFRP at different orientations 90° as shown in Figure 3 and 45° as shown in Figure 4. The tests are also devoted to examine how concrete strength and amount of reinforcement affect the performance of these RC beams.

Figure 3: Beams with vertical CFRP sheets

Figure 4: Beams with inclined CFRP sheets

5. Test setup

All RC beams were tested and loaded at three-points by using UTM at the Concrete Research Laboratory (CRL) of Cairo University. The beams were loaded up to major collapse under a constant loading rate of (10 kN/min). At mid-span, LVDT was placed at bottom surface of beams to measure the mid-span deflection as shown in Figure 5.

Figure 5: Control beam test

6. Experimental results and discussions

The focus of the current experimental program is to measure deflection and load carrying capacity at mid-span of beams, and to clearly illustrate failure crack pattern for each beam. For most of the tested RC beams, shear failure was dominant, while those strengthened using inclined strips of CFRP sheet failed in flexure. Table 4 summarizes the experimental results including maximum deflection, load, and failure mode for the RC beams considered in this research study.

The failure modes of both beams (B1-control-15) and (B7-control-25) were shear failure as shown in Figure 6 and Figure 7. At loads of 78.0 kN and 90.0 kN, shear cracks started in both beams respectively. Shear cracks propagated at middle of shear span. Beams were loaded up to failure at 82.4 kN and 120.0 kN, respectively.

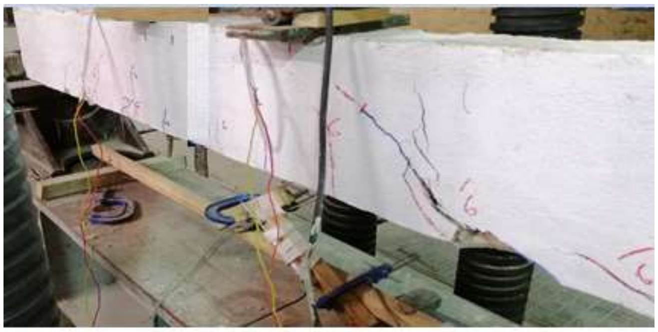

Figure 6: Tested RC beam (B1-control-15)

Figure 7: Tested RC beam (B7-control-25)

Low strength beams (B2-1V-15) and (B3-1V-1L-15) with vertical CFRP strips concrete (15 MPa) beams, the failure modes were still failed in shear with no significant effect for bottom CFRP layers (failure loads were 106, and 102.4 kN, respectively) as shown Table 4. CFRP strips were stiff enough to be ruptured but it was peeled out with a thin layer of concrete cover as shown in Figure 8 and Figure 9.

Figure 8: Tested RC beam (B2-1V-15) shear failure

Figure 9: Tested RC beam (B3-1V-1L-15) shear failure

Table 4: Experimental results of all tested beams

Groups	Beam code	Fcu (MPa)	As	Pu (kN)	Diff. Load %	Δu (mm)	Failure
1	B1-control-15	15	3 Ø12	82.4	-	7.7	Shear
	B2-1V-15	15	3 Ø12	106.0	29	10.0	Shear
	B3-1V-1L-15	15	3 Ø12	102.4	24	8.3	Shear
	B4-1V-2L-15	15	3 Ø12	103.7	26	8.0	Shear
	B5-1I-15	15	3 Ø12	151.7	84	13.4	Flexural
2	B7-control-25	25	5 Ø12	120.0	-	7.9	Shear
	B8-1V-25	25	5 Ø12	153.7	28	7.4	Shear
	B9-1I-25	25	5 Ø12	218.6	82	22.2	Flexural
3	B6-1V-15	15	5 Ø12	138.5	-	6.0	Shear
	B8-1V-25	25	5 Ø12	153.7	11	7.4	Shear
4	B5-1I-15	15	3 Ø12	151.7	-	13.4	Flexural
	B10-1I-25	25	3 Ø12	186.4	23	18.8	Flexural
5	B2-1V-15	15	3 Ø12	106.0	-	10.0	Shear
	B6-1V-15	15	5 Ø12	138.5	31	6.0	Shear
6	B10-1I-25	25	3 Ø12	186.4	-	18.8	Flexural
	B9-1I-25	25	5 Ø12	218.6	17	22.2	Flexural

1V: Vertical CFRP U- strips (one layer).
1L: longitudinal bottom CFRP strip (One Layer)
1I: Inclined CFRP U- strips (45o one layer)
2L: longitudinal bottom CFRP strip (Two Layer)

Using inclined CFRP strips in low strength concrete beams (15 MPa) resulted in a dominant change in failure mode to be flexural failure. Failure mode of beam (B5-1I-15) has no clear deboning of CFRP strips at failure. This beam failed at 151.7 kN (Table 4) as flexural, in Figure 10.

Figure 10: Tested RC beams (B5-1I-15) flexural failure

The failure modes of RC beams (B9-1I-25, and B10-1I-25) with normal concrete compressive strength of 25 MPa and strengthened with inclined CFRP strips were clear ductile flexure with significant enhancement in beam carrying capacity considering change in amount of main bottom reinforcement as shown in Figure 11 and Figure 12 respectively. As main reinforcement increases from 3Ø12 to 5Ø12, the beam load capacity increases from 186.4 kN to 218.6 kN as shown Table 4.

Figure 11: Tested RC beams (B9-1I-25) flexural failure

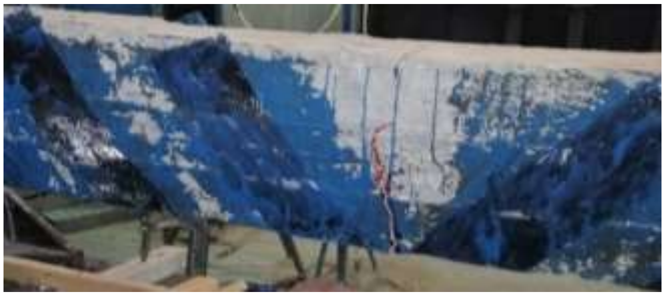

Figure 12: Tested RC beams (B10-1I-25) flexural failure

For RC beams with low strength (15 MPa) and longitudinal reinforcement 3Ø12, the wrapping arrangement effect was studied for five specimens B1-control-15 (without strengthening), B2-1V-15 (U shape), B3-1V-1L-15 (U shape with one bottom layer), B4-1V-2L-15 (U shape with two bottom layers) and B5-1I-15 (45 degree). Figure 13 shows deflection results for these beams. The recorded ultimate load obtained was equal to 82.4 kN, deflection value of about 7.7 mm for the control beam B1-control-15 where shear failure occurred in this beam.

Using vertical CFRP strips (B2-1V-15), the ultimate load increased by 29%, deflection value was 10 mm and failure mode was shear. In addition, using one or two bottom layers of CFRP (B3-1V-1L-15) and (B4-1V-2L-15), the ultimate load increased by 24% and 26%, respectively at deflection values of 8.3 mm and 8 mm. Using a number of bottom layers of CFRP does not give a significant change for strengthened beams shear capacity. Therefore, applying inclined strips of CFRP at 45 degrees (B5-1I-15) resulted in flexure failure with major enhancement for the ultimate capacity load by 84% comparing to the control one, and deflection value was 13.4 mm.

Beams strengthened using vertical strips of CFRP failed in shear, while those strengthened sing inclined strips of CFRP failed mainly in flexure. This was due to significant effect of inclined fibers on increasing shear capacity of RC beams.

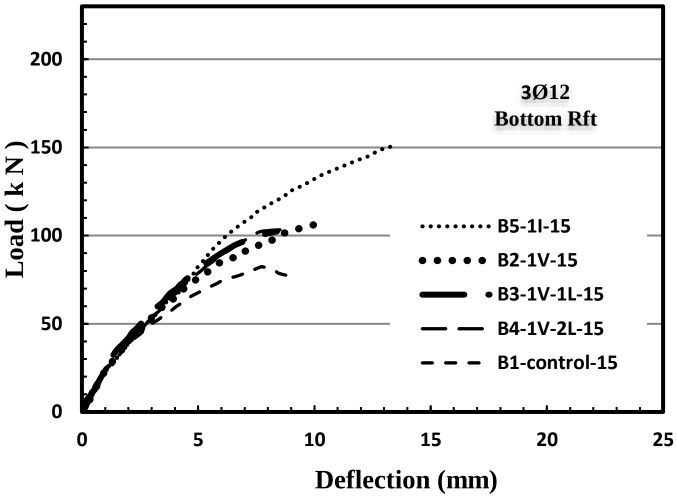

Figure 13: Specimens Load–deflection with different CFRP arrangements (Group 1)

For RC beams with strength of 25 MPa (common design value), longitudinal main reinforcement was considered for all beams as 5Ø12. The wrapping arrangement effect was studied for three specimens B7-control 25, B8-1V-25 (U-wrapping), and B9-1I-25 (45 degree). The mid-span deflection values for these beams are illustrated in Figure 14. For control beam (B7-control 25), the ultimate carrying load was 120 kN, with corresponding deflection value of 7.9 mm and the mode of failure was mainly shear. Using vertical CFRP strips (B8-1V-25), ultimate load enhanced by 28% and corresponding deflection value was 7.4 mm. Using inclined CFRP strips at 45 degrees (B9-1I-25) resulted in flexural failure mode with improved ductility. The ultimate load value increased by 82% relative to that of control beam and the deflection value was 22.2 mm. This was due to major effect of the inclined strips of CFRP in increasing shear capacity.

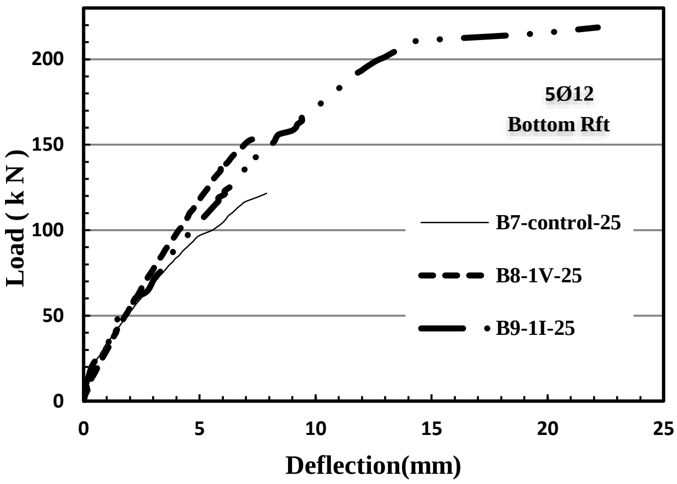

Figure 14: Specimens load–deflection with different CFRP arrangements (Group 2)

For RC beams with Longitudinal Rft 5Ø12 and vertical CFRP strips, the effect of concrete strength (15 MPa, 25 MPa) was studied for two specimens (B6-1V-15) and (B8-1V-25). The experimental deflection results for these beams are illustrated in Figure 15. The ultimate load carried by the low strength beam (B6-1V-15) was 138 kN and the corresponding deflection value was 5.9 mm, while the ultimate load carried by the normal strength beam (B8-1V-25) was 11% above this value at corresponding deflection of 7.4 mm. Both beams have had flexure failure due to the positive effect of CFRP inclination.

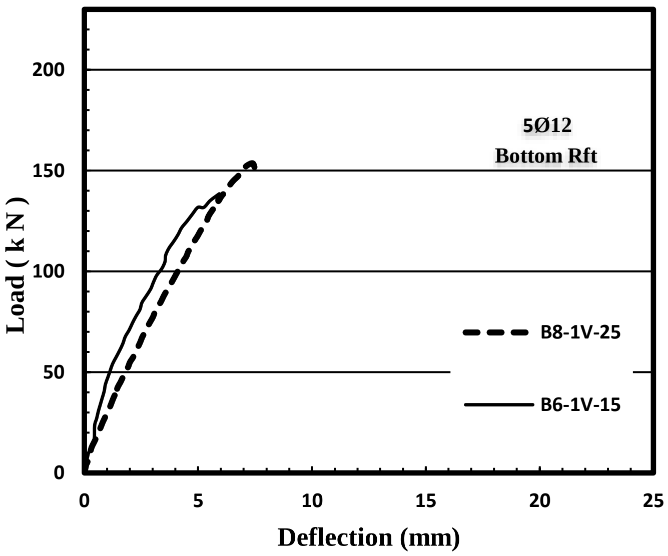

Figure 15: Specimens Load–deflection with different concrete strengths (Group 3)

For RC beams with Longitudinal Rft 3Ø12 and inclined CFRP strips, the effect of concrete strength (15 MPa and 25 MPa) was studied by two specimens B5-1I-15 and B10-1I-25, respectively. The ultimate load carried by the low strength beam B5-1I-15 was 151.0 kN and the corresponding deflection value was 13.4 mm, while the ultimate load carried by the normal strength beam B10-1I-25 was 23% higher than that of beam B5-1I-15 and the corresponding deflection value was 18.8 mm as shown in Figure 16. For both beams, the failure modes were flexure due to the significant impact of using inclined CFRP strips.

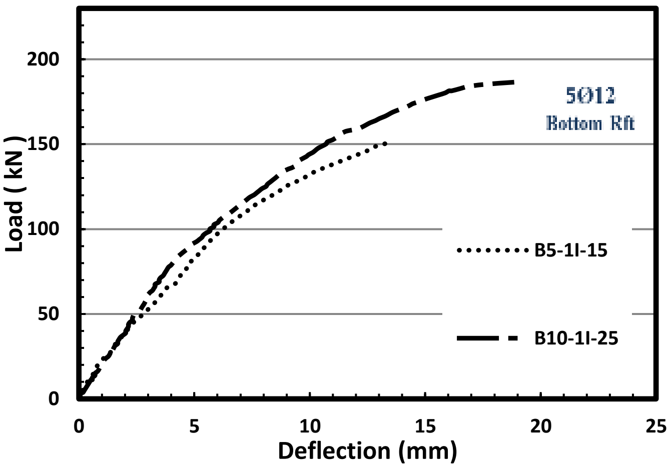

Figure 16: Specimens Load–deflection with inclined CFRP and different concrete strengths (Group 4)

For RC beams with low strength (15 MPa) and vertical CFRP strips, the effect of amount longitudinal Rft was studied for two specimens B2-1V-15 and B6-1V-15. The ultimate load carried by the less Rft beam B2-1V-15 with 3Ø12 bottom Rft was 106 kN and the corresponding deflection value was about 10 mm, while the ultimate load carried by the higher Rft beam B6-1V-15 with 5Ø12 bottom Rft was 31% higher than that of the beam with 3Ø12 and the corresponding deflection value was 6 mm as shown in Figure 17. Both beams failed in shear.

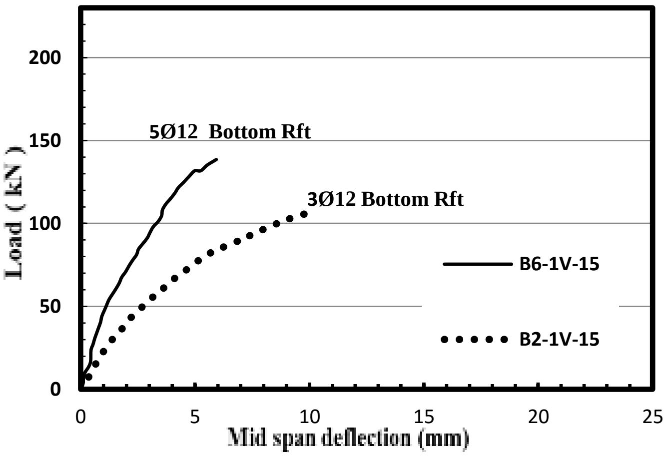

Figure 17: Load–deflection of low strength beams with different Rft ratio (Group 5)

For RC beams with strength 25 MPa and inclined CFRP strips, the effect of amount longitudinal Rft was studied for by specimens B10-1I-25 and B9-1I-25. The ultimate load carried by the beam B10-1I-25 with 3Ø12 was 186.4 kN and the corresponding deflection value was 18.8 mm, while the ultimate load carried by the higher Rft beam B9-1I-25 with 5Ø12 increased by 17% and corresponding deflection value was about 22.2 mm as shown in Figure 18. Both beams failed in flexure, while the improvement in performance is evident by increasing concrete strength, change of fiber alignment from vertical to inclined, and the increase in amount of main Rft.

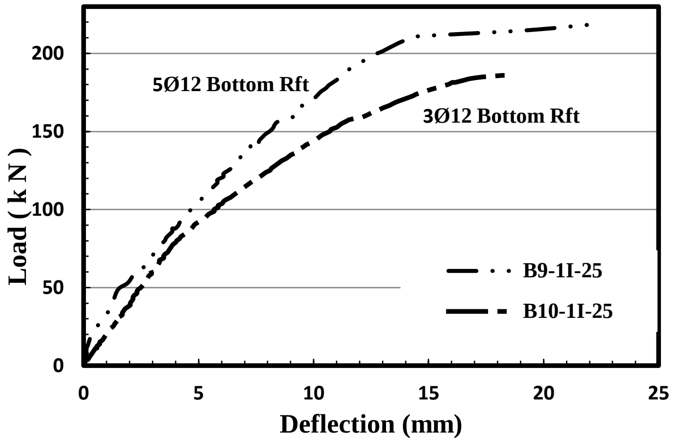

Figure 18: Load–deflection of normal strength beams with different Rft ratio (Group 6)

7. Comparison of results with Design Codes

The load capacities of the experimental work were compared to those estimated and calculated according to the Egyptian code for design (ECP 208., 2005) (1). Generally, for the beams strengthened with CFRP, the results showed that the ECP could be applied safely to estimate ultimate carrying capacities of beams strengthened with strips of CFRP. In this research partially wrapping technique around three sides of the member was used. Figure 19 illustrate the required variables for the calculations of shear strength.

Material strength reduction factor, γf depends on the system of shear strengthening for wrapping CFRP. Except as otherwise indicated, the γf value is:

$$\gamma_f = 1.5 \text{ for full wrapping arrangement} \quad (1)$$

$$\gamma_f = 1.6 \text{ for partially wrapped arrangement} \quad (2)$$

The nominal shear strength mentioned in the ECP 208 code of the enhanced concrete member:

$$q_u = 0.5 q_{cu} + q_{su} + q_{fu} \quad (3)$$

Where:

q_{su} Nominal reinforcement steel shear strength

q_u Nominal applied shear strength

q_{fu} Nominal CFRP shear strength

q_{cu} Nominal concrete shear strength

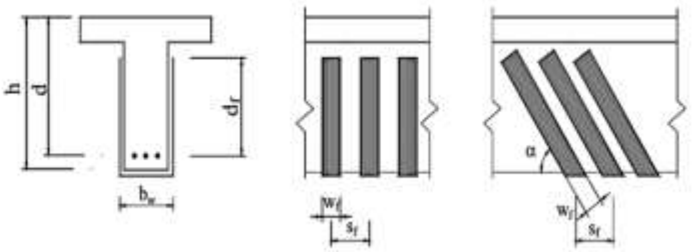

Figure 19: Variables used FRP strengthening evaluation (ECP 208., 2005)

The maximum nominal shear strength is estimated from:

$$q_{umax} = 0.7\sqrt{\frac{f_{cu}}{\gamma_c}} < 3\ MPa \quad (4)$$

The nominal shear strength for concrete is given by:

$$q_{cu} = 0.24\sqrt{\frac{f_{cu}}{\gamma_c}} \quad (5)$$

Where:

f_{cu} is the concrete compressive strength

γ_c is concrete strength reduction factor (1.5)

The nominal reinforcing steel shear strength:

$$q_{su} = \frac{A_{st}}{b \cdot s}\left(\frac{f_y}{\gamma_s}\right) \quad (6)$$

Where:

b is the RC beam width.

A_{st} is the area of stirrup steel

f_y is the stirrup steel yielding stress

γ_s is the steel strength reduction factor (1.15)

s is the stirrups spacing.

The nominal FRP shear strength:

$$q_{fu} = A_f (E_f \varepsilon_{ef} / \gamma_f)(\sin\ \alpha + \cos\ \alpha)\frac{(d_f/d)}{(s_f \times b_w)} \quad (7)$$

$$A_f = 2 n t_f w_f \quad (8)$$

Where:

A_f is the area of FRP external reinforcement and E_f is the FRP tensile modulus of elasticity.

ε_{ef} is the effective strain in FRP reinforcement and γ_f is the reduction factor of FRP.

α is the angle of inclination of FRP, and d is the effective depth of the concrete section.

d_f is the depth of FRP shear reinforcement.

s_f is the distance between the centerlines of the strips.

b_w is the width of the concrete section, and n is the number of plies of FRP reinforcement.

t_f is the nominal thickness for FRP, and w_f is the width of the FRP reinforcing plies.

n is the number of plies of FRP reinforcement.

The effective strain for partial wrapping is calculated from the equations below:

$$\varepsilon_{ef} = k_v \varepsilon_{ju}^{*} \leqslant 0.004 \quad (9)$$

$$L = 23.300/\left(n t_f E_f\right)^{0.58} \quad (10)$$

$$k_\nu = k_1 k_2 L_e/\left(11{,}900\varepsilon_{fu}^{*}\right) \leqslant 0.75 \quad (11)$$

Le is the active bond length.

$$k_1 = (f_{cu}/33.75)^{2/3} \quad (12)$$

$$k_2 = \left(d_f - L_e\right)/d_f \quad \textit{(Three-sided wrap)} \quad (13)$$

Le is the active bond length.

$$k_2 = \left(d_f - 2L_e\right)/d_f \quad \textit{(Tow-sided wrap)} \quad (14)$$

The tested beams load carrying capacities are estimated according to the provisions of code (ECP., 2005) (1) Table 5 shows a comparison analytical load and the experimental results study.

Table 5: The experimental results compared with calculated ones for beams strengthened with CFRP strips.

Beam No	F_{cu} (MPa)	A_s	P_u ECP 208-05	Pu experimental	Diff. Load %
B2-1V-15	15	3 Ø12	104.3	106.0	1.6
B5-1I-15	15	3 Ø12	122.5	151.7	22.4
B8-1V-25	25	5 Ø12	131.4	186.4	41.9
B10-1I-25	25	3 Ø12	145.2	218.6	50.6

For RC beams; with low strength (15MPa) and longitudinal reinforcement 3Ø12, B2-1V-15 and B5-1I-15, their results were close to those of ECP 208-05 (1) (1.6%, and 22.4%) respectively. While for RC beams; with strength of 25 MPa (normal strength of concrete) B8-1V-25 and B10-1I-25 (41.9%, and 50.6%) respectively. The results are higher than ECP 208-05 (1) the comparison shows that the ECP code is conservative in estimating the load capacity of strengthened beams, especially for normal strength concrete.

8. Conclusions

Several significant factors affecting the RC beam shear Capacity were considered in this experimental study these include concrete characteristic compression strength, amount of main reinforcement, and CFRP strips based on experimental results of the current research, the following conclusions would be mentioned:

1. Increasing amount of main Rft and/or concrete compression strength increases the RC beams shear capacity.
2. Strengthening with vertical strips of CFRP increasing shear capacity by 26%, and resulted in shear failure mode.
3. Strengthening using inclined strips of CFRP increasing the capacity of beams by 83%, and resulted in flexural failure mode.
4. The effect of having low in existing RC beams can be compensated by applying with inclined strips in the shear zone. This leads to significant enhancement in the shear capacity and the mode failure.
5. Dominant failure mode for specimens with vertical CFRP strips was peeling of the strips ends out of the concrete surface. This can be avoided by using inclined strips.
6. ECP 208-05 (1) can be used safety in estimating low strength concrete RC beams shear capacity. The code provision is very conservative for normal strength concrete beams.
7. The inclined CFRP strip has a major positive effect on ultimate ductility (deflection) of beams comparing with vertical CFRP strips because of developed shear cracks.
8. Using more than one CFRP layer doesn't affect the ultimate capacity, neither the maximum displacement in case of low compressive strength.

According to these research work conclusions, some research points may be recommended for future works. Loading patterns other than discussed in this research such as cyclic load, Effect of opening, and varied span/depth ratio may be considered for studying the behavior of low strength RC beams. It is recommended to do future research experiments using different product type of CFRP.

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