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ULTIMATE SHEAR OF REINFORCED CONCRETE BEAMS STRENGTHENED BY BONDED CARBON FABRICS

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SUMMARY: This paper presents the behaviour of reinforced concrete beams strengthened with externally bonded carbon fiber reinforced polymer fabrics. A total of eight reinforced concrete with or without composite carbon fabrics beams have been tested in a load system by a point load at one-third of the clear span. The major test variables are the strengthening surface and the spacing between the stirrups. The variation of the ultimate shear force, the deflection and the strains in both stirrups and CFRP fabrics are analyzed. The results indicate that the ultimate strength of the beam increases with an increase of strengthening surface. As decreasing the spacing between the stirrups, the composite fabric contribution to shear capacity of strengthened reinforced concrete beams increases. The trends of variation of deflection and strain in longitudinal steel rebar are similar. Almost all the beams failed in shear but the beams strengthened by composite fabrics at a depth of the beam failed in flexure. After analysing the experimental results, an analytical model to predict the shear contribution of the strengthened RC beam is proposed in this work. The values obtained by the analytical model have shown a close agreement to experimental results.

KEYWORDS: Carbon Fibre, Beam, Shear, Strengthening, Concrete.

INTRODUCTION

Reinforced concrete (RC) beams in general fail in two types: flexural failure and diagonal tension (shear) failure. The shear failure of the RC beam is sudden and brittle in nature. It is less predictable and, because it gives no advance warning prior to failure, it is more dangerous than that the flexural failure. It is why the RC beam must be designed to develop its full flexural capacity to assure a ductile flexural failure mode under extreme loading.

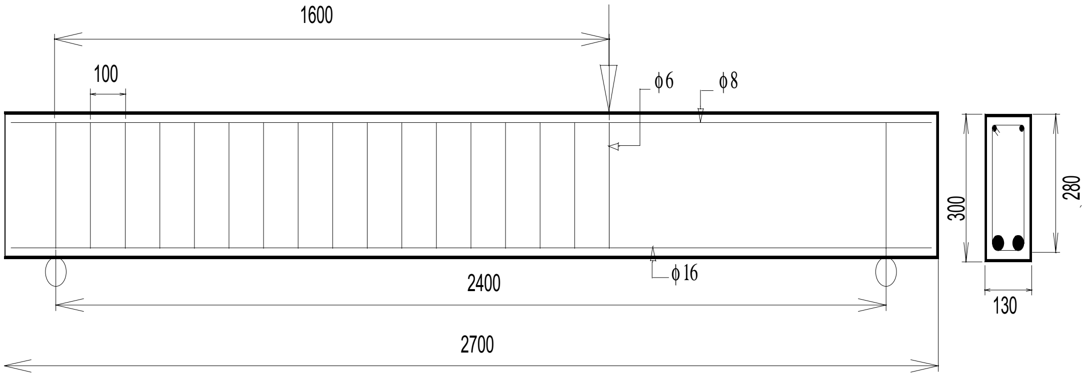


Fig.1 Test reinforced concrete beam geometry (dimension in mm)

Although the probability that structures will be shear deficient is low, failures have occurred due to a variety of factors: mistakes in design calculations and improper detailing of shear reinforcement, construction faults or poor construction practices, charging the function of a structure from a lower service load to a higher service load, and, reduction in or total loss of shear reinforcement steel area causing the corrosion in service environments.

Carbon fibre reinforced polymer (CFRP) materials are being used increasingly in construction. Many studies [1-5] have shown that CFRP materials are an excellent option to be used as external reinforcing because of their high tensile strength, light weight, high fatigue strength, non corrosion, high durability, easy of application in the field and low maintenance cost. Compared to work on strengthening for bending, the studies in the field of CFRP plate bonding for the strengthening in shear have been limited [6-10]. Many published reports shown that the externally bonded CFRP reinforcement can be used to enhance the shear capacity of the beams. The performance of externally bonded CFRP can be improved significantly.

In this work, an analytical model is proposed to predict the ultimate shear strength of RC beams strengthened by bonded carbon fabrics on the lateral surface of the beam. In the literature, numerous theoretical models have been proposed to predict the shear capacity of strengthened RC beam. They consider that the total contribution of the shear capacity of the strengthened RC beam can be obtained by the superposition of three shear strengths: shear strength due to concrete, shear strength due to steel reinforcement and the shear reinforcement due to the composite fabrics. However, the results obtained by the tests in this work have not given this conclusion.

In fact, ultimate shear capacity of strengthened reinforced concrete beam depends principally on a number of factors including compressive strength of concrete, yield strength of shear reinforcement, yield strength of longitudinal rebars, tensile reinforcement ratio, shear span to depth ratio, strength of composite fabrics, composite fabrics shear reinforcement ratio and area of the composite fabrics. The objectives of this experimental program are to investigate the effectiveness in terms of stirrup span to depth ratio influence on shear capacity of strengthened reinforced concrete beams. The study also aims to investigate the variation of composite fabric depth and the tensile reinforcement ratio influences on shear capacity of strengthened RC beam. A total of ten reinforced concrete beams and strengthened reinforced concrete beams varying CFRP depth and spacing between stirrups longitudinal steel reinforcement diameter were investigated in this work. The results of tests on these beams are compared with those of control beams not strengthened with CFRP materials. Furthermore, an analytical expression to predict the CFRP contribution to shear capacity of strengthened reinforced concrete beams is proposed.

EXPERIMENTAL PROGRAM

Two series of strengthened reinforced concrete beams were tested and analyzed. All beams were monotonically loaded by a point load at one third of the clear span. The RC beams were designed to have a deficiency in shear capacity; thus, shear failure was the dominant mode of failure. The RC beams were strengthened in shear with epoxy-bonded CFRP fabrics attached on the two vertical sides in the short span of the beam. The RC beams had a cross section 130-mm wide, 300-mm deep and 2700 mm long. Longitudinal reinforcement consisted of two 16 mm diameter high tension steel rebars in the bottom and two 8 mm diameter rebars in the top of the beam. The web reinforcement consisted of 6-mm diameter closed stirrups, spaced 100 mm center-to center throughout the two third of the span (fig.1).

RC beams were designed to have a deficiency in shear capacity; thus, shear failure was the dominant mode of failure. The spacing between stirrups in short shear span region was varied from 800 mm to 200 mm (fig. 2). Yield strength of longitudinal steel rebars was 550 MPa. The RC beams were strengthened in shear with epoxy-bonded CFRP fabrics attached on the two lateral sides in the short span of the beam. The strengthening surface of CFRP fabrics in shear was varied between 800x150 (mm^2), 800x225 (mm^2) and 800x280 (mm^2) (fig. 2). The values 150 mm, 225 mm and 280 mm correspond to the strengthening depth of the beam section d/2, 3d/4 and the effective depth d, respectively.

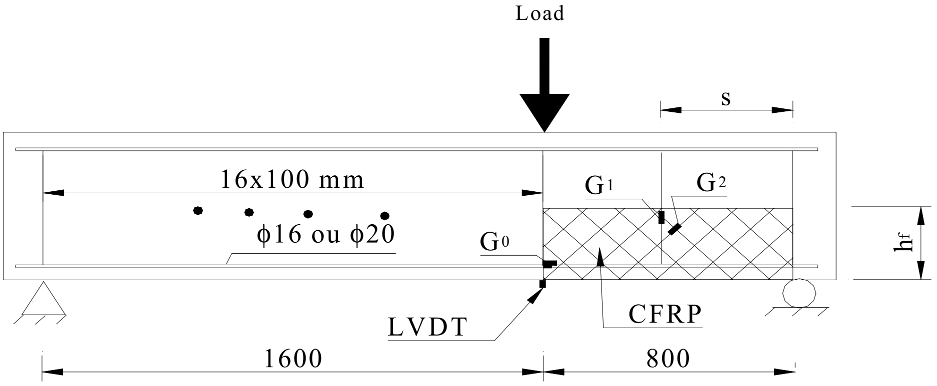


Fig.2. Test reinforced concrete beam geometry (dimension in mm) (h$_f$= 0, 150, 225, 280 mm and s= 800, and 200)

Carbon composite fabrics made up of fibres oriented at 45/135 deg from the longitudinal axe, with an equal distribution of fibres in each direction were employed. The thickness of the fabrics was 1.5 mm. The tensile strength measured on the specimen of the fabrics oriented at 45/-45 deg from the longitudinal axe was 209 MPa and the tensile modulus was 15 GPa. The tensile strength measured on the specimen of the fabrics oriented at the fiber direction was 470 MPa and the tensile modulus was 42.4 GPa.

In order to know the strains developed in the beam during the test, strain gauges were mounted on the longitudinal steel bar surface at the location of one-third of the length. Strain gauges were also mounted on the CFRP fabric surface and on stirrup surface in vertical direction. After mounting, the strain gauges were covered with a protective coating to prevent damage. A linear voltage differential transducer (LVDT) was used to monitor the vertical deflection at one-third span of the beam. The beam was incrementally loaded up to failure. For each increment of the load, the strain in steel bar, in steel stirrup and in composite fabrics and the maximal deflection of the beam were recorded by means of an automatic data acquisition system.

ULTIMATE FORCE

The RC beam dimension, the composite fabric area, the values of ultimate force and the corresponding contribution of composite fabric reinforcement are presented in table 1. Beam B_{00} is the control RC beam of a series of four beams with spacing between stirrups 800 mm and the steel bar diameter 16 mm. Beams B_{01}, B_{02} and B_{03} are the RC beams strengthened by the composite fabrics with area 0.8x0.15 m^2, 0.8x0.225 m^2 and 0.8x0.28 m^2, respectively. Beam B_{20} is the control RC beam for a series of four beams with two longitudinal bar diameter 16 mm and spacing between stirrups 200 mm. Beams $B_{21,}$ B_{22} and B_{23} are the RC beams strengthened by the composite fabrics with the area 0.8x0.150 m^2, 0.8x0.225 m^2, 0.8x0.280 m^2, respectively.

For the series of the beams B_{0x}, table 1 shows that by increasing the strengthening composite fabric area or composite fabric depth from 0, 150mm, 225mm to 280mm, the ultimate force of the RC beam is increased from 41kN, 65kN, 88kN to 85kN, respectively. It can be seen that for a beam strengthened by composite fabrics at three fourth depth of the beam, the ultimate strength increases two times more than that of the control beam. It must be also noted that the ultimate forces for the beam B_{02} and B_{03} are almost identical. The control beam B_{00}, the strengthened beams B_{01} and B_{02} fail as a result of shearing failure in the concrete. However, the beam B_{03} fails in flexion. This result indicated that the resistance in shear has been strengthened enough with a three fourth depth of beam in short span. Therefore, the strengthened area up to the depth of the beam gives an advantage of safety on the shear resistance of the beam.

Table 1: Dimension and the ultimate force of strengthened reinforced concrete beams

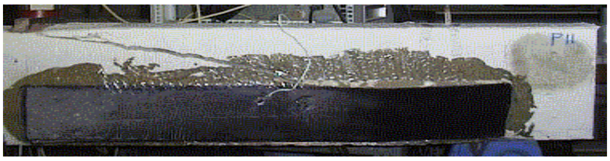
RC beam	Steel bar Diameter (mm)	Spacing of the stirrups (s) (mm)	CFRP Depth (mm)	Ultimate force (kN)
B_{00}	16	800	0	41
B_{01}			150	65
B_{02}			225	88
B_{03}			280	85
B_{20}	16	200	0	61
B_{21}			150	76
B_{22}			225	88
B_{23}			280	87

For the series of beams B_{2x}, table 1 shows also that increasing the composite fabric depth from 0, 150mm, 225mm and 280mm, the ultimate force of the RC beam is increased from 61kN, 76kN, 88kN and 87 kN, respectively. The test results show that the effect of reinforcement by bonded composite fabrics on the ultimate strength is less important in comparison with the series of the beams B_{0x}. For a beam strengthened by composite fabrics at three fourth depth of the beam B_{22}, the increased ultimate force by strengthening is about 27kN against 47kN in the case of beam $B_{02.}$ It is obvious that the effectiveness of external reinforcement is reduced. From the table 1, it also can be seen that the value of ultimate force of the control beam B_{20} is greater than that of the control beam B_{00}. This difference is due to the spacing between stirrups. The spacing between stirrups is 200 mm for the beam B_{20} against 800mm for the beam B_{00}. It is known that the effect of the steel stirrups on the shear resistance of reinforced concrete beam is very important. The test results show that the externally reinforcement effect by strengthening in shear the composite fabrics is not constant. This effect depends greatly on the spacing of the stirrups of the reinforced concrete beam. The ultimate forces for the beam B_{22} and B_{23} are almost identical. Such as the series B_{0x}, the control beam B_{20}, the strengthened beam B_{21} and B_{22} fail as a result of shearing failure in the concrete. The beams B_{23} fails in flexion. This result gives the same results that the shear resistance has been strengthened enough with a three fourth depth of the beam in short span. Therefore, the strengthened area up to the depth of the beam gives not advantage to the ultimate force of the beam.

CRACKS AFTER FAILURE

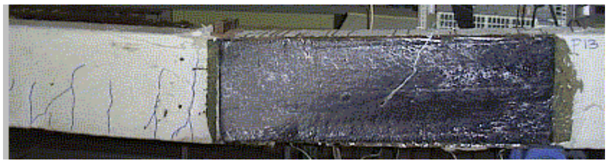
The cracking patterns at the maximum load for reinforced concrete beams as well as strengthened reinforced concrete beams are shown in Fig.3. In beam B_{00}, the shear cracks started at the centre of short shear span. As the load increased, the crack started to widen and propagated towards the location of loading and at the same time towards the location of support along the longitudinal rebars. The cracking patterns show that the angle of critical inclined crack with the horizontal axis is about 45°. For beam B_{01} strengthened by bonded composite fabrics, the shear cracks were more obvious in diagonal direction. The angle of critical inclined crack with the horizontal axis decreased. The angle depends on the short shear span/depth ratio. It's observed from B_{01}, B_{02} and B_{03} that, as the strengthened lateral surfaces increase, the numbers of vertical cracks increase. In the case of that the shear strength of beam after strengthening is enough great, beam B_{03} is failed because of flexion.

Beam B_{00}



Beam B_{01}

Beam B_{02}



Beam B_{03}

Fig.3. Observed cracks of the beams B_{00}, B_{01}, B_{02} and B_{03} after failure

In the series of beams B_{2x}, the failure mode was in a similar manner to that of the series of the beams B_{0x}.

DEFLEXION

Plots of load versus maximum deflection were obtained from the recorded data for the strengthened in shear RC beams B_{01}, B_{02}, B_{03} and the control RC beam B_{00} (fig.4). It can be seen from this figure that for strengthened reinforced concrete beams, as the strengthening area in shear increases, the maximal deflection at the ultimate force increases. Note also that the stiffness of the four beams B_{00}, B_{01} B_{02} and B_{03} are almost identical. The deflections of the beams after cracking increase linearly until the failure of the beams. However, the increasing percentage on the deflexion is reduced with the strengthened area. The maximum deflection value at the ultimate force is 3.7 mm for the beam B_{00}, 6 mm for the beam B_{01}, 8.3 mm for the beam B_{02} and 6.2mm for the beam B_{03}, respectively.

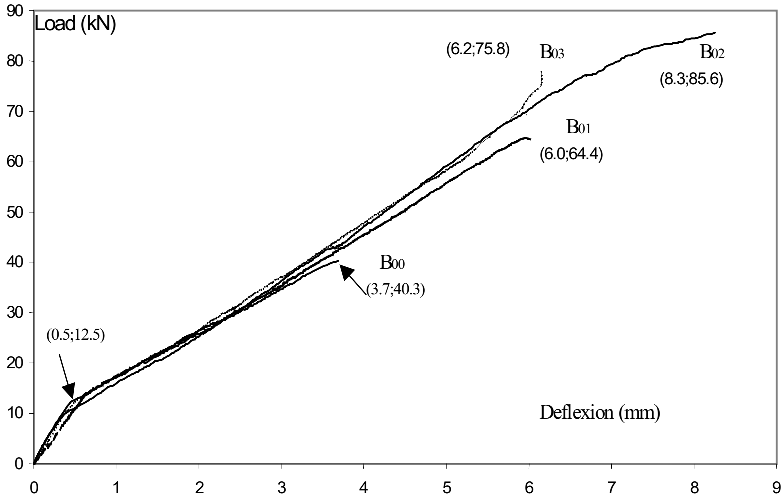


Fig.4. Load plotted against deflexion at the location of one-third length of the beams B_{00}, B_{01}, B_{02} and B_{03}.

Figure 5 shows the load-deflection curves of the control beams B_{20} and the strengthened beam B_{22}. It can be seen from this figure that the stiffness of the beam is slightly improved after strengthening in shear. In comparison with the beam B_{00}, the deflection value of the control beam B_{20} is considerably increased from 3.7mm to 6.3 mm at the ultimate force. The difference is due to the spacing between stirrups of the beam. The deflection value of the strengthened beam B_{22} is found as same as that of the strengthened beam B_{02}, 8.3 mm at the ultimate force. Note also that the effect of strengthening in shear by bonded the carbon fibre fabrics is less important on the beam B_{20} than that on the beam B_{00}.

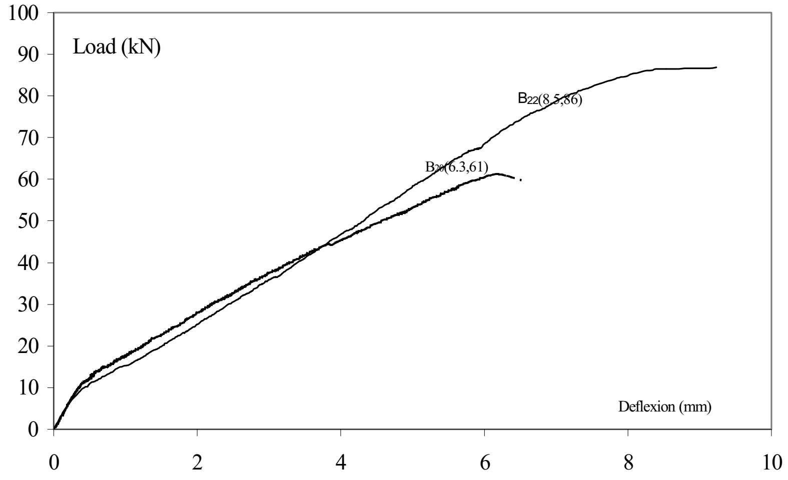


Fig.5: Load plotted against deflexion at the location of one-third length of the beams B_{20}, B_{22}

STRAIN

The strains in stirrup and in composite fabrics are measured in the transversal direction. The load-strain curves obtained by the strain gauge mounted on the stirrup surfaces for the beams

B_{20}, B_{21} and B_{22} are shown in figure 6. Before external reinforcement, the slope of the load-strain curves measured in stirrup of the beam B_{20} increases quickly. After reinforcement, the strains in stirrup of the beams B_{21} B_{22} is almost uncharged before the appearance of the cracks in concrete in shear. The strain value stays very small. The value does not exceed 50 µm/m up to the cracks in concrete. From this value, the strain increases very quickly up to the crushing of the beam. However, the strain measured in stirrup of beam B_{23} increases quickly just after the appearance of the cracks in concrete near a load of about 30 kN.

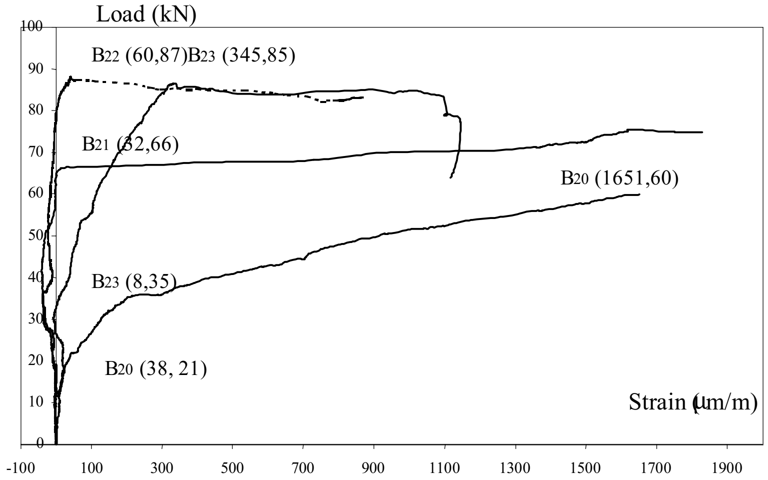


Fig.6: Stirrup strain for beams B_{20}, B_{21}, B_{22} and B_{23}.

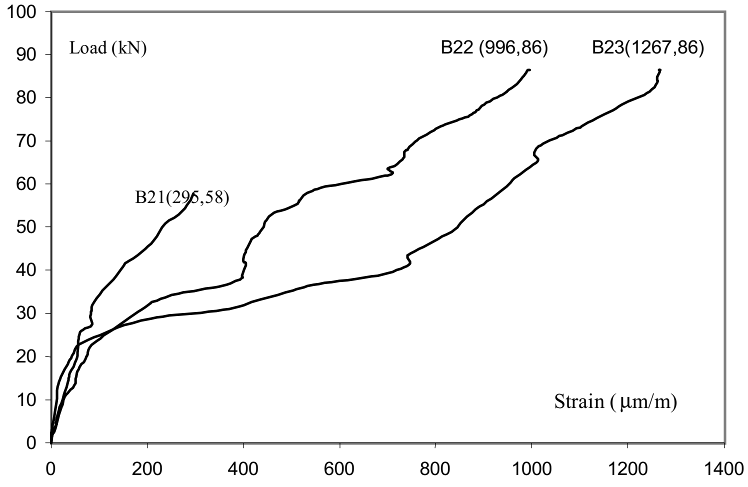


Fig.7: CFRP strain for beams B_{21}, B_{22} and B_{23}

For the strengthened reinforced concrete beams B_{21}, B_{22} and B_{23}, the strains obtained on the CFRP fabric (fig.7) show that by increasing the CFRP fabric depth, the strain develops more quickly at the same loading. It can be seen that the strain in composite fabrics develops faster than that in stirrup during the whole loading.

ESTIMATED SHEAR FORCE

Experimental results shown that the contributions of the CFRP fabrics to shear capacity of strengthened reinforced concrete beam varied with the spacing between the stirrups of the RC beam and the strengthening area on the lateral sides of the RC beam. The total shear strength of strengthened RC beam can be calculated based on shear force V_c due to concrete in absence of the shear reinforcement, the additional capacity due to shear reinforcement V_s alone and the additional capacity due to strengthened external composite reinforcement V_f alone. The concrete shear force V_c and shear reinforcement force V_s can be calculated using Eurocode 2 or ACI design codes.

In this work, the expression to predict ultimate shear stress of RC beams with stirrups used is the model proposed by Russo and Puleri [11]. This model considers the complex interaction between beam, arch and truss resisting mechanism. The expression is given as following:

$$V_u = 0.5bd\left(K_1 K_2 \sqrt[3]{\rho} + \frac{\sqrt{f_c^{'}}}{K_2} \rho_v f_{ye} \right) \qquad (1)$$

Where b = beam width, d = effective depth of cross section of beam, ρ= tension reinforcement ratio (=A_s/bd), ρ_v =stirrups ratio (=A_v/bs), f'_c = compression concrete strength, f_{ye} =yield strength of stirrup reinforcement. The function K_1 and K_2 are given by

$$K_1 = \frac{1}{\sqrt{1 + \frac{d}{25 d_a}}} \qquad K_2 = \sqrt{f_c^{'}} + 250\sqrt{\rho\left(\frac{d}{a}\right)^5}$$

Where d_a is the maximum aggregate size and a is shear span.

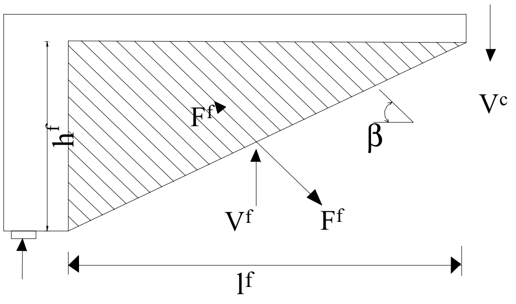


Fig.9. Force in strengthening composite fabrics

Figure 9 shows externally reinforced concrete beam with strengthening carbon fabrics inclined at an angle β. The contribution in shear of composite fabrics can be calculated by following equation:

$$V_f = C \rho_f f_{fe} A_f Sin\beta \qquad (2)$$

Where A_f is the composite fabric area (=$l_f h_f$), ρ_f is the fabric ratio (=2t/b), t is the composite fabric thickness, C is the function taking into account the spacing of stirrup effect, β is the strengthening carbon fabrics inclination with respect to member axis.

The effective CFRP fabric stress, f_{fe}, smaller than its nominal strength, is computed by f_{fe} = R f_{fu}. The reduction coefficient R depends on the CFRP fabric volume ratio and it may be estimated by the following proposed expression:

$$R = \rho_f \frac{A_f}{ad} \tag{3}$$

The proposed expression of C based on the test results is given by:

$$C = \sqrt[3]{\frac{s}{a}} \tag{4}$$

Therefore, the contribution of CFRP reinforcement to shear capacity of the reinforced concrete beam can be estimated by the expression

$$V_f = \sqrt[3]{\frac{s}{a}} \left(\rho_f A_f\right)^2 \frac{f_{fu}}{ad} \sin\beta \tag{5}$$

Table 2 shows that the mean ultimate shear force values measured in tests and calculated using the proposed formula. It is clear that the contribution of the composite fabrics in shear capacity of the RC beam for the shear span 0.8m is different from the shear span 0.2m. In creasing the shear span, the contribution of the composite fabrics in shear capacity of the beam increases. The comparison for the ultimate shear force of the beams indicated that there is a close agreement between the estimated values and the test dates of the beams except for the values of the beams B_{03} and B_{23}. The estimated value for contribution of composite fabrics obtained by the proposed expression is 108 kN for the beam B_{03} and 106 kN for the beam B_{23} against the test results 85 kN for the beam B_{03} and 87 kN for the beam B_{23}, respectively. The two beams did not reach their estimated force, it's because that the two beams B_{03} and B_{23} were crushed because of the flexion.

Table 2: Theoretical and experimental results for the ultimate shear force

Depth of the composite fabrics (m)	Ultimate force (kN)			
	Shear span 0.8 m		Shear span 0.2m	
	Test	Calculus	Test	Calculus
0	41	42.8	61	59.8
0.15	65	66.6	76	74.8
0.215	88	91.7	88	90.6
0.28	85	108	87	106

Conclusions

From present experimental study on the shear behaviour of reinforced concrete beam strengthened by externally bonded carbon fiber reinforced polymer fabrics, it can be observed that the CFRP shear contribution to the shear capacity of the beam depends on many parameters. Major parameters are the surface strengthened by bonded composite fabrics, the composite fabrics shear reinforcement ratio, the shear span to effective depth of beam ratio and the strength of composite fabrics. The experimental results shown that as the composite fabric area increased, the contribution in shear of the CFRP fabrics increased. As increasing the spacing between stirrups, the composite fabric contribution to shear capacity of the beam decreases. The test results show that the externally bonded CFRP reinforcement to enhance the shear capacity of the beam is considerable.

The trends of variation of deflexion and strain in longitudinal steel bar are similar. For a practical design point of view, it's easier to measurer the deflexion. Under load, the strain in CFRP fabrics develops faster than that in steel stirrups. However, the strain value stays small.

An analytical expression to predict the ultimate shear force of strengthened in shear RC beam is presented. In this proposed model, it is admitted that complex interaction exists between concrete, steel reinforcement and CFRP reinforcement. The comparison between the experimental results and calculated values indicated that the proposed expression to predict the contribution in shear of CFRP reinforcement gives acceptable estimates.

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