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Behavior on Shear Strengthening of Precraced/Repair RC Continuous Beams Using CFRP Strips

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ABSTRACT - *This paper presents the results of an experimental investigation for enhancing the shear capacity of reinforced concrete (RC) continuous beams using different CFRP wrapping schemes. A total of five concrete beams were tested and various sheet configurations and layouts were studied to determine their effects on ultimate shear strength and shear capacity of the beams. One beam was kept as control beams, while other beams were precracked and repaired with CFRP strips (i.e. precracked/repaired) with four or three sides bonding. Tests result shows that the effectiveness and shear capacity of the CFRP strengthened specimens. The shear enhancement of the CFRP strengthened beams varied between 18% and 44% over the control beam. This study confirms that the CFRP strip technique significantly enhances the shear capacity of reinforced concrete shear beams. Two prediction models available in literature were used for computing the contribution of CFRP strips and compared with the experimental results.*

KEYWORDS *- CFRP, Continuous Beam, Shear Strengthening*

I. INTRODUCTION

Deterioration of concrete structures is one of the major problems of the construction industry today. Moreover, a large number of structures constructed in the past using the older design codes in different parts of the world are structurally unsafe according to today design codes [1]. Shear failure of RC beams, caused by their brittle nature, has been identified as the most disastrous failure mode, it occurred with no advance warning of distress. Shear deficiency may occur due to many factors such as insufficient shear reinforcement or reduction in steel area due to corrosion, increased service load and construction errors [2]. Bonding plates to the external surface of existing reinforced concrete elements have proved to be an effective and practical means of increasing strength and stiffness [3]. The use of externally bonded fiber reinforced polymer (FRP) reinforcement to strength reinforced concrete structures is becoming an increasingly popular retrofit technique. FRP is a composite material generally consisting of carbon, aramid or glass fibers in polymeric matrix [4]. This research focused on using Carbon Fiber Reinforced Polymer (CFRP) systems consisting of flexible sheets. The objective of this study were to investigate the effectiveness of using externally bonded CFRP strips in repair and strengthen of reinforced concrete continuous beams.

II. SHEAR STRENGTH OF RC BEAM STRENGTHENED WITH FRP SHEET

The nominal shear strength of RC beams strengthened with externally bonded FRP sheets can be computed by equation (1):

$$V_n = V_c + V_s + V_f \qquad (1)$$

To compute the nominal shear strength as given in equation (1), it is important to quantify the contribution of CFRP reinforcement to the shear capacity V_f . This study presents two models used to obtain V_f .

I. KHALIFA MODEL (5)

The contribution of externally bonded FRP sheets to the shear capacity of an RC beam may be calculated from the equation 2.

$$V_f = \frac{A_f f_{fe}(\sin\beta + \cos\beta)d_f}{s_f} \leq \left(\frac{2\sqrt{f'_c}b_w d}{3} - V_s\right) \quad (2)$$

Because CFRP linearly elastic until failure, the effective stress may be computed as follows:

$$f_{fe} = Rf_{fu} \quad (3)$$

1. Reduction Coefficient Based on CFRP

Sheet Fracture Failure The reduction coefficient was established as a $\rho_f E_f$ function of and expressed in equation (4).

$$R = 0.5622(\rho_f E_f)^2 - 1.22(\rho_f E_f) + 0.78 \quad (4)$$

2. Reduction Coefficient Based on CFRP Debonding Failure

After the shear cracks develops, only that portion of the width of CFRP extending past the crack by the effective bonded length is assumed to be capable of carrying shear. The effective width W_{fe} based on the shear crack angle of 45° and the wrapping scheme is expressed in equations (5-a) , (5-b) and (5-c)

$W_{fe} = d_f$ If the sheet is wrapped around the beam entirely (5-a)

$W_{fe} = d_f - L_{eff}$ If the sheet is in the form of a U-wrap (5-b)

$W_{fe} = d_f - 2L_{eff}$ If the sheet is bonded to only the sides of the beam (5-c)

If the sheets is in the form of U-wrap In determining the reduction coefficient for bond, the effective bond length L_{eff} , has to be determined. The effective bond length L_{eff} , is a function of the thickness of the FRP sheet and the elastic modulus of the FRP. As the stiffness of the sheet increases the effective bond length decreases.

$$L_{eff} = e^{6.134 - 0.5\ln(t_f E_f)} \quad (6)$$

The final expression for the reduction coefficient R, for the mode of failure controlled by CFRP debonding is expressed in Eq (7).

$$R = \frac{(f'_{cu})^{2/3} W_{fe}}{\varepsilon_{fu} d_f}\left[199.9 - 6.156(t_f E_f)\right] \times 10^{-6} \quad (7)$$

The above equation is applicable for CFRP axial rigidity $t_f E_f$, ranging from 20 to 90 Gpa (kN/mm).

3. Upper Limit of the Reduction Coefficient

In order to control the shear cracks width and loss of aggregate interlock, an upper limit of reduction coefficient R was suggested.

$$R = \frac{0.006}{\varepsilon_{fu}} \qquad (8)$$

The final reduction coefficient for the CFRP system is taken as the lowest value determined from the two possible modes of failure and upper limit. Note, that if the sheet is wrapped entirely around the beam or an effective anchor is used, the failure mode of CFRP debonding is not being considered. The reduction coefficient is only controlled by CFRP fracture and upper limit.

II. ACI 440 MODEL (6)

The shear strength provided by FRP reinforcement can be determined by calculating the force resulting from the tensile stress in the FRP across the assumed crack. The shear contribution of the FRP shear reinforcement is given by the equation

$$V_f = \frac{A_{fv} f_{fe} (\sin\alpha + \cos\alpha) d_{fv}}{S_f} \qquad (9)$$

The tensile stress in the FRP shear reinforcement at nominal strength is directly proportional to the level of strain that can be developed in the FRP shear reinforcement at nominal strength.

$$f_{fe} = \varepsilon_{fe} E_f \qquad (10)$$

The effective strain is the maximum strain that can be achieved in the FRP system at the nominal strength and is governed by the failure mode of FRP system and of the reinforced concrete member. The subsequent equation provide guidance on determining the effective strain for different configuration of FRP laminates used for shear strengthening of reinforced concrete members.

1. Completely Wrapped Members

For completely wrapped reinforcement concrete column and beam members by FRP, loss of aggregate interlock of the concrete has been observed to occur at fiber strain less than the ultimate fiber. To preclude this mode of failure, the maximum strain used for design should be limited to 0.4% for completely wrapped applications.

$$\varepsilon_{fe} = 0.004 \le 0.75\varepsilon_{fu} \qquad (11)$$

Bonded U-wraps or Bonded Face Piles FRP systems that do not enclose the entire section (two and three sided wraps) have been observed to delaminate from the concrete before the loss of aggregate interlock of the section. The effective strain is calculated using a bond reduction coefficient k_v applicable to shear.

$$\varepsilon_{fe} = k_v \varepsilon_{fu} \le 0.004 \qquad (12)$$

The bond reduction coefficient is a function of the concrete strength, the type of wrapping scheme used and the stiffness of the laminate. The bond reduction coefficient can be computed as follows:

$$k_v = \frac{k_1 k_2 L_e}{11{,}900\,\varepsilon_{fu}} \le 0.75 \qquad (13)$$

The active bond length L_e is the length over which the majority of the bond stress is maintained. This length is given by the following equation:

$$L_e = \frac{23{,}300}{(nt_f E_f)^{0.58}} \qquad (14)$$

The bond reduction coefficient also relies on two modification factors k_1 and k_2, that account for the concrete strength and the type of wrapping scheme used. Expressions for these modification factors are given as follows:

$$k_1 = \left(\frac{f'_c}{27}\right)^{2/3} \qquad (14)$$

$$k_2 = \frac{d_{fv} - L_e}{d_{fv}} \qquad \text{(For U-wraps)} \qquad (15)$$

$$k_2 = \frac{d_{fv} - 2L_e}{d_{fv}} \qquad \text{(For two sides bonded)} \qquad (16)$$

The nominal shear capacity of the strengthened beam can be calculated by using the equation:

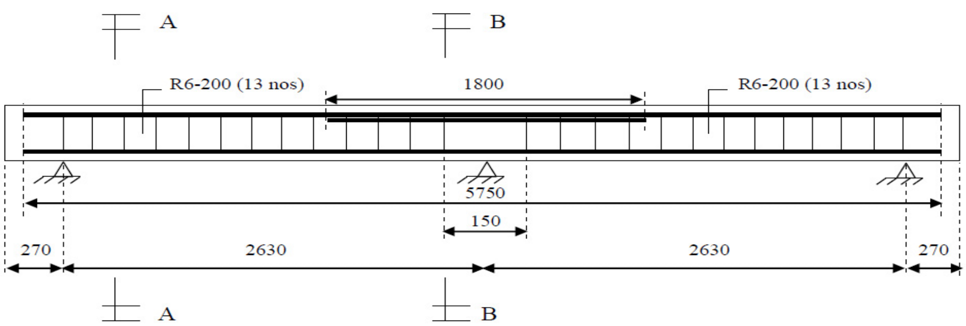
$$\phi V_n = \phi(V_c + V_s + \psi V_f) \qquad (17)$$

An additional reduction factor ψ is applied to the shear contribution of the FRP reinforcement. The reduction factor of 0.85 is recommended for three sides FRP U-wrap or two opposite sides strengthening and 0.95 for fully-wrapped members.

III. EXPERIMENTAL PROGRAM

1. Test Specimens and Materials

The experimental program consisted of testing five full-scale RC continuous beams under four-point loading. All specimens were design according to BS 8110: Part 1: 1997 with identical size of 150x350x5800 mm. All beams have an identical reinforcement details including longitudinal reinforcement in the form of 20 mm and stirrups reinforcement of 6 mm size at 200mm spacing centre to centre. Figure 1 below shows specimen details and the place of strain gauge on reinforcement.



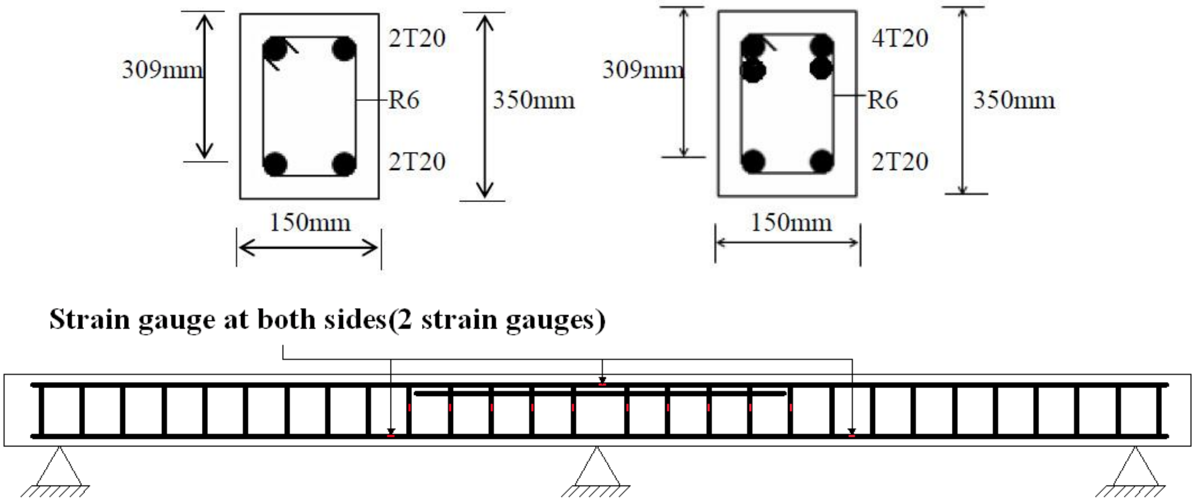


Fig. 1: Reinforcement and cross section details

All beams were cast using ready mix concrete with compressive strength of 30N/mm². Three bars of main reinforcement with length of 600 mm were tested under uniaxial tension using Universal Testing Machine (UTM) to determine the yield strength (see Table 1). For this study, the FRP used was CFRP bi-directional woven carbon fiber fabric. Mechanical properties of the CFRP are shown in Table 2. The type of adhesive used was Sikadur-330, a two part epoxy impregnating resin A and B. Table 3 shows the mechanical properties of the epoxy.

Table 1: Material properties of main reinforcement

Type	Diameter of bar(mm)	Yield Strength (N/mm²)²)
High yield steel	20	545.958
High yield steel	6	313.336

Table 2: Mechanical properties of CFRP [7]

Density	1.75 g/cm
Tensile strength	3'800 N/ mm² (nominal)
Thermal resistance	230’000 N/ mm² (nominal)
Elongation at break	1.5% (nominal)

Table 3: Mechanical properties of Sikadur-330[8]

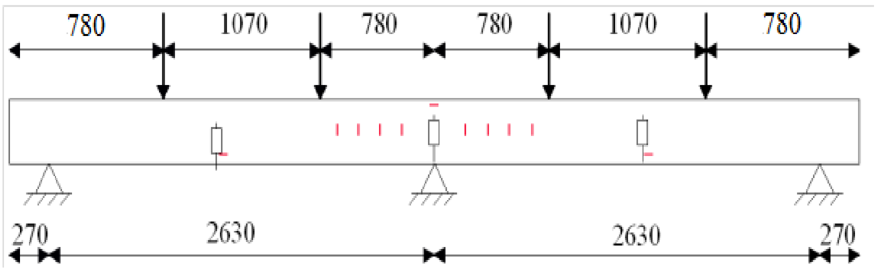
Density	1.3 Kg/L ± 0.1 Kg/L
Tensile strength	30N/mm²
Thermal resistance	Continuous exposure + 45 °C
Elongation at break	0.9 %

IV. STRENGTHENING SCHEME AND TEST SET-UP

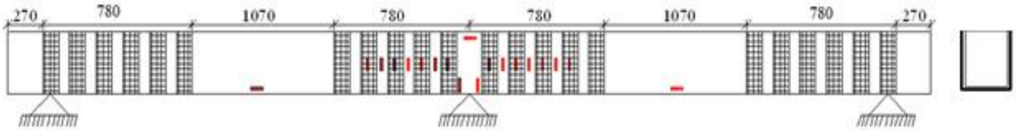
The beams were tested as continuous beam with shear span to effective depth ratio of 2.5. A total of 5 beams of two-span continuous beams strengthened with CFRP sheet includes orientation (90°/0°) and (45°/135°) were investigated with shear span to effective depth ratio of 2.5, two beams are cracked and strengthened with CFRP sheets, while the remaining one beam is kept uncracked as a control. The beams were initially precracked at service load and strengthened with CFRP laminates in the unloaded condition. The test set-up as well as strengthening schemes is shown in Figure 2. Each specimen has different characteristic where for C2.5-C, it was tested with no wrapping and loaded to failure. For C2.5-UA-S, C2.5-LA-S, C2.5-U-S and C2.5-L-S load was applied until 80% from the ultimate load of control beam or until shear crack was obviously appeared on the beam. After that, the load was release to apply the CFRP on the crack beam and then a load of total 10kN was placed on top of the beam and was leave for one week before load it to failure, for more details see table 4.

Table 4: Specimens designation

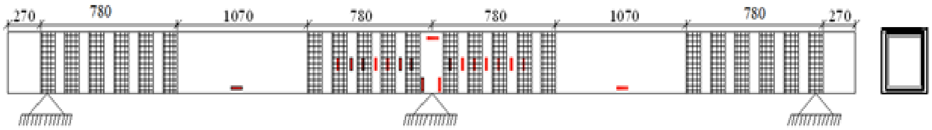
N0.	Specimens	CFRP orientation	Wrapping Schemes	Loading &Strengthening Condition
1	C2.5-C	-	-	Precracked/repaired
2	C2.5-US-S	0/90	4 Sides	Precracked/repaired
3	C2.5-U-S	45/135	3 Sides	Precracked/repaired
4	C2.5-LS-S	0/90	4 Sides	Precracked/repaired
5	C2.5-L-S	45/135	3Sides	Precracked/repaired



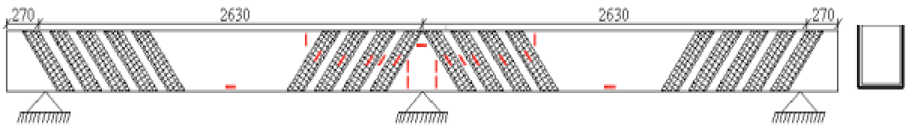
(a) Control beam C2.5-C



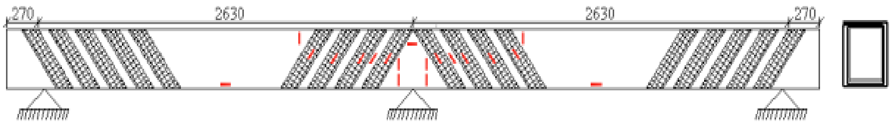
(b) Beam C2.5-US-S (Three Sides –wrap)



(c) Beam C2.5-US-S (Fully –wrap)



(d) Beam C2.5-L-S (Three Sides–wrap)



(e) Beam C2.5-LS-S (Three Sides–wrap)

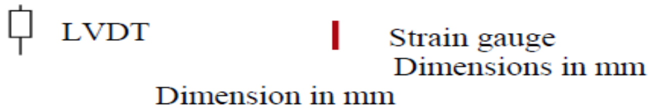


Fig. 2: Test set-up and strengthening schemes

V. EXPERIMENTAL RESULTS

1. Ultimate Load and Modes of Failure

All specimens failed in shear as expected. For control beam, C2.5-C, flexural cracks were started to form at near the mid span at the bottom of the beam at a load approximately 98kN. The shear cracks began to appear at a load of approximately 102Kn and as the load increased, the shear crack widened and propagated up to the final failure at a load level of 286kN. The mode of failure was shear crushing of the concrete. Specimen C2.5-U-S was loaded to 224kN in first cycle of loading then unloaded to zero. The first flexural crack was occurred at 98kN. As the load increased, the flexural cracks were initially appeared and the diagonal shear crack was observed near the middle of the shear span at a load of 196kN. After completing the pre-cracking phase, the beam was strengthened with U-wrapped CFRP strips and sustained with 10kN load for one week. Again the beam was loaded but up to failure. The diagonal cracks were clearly observed at a load of 148kN. The failure mode of the beam occurred at a total applied load of 338kN which is the fracture of CFRP strips along the shear crack. The percentage of ultimate load enhancement was 18% higher than the value of the control beam C2.5-C (see Figure 3 to6). For beam C2.5-UA-S, which was strengthened with CFRP strips, fully wrap (U-wrap) and oriented at 90°/0°, the failure mode of this beam was rupture-shear of CFRP as shown in Figure 4.3. In this beam, the diagonal shear crack was observed at total load of about 212kN. The first crack was observed total load of 100kN. As the load increased, more shear cracks appeared throughout the shear span. When the total load reached 374kN, the contribution of CFRP to shear capacity was 88kN and increased in shear enhancement at 31% higher than the control beam. For beam C2.5-LA-S, which was fully-wrapped (L-wrap) and oriented at 45°/135° with CFRP strips, no cracks were visible on the sides of the beam until 100kN. A diagonal shear crack was observed near the middle of shear spans at a load of 164kN. Finally, the beam failed at a total load of 411kN. Test results shows that there was an increase of 44% in ultimate load capacity compared to control beam C2.5-C. The failure mode of this beam was rupture-shear of CFRP and the contribution of CFRP to the shear capacity was 125kN as shown in Figure 4.5. In specimens C2.5-U-V2 which was fully-wrapped (L-wrap) and oriented at 45°/135° with CFRP strips, the first crack was occurred at 80kN. The diagonal shear cracks were observed at 180kN and the failure of the specimen occurred when the total applied load reaches 381kN. This was an increase of 45% in ultimate load capacity compared to the control beam C2.5-C. The cracks initiated at the location of the supports and extended towards the applied load. At failure, the concrete cover on the topside was extensively damaged. Figure 4.5 shows the shear-CFRP rupture-shear failure of the specimen.

Table 5: Experimental results

Specimen	First Crack load(kN)	Ultimate load (kN)	Shear Force (kN)	Shear Enhancement (%)	Mode of failure
C2.5-C	98	286	94	-	Diagonal shear failure
C2.5-US-S	100	374	123	31	Rupture or shear failure
C2.5-LS-S	64	411	135	44	Rupture or shear failure
C2.5-U-S	98	338	111	18	Rupture or shear failure
C2.5-L-S	80	381	125	33.07	Rupture or shear failure

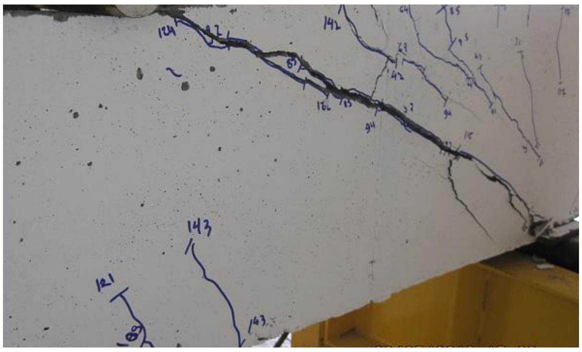


Fig. 3: Cracking and failure pattern of beam C2.5-C

Fig. 4: Cracking and failure pattern of beam C2.5-UA-S

Fig. 5: Cracking and failure pattern of beam C2.5-U-S

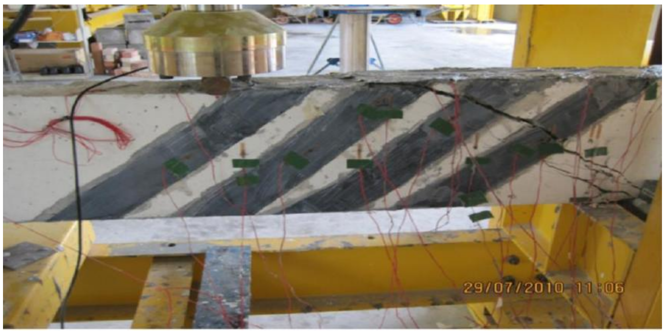


Fig. 6: Cracking and failure pattern of beam C2.5-L-S

2. LOAD-DISPLACEMENT BEHAVIOR

Figure 7and 8 shows the total applied load versus mid-span deflection relationship for all tested specimens. All beams showed very similar stiffness trend to each other. The smallest deflection was observed for beam C2.5-C. After the occurrence of the first crack, in precracked and repaired phase the specimen C2.5-LA-S had the greatest stiffness because of orientation of CFRP. It was also observed that the stiffness of the beam strengthened with orientation 90 degree of CFRP (C2.5-UA-S and C2.5-U-S) was less than that of the beam strengthened with orientation 45degree (C2.5-LA-S and C2.5-L-S). The ultimate load was greater for specimen C2.5-LA-S compared to other specimens. Specimens C2.5-C, C2.5-LA-S , C2.5-UA-S, C2.5-L-S and C2.5-U-S had observed a maximum deflection of 10.87mm, 12.895mm,10.86mm, 11.29mm and 10.84mm at failure load.

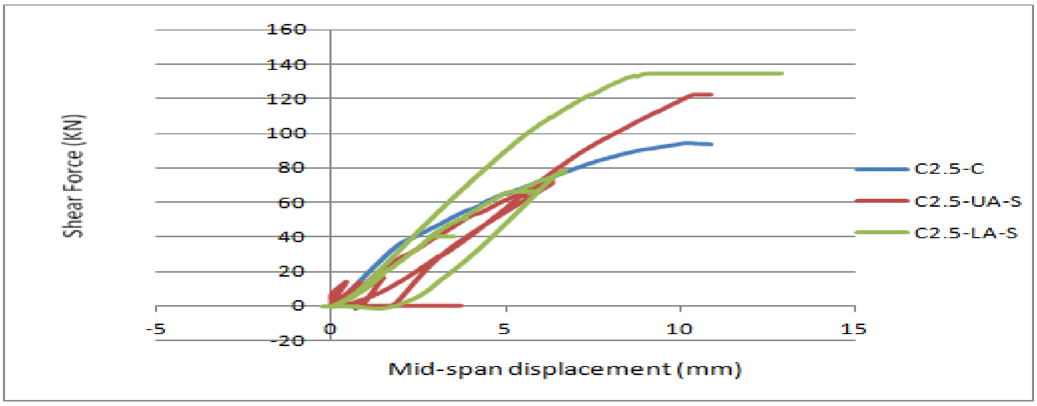


Fig. 7: Ultimate load versus mid-span displacement relationship

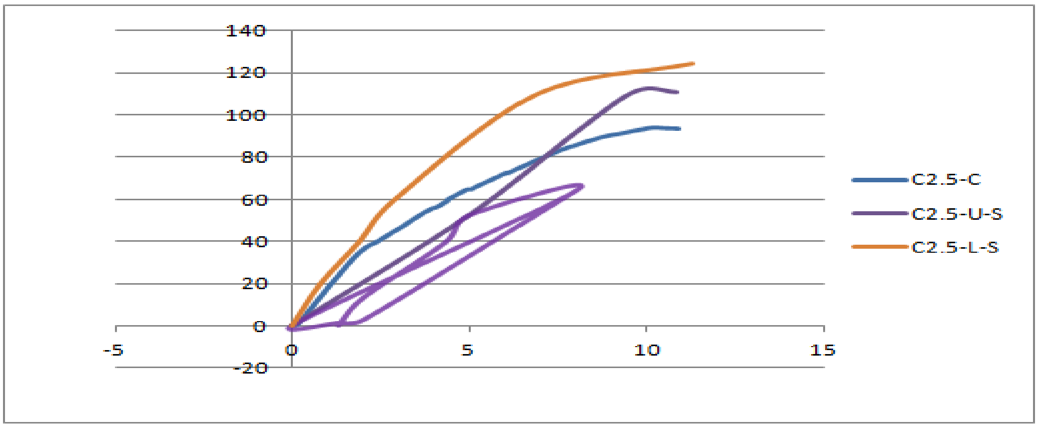


Fig. 8: Ultimate load versus mid-span displacement relationship

3. SURFACE STRAIN IN CFRP STRIPS AND CONCRETE SURFACE

Figures 10, 11, 12,13 and 14 illustrate graphs of local strain distribution in CFRP and concrete strain for specimens C2.5-C, C2.5-UA-S, C2.5-LA-S, C2.5-U-S and C2.5-L-S. For control beam C2.5-C, the strain at location C4 increased rapidly beyond the applied load 91.7 kN by the initiation of crack near the location of the strain gauge. The recorded maximum strain in concrete surface was 1131 μ_{ε} .In precracked /repaired phase, specimen C2.5-UA-S and C2.5-LA-S have recorded maximum strain of 7825 μ_{ε} (strain gauge F3) and 9655 μ_{ε} (strain gauge F3) respectively. The CFRP strain increased slowly until the beams reached a load close to 117.9kN and 131kN respectively. Beyond this point, the CFRP fabric strain increased significantly until failure occurred due to initiation of diagonal shear crack. The strain value of specimen C2.5-UA-S was less than the specimen C2.5-LA-S. From other hand, specimen C2.5-U-S had recorded maximum strain in CFRP at 3210 μ_{ε} (strain location F3). However in specimen C2.5-L-S, the strain value F4 increased gradually till the applied load of 124.7kN.

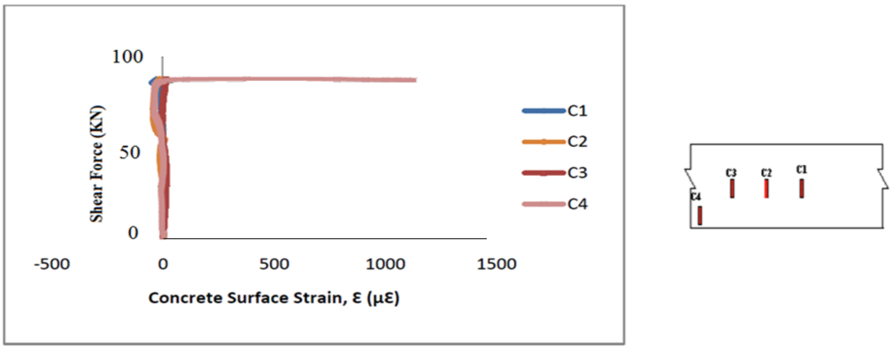


Fig. 10: Graph of Applied Load vs Concrete Surface and CFRP Strain for C2.5-C

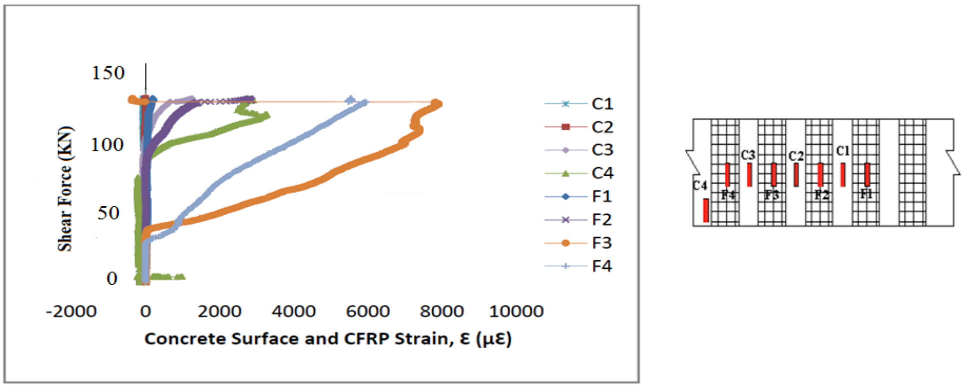


Fig. 11: Graph of Applied Load vs Concrete Surface and CFRP Strain for C2.5-US-S

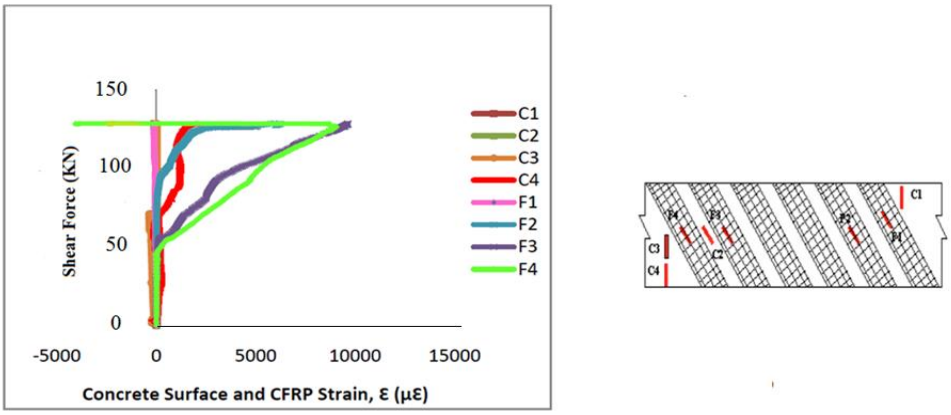


Fig. 12: Graph of Applied Load vs Concrete Surface and CFRP Strain for C2.5-LS-S

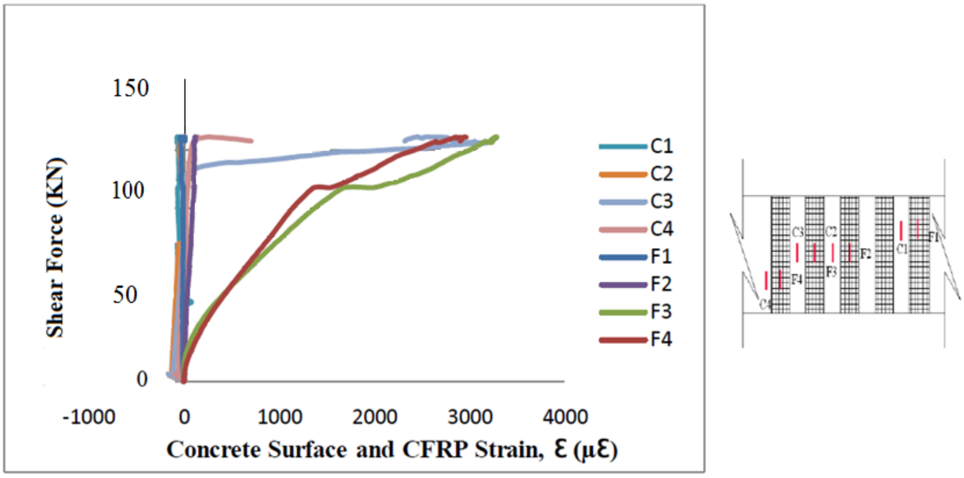


Fig. 13: Graph of Applied Load vs Concrete Surface and CFRP Strain for C2.5-U--S

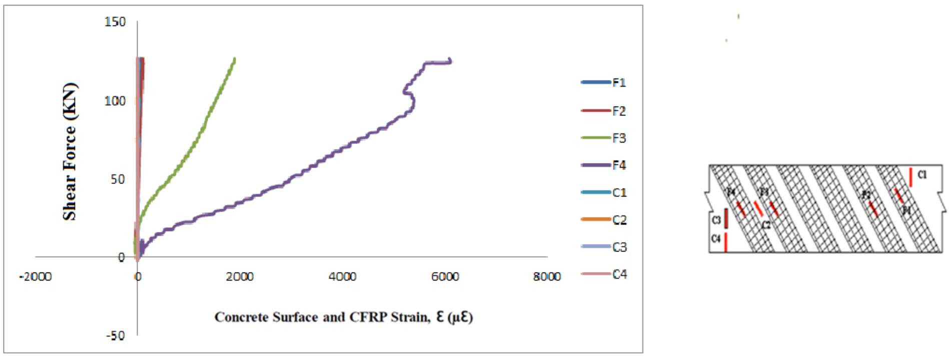


Fig. 14: Graph of Applied Load vs Concrete Surface and CFRP Strain for C2.5-U--S

VI. THE COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS

The comparison of experimental and theoretical results of the control and precracked/repaired continuous beams are shown in Table 6. The shear capacity contributed by the external CFRP reinforcement was estimated by subtracting the shear strength of the reference beam from the CFRP strengthened beam. The strip technique had proved that the shear capacities of the precracked/repaired continuous beams ranging from 18% to 44% over the control beam. The shear capacity of these continuous beams was theoretically computed using ACI 440 Format and Khalifa Model. The shear strength of the strengthened beams is computed by adding the contribution of shear strength of external CFRP reinforcement 'Vf'. It can be seen that the experimental values of the strengthened for all beams C2.5-C, C2.5-US-S, C2.5-LS-S, C2.5-U-S, and C2.5-L-S. From the overall discussion, it can be concluded that the predicted theoretical results of the continuous beams especially ACI model shows reasonable accuracy with the experimental results.

Table 6: Comparision of Experimental and Theoretical results

Specimens	Theoretical value		Exp. Results	$\frac{V_{f,\exp}}{V_{f,theory}}$	
	V_f KN		$V_{f,\exp}$ KN	Khalifa Model	ACI 440 Model
	Khalifa Model	ACI 440 Model			
C2.5-C	-	-	-	-	-
C2.5-US-S	46.1	27.9	29	0.63	1.04
C2.5-LS-S	65.18	39.45	41	0.63	1.04
C2.5-U-S	46.1	27.9	17	0.37	0.61
C2.5-L-S	62.9	39.45	31	0.5	0.79

VII. CONCLUSION

The test results indicated that strengthening of RC continuous beams using externally bonded CFRP strips can be used to enhance the shear capacity of continuous T-beams. For beams tested in the experimental program, the shear capacity increased at a ranged from 18% to 44 %. An increase in number of layer of CFRP strips has resulted in stiffer and stronger beams. It was also observation and analysis of strain of CFRP strips, repaired beams have shown an obvious increased of CFRP strain. The elongation of strain in CFRP due to the weaken condition and pre-cracked prior to being wrapped with CFRP strips. The elongation of CFRP shows an effectiveness of the CFRP in resisting the sheer force of the beam. However, the magnitude of the strain on the location of strain gauge with respect to crakes.

ACKNOWLEDGMENT

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NOTATION

av- shear span
Af -area of CFRP shear reinforcement = 2 tf wf
bw -width of the web of beam cross section (ACI format)
d -depth from the top of the section to the tension steel reinforcement centroid
df -effective depth of the CFRP shear reinforcement (usually equal to d for rectangular sections and d-ts for T-sections)
Ef -elastic modulus of FRP (GPa)
f 'c -nominal concrete compressive strength in MPa (ACI format)
ffu -ultimate tensile strength of the FRP sheet in the direction of the principal fibers
fy -yield strength of steel reinforcement
Le -effective bond length (mm)
R -reduction coefficient (ratio of effective average stress or strain in the FRP sheet to its ultimate strength or elongation)
s -spacing of steel stirrups
sf -pacing of FRP strips
tf -thickness of the FRP sheet on one side of the beam (mm)
Vc- nominal shear strength provided by concrete
Vf- nominal shear strength provided by FRP shear reinforcement (ACI format)

Vn -nominal shear strength (ACI format)
Vs- nominal shear strength provided by steel shear reinforcement (ACI format)
Vu -factored shear force at section (ACI format)
wfe -effective width of FRP sheet (mm)
α- angle between inclined stirrups and longitudinal axis of member
β -angle between the principal fiber orientation and the longitudinal axis of the beam
εfe -effective strain of FRP
εfu -ultimate tensile elongation of the fiber material in the FRP composite
φ -strength reduction factor (ACI format) factor for concrete (Eurocode format) , γc =1.5

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