Study on Shear Strengthening of RC Continuous Beams with Different CFRP Wrapping Schemes

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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 strengthened with externally bonded CFRP strips with four or three sides bonding and one or two layers of CFRP strips. From the test results, it was found that all schemes were found to be effective in enhancing the shear strength of RC beams. It was observed that the strength increases with the number of sheet layers and four sides wrap provided the most effective strengthening for RC continuous beam. Beam strengthened using this scheme showed 54% increase in shear capacity as compared to the control beam. 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

1. 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.

2. 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 .

2.1 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.

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

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

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

2.1.1Reduction Coefficient Based on CFRP Sheet Fracture Failure

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

$$R = 0.56(\rho_f E_f)^2 - 1.22(\rho_f E_f) + 0.78 \qquad (4)$$

2.1.2Reduction 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) and (5-b).

$$w_{fe} = d_f \qquad (5\text{-a})$$

If the sheets is wrapped around the beam entirely

$$w_{fe} = d_f - L_{eff} \qquad (5\text{-b})$$

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.

$$L_{eff} = e^{6.134 - 0.58\ln(t_f E_f)} \qquad (6)$$

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

$$R = \frac{(f'_c)^{\frac{2}{3}} w_{fe}}{\varepsilon_{fu} d_f}(738.93 - 4.06(t_f E_f))10^{-6} \qquad (7)$$

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

2.1.3Upper 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.

2.2 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:

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

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.

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

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.

2.2.1Completely 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.

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

2.2.2Bonded 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.

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

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:

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

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:

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

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:

$$k_1 = \left(\frac{f'_c}{27}\right)^{2/3} \quad (15)$$

$$k_2 = \frac{d_{fv} - L_e}{d_{fv}} \quad \text{(for U-wraps)} \quad (16)$$

$$k_2 = \frac{d_{fv} - 2L_e}{d_{fv}} \quad \text{(for two sides bonded)} \quad (17)$$

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

$$\phi V_n = \phi(V_c + V_s + \psi V_f) \quad (18)$$

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.

3. EXPERIMENTAL PROGRAM

3.1 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 center to center. Fig. 1 below shows specimen details.

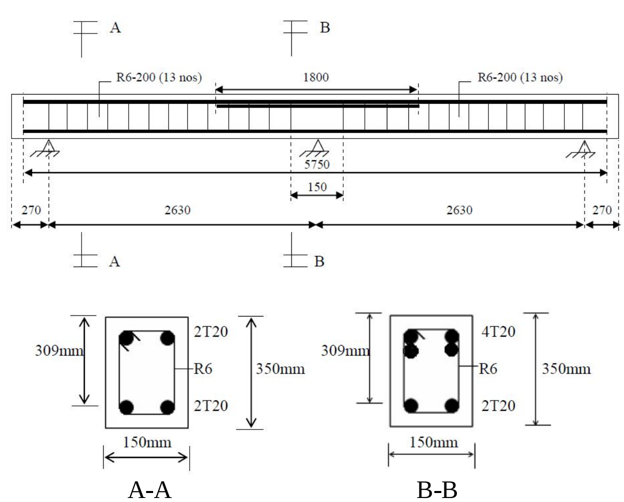


Fig. 1: Reinforcement and cross section details

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)	Average strength
High yield steel	20	527.803	545.958
		539.813	
		570.258	

Table 2: Mechanical properties of CFRP [7]

Density	1.75 g/cm³
Tensile strength	3'800 N/mm2 (nominal).
Tensile E-modulus	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 %

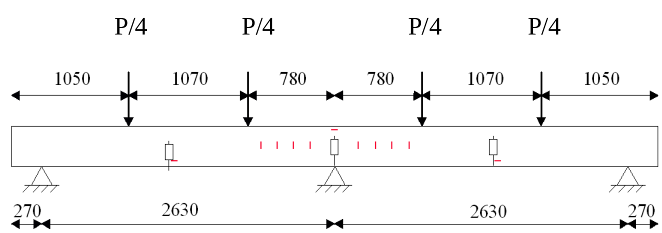
3.2 Strengthening Scheme and Test Set-up

The beams were tested as continuous beam with shear span to effective depth ratio of 2.5. One beam was not strengthened and was considered as a reference beam and four beams were strengthened using externally bonded CFRP strips with different schemes. The test set-up as well as strengthening schemes are shown in Fig. 2.

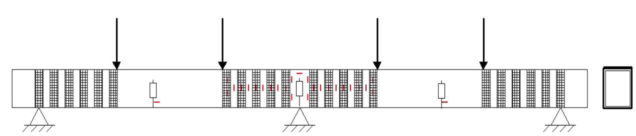
Each specimen has different characteristic where for C2.5-C, it was tested with no wrapping and loaded to failure. For C2.5-UA-V, it was wrapped with one layer of CFRP at four sides of the beam with orientation of 0/90º, while for C2.5-U-V, it was wrapped with one layer CFRP at three side of the beam with orientation of 0/90°. For C2.5-UA-V2, it was wrapped with two layers of CFRP at four sides of the beam with orientation of 0/90º and also for C2.5-U-V2, it was wrapped with two layers of CFRP but at three sides of the beam with orientation of 0/90°. Table 4 shows the specimens designation.

No.	Specimen	CFRP Orientation (°)	Wrapping Schemes	Loading & Strengthening Condition
1	C2.5-C	-	-	-
2	C2.5-UA-V	0/90	4 sides	Initially Strengthened (1 layer)
3	C2.5-U-V	0/90	3 sides	Initially Strengthened (1 layer)
4	C2.5-UA-V2	0/90	4 sides	Initially Strengthened (2 layer)
5	C2.5-U-V2	0/90	3 sides	Initially Strengthened (2 layer)

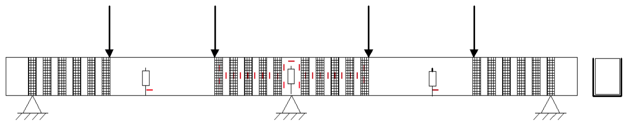
Table 4: Specimens designation



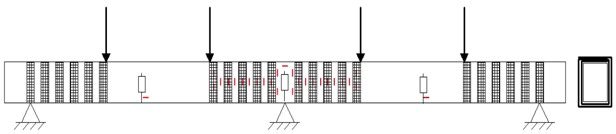
(a)Control beam C2.5-C



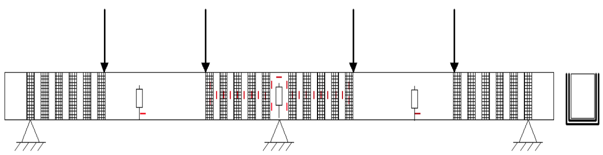
(b)Beam C2.5-UA-V (fully-wrap)



(c)Beam C2.5-U-V (U-wrap)



(d)Beam C2.5-UA-V2 (2 layers fully-wrap)



(e)Beam C2.5-U-V2 (2 layers U-wrap)

LVDT Strain gauge

Dimensions in mm

Dimension in mm

Fig. 2: Test set-up and strengthening schemes

4. EXPERIMENTAL RESULTS

4.1 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.

For specimens C2.5-UA-V which was fully-wrapped with CFRP strips, no cracks were visible on the sides of the beam until 121kN. A diagonal shear crack was observed near the middle of shear spans at a load of 227kN. Finally, the beam failed at a total load of 380kN. Test results shows that there was an increase of 33% in ultimate load capacity compared to control beam C2.5-C.

For specimens C2.5-U-V which wrapped three sides with CFRP, the first crack was occurred at 115kN at the bottom mid span of the beam. This beam exhibited the first crack at a higher load than the control beam C2.5-C due to the presence of the external bonded CFRP system. The diagonal shear cracks were observed at 218kN and the corresponding failure load occurred at 356kN. The enhancement of the load is 24.5% higher than the control beam.

On the other hand, the first crack for beam C2.5-UA-V2 was developed at a load of 129kN. The diagonal shear cracks were observed at 248kN. As the load increased, the diagonal cracks were extending. The total ultimate load was recorded at 439kN with 53.5% increase in load capacity over the control beam C2.5-C.

For specimens C2.5-U-V2 which was wrapped at three sides of the beam, the first crack was occurred at 120kN. The diagonal shear cracks were observed at 236kN and the failure of the specimen occurred when the total applied load reaches 414kN. This was an increase of 45% in ultimate load capacity compared to the control beam. Table 5 shows the first cracks load, ultimate load, contribution of CFRP and the modes of failure for all beams. Fig. 3 to 7 show cracking patterns and failure modes of the beams.

Table 5: Experimental results

Specimen	First crack load (kN)	Ulti-mate load (kN)	Shear force (kN)	Shear Enhanc-ement (%)	Mode of failure
C2.5-C	98	286	94	-	Shear
C2.5-UA-V	121	380	124	32.9	Shear-CFRP rupture
C2.5-U-V	115	356	117	24.5	Shear-CFRP rupture & peeling
C2.5-UA-V2	129	439	144	53.5	Shear-CFRP rupture
C2.5-U-V2	120	414	136	44.8	Shear-CFRP rupture & peeling

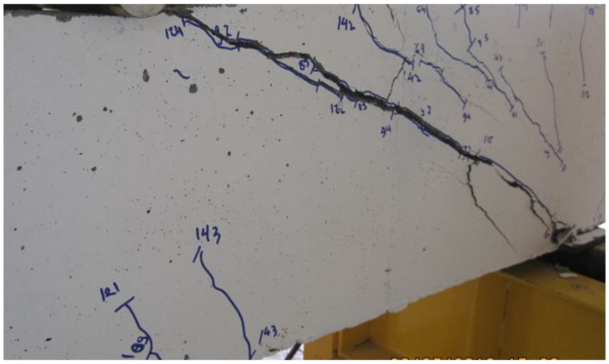


Fig. 3: Cracking and failure pattern of beam C2.5-C

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

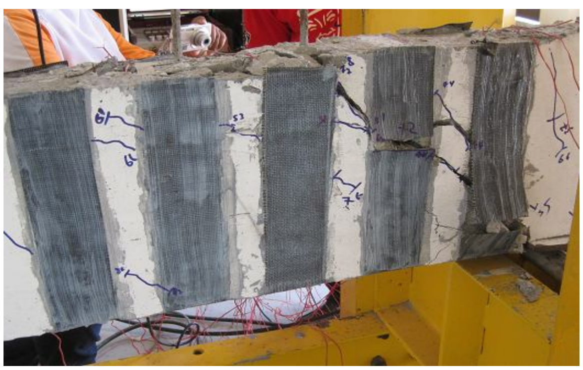


Fig. 5: Cracking and failure pattern of beam C2.5-U-V

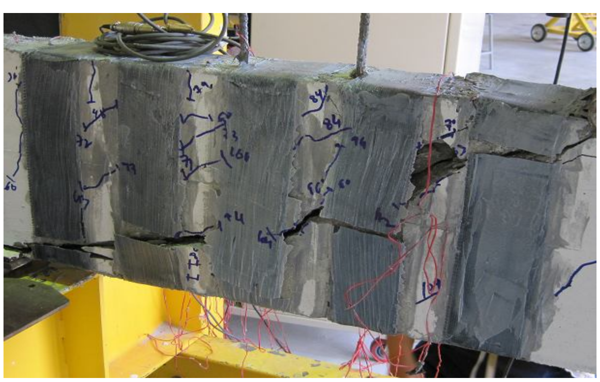


Fig. 6: Cracking and failure pattern of beam C2.5-UA-V2

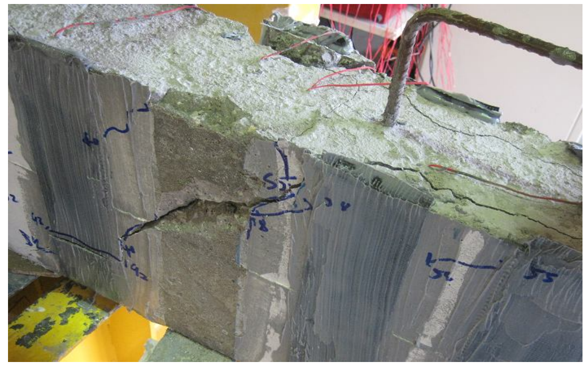


Fig. 7: Cracking and failure pattern of beam C2.5-U-V2

4.2 Load-Displacement Behavior

Fig. 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. It was also observed that the stiffness of the beam strengthened with one layer of CFRP (C2.5-UA-V) was less than that of the beam strengthened with two layer of CFRP (C2.5-UA-V2). Apart from that, it was also observed that beams wrapped four sides with CFRP strips were stiffer than beams wrapped three sides with CFRP strips.

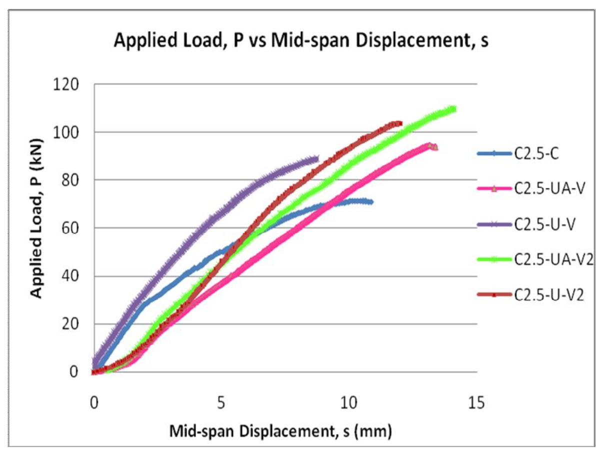


Fig. 8: Ultimate load versus mid-span displacement relationship

4.3 Surface Strain in CFRP Strips and Concrete Surface

The applied load versus strain in CFRP strips and concrete surface of the specimens C2.5-C, C2.5-UA-V, C2.5-U-V, C2.5-UA-V2 and C2.5-U-V2 are shown in Fig. 9,10,11,12 and 13 respectively. For control beam C2.5-C, the maximum strain in concrete at failure was 378με. In specimens C2.5-UA-V2, the strain gauge showed an abrupt increase in concrete strain at an applied load of P, 65kN. This sudden increase in the strain gauge maybe due to the widening of the diagonal shear crack. The recorded maximum strain in CFRP was around 7500με in specimen C2.5-UA-V2. Specimen C2.5-UA-V2 had a similar orientation of CFRP and position the strain gauges as in specimen C2.5-UA-V but the different is the number of CFRP layers. There was a sudden increase in concrete strain probably because of the propagation of diagonal crack underneath the CFRP strips. From the graphs, we can see that the wrapping scheme of the CFRP strip affected the composite strain where beams with fully wrapped CFRP get higher strain than the u-wrapped CFRP beams. Apart from that, the CFRP strips showed an elongation of the CFRP strips indicating the effectiveness of the CFRP strip resisting shear.

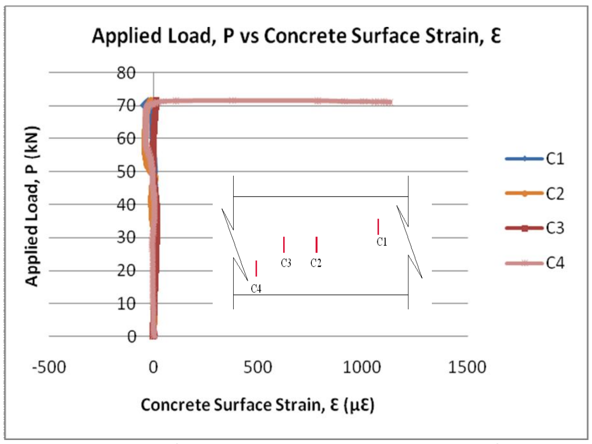


Fig. 9: Graph of Applied Load vs Concrete Surface and CFRP Strain for C2.5-C

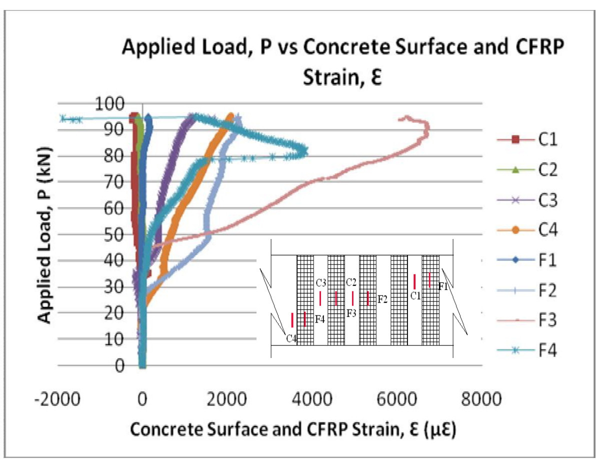


Fig. 10: Graph of Applied Load vs Concrete Surface and CFRP Strain for C2.5-UA-V

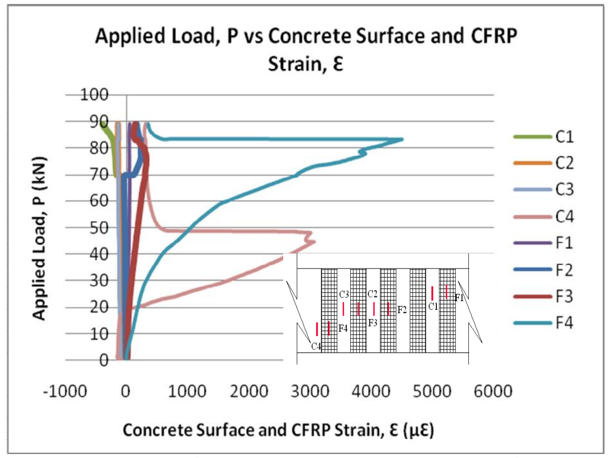


Fig. 11: Graph of Applied Load vs Concrete Surface and CFRP Strain for C2.5-U-V

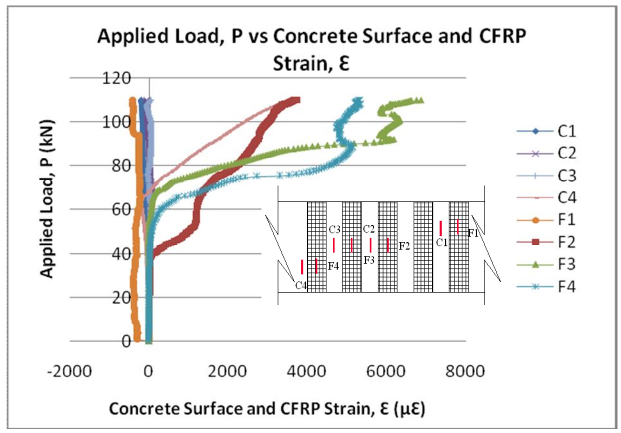


Fig. 12: Graph of Applied Load vs Concrete Surface and CFRP Strain for C2.5-UA-V2

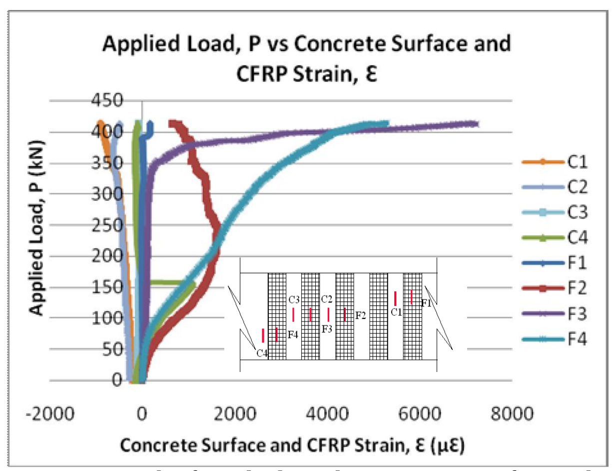


Fig. 13: Graph of Applied Load vs Concrete Surface and CFRP Strain for C2.5-U-V2

5. 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 beams. For beams tested in the experimental program, the shear capacity increased at a ranged from 24.5% to 53.5 %. It was also observed that increasing amount of CFRP may not result in significant increase of the shear capacity. Apart from that, beams which wrapped four sides with CFRP had a higher capacity than those which wrapped three sides with CFRP.

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NOTATION

a_v- shear span
A_f -area of CFRP shear reinforcement = 2 tf wf
b_w -width of the web of beam cross section (ACI format)
d -depth from the top of the section to the tension steel reinforcement centroid
d_f -effective depth of the CFRP shear reinforcement (usually equal to d for rectangular sections and d-ts for T-sections)
E_f -elastic modulus of FRP (GPa)
f'_c -nominal concrete compressive strength in MPa (ACI format)
f_{fu} -ultimate tensile strength of the FRP sheet in the direction of the principal fibers
f_y -yield strength of steel reinforcement
L_e -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
s_f -pacing of FRP strips
t_f -thickness of the FRP sheet on one side of the beam (mm)
V_c- nominal shear strength provided by concrete
V_f- nominal shear strength provided by FRP shear reinforcement (ACI format)
V_n -nominal shear strength (ACI format)
V_s- nominal shear strength provided by steel shear reinforcement (ACI format)
V_u -factored shear force at section (ACI format)
w_{fe} -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
ε_{fe} -effective strain of FRP
ε_{fu} -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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