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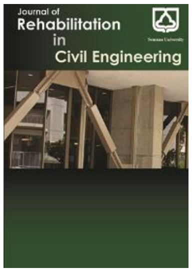

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An Experimental Study on Shear Strengthening of RC Lightweight Deep Beams Using CFRP

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ABSTRACT

This paper presents the results of an experimental investigation on shear strength enhancement of reinforced concrete deep beams externally reinforced with fiber reinforced polymer (FRP) composites. A total of six deep beam specimens of two different classes, as-built (unstrengthened) and retrofitted were tested in the experimental evaluation program. Two composite systems namely carbon/epoxy laminates and carbon/epoxy sheets were used for retrofit evaluation. A comparative study of the experimental results with published analytical models, including the ACI 440 model, was also conducted in order to evaluate the different analytical models and identify the influencing factors on the shear behavior of FRP strengthened reinforced concrete deep beams. Experimental results indicated that the composite systems provided substantial increase in ultimate strength of strengthened beams as compared to the as-built beam specimen. The strength gain caused by the CFRP sheets was in the range of 30-58% Analytical Comparison indicated that the shear span-to-depth ratio (a/d) is an important factor that actively controls the shear failure mode of beam and consequently influences on the shear strength enhancement.

1. Introduction

Behavior of a reinforced concrete beam in shear is very complex in nature and difficult to predict accurately. For this reason, the shear capacity of beams in most codes of practice is empirical or semi-empirical. The shear behavior of RC beams depends on the size of the specimen, reinforcement type and detailing as well as the type and position of applied loading. Besides the concrete shear resistance capacity, additional contributions come from external and/or internal reinforcements of a RC beam specimen. Provided reinforcements help in improving the failure nature, brittle to ductile, to some extent. External shear strengthening using FRP composites gained popularity over steel because of several reasons including material cost, lightweight feature and ease of application. Moreover FRP has more reliable bond line strength as compared to steel where corrosion at the interfaces unavoidable in the presence of moisture [1].

Numerous studies reported a remarkable increase in the shear strength of shallow RC beams when strengthened with externally bonded FRP system [2-4]. Triantafillou reported that the gain in shear strength caused by FRP was primarily dependent on the number of FRP layers and the amount of internal shear steel reinforcement. The FRP shear strengthening system was found more effective when the fibers were oriented in a direction perpendicular to the potential diagonal shear cracks. Deniaud and Cheng presented a review summary of several shear design methods for reinforced concrete beams strengthened with composites Very few researchers investigated the effective of externally bonded FRP system as an external reinforcement to strengthening RC deep beams [5-7]. Zhang and Moren reported that the contribution of the externally bonded FRP system to the shear strength decreased as the shear span-to-depth ratio was reduced. Vertical FRP shear strengthening resulted in a 79% increase in the shear strength at a shear span-to-effective depth ratio of 1.875 whereas only a 46% strength gain was recorded at a shear span-to-effective depth ratio of 1.25. This indicates that the effectiveness of the FRP system decreases as the beam behavior changes from a shallow beam action to a deep beam action. Islam, Mansur and Maalej reported that reported that use of externally bonded FRP systems leads to enhance of shear strengthening up to 40%. Maaddawy and Sherif reported that structural response of RC deep beams with opening was primary dependent on the degree of the interruption of the natural load path.

Over past few years, a number of theoretical investigations to predict the shear capacity of reinforced concrete beams strengthened externally with FRP wet layup laminates or precured strips were done and analytical models were developed based on different theoretical assumptions and experimental observations. Triantafillou and Antonopoulos proposed theoretical model to compute the shear strength capacity of a beam strengthened with externally applied FRP [8]. Lateran, this proposed model was calibrated using seventy-five published experimental test results [8] which resulted in an expression to predict the effective strain in FRP laminates. In year 2001, Matthys and Triantafillou [9] made slight modification of Triantafillou and Antonopoulos [8] expression of effective strain and indicated that in addition to all other influential factors, effective strain in FRP is also a function of the beam shear span-to-effective depth ratio. However, Matthys and Triantafillou [9] made this comment on the basis of the least square fitting of experimental results collected from past literatures. Colotti, Spadea and Swamy developed a theoretical model based on the truss analogy method in conjunction with the theory of plasticity [10]. They reported that the theoretical model provided good correlation with past experimental results. The recent edition of the ACI 440 [11] proposed a theoretical model to compute the enhancement of shear strength of RC beams using external FRP laminates. They focused on the developed effective strain in composites at failure which varies depending upon the variability of composite material properties, dimensions and the application techniques. Therefore, it is extremely difficult to make any generalize solution for the shear strength enhancement of structural members using external FRP composite reinforcements.

2. Test Program

2.1. Details of the structurally deficient beam

The six deep beams constructed were identical in every respect. Each beam was 1500mm long with a rectangular cross-section, 120(mm) wide and 500(mm) in overall depth (500mm). As shown in Fig.1, the flexural reinforcement consisted of 4T16 deformed bars of yield strength 400MPa. These bars were placed in two layers and were welded to 10mm thick steel plates at both ends to provide the necessary anchorage. The shear reinforcement consisted of one layer of deformed bars having 150(mm) square openings. The bars diameter was 6(mm). the minimum web reinforcement requirements by ACI code [12] are not available by this value. A 20(mm) thick and 100(mm) long steel plate was used at each loading and reaction points covering the full width of the beams (Fig.1).

Concrete having average 28 days cube strength of 30 MPa was made from ordinary Portland cement, river sand, crushed gravel of 10mm maximum size and leca (Light Expanded Clay Aggregate) of 3-10mm size. The aggregate cement ratio 5.1 by weight and the water-cement ratio were 0.49 by weight.

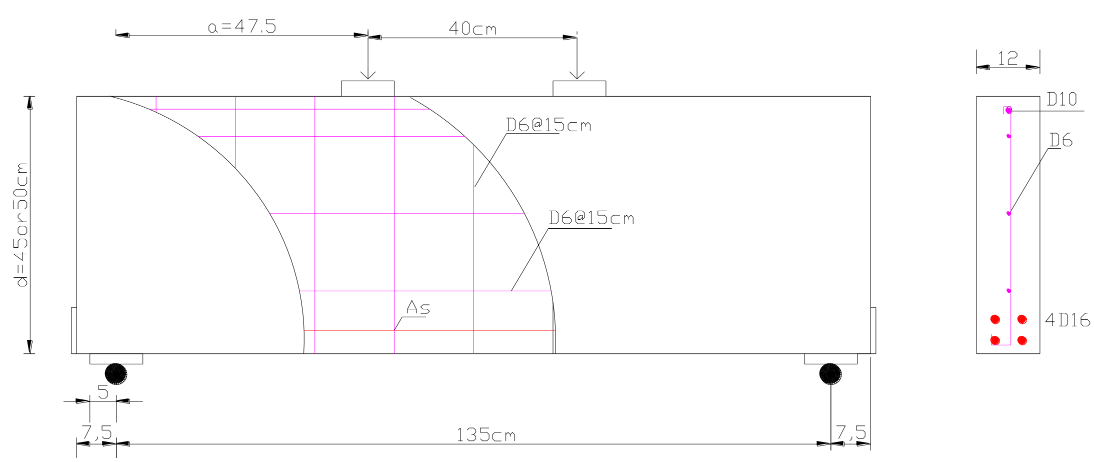
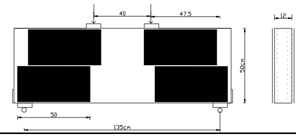
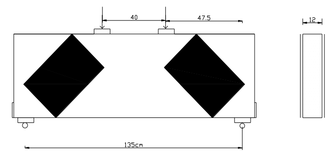
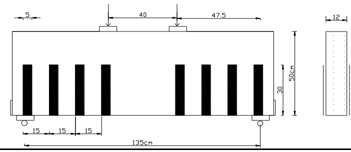
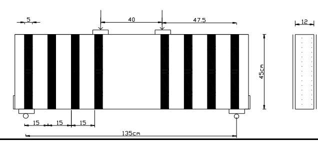
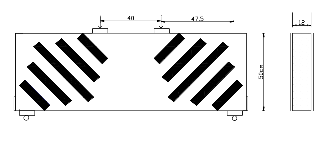


Fig. 1. Dimension and internal reinforcement details of reference deep beam specimen

Table 1. Strengthening Scheme of the Tested Deep Beams

Row	Name	Strengthening Type	S_f	Fibers Angle	Strengthening Configuration
1	REF-a	None		-	Without strengthening
2	CONa-VW(C)	CFRP Sheet	_	90	
3	CONa-DW(C)	CFRP Sheet	-	45	
4	CONa-VS1	CFRP Laminae	15 cm	90	
5	CONa-VS2	CFRP Laminate	15 cm	90	
6	CONa-DS	CFRP Laminate	15 cm	45	

2.2. Strengthening Materials and Method

Two different FRP types have been used to strengthen the basic beams. These are: CFRP sheets and CFRP laminates. The parameters investigated were the angle of fibers respect to longitudinal axis of beam and type of FRP. The different strengthening scheme for each beam presented in the Table I. Instead of providing the strengthening material (FRP) throughout the beam surface, strengthening materials was used only in the shear span across the potential failure region.

Table 2. Properties of strengthening materials

Type of FRP	Thickness (mm)	Width(mm)	Tensile Strength(MPa)	Tensile modulus of elasticity(GPa)	Failure strain(%)
CFRP laminate	1.200	50	3000	165	1.8
CFRP sheet	0.176	-	4000	240	1.6
GFRP sheet	0.300	-	1700	77	2.2

The mechanical properties of the strengthening materials and epoxy resin, as reported by the manufacturers are shown in Table II and III, respectively.

2.3. Instrumentation and Test Procedure

The beams were simply supported having a clear span of 1350mm and tested under two symmetrical point loads, thus given a ratio of 2.7 and an ratio of 0.95, where is the shear span (as shown in Fig.1). The load was applied using a servo controlled hydraulic actuator with a maximum capacity of 1000kN. Mid-span deflection of the beams was measured by LVDTs.

3. Test Results

3.1. Load Deflection Behavior

The load vs. mid-span deflection of the beams plotted in Figs. 2-3 can be seen to be typical of those generally observed for a deep beam with a small ratio. All deep beams demonstrated a nearly linear response up to failure because the flexural reinforcement didn't yield. It was noted that strengthening by externally bonded of CFRP sheets and laminates resulted in an increase in the stiffness when comparing with the reference beam. The highest stiffness being exhibited by deep beams that strengthened with 45 angle of fibers respect to longitudinal axis of beam.

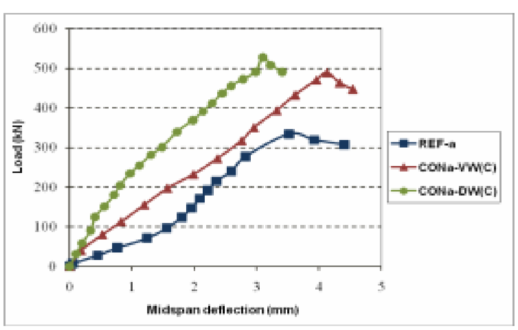


Fig. 2. load-deflection behavior of deep beams strengthened with CFRP sheets.

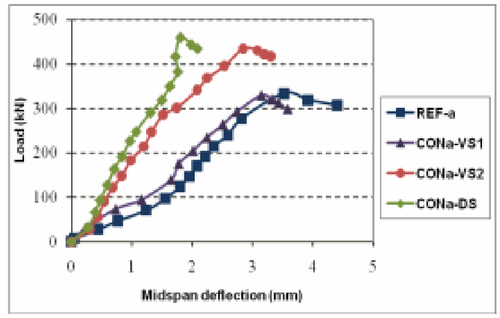


Fig. 3. load-deflection behavior of deep beams strengthened with CFRP Laminates

3.2. Ultimate Strength and Mode of Failure

All the beams failed in shear. The parent beam REF-a failed by diagonal splitting between the load point and support point in shear-span as can be seen in Fig.4a. Beam CONa-VW(C) which was strengthened by CFRP sheets in normal orientation, failed at a load %46 higher than the parent beam. Failure occurred by crushing of the concrete under the sheets (Fig.4b). In beam CONa-DW(C) which was strengthened by CFRP sheets in diagonal direction, the failure occurred by delamination of CFRP sheet and crushing of the concrete under the sheets. Beam showed a %58 increase in ultimate strength (Fig.4c).

In beam CONa-VS1, failure due to the delamination of the second laminate from left. The failure load of 330kN was close to that of the parent beam because the CFRP laminates were not activated (Fig.4d). Beam CONa-VS2 showed a %30 increase in ultimate strength. The failure of this beam was initiated due to the separation of the lower end of the bottom laminate from the concrete surface. Shortly afterwards, the other laminates gave way one after another in succession starting from the lower end. Complete failure occurred by splitting diagonal and delamination of second and third laminates from right (Fig.4e). Closer observations revealed that the separation of the FRP laminates was associated with

Table 3. Properties of epoxy

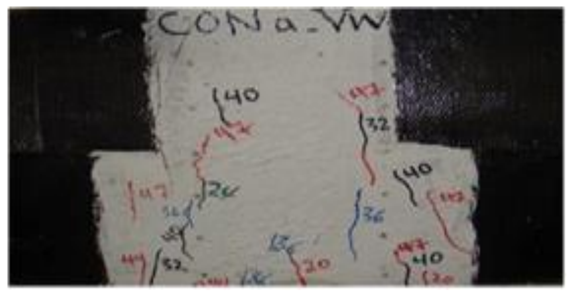
	Resin	Hardener
Density (g cm^{-3})	1.15	0.98
Special gravity	1.80	2.00
Flexural strength (Kg cm^{-2})	450-550	300-400

The beam CONa-DS was strengthened with the CFRP laminates in diagonal orientation, failure along a shear plane at the out of the strengthening confine, end of laminates, occurred. At failure, delamination of the laminate of up of right support was noted (Fig.4f).

It may be noted that CFRP sheets in normal orientation performed better than CFRP laminates in normal orientation. This becomes obvious when the results of beams CONa-VW(C) and CONa-VS2 with an additional web reinforcement ratio of 0.23% and 0.40%, respectively (calculated from the volume of additional web reinforcement divided by the volume concrete in shear span), as presented in Table 4, are compared. Also, FRP fibers in diagonal orientation showed significant increase in ultimate capacity over that of FRP fibers in normal orientation.

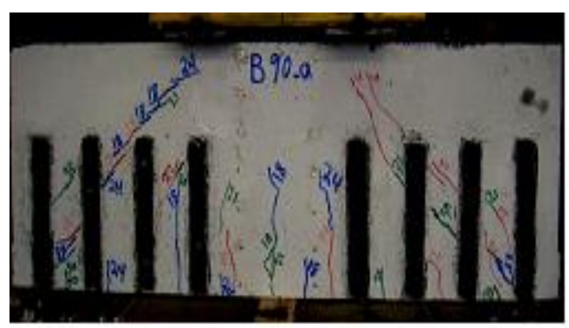
However, CFRP sheets and CFRP laminates all can be considered suitable for shear strengthening a deep beam. The ultimate load carrying capacity of all the beams along with the nature of failure, load causing the initial cracks and shear enhancement are given in Table IV.

(a)



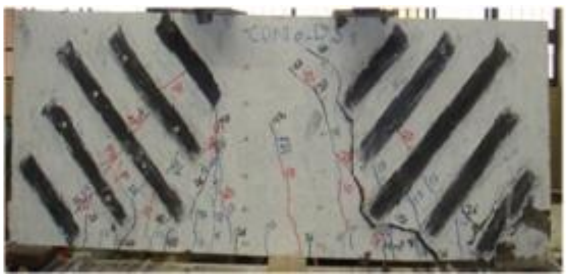
(b)

(c)



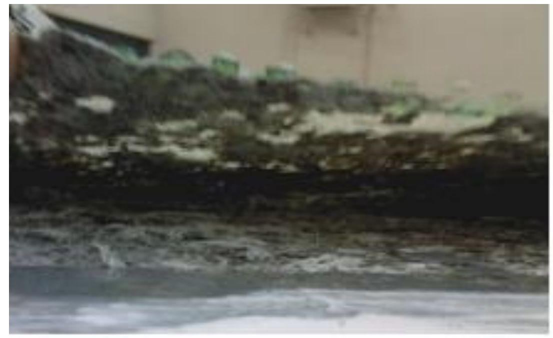
(d)

(e)



(f)

Fig. 4. Failure mode of test beams



(a)

(b)

Fig. 5. Delamination of FRP composites a) CFRP sheets b) CFRP Laminates.

Table 4. Test Results

Beam	**Load at Initial Crack (kN)**	**Ultimate Load (kN)**	**Shear Enhancement (%)**	**Nature of Failure**
REF-a	81	334	-	Shear Failure
CONa-VW(C)	111	489	46	Crushing of Concrete under CFRP Sheets
CONa-DW(C)	123	528	58	Shear Failure +Crushing of Concrete under CFRP Sheets
CONa-VS1	90	330	-	Shear Failure + Delamination of CFRP Laminates
CONa-VS2	98	434	30	Shear Failure + Delamination of CFRP Laminates
CONa-DS	104	460	37.7	Shear Failure + Delamination of CFRP Laminates

4. Analytical Study

In the recent past, few analytical models are developed by researchers to theoretically predict the shear strength capacity of an externally FRP reinforced beam specimen. In this paper, three models are used to study the predicted shear strength capacity of the strengthened deep beam specimens and compare those with experimental result. The analytical model is described in the following part of this paper.

4.1. ACI 440 Model

The model proposed by ACI 440 [11] is applicable to reinforced concrete beams with externally applied FRP reinforcement. According to this model, the nominal shear strength of concrete is.

$$V_n = V_c + V_s + \psi_f V_{frp} \qquad (1)$$

Where ψ_f is the additional reduction factor given in Table 10.1 of the ACI 440 [11] document. For comparison purpose, as there is no reduction factor considered

during experiment, Eq.(1) is modified as

$$V_n = V_c + V_s + V_{frp} \qquad (2)$$

Where the shear strength contribution from FRP is

$$V_f = \frac{A_{fv} E_f \varepsilon_{fe} d_f (\sin\alpha + \cos\alpha)}{s_f} \qquad (3)$$

The effective strain, ε_{fe} in FRP is assumed to be smaller than the ultimate strain, ε_{fu}. This can be computed as

$$\varepsilon_{fe} = \begin{cases} 0.004 \le 0.75\varepsilon_u & \text{for completely wrapped beams} \\ k_v \varepsilon_{fu} \le 0.004 & \text{for beams with two or three sides laminated} \end{cases} \qquad (4)$$

$$k_v = \frac{k_1 k_2 l_e}{11900\varepsilon_{fu}} \le 0.75 \qquad (5)$$

$$L_e = \frac{23300}{(nt_f E_f)^{0.58}} \qquad (6)$$

$$k_1 = \left(\frac{f_c}{27}\right)^{\frac{2}{3}} \qquad (7)$$

$$k_2 = \begin{cases} \dfrac{d_f - L_e}{d_f} & \text{for U-wraps} \\ \dfrac{d_f - 2L_e}{d_f} & \text{for two sides laminated} \end{cases} \qquad (8)$$

Where, f_c and E_f are in MPa

4.2. Colotti et al. model

Colotti et al. [10] proposed that the total contribution of shear reinforcement can be expressed as

$$\psi = \psi_i + \psi_e \qquad (9)$$

The internal shear strength contribution coming from the internal steel reinforcement is

$$\psi_i = \frac{A_{st} f_y}{bsf_c} \qquad (10)$$

Where as, the external contribution form FRP is

$$\psi_e = \frac{2w_f t_f}{bs_f f_c} f_{fe}$$

for completely wrapped beams

$$\psi_e = \min\left(\frac{w_f d_f}{bs_f f_c}\tau_u ; \frac{2w_f t_f}{bs_f f_c}\right) \qquad (11)$$

for beams with two or three sides laminated

$$V = (\tau / f_c) b d_v f_c \qquad (12)$$

Where τ / f_c is the minimum of that obtained the following failure cases: (4)

From the following failure cases :

Failure case (1)

$$\tau/f_c = \frac{1}{2}\left[\sqrt{1+\alpha^2}-\alpha\right]+\psi\alpha$$

$$0 \le \psi \le \psi_0 = \frac{\sqrt{1+\alpha^2}-\alpha}{2\sqrt{1+\alpha^2}}$$

$$\tau/f_c = \sqrt{\psi(1+\psi)} \qquad \psi_0 \le \psi \le 0.5$$

$$\tau/f_c = \frac{1}{2} \qquad \psi > 0.5 \qquad (13)$$

Failure case (1)

For $\psi \le \psi_0$

$$\tau/f_c = \frac{1}{2}\left[\sqrt{4\eta(1-\eta)+\alpha^2}-\alpha\right] \qquad \eta \le 0.5$$

(14)

$$\tau/f_c = \frac{1}{2}\left[\sqrt{1+\alpha^2}-\alpha\right] \qquad \eta > 0.5$$

For $\psi > \psi_0$

$$\tau/f_c = \psi\left[\sqrt{\frac{2\eta}{\psi}+\alpha^2}-\alpha\right] \qquad (15)$$

Where $\eta = \frac{A_{st} f_{ly}}{bd_v f_c}$ and $\alpha = \frac{a}{d_v}$.

4.3. Triantafillou and Antonopoulos [8] Model

According to this model,

$$V_n = V_c + V_s + V_{frp} \le V_{R2} = 0.45 v_{co} f_c bd \qquad (16)$$

Where

$$V_f = \frac{A_{fv} f_{fe} d_f (\sin\beta + \sin\beta)}{S_f} \qquad (17)$$

Tensile strength of concrete, $f_{ct} = 0.3(f_c)^{2/3}$, concrete shear resistance, $\tau_R = 0.25 f_{ct}$, $k = 1.6 - d \ge 1$(d is in m), $\rho_l = \frac{A_{sl}}{bd}$, $\rho_f = \frac{A_f}{bs_f}$ and $v_{co} = 0.7 - f_c/200 > 0.5$ (f_c is in MPa).

The effective strain in this model expected was

$$\varepsilon_{fe} = 0.17\left(\frac{f_c^{2/3}}{E_f \rho_f}\right)^{0.30} \varepsilon_{fu}$$

For beams fully wrapped with CFRP

$$\varepsilon_{fe} = \min\left[0.00065\left(\frac{f_c^{2/3}}{E_f \rho_f}\right)^{0.56}; 0.17\left(\frac{f_c^{2/3}}{E_f \rho_f}\right)^{0.30} \varepsilon_{fu}\right]$$

For two or three sides with CFRP laminated

$$\varepsilon_{fe} = 0.048\left(\frac{f_c^{2/3}}{E_f \rho_f}\right)^{0.47} \varepsilon_{fu}$$

For beams fully wrapped with AFRP (18) (15)

5. Comparison

Results from both analytical and the experimental studies are shown in Table V and Fig.6. Shows the comparison of total shear capacity of deep beam specimen strengthened with CFRP and GFRP composites. As this figure indicates, the ACI 440[11] model is always providing shear strength of a FRP strengthened deep beam higher than these obtained from the experimental program. This can be attributed to the fact that this model has not considered the shear-to-depth ratio (a/D) of the deep beam in calculation of the shear strength. Hence, from this results it is evident that shear-to-depth ratio has an important effect on the shear strength capacity of RC FRP strengthened deep beams.

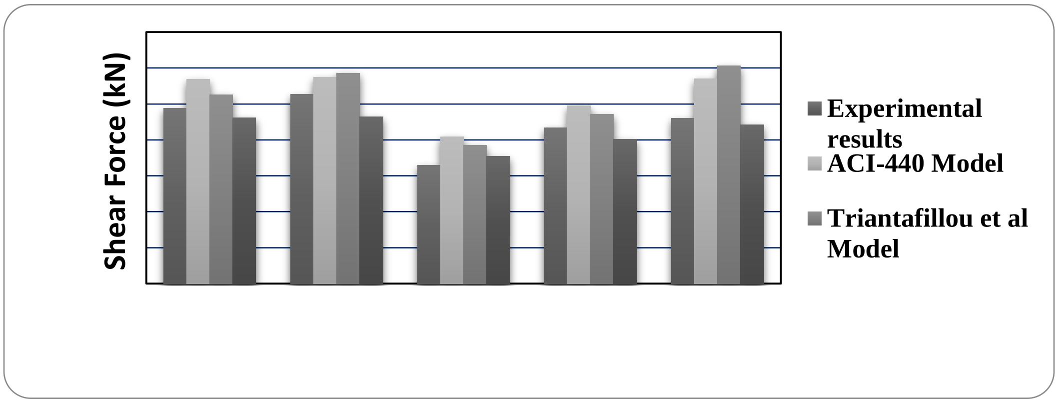


Fig. 6. Comparison of experimental results with theoretical values of strengthened beams

Table 5. Summary of Comparison of Experimental and Theoretical Results

Beam	Experimental results	ACI-440		Triantafillou et al		Colloti	
	V_u (kN)	V_u (kN)	Presence of different	V_u (kN)	Presence of different	V_u (kN)	Presence of different
CONa-VW(C)	244.5	284.3	16	284.3	7.5	231.3	5.4
CONa-DW(C)	264	287.1	8.7	293.3	11	232.3	12
CONa-VS1	165	204.3	23.8	192.7	16.8	177.4	7.5
CONa-VS2	217	247.7	14	235.8	8.6	201	7.3
CONa-DS	230	285.1	24	303	31.7	221.4	3.7

6. Conclusion

Based on testing eight deep beams and the analytical study, the following conclusions can be drawn:

1) Use of CFRP sheets or laminates and GFRP sheets for strengthening reinforced lightweight concrete is an effective method to increase its ultimate carrying capacity. An enhancement of shear strength was up to 58%.

2) The ductility of deep beams that strengthening with CFRP sheets or laminates is significantly reduced.

3) The best scheme used to strengthen lightweight concrete deep beams is to attach FRP sheets or laminates in the diagonal orientation.

4) The ACI 440[11] model does not consider the shear-to-depth ratio in prediction of the shear strength enhancement of a reinforced lightweight concrete deep beam strengthened with externally bonded FRP composites. For Lesser ratio (e.g. $\frac{a}{D} = 0.95$, as it is taken in the present experimental program), the experimental shear strength capacity is always less than those predicted by the ACI 440[12] model.

5) Similar to the ACI 440[11] model, Triantafillou and Antonopoulos[9] model always results in higher shear strength. This can be attributed to the fact that this model

does not consider the shear span-to-depth ratio(a/d).

6) Colotti et al.[10] model provides nearly the same estimation of the shear capacity of FRP strengthened beams as compared to experimental result in all two lamination schemes reported in this paper.

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