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Shear Strengthening of Continuous RC Beams Using Externally Bonded CFRP Sheets

Ahmed Khalifa, Gustavo Tumialan, Antonio Nanni, and Abdeldjelil Belarbi

Synopsis: This paper presents the results of an experimental investigation on the response of continuous reinforced concrete (RC) beams with shear deficiencies, strengthened with externally bonded carbon fiber reinforced polymer (CFRP) sheets. The experimental program consisted of nine full-scale, two-span, continuous beams with rectangular cross section. The tested beams were grouped into three series. Three beams, one from each series, were not strengthened and taken as reference beams, whereas, six beams were strengthened using different schemes. The variables investigated in this study included the amount of steel shear reinforcement, amount of CFRP, wrapping schemes, and $90^0/0^0$ ply combination. The experimental results indicated that the contribution of externally bonded CFRP to the shear capacity of continuous RC beams is significant and is dependent on the tested variables. In addition, the test results were used to validate shear design algorithms. The proposed algorithms show good correlation with the test results and provided conservative estimates.

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INTRODUCTION

Shear collapse of RC members is catastrophic and occurs with no advance warning of distress. Existing RC beams with shear deficiencies ultimately need strengthening. Deficiencies may occur due to factors such as insufficient shear reinforcement, reduction in steel area due to corrosion, increased service load, and design/construction defects. In such situations, it has been shown that externally bonded FRP sheets increase the shear capacity significantly (1, 2). At present, most of the studies have specifically addressed simply supported beams.

The objectives of this study were to investigate the shear behavior and mode of failure of continuous RC beams strengthened with CFRP sheets and to validate a proposed shear design approach (3, 4).

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EXPERIMENTAL PROGRAM

Test Specimens and Materials

The experimental program consisted of nine full-scale, two-span, continuous RC beams with a rectangular cross section of 150 by 305 mm. The beams were grouped into three series labeled CW, CO, and CF (Fig 1). Each series had different longitudinal and transverse steel reinforcement ratios.

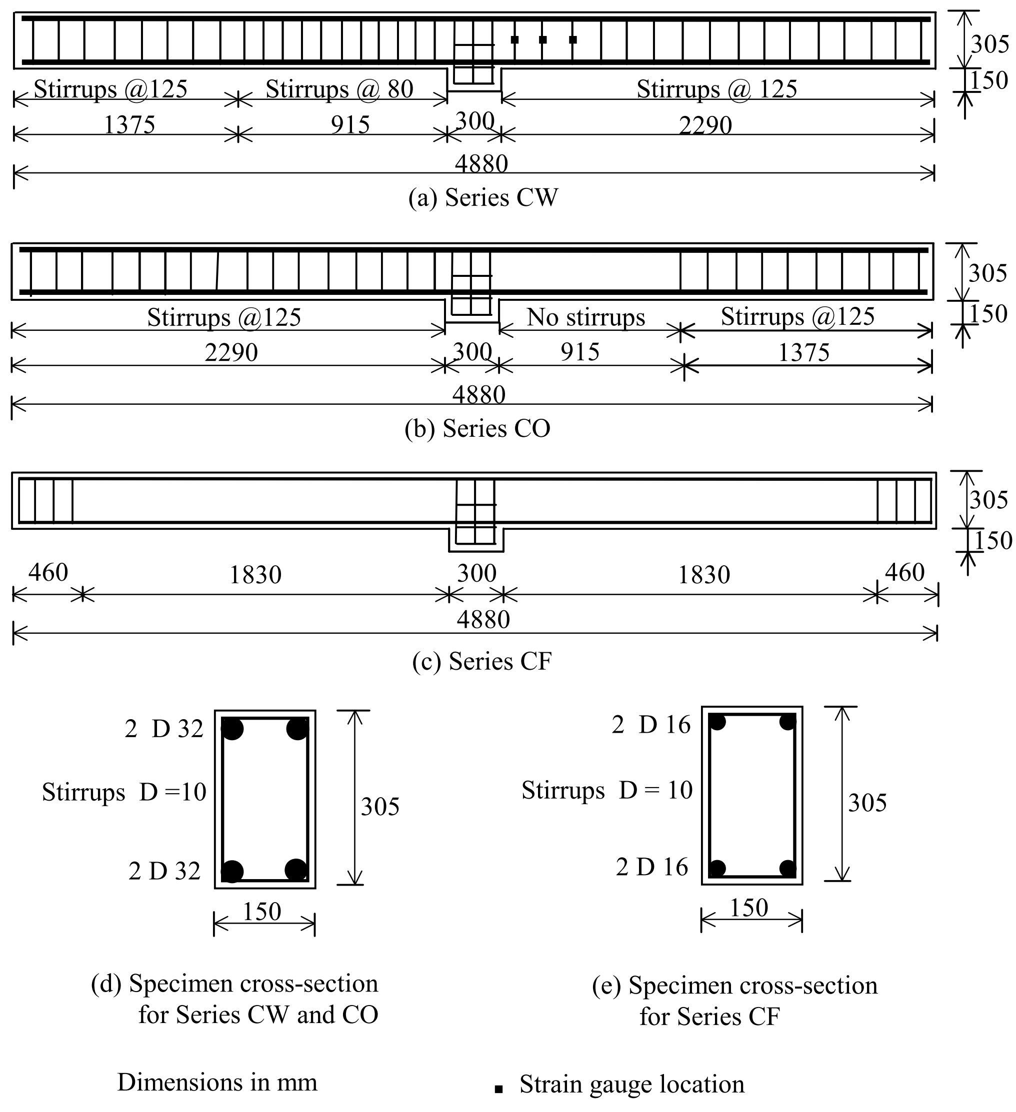

Figure 1. Beam specimens detailing and dimensions

Series CW consisted of two beams tested over a total span of 4,880 mm as shown in Fig. 1(a). The central support consisted of a 300-mm offset intended to represent the intersection with a column. The concrete strength was 27.5 MPa. In this series, two 32-mm bars were used as longitudinal reinforcement for both top and bottom face of the cross section to favor shear failure. The beams were reinforced with 10-mm stirrups throughout. The stirrup spacing in the shear span of interest was selected to force failure in that span. For each beam, six strain gauges were attached to three stirrups to monitor the stirrup strain during loading.

Series CO consisted of three beams, and had similar longitudinal reinforcement as that of series CW (Fig. 1(b)). No steel stirrups were provided in the tested shear span. The concrete strength for this series was 20.5 MPa.

Four beams were tested in series CF (Fig. 1(c)). The concrete strength for this series was 50 MPa. The beams were reinforced with two 16-mm longitudinal steel bars on both top and bottom faces with no shear reinforcement.

The mechanical properties of the materials used for manufacturing the test specimens are listed in Table 1. Fabrication of the specimens including surface preparation and CFRP installation is described elsewhere (4).

Table 1 – Materials properties

Material	Specifications	Compressive strength (MPa)	Yield point (MPa)	Ultimate tensile strength (MPa)	Modulus of elasticity (GPa)
Concrete	Series CW	27.5	----	----	25
	Series CO	20.5	----	----	22
	Series CF	50.0	----	----	33
Steel	D = 32 mm	----	460	730	200
	D = 16 mm	----	430	700	200
	D = 10 mm	----	350	530	200
CFRP*	t = 0.165 mm	----	----	3500	228

*Fiber only

Strengthening Schemes and Test Set-up

One beam from each series (CW1, CO1, and CF1) was not strengthened and was considered as a reference beam, whereas six beams were strengthened with externally bonded CFRP sheets following different schemes. The test setup as well as the strengthening schemes are shown in Fig. 2.

In series CW, beam CW2 was strengthened with two CFRP plies having perpendicular fiber directions ($90^0/0^0$). The first ply was attached in the form of continuous U-wrap with fiber direction oriented perpendicular to the longitudinal axis of the beam (90^0). The second ply was bonded to the two sides of the beam with fiber direction parallel to the beam axis (0^0). This ply may provide additional resistance to the horizontal component of the crack opening.

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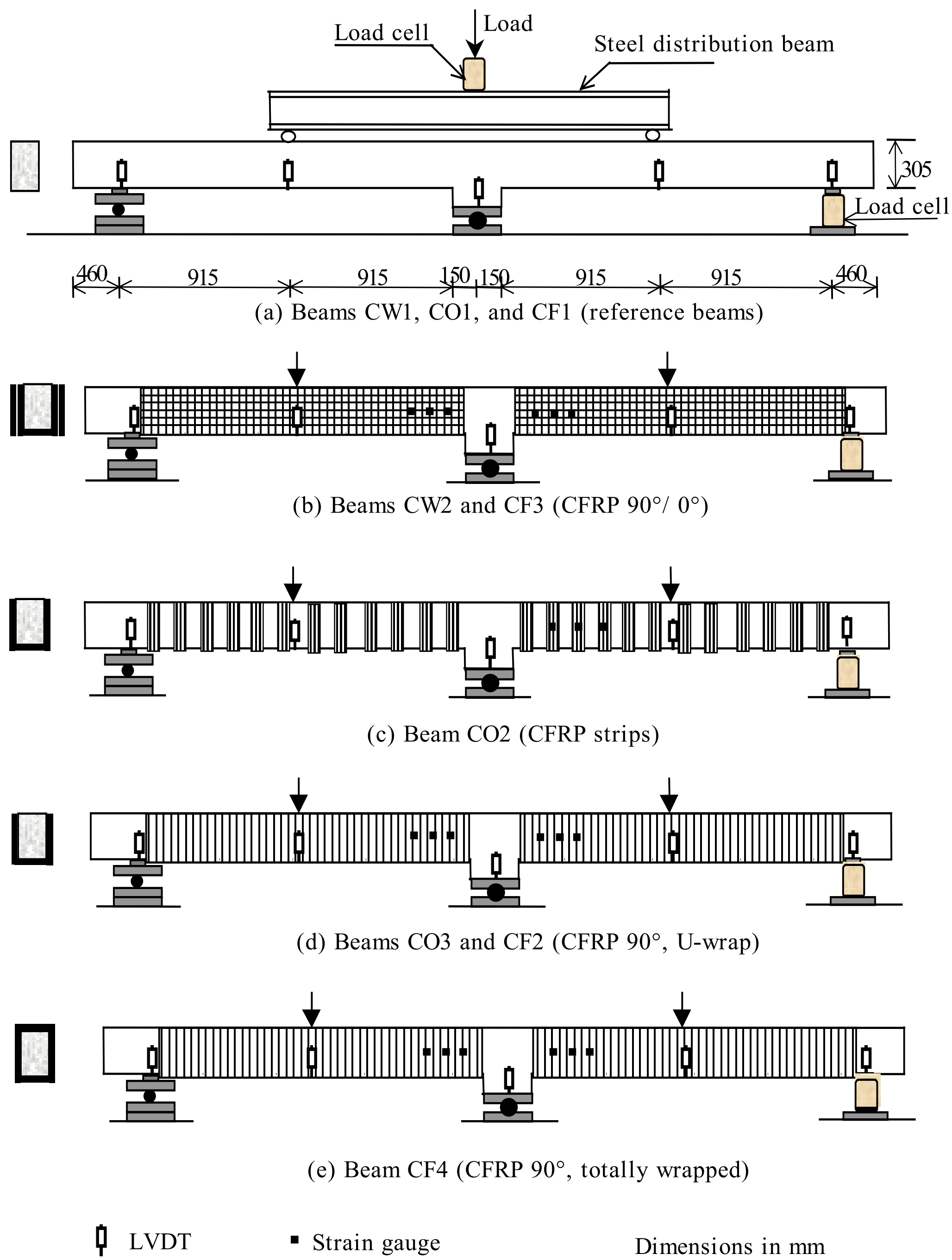

Figure 2. Test set-up and strengthening schemes

Two beams were strengthened in series CO. Beam CO2 was strengthened with one-ply CFRP strips in the form of a U-wrap with 90^0 fiber orientation. The strip width was 50 mm with center-to-center spacing of 125 mm. Beam CO3 was strengthened with one-ply continuous U-wrap.

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In series CF, three beams were strengthened. Beam CF2 was strengthened with one-ply continuous U-wrap. Beam CF3 was strengthened with two CFRP plies having perpendicular fiber directions ($90^0/0^0$). Beam CF4 was totally wrapped with one-ply CFRP sheets. The sheets were attached to the four sides of the beam with an overlap on the top side. Even though total wrapping may not be possible in the field, this case is representative of the upper threshold.

Specimens were tested as continuous beams under concentrated loads applied to the mid-point of each span. Two load cells were used to monitor total applied load and reaction at the span of interest. This allowed the computation of the exact shear force in the span of interest, independently of re-distribution phenomena. The load was applied progressively in few cycles, usually one cycle before cracking followed by three cycles to ultimate. The shear force versus deflection curves shown in this study are the envelopes of these load cycles. Five linear variable differential transformers (LVDTs) were used for each test to monitor the vertical displacement at various locations as shown in Fig. 2. Of these five LVDTs, one was placed at each support to monitor support movement. Three strain gauges were attached directly to the FRP on the sides of each strengthened beam of series CW and CO, and six in beams of series CF as shown in Fig. 2. The strain gauges were oriented in the vertical direction and located at mid-height with distances of 175, 300, and 425 mm from the face of the central support.

Test Results and Discussion

In the following discussion, reference is always made to the weak shear span (span of interest).

Series CW: A diagonal crack was observed in beam CW1 close to the middle of the shear span when the load was approximately 150 kN. As the load increased, more diagonal shear cracks formed throughout, widened and propagated up to failure, as shown in Fig. 3, at a load of 508 kN which corresponded to a shear force of 175kN. In beam CW2, strengthened with CFRP ($90^0/0^0$), the cracks on the beam sides and bottom were not visible because of the wrapping. Longitudinal cracks were observed on the beam topside at total applied load of 530 kN. The cracks initiated close to the position of the applied load and extended towards the middle support. At failure, the concrete cover on the top side was extensively damaged (Fig. 4). The failure occurred at a total load of 623 kN with a corresponding shear force of 214 kN, a 22% increase in shear capacity as compared to CW1. The applied shear force versus mid-span deflection curves for beams CW1 and CW2 are shown in Fig. 5. The maximum CFRP strain measured at failure in beam CW2 was about 0.0027 mm/mm, which corresponded to 17% of the ultimate strain. This indicates that CFRP can be stretched further and thus increase the shear capacity if properly used.

Figure 3. Final failure of beam CW1

Figure 4. Final failure of beam CW2

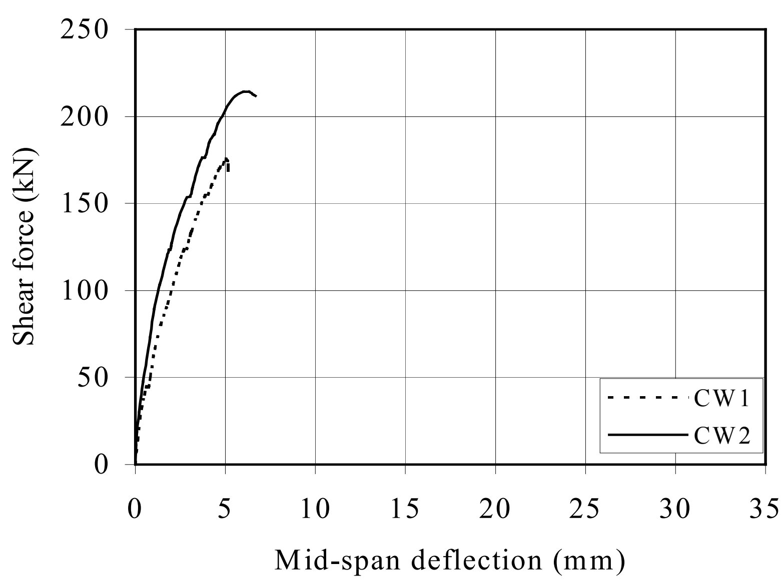

Figure 5. Shear force versus mid-span deflection for beams of series CW

$$R = 0.5622(\rho_f E_f)^2 - 1.2188(\rho_f E_f) + 0.778 \qquad (3)$$

$$R = \frac{(f'_c)^{2/3} w_{fe}}{\varepsilon_{fu} d_f}\left[738.93 - 4.06(t_f E_f)\right] \times 10^{-6} \qquad (4)$$

$$R = \frac{0.006}{\varepsilon_{fu}} \qquad (5)$$

In the above equations, E_f is the elastic modulus of CFRP in GPa, ρ_f is the CFRP area fraction ($\rho_f = (2t_f/b_w)(w_f/s_f)$), t_f is the thickness of CFRP in mm, b_w is the width of the beam cross section in mm, w_f is the width of CFRP strip (Fig. 10 shows the dimensions used to define d_f, w_f, β, and s_f), s_f is the spacing of CFRP strips (the maximum spacing, s_{fmax}. was suggested equal to $w_f + d/4$), and f'_c is the nominal concrete compressive strength in MPa. Note that, Equation 3 provides R for failure mode controlled by CFRP fracture and applicable for $\rho_f E_f \leq 0.7$ GPa, whereas Equation 4 describes the failure mode controlled by CFRP debonding and applicable for CFRP axial rigidity, $t_f E_f$, ranging from 20 to 90 GPa. Equation 4 may be disregarded if the sheet is wrapped entirely around the beam or an effective end anchor is used.

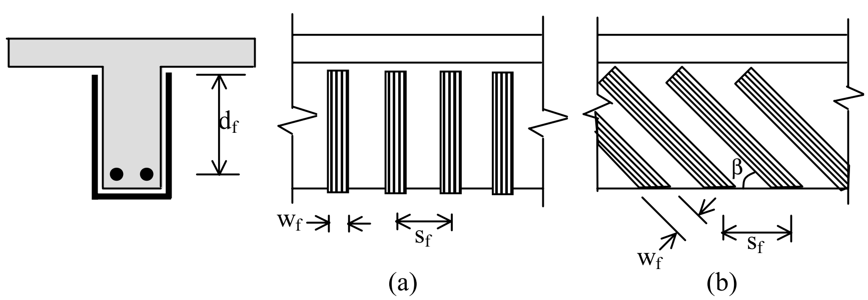

Figure 10. Dimensions used to define the area of FRP (a) Vertical FRP strips. (b) Inclined strips

The shear contribution of the CFRP, V_f, may then be found from the following expressions:

$$f_{fe} = R\, f_{fu} \qquad (6)$$

$$V_f = \frac{A_f f_{fe}(\sin\beta + \cos\beta) d_f}{s_f} \leq \left(\frac{2\sqrt{f'_c}\, b_w d}{3} - V_s\right) \qquad (7)$$

Where, A_f is the area of CFRP shear reinforcement ($A_f = 2t_f w_f$), β is the angle between fiber orientation and longitudinal axis of beam, and V_s is the nominal shear strength provided by stirrups. Note that if continuous vertical sheets are used, w_f and s_f should be equal.

The shear capacity of the beam may finally be computed from:

$$\phi V_n = 0.85(V_c + V_s) + 0.70V_f \quad (8)$$

Where ϕ is the strength reduction factor (suggested equal to 0.7 for CFRP contribution), V_n is the nominal shear strength, V_c is the nominal shear strength provided by concrete.

Shear Capacity of a CFRP Strengthened Section-Eurocode Format

The proposed design equation (Eq. 7) for computing the contribution of CFRP reinforcement may be rewritten in Eurocode format as Equation (9).

$$V_{fd} = \frac{A_f \left(f_{fe}/\gamma_f\right)\left(0.9d_f\right)\left(1+\cot\beta\right)\sin\beta}{s_f} \quad \leq \quad \left[V_{Rd2} - \left(V_{Rd1} + V_{wd}\right)\right] \quad (9)$$

Where V_{fd} is the design shear contribution of CFRP to the shear capacity, γ_f is the partial safety factor for CFRP materials (suggested equal to 1.3), V_{Rd2} is the maximum design shear force that can be carried without web failure, V_{Rd1} is the design shear capacity of concrete, and V_{wd} is the design contribution of steel shear reinforcement.

Comparison between Test Result and Calculated Values

The computed design contributions of CFRP in ACI code format, including the ϕ factor, to the shear strength of the tested beams CW2, CO2, and CO3 were 24.6, 16.5, and 41 kN, respectively. Compared to the experimental contributions, 39, 40, and 65 kN, the design algorithms give acceptable and conservative results.

CONCLUSIONS

In this study, the shear behavior and modes of failure of two-span continuous RC beams strengthened with CFRP sheets were investigated. The test results indicated that the externally bonded reinforcement can be used to enhance the shear capacity of the beams in positive and negative moment regions. For the beams tested in the experimental program, increases in shear strength ranged from 22 to 135%. Test results also indicated that the CFRP contribution is enhanced to a large degree for beams without stirrups than for beams with adequate steel shear reinforcement. The test results were used to validate design algorithms for computing the shear contribution of externally bonded CFRP sheets. The calculated values gave conservative results.

ACKNOWLEDGEMENTS

This work was conducted with partial support from the University Transportation Center on Advanced Materials and Non-Destructive Testing (NDT) Technologies based at the University of Missouri - Rolla. The Egyptian Cultural and Educational Bureau provided support to the first author.

REFERENCES

(1) Arduini, M., Nanni, A., Di Tommaso, A., and Focacci, F., "Shear Response of Continuous RC Beams Strengthened with Carbon FRP Sheets," Non-Metallic (FRP) Reinforcement for Concrete Structures, Proceeding of the Third Symposium, Vol. 1, Japan, Oct. 1997, pp. 459-466.

(2) Triantafillou, T.C., "Shear Strengthening of Reinforced Concrete Beams Using Epoxy-Bonded FRP Composites," ACI Structural Journal, Vol. 95 No. 2, March-April 1998, pp. 107-115.

(3) Khalifa, A., Gold, W., Nanni, A., and Abdel -Aziz M. I., "Contribution of Externally Bonded FRP to the Shear Capacity of RC Flexural Members," Journal of Composites for Construction - *ASCE*, Vol. 2, No. 4, Nov. 1998, pp. 195-202.

(4) Khalifa, A., "Shear Performance of Reinforced Concrete Beams Strengthened with Composites," Ph.D Thesis, Structural Engineering Department, Alexandria University, Egypt, 1999.

(5) Maeda, T., Asano, Y., Sato, Y., Ueda, T., and Kakuta, Y., "A Study on Bond Mechanism of Carbon Fiber Sheet," Non-Metallic (FRP) Reinforcement for Concrete Structures, Proceeding of the Third Symposium, Vol. 1, Japan, Oct. 1997, pp. 279-286.

(6) Miller, B., " Bond between Carbon Fiber Reinforced Polymer Sheets and Concrete," MSc Thesis, Department of Civil Engineering, University of Missouri, Rolla, MO, 1999.

Khalifa, A., Tumialan, G., Nanni, A. and Belarbi, A., "Shear Strengthening of Continuous RC Beams Using Externally Bonded CFRP Sheets," SP-188, American Concrete Institute, Proc., 4th International Symposium on FRP for Reinforcement of Concrete Structures (FRPRCS4), Baltimore, MD, Nov. 1999, pp. 995-1008.

Keywords: Bond; Carbon fiber; Continuous beam; Externally bonded reinforcement; Fiber reinforced polymer (FRP); Flexural strength; Reinforced Concrete; Shear strength; Strengthening