Experimental study on the shear behavior of GFRP reinforced concrete beams strengthened using CFRP sheets

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Abstract. This paper presents the results of an experimental investigation on the shear capacity of reinforced concrete beams. The beams under consideration are reinforced with glass fiber-reinforced polymer (GFRP) bars. Also, the effect of shear strengthening on such beams is studied. For this purpose a total of four beams were tested where two served as control beams, while the other two were strengthened using U shape carbon fiber-reinforced polymer (CFRP) sheets, bonded externally. Each beam is 2.4 m long, simply supported and subjected to a four-point load under displacement control mode. The strengthened beams showed a noticeable increase in the load-bearing capacity of the specimen. The failure load recorded of these specimens was 208 kN, an increase of 25%. Moreover, the mode of failure changed from pure shear to concrete crushing in the compression zone. The results indicate that using CFRP sheets to strengthen GFRP reinforced beams is a viable option. However, the results also suggest that the known adverse interaction between EB-CFRP and conventional steel stirrups could be applicable between EB-CFRP and GFRP shear reinforcement in strengthened beams. Therefore the predicted EB-CFRP shear capacity by ACI 440.2R turned to be unconservative when compared to the experimental results.

1. Introduction
Concrete and steel as being commonly used construction materials have an extensive track record for over 150 years. Design methods and applications of these materials have been already established and advanced. However, the fiber-reinforced polymers (FRP) is a newly introduced material to the construction industry. And some of the behavioral aspects of this material are not yet established. FRP is a composite material made of polymer matrices reinforced with fibers. The fibers are usually glass, carbon, aramid, or basalt. While polymer can be epoxy, vinyl ester, or polyester thermosetting plastic [1]. Such materials (FRP) can be used as internal reinforcement in form of reinforcement bars or as an external reinforcement in form of warp fabric sheet or strip for strengthening or repair of existing deficient structural members [2]–[4]. FRPs are known for their durability, non-corrosiveness, lightweight, high strength to weight ratio, nonmagnetic, and ease in usage [5].

Under severe environmental conditions structures are prone to deterioration particularly due to corrosion of traditional steel reinforcement. To tackle this drawback associated with steel reinforcement, the FRP bars have emerged as a possible alternative to steel bars. The use of GFRP rebars as reinforcement has been intensively studied in the literature [6]–[9]. Some of these studies undertook the bonding behavior between the FRP reinforcement and concrete. While other researchers studied the shear and the flexural capacity of structural members containing these types of reinforcements [10]–[12]. For instance, Kassem et al. [7] evaluated the flexural behavior of 24 beams specimens reinforced with different types of FRP bars. It was concluded that the sand coated bars had better bond compared to the bars with ribbed surface. All the tested beams eventually failed due to...
concrete crushing which is the preferred mode of failure in FRP reinforced beams. In addition the paper reported that the CSA S806-02 model was better fitting the experimental data.

Owing to its superior durability, the FRP strip can be externally bonded to a concrete member to restore or even improve its load-carrying capacity. For instance, it can be used for upgrading the bridge capacity in case of higher traffic volume, seismic retrofitting, or even adding another floor to an existing building [13]. Although the use of FRP as an internal and external reinforcement is widely reported in a conventional reinforced member [3]. The use of glass fiber reinforced polymer (GFRP) stirrups as shear reinforcement of a beam is not well studied. On the other hand, strengthening the beams using the growing technique of externally bonded carbon fiber reinforced polymer (EB-CFRP) sheets has been widely studied in the literature. However, shear strengthening using EB-CFRP is still a matter of research [14-17]. Moreover, there does not exist a study in the literature that investigates the shear strengthening of GFRP reinforced concrete beams.

In the current study beams with GFRP bars used as longitudinal and shear reinforcement is studied. One of the two objectives was to investigate the use of GFRP bars as replacement to the conventional steel which is prone to corrosion. The studied beams were intentionally designed to be shear deficient for achieving the second objective of the study which is shear strengthening using EB-CFRP technology. A total of four beams which are part of an ongoing extensive research project, were considered in this experimental research paper.

2. Experimental Program

2.1. Materials and Test Specimens

The concrete mix used to cast the test specimens was OPC based with an average 28 days compressive strength of 50 MPa. The mix proportions of the concrete used to cast the beams are shown in Table 1. The test specimens were reinforced with GFRP longitudinal bars and stirrups. The GFRP longitudinal bars and stirrups were manufactured and provided by Pultron composites company under the product name MateenBar ($f_{cu}=690$ MPa, $E_f = 51 \pm 2.5$ GPa, and $\varepsilon_{fu}=0.0135$). For shear strengthening of the test specimens, a uni-directional carbon fiber reinforced polymer (CFRP) fabric sheets provided by Conmix LTD was used ($f_{cu}=4000$ MPa, $E_f = 230$ GPa, and $\varepsilon_{cu}=1.8 \%$).

The test specimens were 2400 mm long beams with a rectangular cross-section of 200 x 300 mm, and an effective depth of 250 mm and an active span of 2100 mm (see Figure 1). The control beams were designed as per the ACI 440.1R-06 guideline such that the shear failure will be the dominant mode of failure even in addition to strengthening. Therefore, the beams were over reinforced in flexural by placing #22 GFRP bars in tension zone and also 2#10 in the compression zone. While only minimum shear reinforcement was considered by using #8 GFRP stirrups spaced at 200mm c/c. A total of four beams were cast where two were tested to failure without strengthening served as control beams and two were strengthened in shear prior to testing.

| Constituent          | Quantity | Unit |
|----------------------|----------|------|
| OPC                  | 365      | kg/m³ |
| 20mm aggregates      | 646      | kg/m³ |
| 10mm aggregates      | 290      | kg/m³ |
| 5mm fine aggregates  | 530      | kg/m³ |
| Dune sand            | 369      | kg/m³ |
| Superplasticizer     | 4        | Liter/m³ |
| Water                | 175      | Liter/m³ |

Table 1. Concrete mix proportions
2.2. Strengthening Methodology
In this study, two out of four GFRP reinforced beams were strengthened in shear using one layer of EB-CFRP discrete sheets (strips) in a U shape configuration. The strips were 130 mm wide and spaced at 200 mm center to center of the strips (net spacing of 70 mm). The strips were bonded vertically to the sides and soffit of the beams by adopting the wet layup application. It should be mentioned that prior to bonding and encapsulation of the CFRP strips, surface preparation was executed. Therefore, the surface of the beams was first ground, and surface irregularities were leveled using mortar then a primer coat was applied. In addition, the corner of the beams were chamfered to prevent stress concentration. Figure 2 shows the layout of strengthening along with a photo showing the application of EB-CFRP on to the beams.

![Figure 1. Test specimens’ dimensions and reinforcement details](image)

(a) Schematic layout of EB-CFRP strengthening

(b) Application of EB-CFRP sheets to the studied specimens
2.3. Test Setup and Instrumentation

The beams were tested under a four-point static loading in a simply supported configuration as shown in Figure 3. The load was applied using a hydraulic actuator with a rate of 0.01 mm/sec in a displacement control mode. A linear variable displacement transducer (LVDT) was deployed under the beam in the midspan to measure the beam deflection during test. Meanwhile, electrical resistance surface mounted strain gauges were attached to EB-CFRP sheets to measure the strain development under the load.

![Figure 3. Schematic diagram of the test set up](image)

2.4. Test Results

Figure 4 shows a photo of the control beam and a strengthened beam after failure. As can be seen in Figure 4a, the control beams failed in shear evident from diagonal shear crack on both the shear spans as expected. The control beams resisted an average maximum load of 165 kN and a maximum deflection of 25 mm (see Figure 5) prior to collapse due to the major shear crack. However, the strengthened beams failed due to concrete crushing at the compression zone. The average maximum load and maximum deflection for the strengthened beams were 208 kN and 45 mm respectively as shown in Figure 5.

![Figure 4. Wrapping configuration and process](image)
3. Discussion

3.1. Shear Strength Increment and Failure Modes

The shear strength of the beams which is half of the registered applied ultimate load are presented in Table 2 along with maximum deflection and failure modes. The shear strength of the reference beams is recorded directly from the testing device. Similarly, for the total shear capacity of strengthened beams. However, the contribution of the EB-CFRP sheets to the shear strength can be calculated by subtracting the shear strength of the control beams from that of the strengthened beams.

| ID   | Ultimate Load P (kN) | Shear Capacity Vn (kN) | Increase in Shear Capacity (%) | Deflection at Failure (mm) | Failure mode          |
|------|----------------------|------------------------|-------------------------------|---------------------------|-----------------------|
| Ctr1 | 173                  | 87                     | NA                            | 24                        | Diagonal Shear Crack  |
| Ctr2 | 157                  | 79                     | NA                            | 27                        | Diagonal Shear Crack  |
| Str1 | 208                  | 104                    | 20                            | 45                        | Concrete Crushing     |
| Str2 | 208                  | 104                    | 32                            | 45                        | Concrete Crushing     |
3.2. Guidelines Predictions

The internal shear reinforcement used were based on the prediction model of ACI 440.1R:

\[ V_n = V_c + V_f \quad (1) \]

Where, \( V_c \) is the shear contribution of the concrete for an FRP-reinforced member:

\[ V_c = \frac{2}{5} \sqrt{f'_c b_w c} \quad (2) \]

\[ c = kd \quad (3) \]

\[ k = \sqrt{2 \rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f \quad (4) \]

\[ \rho_f = \frac{A_f}{b_w d} \quad (5) \]

And, \( V_f \) is the FRP stirrups contribution in shear:

\[ V_f = \frac{A_{fv} f_{v} d}{S} \quad (6) \]

A minimum shear reinforcement was provided:

\[ A_{fv, min} = 0.35 \frac{b_w s}{f_{fv}} \quad (7) \]

\[ S = \frac{\Phi A_{fv} f_{v} d}{V_u - \Phi V_c} \quad (8) \]

\[ f_{fv} = 0.004 E_f \leq f_{fb} \quad (9) \]

Where \( b_w \) is the web width, \( c \) is cracked transformed section neutral axis depth, \( d \) is the distance from the compression zone to tension reinforcement, \( S \) is spacing of FRP stirrups, \( f_{fv} \) is the tensile strength of FRP, \( E_f \) is the elastic modulus of FRP reinforcement, \( \rho_f \) is FRP reinforcement ratio, \( n_f \) is modular ratio, and \( f_{fb} \) the allowable stress in the stirrup at the location of a bend.

It was decided to strengthen the beams such that the shear strength of the beams will be increased by at least 30%. To obtain the targeted increase in shear strength, ACI 440.2R guideline was adopted to design the strengthening configuration and specify the required width and spacing of CFRP sheets. Only one layer of EB-CFRP sheets with a thickness of 0.168 mm, width of 130 mm, and spacing of 200 mm was used. The predicted contribution of EB-CFRP sheets to shear strength of the beams is calculated using following equations:

\[ V_{frp} = \psi \cdot \frac{A_{frp} \cdot f_{frp,e} \cdot (\cos \alpha + \sin \alpha) \cdot d_{frp}}{s_{frp}} \quad (10) \]

\[ A_{frp} = 2 \cdot n \cdot t_{frp} \cdot w_{frp} \quad f_{frp,e} = \varepsilon_{frp,e} \cdot E_{frp} \quad (11) \]
Where, $\Psi$ is the reduction factor equal to 0.85, $A_{frp}$ is the area of CFRP sheet, $f_{frp,e}$ is CFRP effective stress at failure, $d_{frp}$ is the CFRP effective height, $S_{frp}$ is the spacing between two adjacent FRP discrete sheets, $\alpha$ is the angle of fiber orientation, $n$ is the number of CFRP layers applied, $t_{frp}$ is the thickness of CFRP sheet, $w_{frp}$ is the width of one discrete sheet, $\varepsilon_{frp,e}$ is CFRP effective strain at failure, $E_{frp}$ is FRP elastic modulus, $\varepsilon_{frp,u}$ is CFRP ultimate strain, $L_e$ is the CFRP effective length, $k_v$ is bond dependent coefficient, $k_1$ is modification factor to account for concrete strength, and $k_2$ is modification factor to account for FRP wrapping scheme.

Table 3 shows the experimental values of shear strength contribution by concrete, GFRP, and EB-CFRP along with the shear capacity predictions by ACI models namely ACI 440.1R and ACI 440.2R. Comparison of the experimental values with that of the model predictions reveals that the ACI 440.1R reasonably predicts the shear strength of control beams with a ratio ($V_{exp}/V_{ns,pre}$) of 1.2. However, the ACI 440.2R model overestimated the shear contribution provided by EB-CFRP sheets. The experimental value of EB-CFRP shear contribution was calculated by simple subtraction of $V_{nc}$ ($V_c+V_f$) from $V_{ns}$ ($V_c+V_f+V_{FRP}$). This turned to be an average of 21 kN while the model prediction was 42 kN. Therefore, the ratio of $V_{exp}/V_{FRP}$ is less than 1 for the case of strengthened beams. Which indicates that there is possibility of an interaction between GFRP stirrups and CFRP sheets similar to the case of normal steel reinforced concrete strengthened beams that affects the model predictions. However, further investigation is needed to address this issue.

### Table 3. Comparison of guidelines predictions with experimental results

| ID  | Shear Capacity $V_{exp}$ (kN) | ACI 440.1R Model Predictions $(V_c+V_f)_{pre}$ (kN) | ACI 440.2R Model Predictions $V_{FRP,pre}$ (kN) | ACI Model Predictions $V_n(V_c+V_f+V_{FRP})$ (kN) | $V_{exp}/V_{ns,pre}$ |
|-----|-----------------------------|-----------------------------------------------|-----------------------------------------------|-------------------------------------------------|-----------------------|
| Ctr1| 87                          | 72                                           | -                                            | 72                                              | 1.2                   |
| Ctr2| 79                          | 72                                           | -                                            | 72                                              | 1.1                   |
| Str1| 104                         | 72                                           | 42                                           | 114                                             | 0.9                   |
| Str2| 104                         | 72                                           | 42                                           | 114                                             | 0.9                   |

### 4. Conclusions

This work looks at the shear behavior of GFRP reinforced concrete beams and the applicability of using CFRP sheets for strengthening such composite systems. The following conclusions can be drawn from this work:
1. GFRP shear reinforcement is a viable alternate to traditional steel reinforcement in shear.

2. The prediction model as put forward by ACI 440.1R for GFRP reinforced concrete beams gives accurate prediction to the ultimate shear load capacity.

3. Discrete CFRP sheets may be used to strengthen GFRP-concrete composite systems in shear. The current work indicate that an average strength gain of 25% was achieved using a single layer of CFRP sheet. The deflection behavior of the strengthened beams was also altered significantly, with both specimens behaving in a ductile manner with a maximum mid-span deflection of 40mm (an increase of 60%).

4. The strengthening model as proposed by ACI 440.2R over predicts the shear capacity provided by EB CFRP sheets. This may indicate a possible interaction between the GFRP shear stirrups and the CFRP sheets, as also reported for traditional steel shear reinforced beams. However further investigation is need to investigate this interaction.

5. References
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Acknowledgments
The authors would like to acknowledge the support provided by Pultron Composites company for providing the GFRP bars and Conmix LTD for supplying the CFRP sheets. The project was funded by grant number (1602040128-P) from University of Sharjah. The help of Sustainable Construction Material & Structural System research group and contribution of Eng. Ahmed Shweiki during testing is also appreciated.