# SHEAR BEHAVIOR OF RC T-BEAMS STRENGTHENED WITH CFRP WRAPS

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## ABSTRACT

The use of carbon fiber reinforced polymer (CFRP) laminates as an effective and versatile technique for strengthening reinforced concrete structures has developed extensively in recent years. The present study investigates the shear response, including the load-carrying capacity and mode of failure, of simply supported reinforced concrete T-beams strengthened with CFRP fabrics. The experimental program consisted of eight large-scale simply supported beams subjected to a symmetrical arrangement of two patches of loads. The variables investigated include the shear span to effective depth ratio, a/d and the method of shear strengthening using CFRP fabrics. Test results indicated that the contribution of CFRP fabrics to the shear capacity was significant. The gain in shear strength ranged from 59% to 104% depending mainly on the parameters investigated. Results were compared with the predictions following the shear provisions of ACI Committee 440. The comparison revealed that the provisions are conservative.
**Keywords:** *Shear Strengthening, RC T-Beams, Composite Materials, CFRP Fabrics*

## INTRODUCTION

Strengthening of RC structures using epoxy-externally-bonded fiber-reinforced polymer (FRP) composites have recently gained acceptance in the construction field. FRP composites present many advantages particularly with regard to resistance to corrosion and ease of execution. However, the used composite material system may need a protective system for fire resistance [1]. As a result, extensive research work on various aspects has been published in the last decade [2]. Most of the research studies, however, were undertaken for flexural strengthening and for retrofit of circular columns. Investigations on shear strengthening with FRP are few and mostly limited to beams with rectangular cross-section and a shear span to effective depth ratio between 2.5 and 4.5 [3-7].

Reinforced concrete T-beams represent a more challenging condition compared to rectangular beams as the flange reduces the web height available for FRP bonding. Khalifa *et al.* [8] presented test results of five T-beams strengthened in shear with CFRP fabrics in the form of side strips or U-wraps with and without end anchor. All specimens were tested as simple beams with a shear span to depth ratio, a/d of 3. Debonding of CFRP was reported to be the cause of failure for all test beams except the beam that was strengthened with U-wraps anchored at the corner of flange-web. Incidentally, the U-anchor scheme presented by Khalifa *et al.* [8] was impractical. Experimental investigation conducted by Deniaud and Cheng [9] on five T-beams strengthened externally in shear using three types of FRP: uniaxial glass fiber, uniaxial carbon fiber and triaxial glass fiber, yielded comparable results. Despite the U-wraps were extended underneath the flange to provide a minimum anchorage length of 100 mm, the typical failure mode was characterized by de-bonding and peeling of the FRP sheets above the concrete shear crack. On the other hand, wrapped T-beams with an a/d ratio of 2 was reported [10] to be typically failed in diagonal compression following peeling and rupture of CFRP fabric near the beam support, although they were strengthened with U-wraps of unanchored ends. Since the premature failure of bonded CFRP fabric through peel-off was reported to be the common cause of failure, it is essential to be aware of the strengthening method adopted. Further, good preparation of the concrete surface beneath the fabric as well as efficient anchorage for the fabric in regions of stress concentration is beneficial.

The objective of this study was to evaluate the performance of externally bonded CFRP fabrics in enhancing the load-carrying capacity in shear of reinforced concrete T-beams. The study presents the experimental results of T-beams strengthened with CFRP fabrics. Relating to the shear span-to-effective depth ratio, the effectiveness of various but practical strengthening schemes was investigated. In addition, the compliance of ACI 440 provisions [11] with respect to the shear strengthening of T-beams was also reviewed.

## EXPERIMENTAL PROGRAM

The main parameters studied in this investigation are the effect of shear span to effective depth ratio, and the most effective shear strengthening scheme including CFRP end anchorage.

### Test Specimens

Eight reinforced concrete beam specimens were tested and classified into two series identified S1 and S2 depending on the shear span to effective depth ratio (a/d). The a/d ratio was 1.70 for the beams of Series S1 and 2.50 for the beams of Series S2. The specimens were designed to fail in shear, and had identical dimensions and reinforcement, refer to Fig. 1.

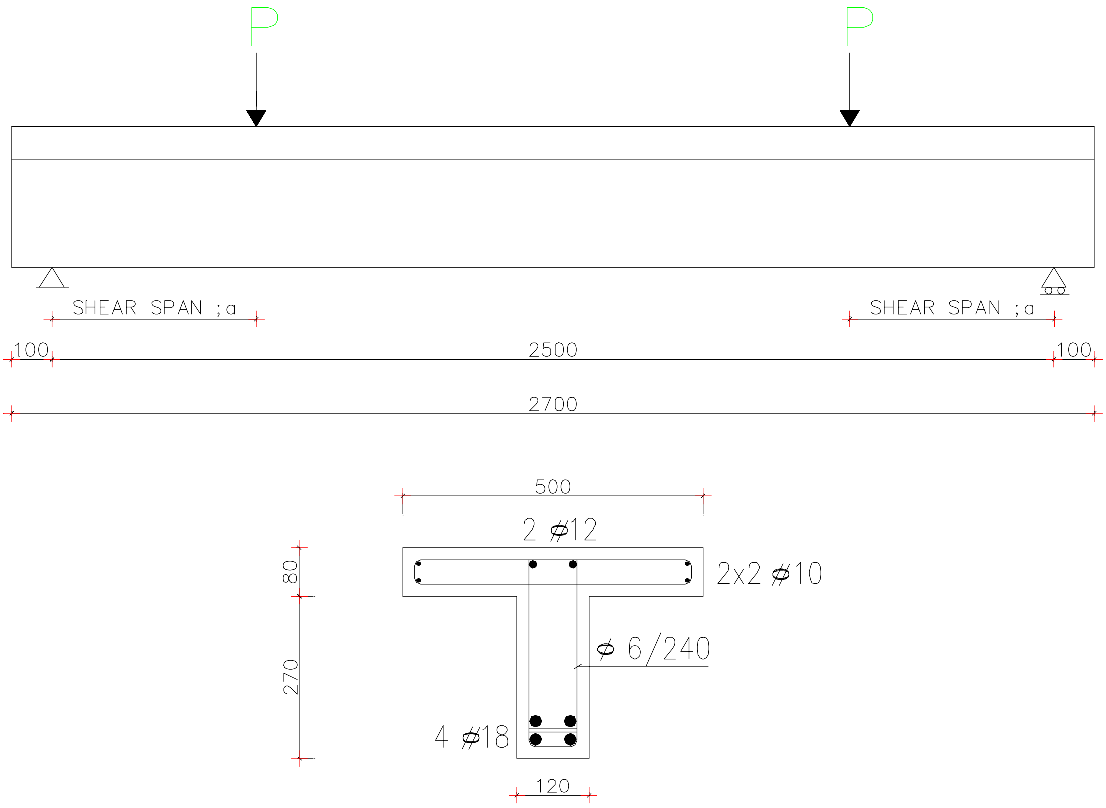


Fig. 1 Typical concrete dimensions and steel reinforcement

**Strengthening Configuration**

Considering the strengthening pattern, each beam of Series S1 had a resembling one in Series S2. The corresponding specimens of Series S1; B1, B2, B3, and B4 in Series S2 are B5, B6, B7, and B8, respectively. Beam Specimens B1 and B5 were tested without CFRP reinforcement to serve as control specimens. The rest of the beam specimens were reinforced with externally bonded CFRP strips having uni-directional fibers in the form of U-wraps. The surface of the concrete beneath the wraps were roughened and then leveled before sticking on the wraps using epoxy adhesive. The U-wraps were terminated underneath the beam flange for Specimens B4 and B8, whereas they were extended 100 mm cemented to the flange intrados for Specimens B2, B3, B6, and B7. In addition, Specimens B2 and B6 had 25x25x5 mm steel angles riveted to the beam at the web-flange intersections to avoid debonding of the CFRP fabric. Figure 2 sketches the aforementioned strengthening patterns.

The mechanical properties of the materials used, including concrete, steel reinforcement, and CFRP strips, are summarized in Table 1. Detailed characteristics of the materials and the method of fabrication of the test beams are presented elsewhere [12].

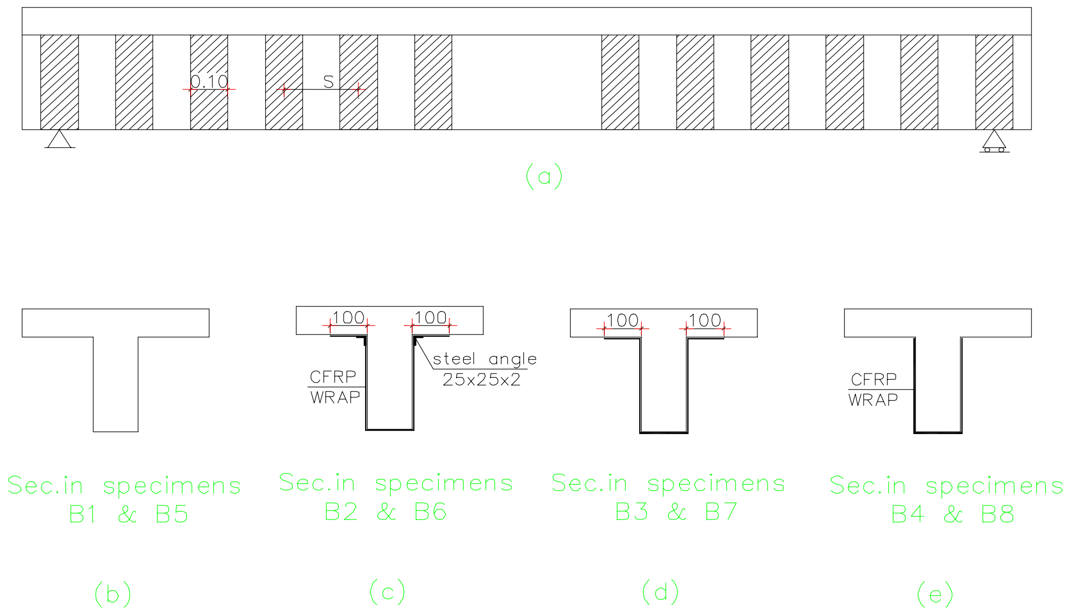



Fig. 2 Strengthening schemes

Table 1: Material properties

| Material | Diameter (Thickness) (mm) | Yield strength (MPa) | Compressive strength (MPa) | Tensile strength (MPa) | Modulus of elasticity (GPa) |
|---|---|---|---|---|---|
| Concrete | -- | -- | 34.33 | 3.93 | 25.7 |
| Steel RFT. | 6 | 240.0 | -- | 360.0 | 196.2 |
| | 12 | 274.6 | -- | 415.2 | 196.2 |
| | 18 | 392.4 | -- | 569.0 | 196.2 |
| CFRP fiber | 0.176 | -- | -- | 3873.5 | 244.6 |

**Test Setup and Instrumentation**

Three Linear Voltage Displacement Transducers (LVDTs) were arranged at midspan to monitor the deflection of the beam and to measure the compressive and tensile strains in concrete. An additional LVDT was fastened at the middle of the shear span to measure the diagonal strain in the concrete. Electrical resistance strain gauges were fastened to the specimen's longitudinal bars, stirrups, and CFRP fabrics to measure the strains at different loading levels, Fig. 3. All instruments were connected to a high-speed data acquisition system that made it possible to monitor the response of the specimens throughout the test.

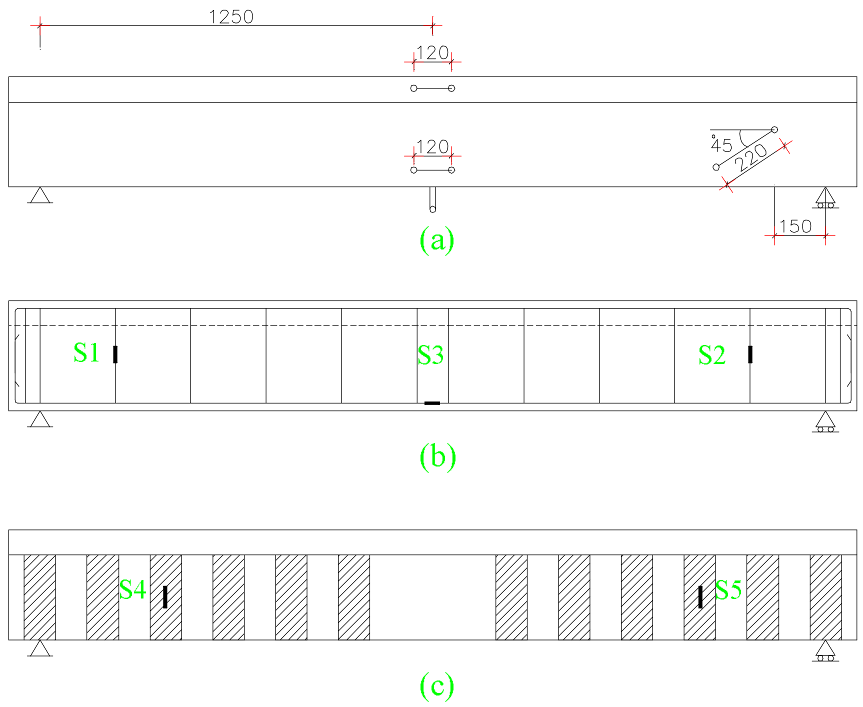



Fig. 3 Instrumentation of test specimens: a) LVDT's on concrete surface; b) Strain gauges on steel RFT; c) Strain gauges on fibers

**Test Procedure**

All specimens were tested under a symmetrical arrangement of two-patch loads applied at the beam's top face, as shown in Fig. 1. The loads were imposed using displacement-controlled movements of hydraulic jacks following a specified displacement history. Specimens were not loaded nor pre-cracked before strengthening them representing the case of upgrading rather than retrofitting. Testing was terminated when the load at a given displacement was degraded to about 80% of the ultimate load, i.e. about 20% loss in the vertical load-resisting capacity.

## RESULTS AND DISCUSSION

**Test Beams of Series S1 (a/d=1.7)**

For the control Specimen B1, shear cracking commenced in the middle of the shear spans at a load of 116 kN. The formation of new inclined cracks with widening of the old ones continued up to failure. The test beam failed in a mode of shear failure characterized by concrete spalling in the beam web and local crushing near the support. The ultimate load was 239 kN. At failure, the strain in the longitudinal tension bars remained below the yield value. On the other hand, the strain in the steel stirrups reached the yield strain at 49% of the ultimate load as shown in Fig. 4.

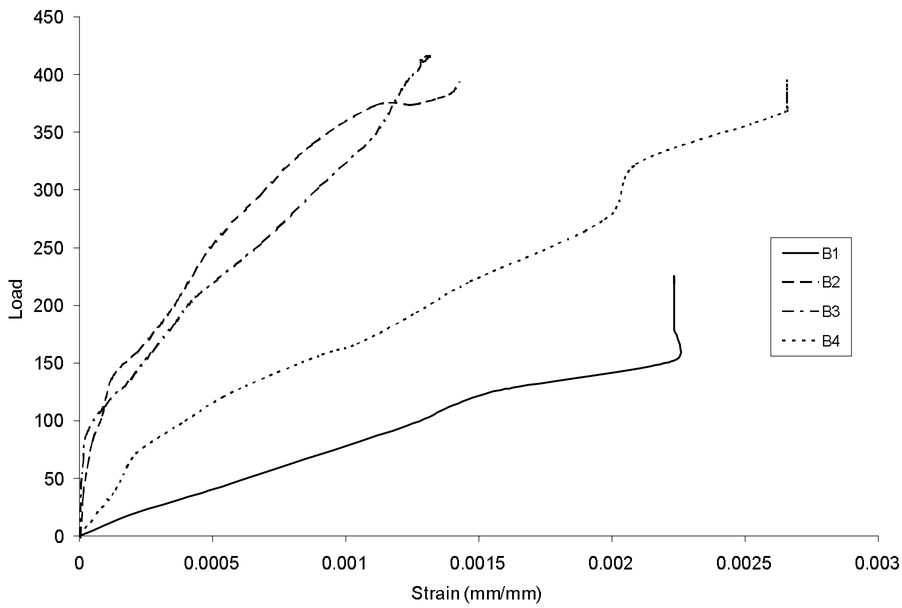



Fig. 4 Variation of strain in steel stirrups of Series S1

Referring to the observed behavior of test Specimens B2, B3, and B4, the shear strengthening using CFRP strips with different techniques had a slight effect on the onset of shear cracking as indicated in Table 2. The enhancement in the cracking load of Specimens B2 and B4 was 12% and 7% respectively, revealing that the strengthening pattern had practically no effect on the cracking load. Yet, reducing the spacing between the strips of these specimens by 25% resulted in an increase of 30% in the cracking load; refer to Specimen B3. Experimental data reported on beams with rectangular cross-section [6] showed that the influence of CFRP fabrics on the initiation of the shear cracking was insignificant.

Table 2: Test specimens and results

| Specimen | | Spacing between CFRP wraps (mm) | a/d | Load | | | Mode of failure |
|---|---|---|---|---|---|---|---|
| | | | | Flexure cracking (kN) | Shear cracking (kN) | Ultimate (kN) | |
| Series S1 | B1 | -- | 1.7 | 57.9 | 113.8 | 234.5 | Shear |
| | B2 | 200 | | 62.8 | 127.5 | 405.9 | Shear |
| | B3 | 150 | | 68.7 | 147.2 | 415.9 | Shear |
| | B4 | 200 | | 60.8 | 121.6 | 395.1 | Shear |
| Series S2 | B5 | -- | 2.5 | 47.1 | 98.1 | 155.0 | Shear |
| | B6 | 200 | | 51.0 | 117.7 | 314.9 | Shear-compression |
| | B7 | 150 | | 54.9 | 135.4 | 298.2 | Shear |
| | B8 | 200 | | 49.1 | 107.9 | 246.2 | Fiber debonding |

On the other hand, the enhancement in the load-carrying capacity in shear for Specimens B2, B3, and B4 was 74%, 78%, and 69% respectively, as shown in Table 2. All specimens exhibited a mode of shear failure. The typical behavior as the specimens were approaching the failure, was characterized by crushing of the web concrete followed by curling and rupture of some of the wraps. Partial peeling of the wraps was observed in Beam B3 at about 91% of the ultimate load, Fig. 5. For all specimens, the maximum strain in the steel stirrups exceeded the yield value whereas the strain in the wraps was far below the ultimate value. The maximum strains recorded in the wraps were 5% and 7% of the ultimate strain for Beams B3 and B4, respectively. Figure 6 shows the load versus strain in the CFRP wraps pointing out the dependency of the results obtained with the strain gauges on their position relative to the cracks. The strain gauge situated along the wraps of Beam B2 was inoperative.

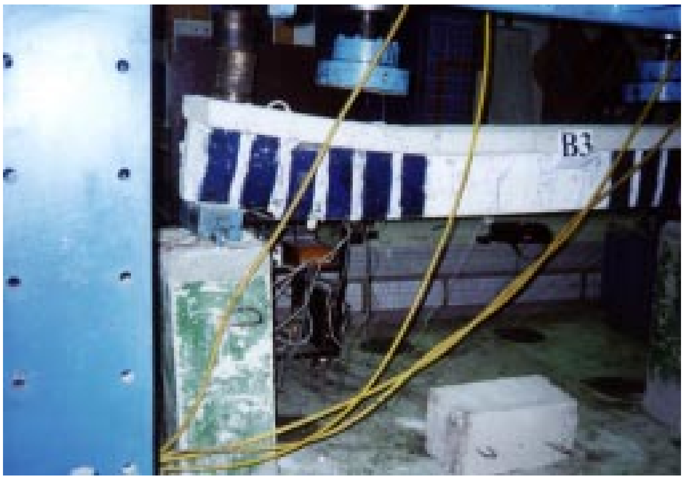
Referring to Fig. 7, the strengthened beams followed a comparable load-deflection pattern up to failure even though their strengthening scheme was different. The shown behavior reveals the expected decline in ductility of the strengthened beams. The midspan deflection of Specimens B2, B3, and B4 was about 55% of that of the control specimen at its ultimate (peak) load.

**Test Beams of Series S2 (a/d=2.5)**

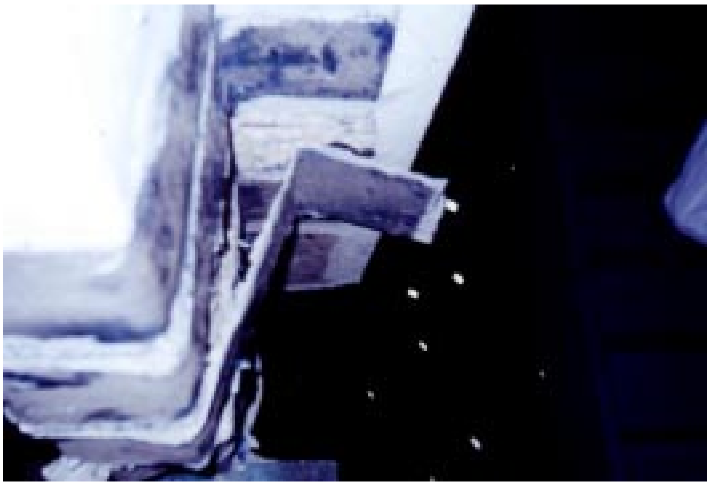
The overall behavior of the control Specimen B5 was comparable to that of Specimen B1. The shear cracking initiated in the middle of the shear span at a load of 98.1 kN. The load-carrying capacity of the specimen was limited by a mode of shear failure at a load of 155 kN. The maximum strain in the longitudinal tension bars was below the yield value, whereas the strain in the steel stirrups reached the yield strain.

Compared to the results of Specimen B5, the enhancement in the shear cracking load of test Specimens B6, B7, and B8 was 20%, 38%, and 10% respectively; whereas the enhancement in the load-carrying capacity in shear was 104%, 93%, and 59% respectively, as shown in Table 2. Specimens B6 and B7 exhibited a mode of shear failure characterized by splitting of the web concrete along the line joining the load pad and the beam support, followed by horizontal rupture of the CFRP strip near the support. The failure of Specimen B8 appeared to be due to debonding of the wraps. Peeling of the strip at the middle of the shear span was observed at about 87% of the ultimate load, as shown in Fig. 5. For all specimens, the maximum strain in the steel stirrups exceeded the yield value whereas the strain in the wraps was far below the ultimate value. Figure 8 illustrates the load versus midspan deflection relationships for Series S2 beams.

Comparison of test results evinces that the effectiveness of CFRP wraps in enhancing the shear capacity of test specimens was directly proportional to the shear span to depth ratio; a/d. Such a correlation may justify the occurrence of debonding failure for Specimen B8 (a/d=2.5) whereas the parallel Specimen B4 (a/d=1.7) failed in shear. Therefore, it is recommended to extend the ends of the U-wraps parallel and cement them to the flange intrados, particularly for beams with moderate a/d ratios. Further, providing fastening angles for CFRP wraps at the flange-web intersection is beneficial. Specimens provided with such angles (B2 and B6), practically attained the shear




(a)



(b)


(c)

Fig. 5 Modes of failure: a) Typical failure; b) Peeling (B3); c) Debonding (B8)

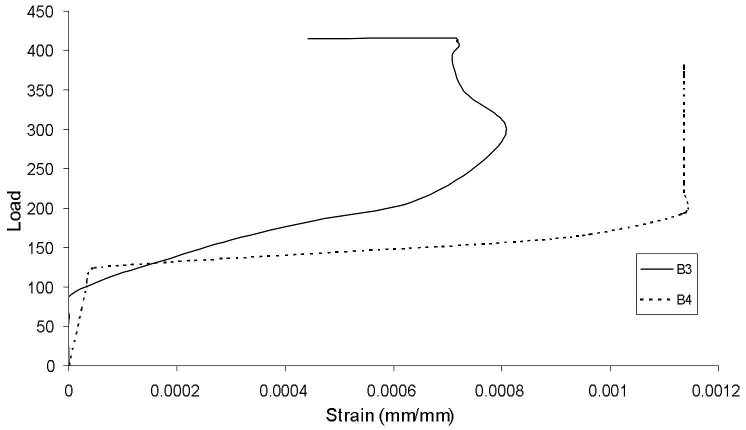



Fig. 6 Variation of strain in CFRP wraps of Series S1

capacities of the corresponding specimens without corner anchors (B3 and B7) even though the latter had 33% excess in fiber ratio. In the range of the a/d investigated, an utmost increase of 40% in the effectiveness of CFRP fabric was achieved. Test data presented by Khalifa and Nanni [6] pointed out the influence of the a/d ratio on the shear contribution of CFRP wraps for specimens with a/d ratios of 3 and 4. The contribution was reported to increase with increasing a/d ratio. It is obvious that the significance of vertical compressive stresses on the shear response of the beam prevails on as the a/d ratio decreases. A close investigation of the expected two-dimensional stress condition resulting from the interaction of compressive stresses with the coexistent shear stresses, may suggest the use of CFRP fabrics with bi-directional fibers for shear strengthening of beams with a/d ratios close to 1.70. Results reported by Chaallal *et al.* [10] on T-beams with an a/d ratio of 2 and strengthened in shear using bi-directional CFRP fabric, are inconsistent as the utmost enhancement in the shear capacity was reported to be 26.7%.

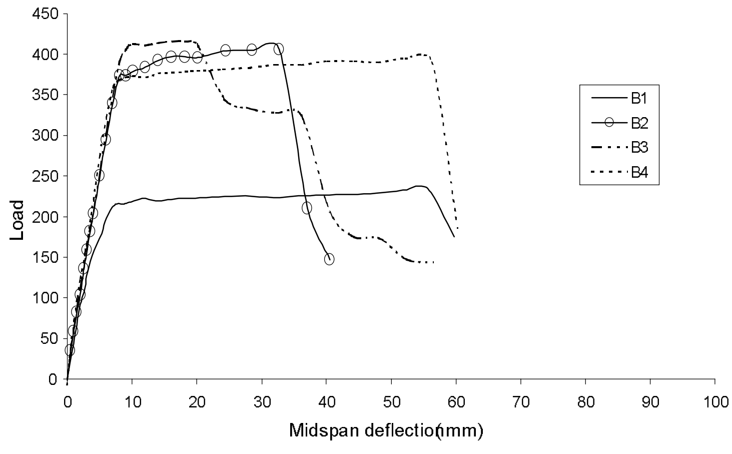



Fig. 7 Load versus midspan deflection of Series S1

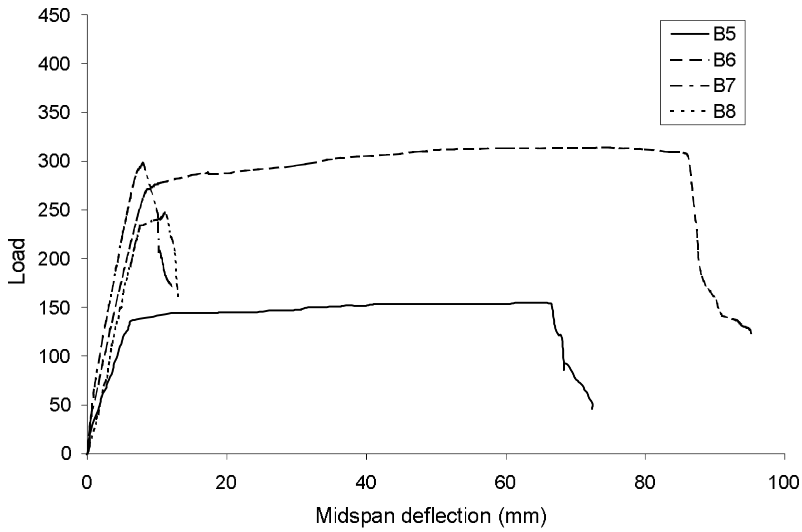



Fig. 8 Load versus midspan deflection of Series S2

## COMPARISON WITH ACI-440 SHEAR PROVISIONS

According to ACI-440 [11], the shear strength of beams strengthened with FRP laminates is established by the individual shear contributions of concrete, steel stirrups, and FRP laminates. The shear provisions set by ACI-318 for RC sections were accepted to limit the contributions of concrete and steel reinforcement. The CFRP laminates were handled as if it were added shear reinforcement having its own characteristics. Thus, the contribution of CFRP reinforcement to the shear strength; $V_f$ may be expressed as:

$$V_f = \frac{A_{fv}\,(R\,f_{fu})\,(\sin\alpha + \cos\alpha)\,d_f}{s_f} \quad \ldots (1)$$

where $A_{fv}$ = cross-sectional area of fiber strip on both sides of web

$R$ = reduction factor for ultimate strength; exercised for test beams to be 0.21

$f_{fu}$ = ultimate strength of fiber

$\alpha$ = inclination angle of strip with respect to the beam axis

$d_f$ = effective depth of strip

$s_f$ = spacing of fiber strips

Equation (1) was applied to the test specimens. The analytical results as compared to the test results are summarized in Table 3. The experimental shear contribution of fibers to the strength of a specific beam is figured as the difference between its load-carrying capacity and that of the control beam. A close examination of the results reveals that the shear provisions of ACI Committee 440 accept the debonding of fibers as the dominant mode of failure for strengthened beams. To the point, all test specimens failed as a result of rupture of fibers, excluding Specimen B8 that failed as a consequence of debonding of some of the CFRP wraps. The predictions for Series S1 beams (a/d=1.7) ranged from 43% to 55% of the test results, which are considered very conservative. In Series S2 (a/d=2.5), the shear contribution ($V_f$) for Specimen B6 provided with fastening angles, was 47%. Acceptable predictions were achieved for Specimens B7 and B8 where $V_f$ is given in Table 3 as 70% and 82% of the test data respectively. In conclusion, the requirements provided by ACI 440 for shear strengthening can be conservatively applied to RC beams using strengthening methods presented in this investigation.

Table 3: Comparison between test results and ACI-440 predictions

<table>
<tr><th colspan="2" rowspan="2">Specimen</th><th colspan="2">Experimental Results</th><th>ACI-440</th><th rowspan="2">$V_{f\,th}$ / $V_{f\,exp}$</th></tr>
<tr><th>$V_c$+$V_s$ (kN)</th><th>$V_{f\,exp}$ (kN)</th><th>$V_{f\,th}$ (kN)</th></tr>
<tr><td rowspan="4">Series S1</td><td>B1</td><td rowspan="4">117.23</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>B2</td><td>85.74</td><td>37.47</td><td>0.43</td></tr>
<tr><td>B3</td><td>90.74</td><td>50.03</td><td>0.55</td></tr>
<tr><td>B4</td><td>80.30</td><td>37.47</td><td>0.46</td></tr>
<tr><td rowspan="4">Series S2</td><td>B5</td><td rowspan="4">77.50</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>B6</td><td>79.95</td><td>37.47</td><td>0.47</td></tr>
<tr><td>B7</td><td>71.61</td><td>50.03</td><td>0.70</td></tr>
<tr><td>B8</td><td>45.61</td><td>37.47</td><td>0.82</td></tr>
</table>

## CONCLUSIONS

In view of the limited tests presented in this study, the following conclusions can be drawn:

1- Regardless the strengthening pattern, the shear strengthening using CFRP fabric had a minor effect on the shear cracking load. However, a reduction in the spacing between the strips by about 25% resulted in an increase in the cracking load of 30% and 38% for beams with a/d ratio of 1.7 and 2.5 respectively.

2- The contribution of CFRP fabrics to the shear capacity is significant and directly proportional to the shear span to effective depth ratio. The increase in the shear capacity ranged from 69% to 78% for beams with a/d of 1.7 and from 59% to 104% for beams with a/d of 2.5.

3- Extending the ends of the U-wraps beneath the flange intrados, and providing fastening angles for the wraps at the flange-web intersection are beneficial. Specimens provided with such angles, practically attained the shear capacities of the corresponding specimens without corner anchors even though the latter had 33% excess in fiber ratio.

4- CFRP wrapping limits the strains and leads to a local decrease in ductility. There is a need for a design criterion to provide the minimum allowable ductile behavior for strengthened beams.
5- As the shear provisions of ACI Committee 440 accept the debonding of fibers as the dominant mode of failure for strengthened beams, the predictions of ACI 440 for the test specimens were conservative. The predictions for beams with a/d of 1.7 ranged from 43% to 55% of the test results, whereas for beams with a/d of 2.5 ranged from 47% to 82%.

## ACKNOWLEDGEMENT

The authors would like to acknowledge MBrace Egypt for providing the CFRP fabrics and the adhesive material. The authors would also like to extend their grateful thanks to the staff in the Reinforced Concrete Laboratory at the Housing and Building Research Center in Egypt.

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