0350

# SHEAR PERFORMANCE OF RC MEMBERS STRENGTHENED WITH EXTERNALLY BONDED FRP WRAPS

**AHMED KHALIFA[1], ABDELDJELIL BELARBI[2] And ANTONIO NANNI[3]**

## SUMMARY

This study presents the shear performance and the modes of failure of reinforced concrete (RC) beams strengthened with externally bonded carbon fiber reinforced polymer (CFRP) wraps. The experimental program consisted of testing twenty-seven, full-scale, RC beams. The variables investigated in this research study included steel stirrups (i.e., beams with and without steel stirrups), shear span-to depth ratio (i.e., a/d ratio 3 versus 4), CFRP amount and distribution (i.e., continuous wrap versus strips), bonded surface (i.e., lateral sides versus U-wrap), fiber orientation (i.e., $90^0/0^0$ fiber combination versus $90^0$ direction), and end anchor (i.e., U-wrap with and without end anchor). As part of the research program, the experimental study examined the effectiveness of CFRP reinforcement in enhancing the shear capacity of RC beams in negative and positive moment regions, and for beams with rectangular and T-cross section. The experimental results indicated that the contribution of externally bonded CFRP to the shear capacity is significant and dependent upon the variable investigated.

## INTRODUCTION

Strengthening and rehabilitation of existing reinforced concrete (RC) structures is becoming an important issue in situations such as demand in the increase of service load levels, repair due to degradation of a member, design/construction defects, and response to requirements of newly developed design guidelines. Carbon fiber reinforced polymer (CFRP) sheets continue to show great promise for use in these situations (ACI 440, 1996). These materials are excellent for external strengthening because of their high tensile strength, light weight, resistance to corrosion, superior durability, and cost-effective installation process.

Shear failure of RC beams, caused by their brittle nature, has been identified as the most disastrous failure mode; it occurs 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. In addition, there is an urgent need to upgrade shear resistance of older RC structures to meet current seismic design standards in regions with high seismicity. In these situations, externally bonded CFRP reinforcement is used to wrap the beam cross-section with fibers in the transverse direction and thus enhances the shear resistance of the beam (Chajes et al. 1995, Taerwe et al. 1997, and Triantafillou 1998). The strengthening is achieved by having CFRP reinforcement laid in a way to cross diagonal cracks similarly to internal stirrups to provide the shear resistance and restrict the growth of diagonal cracks and therefore reduces their progression into the compression

zone. Thus large uncracked concrete area is available at the head of the crack and thereby increases the part of shear force carried by concrete. To date, only a limited number of studies has specifically addressed shear strengthening with FRP. The parameters affecting the shear strength of the strengthened beams need to be investigated and this study will address that research void and set the plan for further research.

[1] *Structural Engineering Department, Faculty of Engineering, Alexandria University, Alexandria 21544, Egypt*
[2] *Department of Civil Engineering, University of Missouri-Rolla, Rolla, MO 65409,USA*
[3] *Department of Civil Engineering, University of Missouri-Rolla, Rolla, MO 65409,USA*

The objectives of this study were to: (1) investigate the shear performance and mode of failure of RC beams after strengthening with externally bonded CFRP sheets, (2) examine the effectiveness of CFRP reinforcement in enhancing the shear capacity of RC beams in negative and positive moment regions, as well as RC beams with rectangular and T-cross section; (3) address the variables affecting the shear capacity of strengthened beams such as: steel stirrups, shear span-to depth ratio, CFRP amount and distribution, bonded surface, fiber orientation, and end anchor. To fulfill these goals, twenty-seven full-scale, RC beams design to fail in shear, were constructed and strengthened with different CFRP configurations and full study was carried out.

## EXPERIMENTAL PROGRAM

### Test Specimens, Test Setup, and Materials

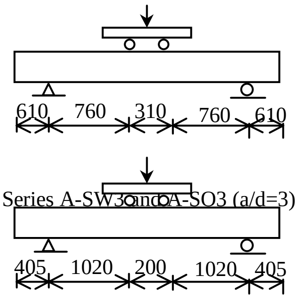
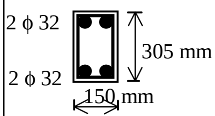
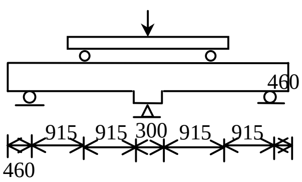
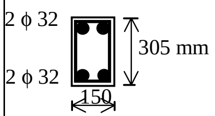
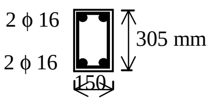
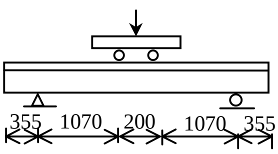
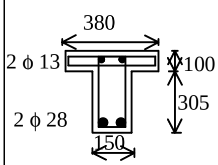
The beam specimens tested in this experimental program were grouped into three main series designated as A, B, and C. In Series A, twelve full-scale rectangular beam specimens were tested. The variable investigated in this test series included steel stirrups, shear span-to-depth ratios (a/d ratios), CFRP amount and distribution. The specimens were grouped into two main groups designated as A-SW for beams with stirrups and A-SO for beams without stirrups in the shear span of interest. The stirrups were made from deformed steel bars with 10-mm diameter bars, with yield stress of 350 MPa, ultimate tensile strength of 530 MPa, and modulus of elasticity of 200 GPa. Four 32-mm bars with yield stress of 460 MPa were used as longitudinal reinforcement with two being placed at top and two at bottom face of the cross section. Each main group (i.e., Groups A-SW and A-SO) was subdivided into two subgroups according to shear span-to-depth ratio namely: a/d = 3 and 4, and resulting in the following four Subgroups: A-SW3, A-SW4, A-SO3, and A-SO4. All specimens of Series A were tested as simply supported beams subjected to a four-point load. A universal testing machine with 1800 kN capacity was used to apply a concentrated load on a steel distributed beam used to generate the two concentrated loads. A summary of structural system, cross-section dimensions and details, shear span-to-depth ratio (a/d), steel shear reinforcement, and CFRP strengthening configurations is listed in Table 1.

In the negative moment regions of continuous beams, shear cracks initiates from the top of the section. In this case, the U-wrap FRP reinforcement may not be able to control the initiation of these cracks, and may have less effectiveness to enhance shear capacity. However, most of the past research has dealt with shear strengthening of simply supported beams (strengthening in positive moment regions) and shear strengthening in negative moment regions has not been addressed. To fill this gap, nine full-scale, two-span-continuous rectangular beam specimens were fabricated and tested (Series B). The variables investigated in this test series included steel stirrups, CFRP amount and distribution, and CFRP wrapping schemes. The specimens of Series B were subdivided into three groups designated as B-CW, B-CO, and B-CF. Each group had different longitudinal and shear steel reinforcement ratios as shown in Table 1. The 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 in the test span. This allowed the computation of the exact shear force in the span of interest.

In Series C, six full-scale, T-section RC beams were strengthened with different CFRP configurations and tested. T-section beams are of great importance because they are the most commonly used in practice. Also, they represent a more challenging case than rectangular beams due to the flange that reduces the FRP bonded length over the web. The specimens were strengthened with different CFRP configurations. The selected parameters were; (a) CFRP amount and distribution (i.e., continuous wrap versus strips); (b) bonded surface (i.e., lateral sides versus U-wrap); (c) fiber orientation (i.e., $90^0$-$0^0$ fiber combination versus $90^0$ direction); and (d) end anchorage (i.e., U-wrap with and without end anchor). All specimens were tested as simple beams using a four-point loading with shear span-to-depth ratio (a/d) equals to 3. A steel distribution beam used to generate the two concentrated loads.

The composite strengthening system that was used in this research program was provided by Master Builder Technologies, Inc. According to the manufacturer's information, the tensile strength of CFRP sheet is 3790 MPa, the modulus of elasticity is 228 GPa, and the design thickness is 0.165 mm (fiber only). Fabrication of the specimens including surface preparation and CFRP installation is described elsewhere [Khalifa 1999].

**Table 1. Summary of Test Specimens**

| No. | Specimen designation | Structural system and test set-up (dimensions in mm) Simply supported beams | Cross-section details | a/d ratio | Concrete strength (f′c) (MPa) | Shear reinforcement: Steel stirrups in test region | Shear reinforcement: CFRP |
|---|---|---|---|---|---|---|---|
| 1 | A-SW3-1 |  Series A-SW3 and A-SO3 (a/d=3) |  | 3 | 19.3 | ϕ10@125mm | ---- |
| 2 | A-SW3-2 | | | 3 | 19.3 | ϕ10@125mm | Two plies (90°/0°) |
| 3 | A-SW4-1 | | | 4 | 19.3 | ϕ10@125mm | ---- |
| 4 | A-SW4-2 | | | 4 | 19.3 | ϕ10@125mm | Two plies (90°/0°) |
| 5 | A-SO3-1 | | | 3 | 27.5 | ---- | ---- |
| 6 | A-SO3-2 | | | 3 | 27.5 | ---- | U-wrap strips, 50 @ 125mm |
| 7 | A-SO3-3 | | | 3 | 27.5 | ---- | U-wrap strips, 75 @ 125mm |
| 8 | A-SO3-4 | | | 3 | 27.5 | ---- | One ply continuous U-wrap |
| 9 | A-SO3-5 | | | 3 | 27.5 | ---- | Two plies (90°/0°) |
| 10 | A-SO4-1 | | | 4 | 27.5 | ---- | ---- |
| 11 | A-SO4-2 | Series A-SW4 and A-SO4 (a/d=4) | | 4 | 27.5 | ---- | U-wrap strips, 50 @ 125mm |
| 12 | A-SO4-3 | | | 4 | 27.5 | ---- | One ply continuous U-wrap |
| 13 | B-CW1 | Continuous beams  |  | 3.6 | 27.5 | ϕ10@125mm | ---- |
| 14 | B-CW2 | | | 3.6 | 27.5 | ϕ10@125mm | Two plies (90°/0°) |
| 15 | B-CO1 | | | 3.6 | 20.5 | ---- | --- |
| 16 | B-CO2 | | | 3.6 | 20.5 | ---- | U-wrap strips, 50 @ 125mm |
| 17 | B-CO3 | | | 3.6 | 20.5 | ---- | One ply continuous U-wrap |
| 18 | B-CF1 | |  | 3.6 | 50 | ---- | ---- |
| 19 | B-CF2 | | | 3.6 | 50 | ---- | One ply continuous U-wrap |
| 20 | B-CF3 | | | 3.6 | 50 | ---- | Two plies (90°/0°) |
| 21 | B-CF4 | | | 3.6 | 50 | ---- | One ply, totally wrapped |
| 22 | C-BT1 | Simply supported beams  |  | 3 | 35 | ---- | ---- |
| 23 | C-BT2 | | | 3 | 35 | ---- | One ply continuous U-wrap |
| 24 | C-BT3 | | | 3 | 35 | ---- | Two plies (90°/0°) |
| 25 | C-BT4 | | | 3 | 35 | ---- | U-wrap strips, 50 @ 125mm |
| 26 | C-BT5 | | | 3 | 35 | ---- | Two sides strips 50 @ 125 |
| 27 | C-BT6 | | | 3 | 35 | ---- | U-wrap with end anchor |

## Strengthening Schemes

Of the twenty-seven specimens, one from each subgroup (eight specimens) was not strengthened and was considered as a control specimen, whereas nineteen specimens were strengthened with externally bonded CFRP sheets using different schemes.

Specimens A-SW3-2, A-SW4-2, A-SO3-5, B-CW2, B-CF3, and C-BT3 were 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 the fiber direction oriented perpendicular to the longitudinal axis of the specimen ($90^0$). The second ply was bonded on the two sides of the specimen with the fiber direction parallel to the beam axis ($0^0$). This ply (i.e., $0^0$

ply) was added to investigate the impact of horizontal restraint on shear strength. Specimens A-SO3-4, A-SO4-3, B-CO3, B-CF2, and C-BT2 were strengthened with one-ply continuous U-wrap ($90^0$).
Specimen C-BT6 was strengthened with one-ply continuous U-wrap ($90^0$). The ends of the U-wrap were anchored to the flanges on both sides of the specimen using a proprietary U-anchor system developed at University of Missouri-Rolla (UMR). The purpose of using the end anchor was to address the problems associated with the debonding of FRP from the concrete surface and to allow a better exploitation of the strengthening system. A cross section showing details of the U-anchor system is given in Figure 1. The installation procedure of the end anchor is described elsewhere [Khalifa et al. 1999 a].

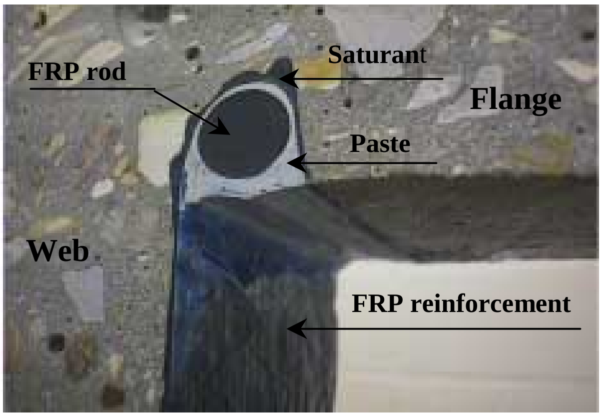



**Figure 1. Details of the U-Anchor at the corner of flange-web**

Specimen B-CF4 was totally wrapped with one-ply CFRP sheets. The sheets were attached to the four sides of the specimen with an overlap on the topside. Even though total wrapping may not be possible in the field, this case is representative of the upper threshold.

Specimens A-SO3-2, A-SO4-2, B-CO2, and C-BT4 were strengthened with one-ply CFRP strips in the form of U-wrap with ($90^0$). The strip width was 50 mm with center–to-center spacing of 125 mm. Specimen A-SO3-3 was strengthened in a manner similar to that of Specimen A-SO3-2 but with strip width equal to 75 mm. Specimen C-BT5 was strengthened with CFRP strips attached only on the two beams sides with $90^0$ fiber orientation. The strips width and spacing were similar to Specimen C-BT4.

## TEST RESULTS AND DISCUSSIONS

The test results confirm that the strengthening technique using CFRP sheets can be used to increase significantly shear capacity. The recorded CFRP strain of the tested specimens indicates that the failure of CFRP system occurs at an average effective stress level below nominal strength due to stress concentrations or debonding of CFRP from concrete surface.

### Failure Modes

The failure mode of the control specimens was shear compression failure while the failure mode of the strengthened specimens was either CFRP debonding, concrete splitting on a vertical plane, or flexural failure. Figure 2 shows examples of the observed failure modes. In each specimen failed by CFRP debonding, the final crack pattern was approximately similar to the control specimen. The failure initiated due to debonding of the CFRP from concrete surface with spalled concrete attached to it, followed directly by shear compression failure. The location of the debonding area varied according to the wrapping schemes. For specimens strengthened with U-wrap configuration, the debonding area was above the diagonal shear crack (Figure 2 (a)). In Specimen C-BT5, strengthened with CFRP strips attached to the specimen sides only, the location of debonding area was below the main shear crack as shown in Figure 2(b). The specimens failed by concrete splitting were beams with rectangular cross-sections and beams strengthened with either two perpendicular plies $90^0/0^0$ or one ply continuous U-wrap. No cracks were visible on the sides or bottom of the test specimen due to the FRP wrapping. Before the failure, a longitudinal crack formed on the top surface of the specimen. The crack initiated close to the position of applied load and extended towards the support then the failure occurred by concrete splitting on a vertical plane as shown in the Figure 2 (c). The shear capacity of the strengthened specimens of Group B-CF and Specimen C-BT6 was higher than their flexural capacity. For those specimens, the failure was controlled by flexural (Figure 2 (d)).

(a) Specimen A-SO3-2 (Debonding of CFRP over shear crack)

(b) Specimen C-BT5 (Debonding of CFRP below shear crack)

(c) Specimen A-SO3-5 (concrete splitting)

(d) Specimen B-CF4 (flexural failure)

**Figure 1. Examples of Failure Modes of some Test Specimens**

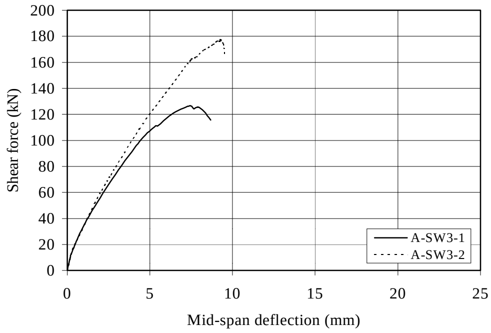
**Shear Force-Deflection Curves**

The shear force versus the mid-span deflection curves of the tested beams are shown in Figure 3. For all test series, the strengthened specimens showed a higher failure load compared to the control specimens. In Subgroup A-SW4, the mid-span deflection of the strengthened Specimen A-SW4-2 at ultimate was about 2.5 times the deflection of the control Specimen A-SW4-1. In Subgroup A-SO3 and Group B-CO (Figures 3 c & f), the strengthened specimens had a more brittle behavior than the control specimen. In Group B-CF (Figure 3 (g)), the Specimen B-CF4, strengthened with totally wrapped CFRP sheets showed a large plateau and a notable increment in ductility. In Series C (Figure 3 (h)), the Specimen C-BT6, strengthened with U-wrap continuous CFRP sheets with end anchor, showed significant increase in the shear capacity compared to other specimen in the series. In addition, Figure 3 (h) indicates that Specimen C-BT6 gained more stiffness and ductility. The additional ductility was obtained from the flexural failure mode. The mid- span deflection of Specimen C- BT6 at failure was about 3 times the deflection of Specimen C-BT2, strengthened with U-wrap continuous CFRP sheets without end anchor, at ultimate.

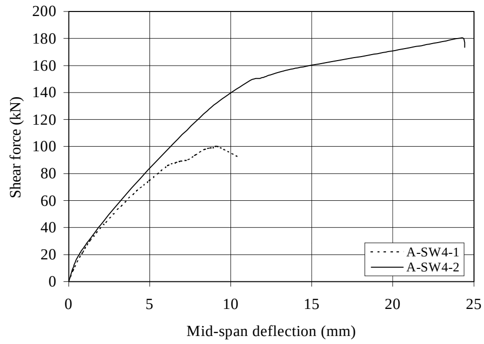
***Evaluation of the Test Results***

The summary of the test results for all of the beam specimens are detailed in Table 2.

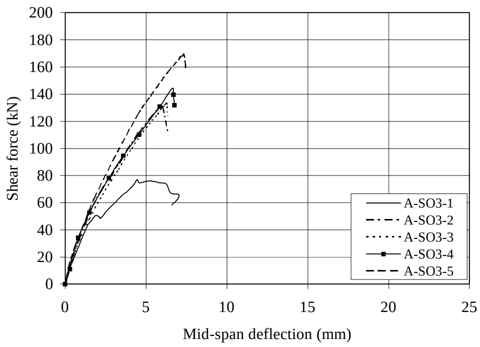
Series A: For the specimens tested in this series, increases in shear strength of 40 to 138% were achieved. The test results indicated that contribution of CFRP benefits the shear capacity at a greater degree for beams without shear reinforcement than for beams with adequate shear reinforcement. In addition, the contribution CFRP reinforcement was influenced by the a/d ratio and appeared to increase with increasing the a/d ratio. Based upon the test results of



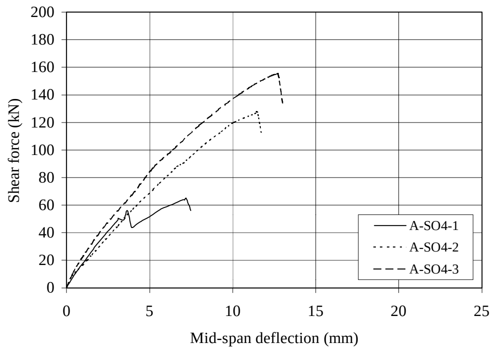

(a) Subgroup A-SW3



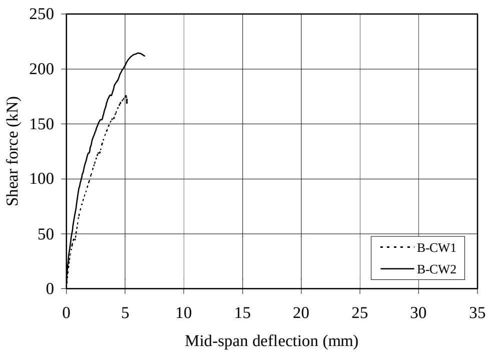

(b) Subgroup A-SW4



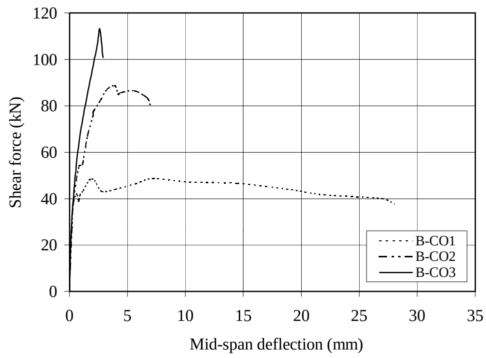

(c) Subgroup A-SO3



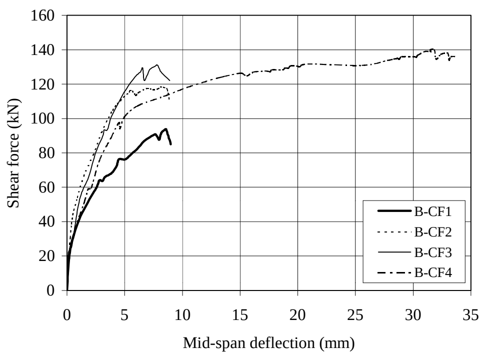

(d) Subgroup A-SO4



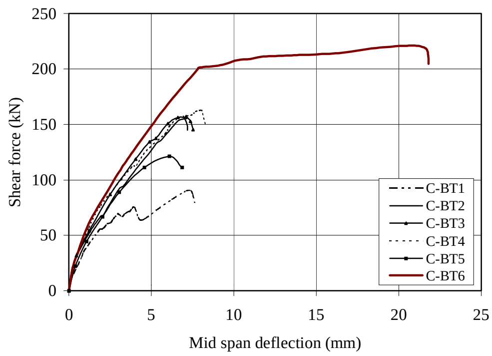

(e) Group B-CW




(f) Group B-CO




(g) Group B-CF




(h) Series C

**Figure 3. Shear Force versus Mid-span Deflection for the Tested Specimens**

Specimens A-SO3-2 and A-SO3-4, increasing the amount of CFRP may not result in a proportional increase in the shear strength. The CFRP amount used to strengthen Specimen A-SO3-4 was 250% of that used in Specimen A-SO3-2, which resulted in a minimal (10%) increase in shear capacity. Moreover, the results of Subgroup A-SO3 indicated that the added $0^0$ ply improved the shear capacity by providing horizontal restraint.

Series B: In this test series, 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 could be used to enhance the shear capacity of the beams in positive and negative moment regions. For the beam specimens tested in this series, increase in shear strength ranged from 22 to 135%.

Series C: In this test series, the shear performance of the T beams strengthened with CFRP sheets was investigated. For the beam specimens tested in this series, increase in shear strength of 35 to 145% was achieved. The test results indicated that the performance of CFRP could be improved significantly if adequate anchorage is provided. On other hand, applying CFRP to the beam sides only is less effective than a U-wrap. The test results of this series also indicated that there exists an optimum amount of FRP, beyond which the strengthening effect become inefficient.

**Table 2. Summary of the Test Results**

| No. | Specimen designation | Failure mode | Maximum vertical CFRP strain measured at ultimate (mm/mm) | Total applied load at ultimate (kN) | Total applied shear force at ultimate (kN) | Contribution of CFRP to the shear capacity (kN) | CFRP strengthening effectiveness ratio % |
|---|---|---|---|---|---|---|---|
| 1 | A-SW3-1 | Shear | ---- | 253.0 | 126.5 | 0.0 | ---- |
| 2 | A-SW3-2 | Splitting | 0.0023 | 354.0 | 177.0 | 50.5 | 40 |
| 3 | A-SW4-1 | Shear | ---- | 200.0 | 100.0 | 0.0 | --- |
| 4 | A-SW4-2 | Splitting | 0.0019 | 361.0 | 180.5 | 80.5 | 80 |
| 5 | A-SO3-1 | Debonding | ---- | 154.0 | 77.0 | 0.0 | --- |
| 6 | A-SO3-2 | Debonding | 0.0047 | 262.0 | 131.0 | 54.0 | 70 |
| 7 | A-SO3-3 | Debonding | 0.0052 | 266.0 | 133.5 | 56.5 | 73 |
| 8 | A-SO3-4 | Debonding | 0.0045 | 289.0 | 144.5 | 67.5 | 87 |
| 9 | A-SO3-5 | Splitting | 0.0043 | 339.0 | 169.5 | 92.5 | 120 |
| 10 | A-SO4-1 | Shear | ---- | 130.0 | 65.0 | 0.0 | --- |
| 11 | A-SO4-2 | Debonding | 0.0062 | 255.0 | 127.5 | 62.5 | 96 |
| 12 | A-SO4-3 | Splitting | 0.0043 | 310.0 | 155.0 | 90.0 | 138 |
| 13 | B-CW1 | Shear | ---- | 508.0 | 175.0 | 0.0 | ---- |
| 14 | B-CW2 | Splitting | 0.0027 | 623.0 | 214.0 | 39.0 | 22 |
| 15 | B-CO1 | Shear | ---- | 220.0 | 48.0 | 0.0 | ---- |
| 16 | B-CO2 | Debonding | 0.0047 | 265.0 | 88.0 | 40.0 | 83 |
| 17 | B-CO3 | Debonding | 0.0037 | 330.0 | 113.0 | 65.0 | 135 |
| 18 | B-CF1 | Shear | ---- | 268.0 | 93.0 | 0.0 | 0.0 |
| 19 | B-CF2 | Flexural | Not available | 337.0 | 119.0 | > 26.0 | > 28 |
| 20 | B-CF3 | Flexural | Not available | 394.0 | 131.0 | > 38.0 | > 40 |
| 21 | B-CF4 | Flexural | Not available | 400.0 | 140.0 | > 47.0 | > 50 |
| 22 | C-BT1 | Shear | ---- | 180.0 | 90.0 | 0.0 | 0.0 |
| 23 | C-BT2 | Debonding | 0.0045 | 310.0 | 155.0 | 65.0 | 72 |
| 24 | C-BT3 | Debonding | 0.0044 | 315.0 | 157.5 | 67.5 | 75 |
| 25 | C-BT4 | Debonding | 0.0100 | 324.0 | 162.5 | 72.0 | 80 |
| 26 | C-BT5 | Debonding | Not available | 243.0 | 121.5 | 31.5 | 35 |
| 27 | C-BT6 | Flexural | 0.0063 | 442.0 | 221.0 | > 131.0 | > 145 |

## CONCLUSIONS

The tests results described in this study indicated that the strengthening technique based on externally bonded CFRP composites can be used to increase significantly shear capacity of RC beams, with efficiency that varies depending on the test variables. For all beams included in this experimental program, results show that an increase in shear strength of 22 to 145% was achieved. Based on the experimental results, analytical investigations, and discussions, the main conclusions are as follows:

- Externally bonded CFRP reinforcement can be used to enhance the shear capacity of RC beams in positive and negative moment regions.
- The FRP strengthening technique is applicable and can increase the shear capacity of rectangular as well as T beams.
- The experimental verification of the end anchor system showed its effectiveness in increasing shear capacity.
- The contribution of CFRP benefits the shear capacity at a greater degree for beams without shear reinforcement than for beams with adequate shear reinforcement.
- The contribution of externally CFRP reinforcement to the shear capacity was influenced by the shear span-to- depth ratio (a/d) and appeared to increase with an increase a/d ratio.
- Increasing the amount of CFRP may not result in a proportional increase in the shear strength because the shear strength is significantly dependent on the interfacial bond between the FRP and concrete. This means that, if FRP debonding failure is not prevented, there is an optimum amount of FRP, beyond which the capacity dose not increase with increasing amount of FRP.
- The presence of $0^0$ ply may improve the shear capacity by providing horizontal restraint to diagonal shear cracks.
- Applying CFRP to the beam sides only was less effective than a U-wrap.
- The recorded CFRP strain of the tested beams indicated that the failure of CFRP system occurs at an average effective stress level below nominal strength due to stress concentrations or debonding of CFRP from concrete surface.

## ACKNOWLEDGEMENTS

This work was conducted with partial support from National Science Foundation (NSF) and Repair of Buildings and Bridges with Composites ($RB^2C$) based at the University of Missouri-Rolla. The Egyptian Cultural and Educational Bureau provided support to the first author.

## REFERENCES

ACI Committee 440, *State-of-the-Art Report on Fiber Reinforced Plastic (FRP) Reinforcement for Concrete Structures*, American Concrete Institute, Detroit, Michigan, 1996, 68 pp.

Chajes, M. J., Januska, T.F., Mertz, D.R., Thomson, T.A., and Finch, W.W., "Shear Strengthening of Reinforced Concrete Beams Using Externally Applied Composite Fabrics," *ACI Structural Journal*, Vol. 92, No. 3, May - June 1995, pp. 295-303.

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

Khalifa, A., Alkhrdaji, T., Nanni, A., and Lansburg, A., "Anchorage of Surface Mounted FRP Reinforcement". *Concrete International*, American Concrete Institute, 1999 a, to appear.

Taerwe, L., Khalil, H., and Matthys, S., "Behavior of RC Beams Strengthened in Shear by External CFRP Sheets," *Non-Metallic(FRP) Reinforcement for Concrete Structures, Proceedings of the Third Symposium*, Vol. 1, Japan, Oct. 1997, pp. 483-490.

Triantafillou, T.C., "Shear Strengthening of Reinforced Concrete Beams Using Epoxy Bonded FRP Composites," *ACI Structural Journal*, Mar.-Apr. 1998, pp. 107-115.