Shear strength enhancement of lightweight aggregate reinforced concrete deep beams by using CFRP strips

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Abstract. In this research, results of an experimental investigation on the shear strengthening of lightweight aggregate reinforced concrete deep beams are presented. A total of eight lightweight aggregate deep beams were cast and tested in the experimental work to study the effect of externally bonded CFRP strips in improving their structural behavior, one of them was unstrengthened to serve as a control beam while the remaining seven beams were strengthened in different orientation, spacing and number of layers of CFRP. The locally available natural porcelanite rocks are used to seek the possibility of producing structural lightweight aggregate concrete. The beams were designed to satisfy the requirements of ACI 318M-14 building code. Results show that the CFRP strips have increased the load carrying capacity for the strengthened deep beams up to 50 % when compared to the unstrengthened control one. The diagonal compression strut crack of unstrengthened control beam is changed to several diagonal cracks in the mid-depth within the shear span of the strengthened beams and exhibited more ductile failure modes. The results also indicate that bonded CFRP system in the shear span was seen to delay the formation of diagonal shear cracks and provided positive restraint to the subsequent growth of cracks. Increasing the amount of CFRP (by increasing the number of layers from one to two layers) results in increase in the ultimate load by about 15%. However, the increase in the spacing between the strips (from 100 to 150mm) led to a decrease in the ultimate load by about 13%.

1 Introduction

Reinforced concrete deep beams are used as load distributing structural units like transfer Girders which are used in multistory buildings to provide column offsets or as horizontal diaphragms, pile caps, foundation walls, and offshore structures. They are also used in construction of bunkers, water tanks and bins where the walls act as vertical beams spanning between the columns supporting and carrying a part of the floor load [1].

According to ACI 318M-14[2] deep beams could be defined as members loaded on one face and supported on the opposite face, in which compression struts can develop between the supports and the applied loads. deep beams have either: \( l_s/h \leq 4.0 \); or \( a/h \leq 2.0 \), where \( l_s \) is the clear span for distributed loads measured from the face of the support, \( h \) is the overall depth, and \( a \) is the shear span length (figure 1).

After inclined cracks formulation in deep beam, it takes on a tied arch behavior, allowing the forces to transfer directly to the supports [3]. Such behavior provides some reserve shear capacity in deep beams which is not found in shallower members. The deep beams shear strength is significantly greater than that of slender beams because of this special capacity of deep beams in redistributing internal forces before failure [4].

The strain is distributed nonlinearly across the depth of the cross section of deep beams and great amount of load is carried to the supports by a compression strut passing through the line joining the applied load and reaction [2, 5].

Shear behavior of reinforced concrete deep beam is very complex, and difficult to predict accurately. This behavior depends on the size of the deep beam,
reinforcement type and detail in addition to the type of the applied load and its position. The total shear resistance of beams depends usually on the shear resistance capacity of concrete and the additional contributions of external and/or internal reinforcement of the beams. In particular, the shear resistance of reinforced concrete beams can be enhanced by externally bonding FRP composite materials. This system may be regarded as additional web reinforcement but fixed externally.

Using FRP materials as external shear strengthening gained popularity over steel plates because of their lightweight feature and the ease of application, moreover, its being available in the form of thin sheets which make very little change to the dimension of the existing members. FRP could play a very important role in retrofitting and strengthening of degraded structures or strength deficient structures that are already in existence.

The four main types of FRP used in the construction industry are: aramid (AFRP), carbon (CFRP), basalt, and glass (GFRP) [6]. Within these fiber groups, there are numerous different performance characteristics available. The fibers have a linear elastic response up to ultimate load with no significant yielding as shown in figure (2). A comparison among some of FRP composites (based on fiber area only) and reinforcing steel in terms of stress-strain relationship is illustrated in figure (2).

![Fig. 2. stress-strain relationship comparison between some of FRP composites and reinforcing steel [7].](image)

2 Strengthening of beams in shear with FRP sheets

The three types of wrapping schemes used to increase the shear strength beams or columns (As stated in ACI Committee 440.2R-08 [8]) are illustrated in figure (3). The most efficient wrapping scheme is FRP Completely wrapped around the section on all four sides (which is most commonly used in column). However, total wrap is not practical from constructability standpoint in the case of beam applications (where an integral slab makes it impractical to completely wrap the member). the shear strength could be improved by wrapping the FRP system around three sides of the member (U-wrap) or bonding to the two opposite sides of the beams [8,9].

In all wrapping systems, the installation of the FRPs can be used continuously along the span of the member or as spaced strips (figure 4). The effective alternative in optimizing the amount of material used is the second one.

![Side bonding U-jacket Fully wrapped](image)

**Fig. 3. Shear strengthening schemes with FRP composites [8].**

![FRP distributions](image)

**Fig. 4. FRP distributions [8, 9].**

Figure (5) shows the orientation of FRP. Aligning FRP fibers transverse to the axis of the member or perpendicular to the shear cracks paths is more effective in providing additional shear strength [10]. This is achieved by the use of inclined strips.

![Vertical strips Inclined strips](image)

**Fig. 5. FRP orientations [9].**

3 Experimental program

3.1 Beam specimen description

A total of eight identical simply supported lightweight aggregate reinforced concrete deep beams were molded and tested to evaluate the effectiveness of the CFRP strengthening schemes on the behavior and shear load carrying capacity of these beams, as well as, studying some parameters related to this field. All beams were strengthened by various configurations of CFRP strips except one which serves as a control beam. The shear span to effective depth ratio (a/d) was chosen to be 1.0.

3.2 Beam Specimen Details
The deep beams were with the same dimensions of (1400 mm span length, 150mm width, 400 mm depth. The internal reinforcement is kept constant as (3Φ16mm for main bars and Φ5 at 100 mm for shear reinforcement in both vertical and horizontal directions). The chosen shear reinforcement ratio \( \rho_s = \rho_{sh} = 0.00262 \) was almost the same to the minimum shear reinforcement ratio recommended by the ACI 318M-2014 Code [2] for both vertical and horizontal directions. Shear reinforcement’s yield strength was 476MPa while for flexural reinforcement is 450MPa. Dimensions and details of the internal steel reinforcement for the tested deep beams are shown in Figures 6 and 7 respectively. Additional reinforcement cages were provided at the points of applied load and supports which connected tightly to the beams reinforcement to avoid premature local failure at those zones.

### 3.3 Concrete mix design

As recommended by ACI 213.2R-03 [11] Committee, a concrete shall be deemed to be a structural lightweight concrete if its compressive strength \( f'_c \) is greater than (17 MPa) at (28 days) and the oven dry density less than (2000kg/m³). Hence, several trial mixes were made by the researchers in order to satisfy these two conditions and reach to an acceptable \( f'_c \) of (26.34 MPa) at (28 days) with an oven dry density of about (1950 kg/m³).

![Deep Beam specimen dimensions](image)

**Fig. 6. Deep Beam specimen dimensions**

![Deep Beam specimen reinforcement details](image)

**Fig. 7. Deep Beam specimen reinforcement details**

### 4 Strengthening system

#### 4.1 CFRP sheets and adhesive

Only seven of the eight deep beams have been strengthened with CFRP strips. Strengthened deep beams were bonded with one or two layers of different orientation and direction of CFRP strips spaced at 100mm center to center. The width of CFRP strips was kept constant at 50 mm with thickness of 0.166 mm. Sika Wrap-300 C/60 unidirectional woven carbon fiber fabric and Sikadure-330 two parts epoxy impregnation resin were used in the present study to strengthen the tested beams. The strengthening process was done after the 28 days of curing of the test beams by about two weeks, when the concrete surface was completely air dried.

Beam specimen strengthening details are illustrated in table 1. The names of the deep beams include the short (DB) which refers to deep beam. DB1 was unstrengthened to serve as a control beam. Deep beams (DB2, DB6, DB7, and DB8) were strengthened with vertical fiber wrap as strips. Each strip was continuous at the bottom face of the beam and exhaustible close to the top surface of beams on both sides. Two layers of CFRP strips were applied, one over the other, for the beams DB6 and DB8. While three strips were used to strengthen DB3 in a horizontal configuration covering all sides of the beam. DB4 was strengthened with both vertical and horizontal strips spaced at (100mm) for both directions. In DB5, four isolated carbon fiber strips of (300 mm length) and (200 mm length) were bonded orthogonally to the diagonal line connecting the loading and the supports points in a symmetrical manner with the (400 mm) strip at the middle as shown in figure 8. The length of the strips No (2) in figure (8 of DB5) was chosen to be 75% of the length of the middle strip. While the length of strip number (3) was equal to 50% of the middle strip length. Decreasing in the strips length was intended to be analogous to a decrease in the bottle shape representation of the strut and tie region.

#### Table 1. Beams specimen strengthening details

<table>
<thead>
<tr>
<th>Beam No.</th>
<th>a/d ratio</th>
<th>a (mm)</th>
<th>Shear Reinf.</th>
<th>No. of Layer s</th>
<th>CFRP Details</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Spacing (mm)</td>
<td>Orientatin</td>
</tr>
<tr>
<td>DB1</td>
<td>1.0</td>
<td>350</td>
<td>Φ5 @ 100</td>
<td>100</td>
<td>Ref. beam</td>
</tr>
<tr>
<td>DB2</td>
<td>1</td>
<td>100</td>
<td>Vertical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DB3</td>
<td>1</td>
<td>100</td>
<td>Horizontal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DB4</td>
<td>1</td>
<td>100</td>
<td>Vertical &amp; Horizontal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DB5</td>
<td>1</td>
<td>100</td>
<td>Inclined</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DB6</td>
<td>2</td>
<td>100</td>
<td>Vertical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DB7</td>
<td>1</td>
<td>150</td>
<td>Vertical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DB8</td>
<td>2</td>
<td>150</td>
<td>Vertical</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.2 CFRP strips installations

The strips of carbon fiber were applied by a manual lay-up process to the external surface of concrete. Resin Chemical reaction hardens the material to a strong lightweight product. The resin serves as the matrix for carbon fiber as concrete action for the steel reinforcing bars. The insulation process was done as described in the following steps:

- The concrete surface was abraded at the locations of gluing carbon fiber strips on concrete.
- The side or/and lower angle of the strengthened specimens have been chamfered to provide a radius of approximately (13 mm) (Figure 9) according to ACI Committee 440.2R-08[8] recommendations.

- Just before composites application on concrete beam, the epoxy resin was mixed according to the manufacturer’s instructions. Then a thin layer of epoxy resin was applied along the concrete substrate in specified locations where the fiber will installed. The strips are placed on top of the epoxy resin coating and bonded to tensile soffit. Then, the resin is squeezed through the portable of the fabric by a special roller.

5 Test setup and loading procedure

The laboratory tests for the all the deep beams were done by a hydraulic testing machine (AVERY Denison testing machine) of (2500 kN) maximum capacity which was available in the structural laboratory of the Building and Construction Engineering Department/ University of Technology (Figure 10). For all tested beams, one dial gauge of (0.01 mm) accuracy capacity was positioned at midspan of each beam to measure the midspan deflection.

6 Results and discussion

6.1 General behavior of deep beam specimens
At the early stages of loading, all the tested deep beams behaved in an elastic manner and they were free of cracks. Gradually, with the increase of the loads, small flexural and shear cracks appeared at the center of the beam and the shear span regions respectively. The first shear cracks appeared at approximately about (16 to 35%) of ultimate loads followed by long and slightly wide cracks that developed in the shear span zone with further increasing of the loads.

The carbon fiber strips (CFRP) in the strengthened deep beams play their role in loads resisting capacity at later stages of loading. The behavior of the strengthened beams under increasing loads was varied according to the type of strengthening, number of layers, spacing between the strips.

The failure planes in all beams were formed along the diagonal cracks joining the loading and the reaction points. The crack patterns in the strengthened specimens were nearly identical to the control deep beam DB2 except that DB2 shows widely spaced and more cracks as compared to strengthened deep beams.

6.2 First cracking and ultimate loads capacity

Test results including first shear cracking and ultimate (maximum) loads gain by carbon fiber strengthening technique are illustrated in Table 2. The elementary or initial cracks developed in the strengthened deep beams at a higher load than their regulate specimen because the CFRP strips provided a good restraint to the cracks growth. Increasing in the first cracking load of the strengthened samples could be attributed to the stiffness increasing due to the CFRP strips suppressing effect. The ratios of ultimate load carrying capacity of the strengthened beams to the control one were computed and given in Table 2. The highest value was recorded for beam specimen DB4 among all the tested beams, which was equal to 145%.

6.3 Crack pattern and failure modes.

Figure 12 shows the failure mode of the tested beams, the vertical orientation of strips in DB2 showed better performance than horizontal placement in DB3. Also, the presence of carbon fiber in addition to internal stirrups provides a better distribution of diagonal cracks throughout the shear span in DB2. The mode of failure of DB5 was started due to the lower end deboning of the middle strip from the concrete surface. Shortly after that, the strip nearest to the middle one on the upper end of the beam gave way, consequently causing the complete failure in a same manner to DB1. The using of transverse strips gives an increase of 60% and 32% respectively, in crack load and

<table>
<thead>
<tr>
<th>Beam No.</th>
<th>CFRP Details</th>
<th>P_{cr}(crack) (kN)</th>
<th>Increasing in crack loads (%)</th>
<th>P_u (kN)</th>
<th>Increasing in ultimate load (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DB1</td>
<td>-</td>
<td>100</td>
<td>-</td>
<td>440</td>
<td>-</td>
</tr>
<tr>
<td>DB2</td>
<td>1, 100 Vertical</td>
<td>160</td>
<td>60</td>
<td>520</td>
<td>18</td>
</tr>
<tr>
<td>DB3</td>
<td>1, 100 Horizontal</td>
<td>120</td>
<td>20</td>
<td>500</td>
<td>14</td>
</tr>
<tr>
<td>DB4</td>
<td>1, 100 Vertical &amp; Horizontal</td>
<td>160</td>
<td>60</td>
<td>640</td>
<td>45</td>
</tr>
<tr>
<td>DB5</td>
<td>1, 100 Inclined</td>
<td>140</td>
<td>40</td>
<td>580</td>
<td>32</td>
</tr>
<tr>
<td>DB6</td>
<td>2, 100 Vertical</td>
<td>120</td>
<td>20</td>
<td>560</td>
<td>27</td>
</tr>
<tr>
<td>DB7</td>
<td>1, 150 Vertical</td>
<td>140</td>
<td>40</td>
<td>460</td>
<td>5</td>
</tr>
<tr>
<td>DB8</td>
<td>2, 150 Vertical</td>
<td>140</td>
<td>40</td>
<td>530</td>
<td>14</td>
</tr>
</tbody>
</table>

The central deflection at first shear cracking and Ultimate loads of the tested beams is presented in figure (11). The central deflection at ultimate load for the tested deep beams is smaller than that of the control beam DB2 (reinforced by internal shear reinforcement only); this probably could be a result of the externally attached carbon fiber strips.
ultimate load compared to that of the control sample. When compared to DB2 which had one layer vertical strips, this increase in the ultimate load was more by about 12% while there is a decrease in crack load by about 14%.

A longitudinal splitting crack was established on the top face of the specimen DB8 at about 450 kN as shown in figure 13. The crack started to the right side of the beams (roller support) and extends towards the support. It could be said that the splitting failure of DB8 happened due to the high longitudinal compressive stress developed at the top of the beam that produce aepisodic tension led to splitting failure. DB8 failed at a total ultimate load of 530 kN with an increase of 20% in ultimate capacity compared with DB1 and an increase about 15% compared with DB7.
6.4 Load Mid-span deflection responses

Load-deflection relationship is essential to describe behavior of the beams under various stages of loading. Table (3) demonstrates the midspan deflection for the tested deep beams to show the additional capacity gained by using CFRP strips. The largest deflection was experienced by DB3. For comparison, the deflections of the beams at first crack load of the control beam (DB1) which was of (100kN) are also shown in table (3). The table shows that the use of carbon fiber composite material results in reduced deflections by about (9 to 80%) when compared at the first crack load. This decrease in deflection is dependent on the type of strengthening pattern. While at the ultimate load, the deflection of the strengthened beams was more than the deflection of unstrengthened beam in companied with increase in shear capacity loading.

Table 3. Comparison between failure load and deflection for the deep beams

<table>
<thead>
<tr>
<th>Beam No.</th>
<th>Deflection at 100kN</th>
<th>Maximum deflection at ultimate load</th>
<th>% decrease of max. deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>%</td>
<td>mm</td>
</tr>
<tr>
<td>DB1</td>
<td>2.18</td>
<td>100</td>
<td>8.30</td>
</tr>
<tr>
<td>DB2</td>
<td>0.8</td>
<td>37</td>
<td>3.60</td>
</tr>
<tr>
<td>DB3</td>
<td>2.12</td>
<td>97</td>
<td>8.30</td>
</tr>
<tr>
<td>DB4</td>
<td>1.1</td>
<td>50</td>
<td>7.60</td>
</tr>
<tr>
<td>DB5</td>
<td>1.8</td>
<td>83</td>
<td>7.35</td>
</tr>
<tr>
<td>DB6</td>
<td>1.59</td>
<td>73</td>
<td>7.20</td>
</tr>
<tr>
<td>DB7</td>
<td>1.72</td>
<td>79</td>
<td>6.50</td>
</tr>
<tr>
<td>DB8</td>
<td>2.38</td>
<td>109</td>
<td>7.80</td>
</tr>
</tbody>
</table>

Figure (14) shows the load-midspan deflection behavior of the deep beams strengthened by vertical carbon fiber strips. The deflection curve of the strengthened deep beams appeared to be identical in shape to their control one (DB1) but with different extremes. Initially, the internal steel reinforcement bars in the strengthened beams carried the majority of the tensile force in the beam cross section. Then, the additional tensile force are carried by the CFRP strips when the internal steel abandon and as a result, an increase of the load carrying capacity of the beams is gained.

Figure (15) shows the curves of load midspan deflection for DB1, DB3, DB4, and DB5which were the control beam and the beams strengthened by horizontal, vertical and horizontal, and inclined CFRP strips, respectively. All curves have somewhat similar character and demonstrated nearly linear response till to the first shear crack load. Response of all strengthened beams of this group shows a typical load-deflection behavior with the sharp drop as soon as their reaching the ultimate loads. It can be observed from figure (16) that the horizontal strips in DB5 have less effect on the load carrying capacity and the maximum deflection value compared with the unstrengthened control deep beam DB1, while the presence of inclined strips in DB5 have a significant effect in improving the load capacity by about 32% as compared with DB1 and 16% as compared with DB3 respectively. Also, these inclined strips play a noticeable role in decreasing the maximum deflection by about 13% compared with the control beam DB1 and the beam with horizontal strips only (DB3). DB4 was the best strengthened deep beam among the all beams in increasing the load carrying capacity by 45% as compared with the control one.

7 Conclusions

The following conclusion could be made based on the experimental results:

Fig. 14. Load-midspan deflection curves for beams with vertical strengthening system

Fig. 15. Load midspan deflection curves for beams with horizontal and inclined strengtheningsystem
1. The use of CFRP strips in the strengthening lightweight aggregate deep beams increases the load carrying capacity by about 45% for the present work. Cracks were smaller and more distributed in the strengthened beams compared with their controls ones.

2. Bonded FRP system in the shear span considerably delayed the formation of diagonal shear cracks and provided positive restraint to the subsequent growth of cracks. The shear crack load of the beams varies from 16 to 35% of their ultimate loads.

3. Compared to control beam, the use of inclined CFRP strips in DB5 gives an increase of 60% and 32% in crack load and ultimate load respectively.

4. Diagonal compression strut crack of unstrenghtened control beams was changed to many small diagonal cracks at mid depth within the shear span of the strengthened beams and exhibited more ductile failure mode with the increased stiffness in tension face.

5. The strengthening accomplished by externally bonded carbon fiber strips, in general, provided restraint to the widening of the diagonal cracks. Thus, it can be concluded that the strip thickness and normal orientation significantly influences the structural performance of the strengthening lightweight deep beams.

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