Structural behavior of SCC continuous deep beam strengthening and retrofitting with carbon fiber reinforced polymer strips

W J Al-Bdari 1, Emeritus Prof Dr. Nabeel Al- Bayati 2, Assist. Prof. Dr. A. S. Al-Shaarbaty 3
1 Civil Engineering Department, University of Technology / Baghdad/Iraq
2 Head of Civil Engineering Department, Ashur University College / Baghdad/Iraq
3 Al-israa University College / Baghdad/Iraq

Email: 41863@student.uotechnology.edu.iq

Abstract. This study presents an experimental work to investigate the structural behavior of continuous self-compacting concrete (SCC) deep beams strengthened and retrofitted with woven carbon fiber reinforced polymer (CFRP) strips and evaluate their shear capacity. The work includes casting and testing fourteen beams specimens. All tested beams have the same dimensions, the same flexural reinforcement and concrete compressive strength with two continuous span and have been subjected to two-point loads. The test specimens were divided into three groups. The first group including eight beams with minimum ratio of shear reinforcement ($\rho_v=\rho_h=0.25\%$) and two parameters considered, shear span to overall depth ratio ($a/h$) and three different schemes of CFRP strip. The second group including four beams without interior vertical and horizontal shear reinforcement ($\rho_v=\rho_h=0\%$) with three different schemes of CFRP strip and control beam. The third group consists of two beams with minimum ratio ($\rho_v=\rho_h=0.25\%$) were firstly loaded to 65% of the ultimate load of control beams, after that the loads were released and then retrofitted by CFRP strip by two different schemes. The experimental results show that the specimens with vertical CFRP strips an increase in ultimate strength load by 32.6% and 20% compared to the control beams.

Keywords: Deep beams, Self-compacting concrete, continuous, retrofitting, Carbon fiber polymer.

Notation
$\rho_v$: The percentage of shear area reinforcement that distributed perpendicular to the longitudinal axis of the beam.
$\rho_h$: The percentage of shear area reinforcement that distributed parallel to the longitudinal axis of the beam.
$a/h$: shear span-to-overall height

1. Introduction
In recent years, there has been a great interest in investigating the behavior of reinforced concrete deep beams that were expressed by large amount of experimental studies of this type of structures. Shear failure has been identified from these experimental studies as the control failure. ACI committee (2014) [1] states deep beams as beams have clear span to effective depth ratio less than 4 or concentrated applied force within 2h from support face. In 1968, Ramakrishnan and Ananthanarayana [2] investigated the behavior of 26 deep beams having ($a/h$) ratio less than 2, which failed by splitting failure of diagonal concrete struts. They concluded that span-to-depth ratio is an important factor governing the failure of
deep beams and can be taken as the basis for the difference of these structures. In 2007, Keun-H. Y, et al. [3] tested twenty-four two-span continuous deep beams. Two types of concrete strengths, arrangement of shear reinforcement, and the ratio of a/d were the variables of the tested beams with same width 160 mm and depth 600mm. Experimental results shows the noticeable effect of a/d on the horizontal and vertical shear reinforcement.

The strength of reinforced concrete deep beams can be increased by application of adhesively bonded carbon fiber to the external face of the beam. Using CFRP materials in strengthening and retrofitting existence structures has gained popularity when upgrading is required to cope with additional loads. CFRP laminates offer higher strength and stiffness with good resistance to corrosion. Belal [4] conducted experimental work to explore the effect of repairing and strengthening deep beam by CFRP laminates. The results presented that there was an improvement in ultimate capacity of reinforced concrete deep beam.

This study presents an investigation of the behavior and ultimate capacity of continuous deep beam conducted with various variables, namely three ratios of a/h, with and without steel shear reinforcements, and strengthening with different configuration of CFRP schemes.

2. Materials
2.1 Steel reinforcement
For deep beams contained shear reinforcement, 5 mm bars at 100 mm was chosen in both horizontal and vertical directions. The yield tensile strength of shear reinforcement was 613 Mpa, whereas for flexural reinforcement was 3 bars with diameter 16 mm at the top and bottom of the beams, having yield tensile strength 564MPa.

2.2 Concrete mix
The materials ordinary Portland cement, fine aggregates (zone II), and coarse rounded aggregates (maximum size 12 mm), Limestone Powder (particle size is less than 0.125 mm), and High-Range Water Reducer (SikaVicoCrete-5930) were used in this experiment to produce the self-compact concrete mix. The fine and coarse aggregates conformed to the Iraqi Specification No.45/1984 [5]. Many trial mixes were made to obtain accepted self-compact mix Characteristics and the requirements of EFNARC (2005) [6] and compressive strength ($f'_c$) was 42 Mpa at 28 days.

2.3 CFRP Products
A unidirectional woven carbon fabric CFRP sheet named (SikaWrap-300 C) was used with special epoxy, with trade name as (Sikadur-330). Table 1 listed the properties of CFRP that is used in this study.

| Product Data                        |                              |
|-------------------------------------|------------------------------|
| **Dry Fiber Density**               | 1.82 g/cm³                   |
| **Laminate Nominal Thickness**      | 0.167 mm                     |
| **Laminate Tensile Strength**       | 3 200 kN/mm², ASTM D 3039    |
| **Laminate Modulus of Elasticity in Tension** | 215 000 N/mm², ASTM D 3039 |
| **Laminate Elongation at Break in Tension** | 1.59 %, ASTM D 3039        |

3. Description of Beam Specimens
A total of fourteen continuous self-compact reinforced concrete deep beams were cast and tested to examine the effect of various parameters on the behavior and shear capacity of these specimens. The parameters included in this study are shear span to total depth ratio (a/h), with and without internal steel shear reinforcement, and different patterns of externally bonded CFRP. In addition, two of these specimens were retrofitted after loaded 65% of their ultimate shear capacity. Each specimen had 2400 mm total length, 150 mm width, and 350 mm depth. The details of the tested beams are presented in table 2. Figures 1 to 4 show the schematic drawings of the tested specimens in this investigation, which illustrates the distribution of CFRP Sheets.
Table 2. Summary of tested beams’ details.

*CFRP woven strip with 50mm width and 0.167mm thicknesses

| Group Symbol | Specimen | a (mm) | \(a/h\) | \(\rho_v = \rho_h\) | CFRP \% of covered area* | Orientation of CFRP strips |
|--------------|----------|--------|---------|-----------------|-------------------------|---------------------------|
| 1            | A1       | 420    | 1.2     | 0.25%           | 0.0%                    | Non                       |
|              | A2       | 420    | 1.2     | 0.25%           | 50%                     | Horizontal                |
|              | A3       | 420    | 1.2     | 0.25%           | 50%                     | Vertical                  |
|              | F1       | 420    | 1.2     | 0.25%           | 100%                    | Full Area                 |
|              | C1       | 315    | 0.9     | 0.25%           | 0.0%                    | Non                       |
|              | C2       | 315    | 0.9     | 0.25%           | 50%                     | Horizontal                |
|              | D1       | 525    | 1.5     | 0.25%           | 0.0%                    | Non                       |
|              | D2       | 525    | 1.5     | 0.25%           | 50%                     | Vertical                  |
| 2            | B1       | 420    | 1.2     | 0.0%            | 0.0%                    | Non                       |
|              | B2       | 420    | 1.2     | 0.0%            | 50%                     | Horizontal                |
|              | B3       | 420    | 1.2     | 0.0%            | 50%                     | Vertical                  |
|              | B8       | 420    | 1.2     | 0.0%            | 50%                     | Inclined                  |
| 3            | E2       | 420    | 1.2     | 0.25%           | 50%                     | Horizontal                |
|              | E3       | 420    | 1.2     | 0.25%           | 50%                     | Vertical                  |

**Figure 1.** Details of the tested beams.
Figure 2. CFRP strengthening pattern of the tested deep beams group 1, 2 and 3.
Figure 3. CFRP strengthening pattern of the tested deep beams group 1, 2 and 3.
Figure 4. CFRP strengthening pattern of the tested deep beams group 1, 2 and 3.

4. Testing Procedure and Measurements
All beams were loaded by application of a single point load divided into two-point loads and rested over three supports. The loads were transferred to the concrete beams through two steel rollers as presented in figure (5). The loading was applied by 10 kN increments. At each increment, the deflection was recorded using a linear variable differential transducer (LVDT) at midspan of the beam. In addition, four strain gauges were located to record the compression and tension strains in concreted surface. All the instruments were monitored and recorded by a data acquisition system connected to a computer.

Figure 5. Test Setup.

5. Experimental Results and Discussions
6.1 Ultimate Load Capacity and Load-deflection Behavior
Experimental results of ultimate strength, and midspan deflection of the tested beams specimens are presented in table 3. While, figures 6 to 8 show the load-maximum deflection behavior of the specimens. The ratios of ultimate strength of the strengthened beams to the control beams of each group where it is listed. Beam C2 had the highest strength among all the tested deep beams, which had the lowest a/h ratio and horizontal strips strengthening.

The experimental test results show that the percentage increase in ultimate strength when full area covered is 32.6% (for F1) compared to control specimen A1. For all tested beams with a/h=1.2 that strengthened with strips in vertical direction gave more enhancement in ultimate capacity percentage (A3 and B3) compared with beams that strengthened in horizontal direction (A2 and B2). The same conclusion can be drawn for deep beam D2, strengthened with vertical CFRP strips, the increase was 20% compared with control beam D1, which had the same a/h=1.5. From table 3, it can be seen that test beam B8 had increased the ultimate load by 31.7%, which is the maximum increase percentage compared with deep beams of same category, which were without any shear reinforcement and a/h ratio was 1.2.

6.2 Retrofitted beams
To study the effect of strengthening for beams that already loaded then need to retrofit, two beam tested by applying load till 65% then removed after that strengthened with two types of schemed, then tested till failure. From table 3, it can be noted that retrofitted deep beams after 65% of ultimate load by CFRP sheets given a good enhancement in the shear strength compared with control beam A1, especially for beam E3, which was strengthened by vertical CFRP sheets. The increase in the shear strength was 13% and 18.5 % for beams E2 and E3, respectively.

Table 3. Cracking load, Ultimate Load Capacity, and Midspan Deflection of The Tested Beams.

| Group Symbol | Specimen | Cracking Load (kN) | Ultimate Load (kN) | Midspan deflection (mm) | Percentage of ultimate capacity |
|--------------|----------|--------------------|--------------------|-------------------------|-------------------------------|
| 1            | A1       | 460                | 920                | 3.23                    | Control beam                  |
|              | A2       | 480                | 1020               | 3.44                    | 10.90%                        |
|              | A3       | 520                | 1060               | 3.58                    | 15.20%                        |
|              | F1       | 680                | 1220               | 3.85                    | 32.60%                        |
|              | C1       | 500                | 1120               | 2.68                    | Control beam                  |
|              | C2       | 520                | 1260               | 3.05                    | 11.60%                        |
|              | D1       | 420                | 800                | 3.51                    | Control beam                  |
|              | D2       | 460                | 960                | 4.25                    | 20.00%                        |
| 2            | B1       | 380                | 820                | 2.95                    | Control beam                  |
|              | B2       | 420                | 920                | 3.31                    | 12.20%                        |
|              | B3       | 480                | 960                | 3.42                    | 15.90%                        |
|              | B8       | 680                | 1080               | 3.89                    | 31.70%                        |
| 3            | E2       | ---                | 1040               | 3.35                    | 13%                           |
|              | E3       | ---                | 1100               | 3.70                    | 18.50%                        |

6.3 Crack Pattern and Mode of Failure
Diagonal shear cracks initiated and propagated from the loading points to the support. These cracks became wider with load increase until failure. The crack pattern is shown in figures 9 to 11 for all deep beam specimens. All the specimens failed in shear. Diagonal splitting failure between the load point and the support point was the main failure mode of the beams. Also, it can be seen from this figure that the
Retrofitting deep beams, E2 and E3, had a different shape of crack pattern in comparison with the previously remarked cracks. The retrofitting beams were failed by concrete crashing and separation of CFRP sheets from concrete.

Figure 6. Load-maximum deflection behavior of group 1 deep beams.

Figure 7. Load-maximum deflection behavior of group 2 deep beams.

Figure 8. Load-maximum deflection behavior of group 3 deep beams.
Figure 9. Cracks patterns of the tested specimens.
6. Conclusion

According to the experimental results, the following conclusions can be drawn:

1- The external bonded strength using shear reinforcements gave an enhancement in the ultimate shear capacity of deep beams in comparison with beams without any reinforcement.

2- For the same group of shear reinforcement ratio, the increase in shear span to depth ratio gives decrease in crack load and ultimate capacity, respectively.

3- The strengthened deep beams by externally bonded CFRP sheets exhibit a higher deflection values with an increase in shear capacity in comparison with the control beams. In addition, the diagonal cracks were changed to critical cracks, which will be the cracks that leads to failure, within the shear spans.

4- The deep beams, which strengthened with inclined CFRP sheets perpendicular expected crack bath had greater ultimate load capacity compared to deep beams strengthened with vertical or horizontal sheets.

5- Strengthening beam with vertical oriented strip scheme more efficiency of beams strengthened with horizontal direction.

6- Retrofitted deep beams with vertical CFRP sheets gives higher shear strength than the horizontally strengthened beams.
References

[1] ACI Committee 318, 2014, “Building Code Requirement for Structural Concrete (ACI 318M-14) and Commentary”, American Concrete Institute, Farmington Hills
[2] Ramakrishnan V and Ananthanarayana Y 1968 Ultimate Strength of Deep Beams in Shear ACI Journal, 65, pp 87-98
[3] Keun H Y Heon-Soo Chung and Ahraf F A 2007 Influence of shear reinforcement on reinforced concrete continuous deep beams ACI Structural Journal Vol. 104 pp 420–429
[4] Bilal I A 2009 Behavior of Reinforced Concrete Deep Beams Strengthened with Carbon Fiber Reinforced Polymer Strips PhD Thesis Dept. of Civil Engineering College of Engineering University of Baghdad
[5] Iraqi Standard Specification No. 45, "Natural Aggregate Resources used in Concrete and Construction", Central Agency for Standardization and Quality Control, Baghdad, 1984
[6] EFNARC: The European Guidelines for Self-Compacting Concrete Specification, Production and Use. European Federation for Specialist Construction Chemicals and Concrete Systems, 2005