Structural behaviour of SCC continuous deep beam strengthened with carbon fiber NSM and hybrid techniques

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Abstract. In this research, results of an experimental investigation on the shear strengthening of normal SCC continuous concrete deep beam are presented. A total of twelve continuous deep beams were cast and tested. The aim of this paper is to study the effect of carbon fiber reinforced polymers (CFRP) through Near Surface Mounted (NSM) and hybrid techniques to improve the structural behaviour and shear resistance capacity of deep beams. Two beams were used as control with no strengthening, while the remaining ten beams were strengthened in different (with and without) steel shear reinforcement, orientation of NSM-CFRP rods, hybrid techniques (combined of EBR-CFRP strip and NSM-CFRP rods). The beams were designed to fail in shear and to match with the requirements of ACI 318M-14 building code. Results showed that the hybrid technique caused an increase in the load carrying capacity for the deep beams up to 58.5% when compared to the beams without strengthened control one.

1. Introduction
From many experimental researches, it has been found that externally bonded FRP (fiber-reinforced polymer) could be used to increase the ultimate shear capacity of reinforced concrete beams (Khalifa, 1999) [1]. NSM-FRP is an attractive technique to retrofitting and strengthening the existing and new structures due to its characteristics beat EBR, essentially from the amelioration performance achieved from redistribution strain resulting in higher imposition of obtainable strain [2] and its more reluctance to many environmental influences due to being stuffed inside the cover of concrete. The sensitivity to temperature can be reduced by using the appropriate type of filler [3]. For retrofitting old important structures the NSM-FRP is the best solution due to low effect of aesthetic [4]. De-bonding of EB-FRP is the main problem and to overcome this point, The NSM technique can be used for shear strengthening [5]. It was found that NSM-FRP presented higher enhancement in shear strength in comparison with EBR-FRP and the contribution if NSM in shear resistance higher about 2.8 time [6]. It is important to apply NSM bars as deep as possible to get significant enhancement in shear strength (to get higher fracture area and more concrete fracture force that’s needed to increase the depth of the NSM bars, which lead to get greater concrete resisting area) [7]. Anchorage systems lead to the appearance of flexural cracks and increase in ductility from 40% to 75% [8].

2. Experimental program
2.1 Beams description and details
The experimental work included casting and testing of twelve continuous two span beams, which were divided into two groups - with and without shear steel reinforcement. All of the specimens were having the same dimensions and the same amount of main reinforcement. Each specimen had an overall length of 2400 mm divided by two spans, each span 1050 mm, width of 150 mm and beam height of 350 mm.
The first group symbol (A) contained five deep beams designed with internal steel stirrups at a spacing lower than the requirements of the ACI 318M-14[9]. The chosen shear reinforcement was Ø 5 at 100 mm for shear in both horizontal and vertical directions and the shear reinforcement ratio ($\rho_v = \rho_h=0.00262$) was almost equal to the minimum shear reinforcement ratio stated by ACI 318M-14. The beams were designed to obtain a shear failure. The second group symbol (B) contained seven beams and had no internal shear reinforcement ($\rho_v= \rho_h = 0.00$); each group had control specimen considered as reference beams. All beams had a flexural reinforcement of $3\phi 16$ mm for main bars top and bottom and for beams that had internal steel stirrups the shear reinforcement's tensile strength was 613MPa while for flexural reinforcement was 564MPa. The actual yield strengths, as determined from tensile tests on three sample specimens according to ASTM A615/A615M-05 [10] and ASTM A496-02[11]. All longitudinal bottom steel reinforcement covers full length of the beams and through the depth to provide sufficient anchorage lengths. The vertical web reinforcement was of closed stirrups and the horizontal web reinforcement as longitudinal bars in both sides of the beam. Horizontal stirrups were anchored at each end with standard hooks.

The internal steel reinforcement details of the tested deep beams are shown in figure 1.

![Figure 1. Details of the internal steel reinforcement of the tested deep beams.](image)

2.2 Concrete Properties and Mix Design

The properties of materials and mix proportion have a great effect on Self-Compacted Concrete (SCC). In this work, the design of SCC concrete mix is based on EFNARC (2005) [12]. The properties of the materials used in this paper are listed as follows:

2.2.1 Cement: An ordinary Portland cement conforming to the Iraqi Standards Specifications IQS N0.5/1984 [13] was used.

2.2.2 The fine aggregates: conforming to grading zone 2 was used based on the requirements of the Iraqi Standard Specification IQS No.45/1984[9] and ASTM C33-03[14].
2.2.3 The coarse aggregates: with maximum nominal size 14 mm, the grading of this aggregate conformed to the Iraqi specification IQS No.45/1984[9] and ASTM C33-03[11].

2.2.4 Limestone Powder: which is locally named “Al-Gubra” and has been used as a filler for concrete production. The limestone particle size is 0.125 mm (Sieve No.200), and it satisfies with EFNARC (2005)[12].

2.2.5 High-Range Water Reducer (super plasticizer): a super plasticizer named (SikaVicoCrete-5930) was used to produce SCC. It is a third generation super plasticizer for concrete and mortar and meets the requirements for super plasticizer.

In this experiment, the cement content was 400 kg/m$^3$, fine aggregate content was 770 kg/m$^3$, course aggregate content was 830 kg/m$^3$, limestone powder contents were 150 kg/m$^3$, water content was 150 lit/m$^3$ and the super plasticizer content was 10 lit/m$^3$; these values satisfy all the values recommended by EFNARC’s mix design method. Compressive strength for test specimens was obtained from testing six cylinders (300 X 150mm) for each batch; three standard cylinders were tested at 28 days from casting day the average of compressive strength was (f'c= 42 MPa) and other three cylinders tested at 74 days with specimens’ test day the average of compressive strength was (f'c= 46 MPa).

2.3 Strengthening system
To enhance the shear strength of continuous deep beams presented in this experimental study, two types of carbon fiber reinforced polymer (CFRP) products were used:

2.3.1 CFRP rod: which is carbon fiber reinforced polymer (CFRP) laminates with a circular cross section were used in NSM technique.

2.3.2 CFRP sheet strip: which is a unidirectional woven carbon fiber fabric with mid-range strengths was used in composite with CFRP rod to produce hybrid strength technique. Table 1 shows the properties of CFRP materials, which is obtained from manufacturer data sheet.

| CFRP Type | Properties                  |
|-----------|-----------------------------|
| CFRP rod  | 12mm Diameter               |
| (Sika CarboDur BC) | Laminate Tensile Strength 3100 N/mm$^2$ |
|           | Laminate Modulus of Elasticity in Tension 148000 N/mm$^2$ |
|           | Laminate Elongation at Break in Tension > 1.70 % |
|           | Density 1.60 g/cm$^3$ |
|           | epoxy Resin Adhesive Sikadur-30 LP |
| CFRP strip | Thickness                    |
| SikaWrap-300 C | Each strip with 50mm width 0.167mm |
|           | Laminate Tensile Strength 3200 N/mm$^2$ |
|           | Laminate Modulus of Elasticity in Tension 2100 N/mm$^2$ |
|           | Laminate Elongation at Break in Tension 1.59 % |
|           | Density 1.82 g/cm$^3$ |
|           | epoxy Resin Adhesive Sikadur-330 |

After specimens have reached the required strength (28 days) the process to prepare the strength beams includes: cutting grooves in each concert side of specimens with square cross section (15 X15 mm) (1.5 diameter of CFRP rod), using water jet and air blast to remove the powdered concrete produced
by the cutting process and all the possible loose materials. A layer of epoxy has been laid (half-way of groove) then a CFRP bar is installed with light pressure to ensure that paste would flow around the bar and fill completely the side of groove. After that the groove is filled with epoxy. The test is done at least two weeks later to allow the epoxy to gain the required strength.

Regarding to specimens that have been strengthened by using hybrid technique, after the completion of the first phase of strengthening by CFRP-NSN and leaving for ten days to ensure that the epoxy paste reaches the required strength and is not affected by any treatment. The second step includes smoothening the outer face of concrete to achieve high strength bonds between adhesive and substrate in addition to chamfering the corner of beams to provide a radius of approximately 13 mm of rounded corner (upper and lower or sides faces depending on type of scheme that is used) ACI Committee 440.2R-08[15] apply layer of epoxy then add CFRP woven strip 50mm width.

In the NSM technique vertical and horizontal reinforcement CFRP rods with 12mm diameter were used, and the second technique hybrid (mirage between NSM techniques and externally bonded CFRP sheet strip) as shown in figures 2 and 3.

Group A: five specimens with minimum steel shear reinforcement were tested. A1 represents control beam without any external strength, while specimens A4 strengthened with NSM-FRP two rods 12 mm from each side of the beam in horizontal direction. For the Hybrid technique (mirage between NSM techniques and externally bonded CFRP sheet strip) A5 is strengthened in vertical direction with 12mm CFRP rods at 175mm c/c. Specimens A6 and A7 are strengthened with two types of CFRP products first NSM-FRP technique and then using CFRP strip 50 mm width one-layer perpendicular to the direction of the CFRP rods and 100 mm c/c between each strip. Figure 2 represents the beam details.

Group B: all seven specimens without interior steel shear reinforcement (psv= psh= 0.00). Beam B1 designed without any external strengthened as control beam. Beams B4, B5, B6 and B7 same as A4, A5, A6 and A7, respectively. Beams B9 and B10 strengthened with NSM-CFRP rods as first then inclined CFRP strip with 45 and 135’ from horizontal beam axis to be perpendicular to the expected cracks that is expected to appear between point load and mid support, Figure (3) represents each beam details in this group.

| Table 2. Summary of tested beams’ details |
|------------------------------------------|
| Group Symbol | Specimen | a (mm) | a/h | v= | ph | CFRP STRIP | CFRP rod |
|---------------|----------|--------|-----|-----|-----|------------|-----------|
|               |          |        |     |     |     | Width 50mm | 12mm dim. |
| A             | A1       | 420    | 1.2 | 0.25% | Non | Non        |           |
|               | A4       | 420    | 1.2 | 0.25% | Non | 2 Ø 12mm Horizontal |       |
|               | A5       | 420    | 1.2 | 0.25% | Non | Ø 12mm 175mm c/c Vertical |       |
|               | A6       | 420    | 1.2 | 0.25% | Horizontal strip 100mm c/c | Ø 12mm 175mm c/c Vertical |       |
|               | A7       | 420    | 1.2 | 0.25% | Vertical strip 100mm c/c | 2 Ø 12mm Horizontal |       |
| B             | B1       | 420    | 1.2 | 0.0% | Non | Non        |           |
|               | B4       | 420    | 1.2 | 0.0% | Non | 2 Ø 12mm Horizontal |       |
|               | B5       | 420    | 1.2 | 0.0% | Non | Ø 12mm 175mm c/c Vertical |       |
|               | B6       | 420    | 1.2 | 0.0% | Horizontal strip 100mm c/c | Ø 12mm 175mm c/c Vertical |       |
|               | B7       | 420    | 1.2 | 0.0% | Vertical strip 100mm c/c | 2 Ø 12mm Horizontal |       |
|               | B9       | 420    | 1.2 | 0.0% | Inclined strip 100mm c/c | Ø 12mm 175mm c/c Vertical |       |
|               | B10      | 420    | 1.2 | 0.0% | Inclined strip 100mm c/c | 2 Ø 12mm Horizontal |       |
Figure 2. Group A (with steel shear reinforcement).
Figure 3. Group B (without shear steel reinforcement).
2.4 Testing Procedure and Measurements

All twelve specimens were loaded by two-point loads and rested over three steel supports. This load was transferred to the deep beams by application of a single point load divided into two-point loads evenly by stiffened W steel shape beam and two steel rollers, see figure (4). The load was applied by a hydraulic testing machine (AVERY Denison testing machine) with maximum capacity of (2500 kN). The tests were carried out in the structural laboratory of the civil Engineering Department/University of Technology. The loading was applied by 10 kN increments. At each increment, the deflection at midspan was recorded using a linear variable differential transducer (LVDT). In addition, four strain gauges were located to record the compression and tension strains in concreted surface. All the instruments were fed into a data acquisition system connected to a computer.

![Figure 4. Specimens rest on and three steel support and W steel beam to transfer load to two-point load.](image)

3. Result and Discussion

Results of the experimental work for ultimate load capacity and midspan deflection of control and strengthened deep beams by NSM-CFRP and hybrid technique are presented in Table 3.

| Group Symbol | Specimen | Cracking Load (kN) | Ultimate Load (kN) | Mid span deflection (mm) | Percentage of ultimate capacity to the control beam |
|--------------|----------|--------------------|--------------------|-------------------------|-----------------------------------------------|
| A            | A1       | 460                | 920                | 3.23                    | Control beam                                 |
|              | A4       | 500                | 1150               | 3.626                   | 25%                                           |
|              | A5       | 460                | 980                | 3.290                   | 6.50%                                         |
|              | A6       | 520                | 1100               | 3.559                   | 19.60%                                        |
|              | A7       | 620                | 1280               | 4.073                   | 39.10%                                        |
| B            | B1       | 380                | 820                | 2.956                   | Control beam                                 |
|              | B4       | 500                | 1040               | 3.748                   | 26.90%                                        |
|              | B5       | 440                | 920                | 3.300                   | 12%                                           |
|              | B6       | 500                | 1020               | 3.677                   | 24.40%                                        |
|              | B7       | 580                | 1180               | 4.254                   | 43.90%                                        |
|              | B9       | 620                | 1200               | 3.893                   | 46.34%                                        |
|              | B10      | 640                | 1300               | 4.217                   | 58.50%                                        |
3.1 Ultimate Load Capacity
For NSM techniques only, it can be noted that the orientation of bars had a great effect on increasing of the ultimate load strength. Whereas, in case of horizontal bars (in the direction of beam axis), the increase percent was 25% and 26.9% for beams A4 and B4, respectively. While, in case of vertical bars (perpendicular to the beam axis), the increment was 6.5% and 12 %, respectively. This was due to the effect of transferring stress from strut critical zone to overall length of CFRP horizontal rod and preventing stress from concentration in a small area, while in vertical NSM bars the stresses caused deboned in concrete cover.

For hybrid techniques, it can be observed that the increment was higher in comparison with NSM techniques only. Whereas, the increment percent was 19.6 % compared with 6.5 % for beams A6 and A5, respectively, and 39.1% compared with 25% for beams A7 and A4, respectively.

The experimental test results show that the maximum increase percentage in ultimate strength obtained from using horizontal bars and inclined woven strips 58.5% for beam B10, while minimum increase was 6.5% for beam strength with NSM in the vertical direction A5.

For both strengthening techniques, NSM and hybrid, the beams without interior shear reinforcement (Group B) showed more enhancement compared to the beams with shear reinforcement (Group A) that had the same type of strengthening.

3.2 Cracking load and load-deflection behavior
During the experimental test, the diagonal shear cracks were formed. These cracks initiated at the center line between the point load and the interior support, which represents the strut zone. These cracks were the critical cracks, which became more and wider till the failure occurred. From results, it was clear that the effect of externally bonded CFRP strip (in hybrid technique) increases the cracking load capacity in beams (A6, A7, B6, B7, B9 and B10) and limited the cracks width compared to the beams that were strengthened with NSM technique only, see figures 5 to 8. Regarding the deflection of tested beam it is noted that deflection was little and increased linearly till beams reached to crack loads then increase became rapid due to the decrease in stiffness of the beam cross section.

![Figure 5. Load-deflection curves for (Group A).](image_url)
Figure 6. Load-deflection curves for (Group B).

Figure 7. Group (A) failure and crack pattern.
4. Conclusion

Based on the experimental results, the following conclusion can be drawn:

1. The orientation of NSM techniques had a great effect on the enhancement of strengthening of beams. Whereas, using horizontal bars the failure accrued in crushed concrete, while in vertical NSM bars the failure happened due to deboned cover around bars.

2. The effect of strengthening by NSM or hybrid techniques increased with the decrease in interior shear reinforcement.

3. Added woven CFRP strips in vertical direction acted like confinement to concrete cross section, and that has led to an increase in the cracking load limit.

4. Using EB-CFRP strips perpendicular to the expected crack path (inclined strips) with NSM – CFRP, gave a great effect in enhancing both the cracking limit load and the total ultimate load carried by the tested beams.

5. There was no significant effect on the mid span deflection at ultimate failure load for NSM techniques only, while there was an effect in hybrid techniques by increasing the maximum deflection before failure.
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