

Strengthening of Continuous SCC Hollow Beams under Shear Stresses Using Warped CFRP Strips

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Abstract
The present paper is deal with shear strength evaluation of continuous self-compacting concrete hollow beams containing internal concrete ribs and externally strengthening by carbon fiber strips (CFRP). Six full-scale beam specimens and series of control specimens were tested. The adopted variables in this study are the number of internal concrete ribs and external U-shape CFRP strips at (45º). Experimental results show that the shear failure was the dominant failure for all tested beams. The cracking and ultimate load are reduced by about (19.6-30.6%) for the hollow beams specimens contains five and three ribs respectively compared with the reference beam. The ultimate load was increased for about (50.7%) for five internal ribs hollow beams strengthened by CFRP strips in compared with the same beams but without strengthening. While, the ultimate load was increased for about (33.46%), for beam specimen who has three internal ribs and strengthened by CFRP, in comparison with the same beams but without strengthening.
Keywords: CFRP Strips, Shear, Continuous Beam, Self-Compacting Concrete, Hollow, Ribs

1. Introduction

Rehabilitation of deteriorated structures has been a major concern in the last years. The deterioration and other factors, like reduction in steel reinforcement area due to corrosion, increase of the service load, and design/construction defects effect on shear capacity (Khalifa, et al 1999). The shear failure has different characters, as compared to bending failure, in which the former is more brittle and often occurs without any forewarning (Täljsten B, Elfgren L 2000). One of the techniques used to strengthen the existing reinforced concrete members involves externally bonding fiber reinforced polymer (FRP) composite materials by means of epoxy adhesives. This technique, improves the structural performance of a member under ultimate load and service load (Neale 2000). The wide use of such strengthening method, for various structures such as buildings and bridges, has demonstrated its efficiency and its convenience (Bakis et al. 2002; Clarke 2000).

The main objective of the present paper is to evaluate, experimentally, the shear behavior of the hollow continuous, self-compacting concrete beams containing transverse internal ribs and strengthened externally with CFRP.

2. Experimental Program

Tests were carried out on six, fully scale, hollow, rectangular section; continuous (rest on three supports) beam specimens under monotonic concentrated load (in the center of each span). To ensure shear failure, the beam specimens have been designed with minimum shear reinforcement. The adopted variables in this study are the number of internal concrete ribs and external U-shape CFRP strips at (45º), while the type of concrete, beams dimensions, shear span-depth ratio (a/d), longitudinal and transverse reinforcement were kept constant for all tested beams.

Furthermore, a series of tests were performed on concrete mixes; therefore, the mechanical properties of hardened and fresh concrete tests were included in this paper.

2.1 Beam Specimens Details

Six full-scale beam specimens were casted and tested in this study. The beams were continuous (rest on three supports) and made with SCC and have a dimensions of (2500mm), (250mm) and (300mm) for length, width and height respectively. The dimensions used for hollow core are (100mm) for width and (150mm) for height and the typical rib thickness was (100mm). It may be noted that, each beam specimen is designated in a way to indicate to the concrete type (SCC), number of internal ribs (R0 or R3 or R5) and orientation of CFRP strips at (45º) as shown in Table (1) and Figures (1) to (6).

Table 1. Details of Tested beams.

Beam	Beam Encoding	Dimensions (mm)			No. of Internal Ribs	Orientation of CFRP Strips
		L	W	H		
B-1*	SCC-R0-00	2500	250	300	-	-
B-2	SCC-R3-00				3	-
B-3	SCC-R5-00				5	-
B-4	SCC-R0-45°				-	45°
B-5	SCC-R3-45°				3	45°
B-6	SCC-R5-45°				5	45°

*Reference Beam (Solid Beam).

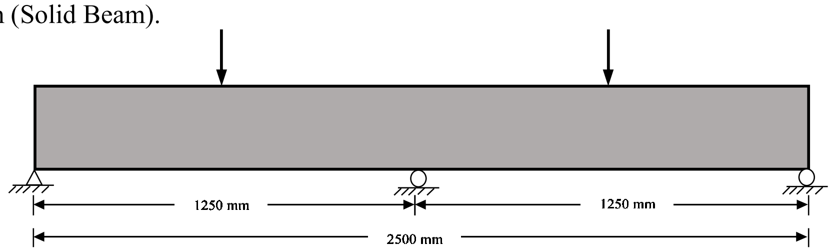


Figure 1. Description of B1 (Control Beam)

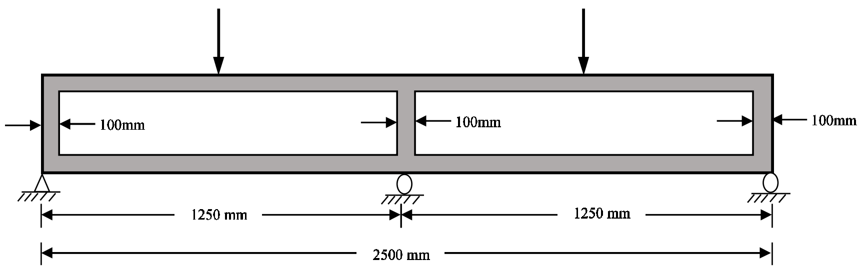


Figure 2. Description of B2

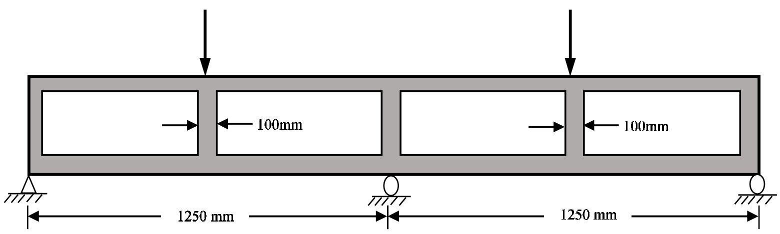


Figure 3. Description of B3

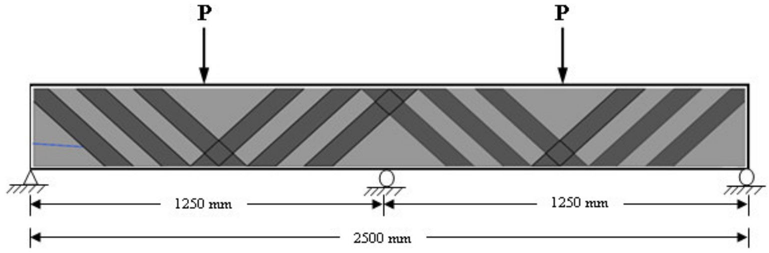


Figure 4. Description of B4

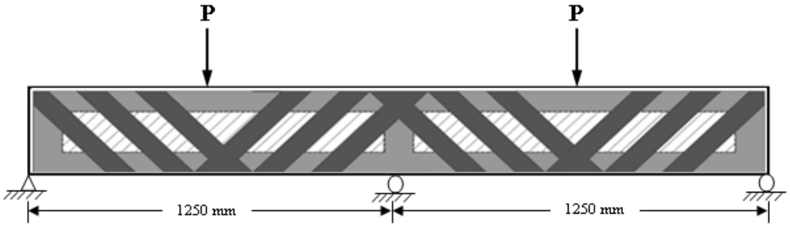


Figure 5. Description of B4

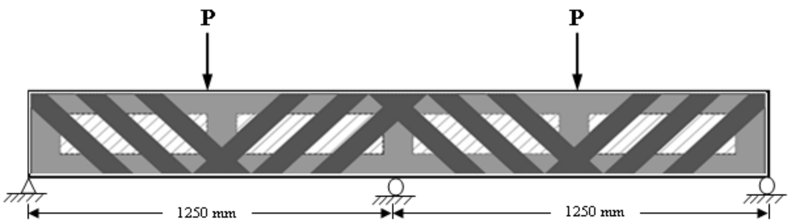


Figure 6. Description of B4

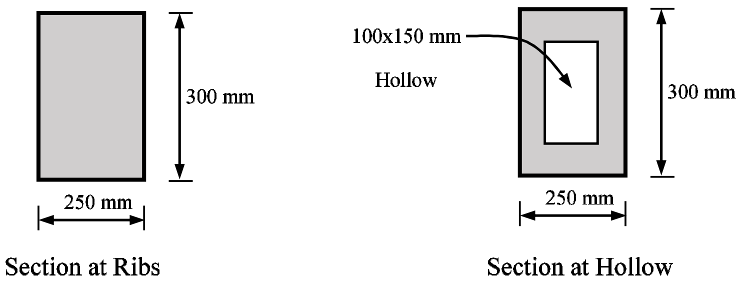


Figure 7. Cross-section of beams

2.2 Beam Specimens Reinforcement

All beam specimens have a similar steel reinforcement. The flexural reinforcement consists of (4Ø20mm) at the bottom (extended throughout the beam length) and (4Ø20mm) at the top (at middle support to resist the negative moments). While, the web reinforcement (shear reinforcement), consists of (Ø8mm@130mm) as stirrups. It may be noted that, to hold the stirrups in place (2Ø6mm) at the top were used as shown in Figures (8).

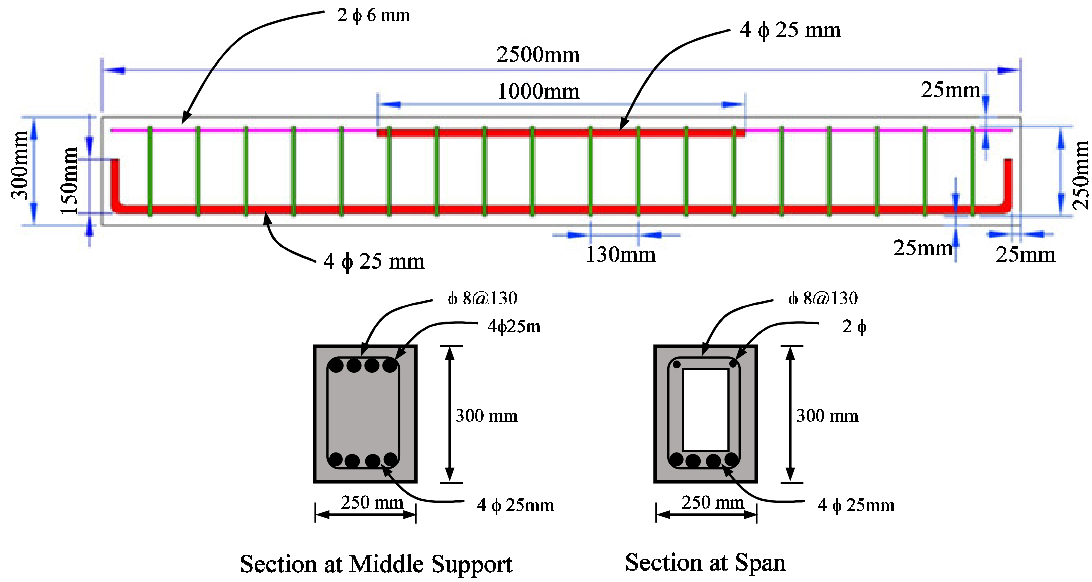


Figure 8. Reinforcement Details for Solid and Hollow Sections

To form the hollows inside the beam specimens, polystyrene blocks are used, due to its lightweight and easy to configure with the required dimension. The dimensions of hollows is kept constant for all hollow beams to be (100x150mm), with length of (1200mm) and (500mm) for the beams that have three and five ribs respectively, as shown in Figure (9).

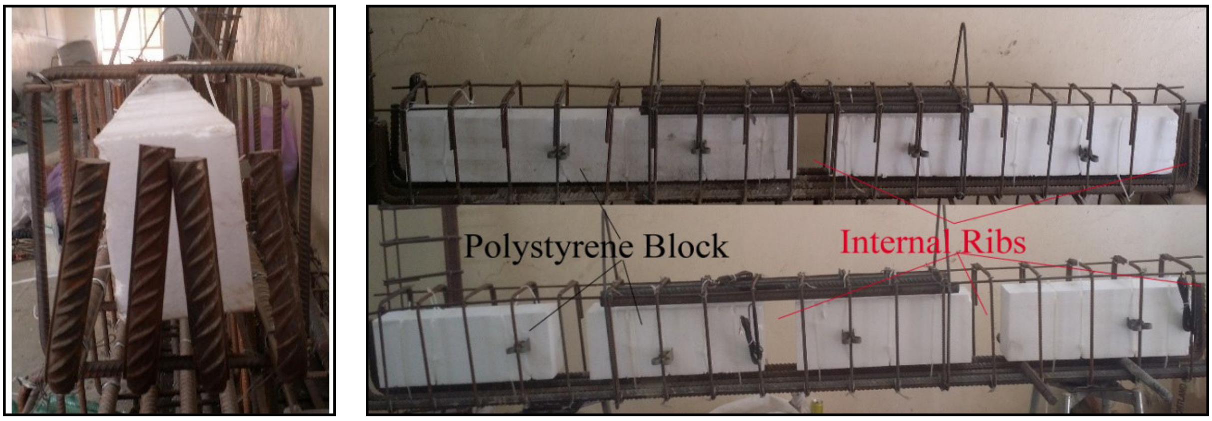


Figure 9. Using of Polystyrene Blocks to form Hollows

For beam specimens strengthening by strips of CFRP, orientated by (45º), Sika Wrap-300 C/60 type and epoxy based impregnating resin Sikadur-330 has been used.

2.3 Materials

In manufacturing the beam specimens, the properties and description of the used materials are reported and presented in Table (2); and the concrete mix proportions are reported and presented in Table (3).

Table 2. Properties of Construction Materials

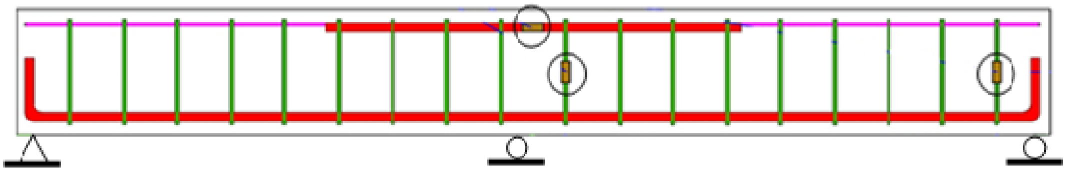
Material	**Descriptions**
Cement	Ordinary Portland Cement (Type I)
Sand	Natural sand from Al-Ukhaider region with maximum size of (4.75mm)
Gravel	Crushed gravel of maximum size (12.5 mm)
Limestone powder	Fine limestone powder (locally named as Al-Gubra) of Jordanian origin
Superplasticizer	Glenium 51 manufactured by BASF Construction Chemicals, Jordan.
Reinforcing Bars	(ϕ20mm) deformed steel bar, having (612.74 MPa) yield strength (f_y) (ϕ8mm) deformed steel bar, having (761.95 MPa) yield strength (f_y) (ϕ6mm) plain steel bar, having (884.19 MPa) yield strength (f_y)
Water	Clean tap water

Table 3. Proportions of Concrete Mix

Material	**Quantity**
Cement (kg/m^3)	450
Fine Aggregate (kg/m^3)	778
Course Aggregate (kg/m^3)	890
Limestone Powder (kg/m^3)	50
Water (kg/m^3)	162.5
Water/Cement Ratio	0.36
Water/ Powder Ratio	0.325
Superplasticizer (L/m^3)	4.5
Superplasticizer/Cement Ratio	0.01

2.4 Test Measurements and Instrumentation

All beams were tested by using the Hydraulic Universal Testing Machine (MFL system) with a maximum range capacity of (3000kN). Vertical deflection was measured at mid-span and the quarter of span by using dial gauge of (0.01mm/div.) accuracy at every load stage. The gage is placed under the bottom face of the tested beams. The strains were measured by means of strain gauges attached in different locations as shown in Figure (10).



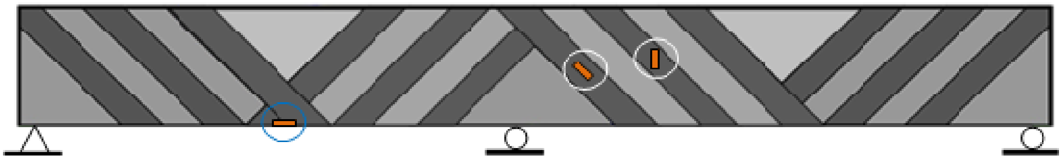


Figure 10. Strain Gauges Locations in Steel, Concrete and CFRP

2.5 Test Procedure

The beam specimens were tested at age of (28 days), where they were prepared by cleaning them and paint with white color, in order to detect the propagation of cracks. The beam specimens have been placed on the testing machine with clear spans of (1210mm). Dial gauges were placed in their location in mid span (at 605mm from the support) and quarter span (at 302.5mm form the middle support). The strain gauges have been connected with a data logger (TML/ TC-32K). All beams have been tested under monotonic loading, up to failure, with single concentrated loads applied at the mid-span of each span of beams as shown in Figure (11).

Initially, each beam is loaded with small load to ensure that the dial a gauge is in touch with the bottom faces of beams and the strain gauges is working correctly. After that, the load increased regularly at (1.0 kN/sec) and the readings taken every (10 kN). When the beams reached advanced stage of loading, smaller increments of load were applied until failure, as the load indicator stopped in recording or returned back and the deflection increased very fast without any increase in applied load. Throughout the test, all necessary measurements and notices were recorded.

Figure (11) Beam Specimen Setup

3. Results and Discussion

As mentioned before, the objective of this paper is to study the influence of the hollow core and strengthening with CFRP on the shear behavior of continuous reinforced concrete beams.

During the experimental work, ultimate loads, load versus deflection and strains were recorded. Photographs for the tested beams are taken to show the crack pattern and some other details. The recorded data, general behavior and test observations are reported as well as recognizing the effects of various parameters on the shear behavior.

3.1 General Behavior

At early stages of loading, several cracks initiated near the middle support (at maximum shear), with further loading, these cracks appeared near to the support edge and extended upwards, toward the load point, and became wider in shear spans. One or more cracks propagated faster than the others and reached the compression flange (near applied load), where crushing of the concrete near the positions of applied loads had occurred due to high concentrated stresses under load, Figure (12).

Figure (12) Crack Pattern

3.2 Failure Mechanism of SCC Beams

Shear failure compared with other failures is more devastating due to sudden failure. Shear failure starts from the critical section at high shear zone near middle support. The failure is usually occurring without giving any alarming alerts. Therefore, shear failure considered to be more dangerous for structure than flexural failure (Jumaat and Alam 2011). Diagonal cracks start from support to applied load and these diagonal cracks formed on either side or both sides together in RC beam and failure occurred by widen of shear cracks in RC beam (Täljsten 2003). The failure mode of the control beam was diagonal splitting failure on vertical plane, while the failure mode of the strengthened beams were either CFRP debonding or CFRP rupture, Figure (13) shows examples of the observed failure modes. For beam specimens strengthened by CFRP at (45º), the debonding area was above the shear crack as shown in Figure (13-b).

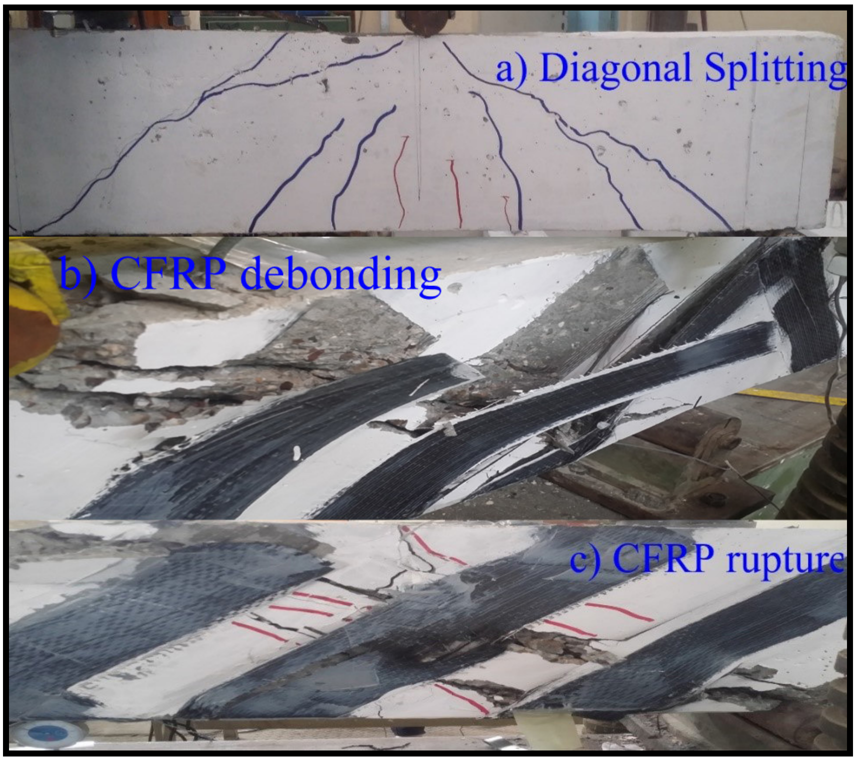


Figure 13. Mode of Failure of Tested Beams

Before the failure of beam specimens with warping CFRP, longitudinal cracks form on the top surface of specimens. The crack initiated close to the position of applied load and extended towards the middle support as shown in Figure (14).

Figure 14. Cracks on the Top Surface of Beam Specimens

3.3 Ultimate Load

The ultimate load and the variation in the load capacity are reported and presented in Table (4). The beam specimen (SCC-R0-00) featured one principal crack and finer cracks parallel to principal crack deployment of an average angle of (45°) from the support to the load point, which is typical of continuous beam behavior. The ultimate load was attained as the principal crack extended deeper into the compression zone. The mode of failure was diagonal splitting failure with ultimate load of (915 kN).

Table 4. Ultimate Load and Gain in Shear

Beam	**Beam Encoding**	**Ultimate Load kN**	**(±) Load kN**	**(±) Load %**	**Mode of Failure**
B-1*	SCC-R0-00	915	0	0	diagonal splitting failure
B-2	SCC-R3-00	635	-280	-30.6	diagonal splitting failure
B-3	SCC-R5-00	735.5	-179.5	-19.62	diagonal splitting failure
B-4	SCC-R0-45°	1170	255	27.87	CFRP debonding and rupture
B-5	SCC-R3-45°	847.5	-67.5	-7.38	CFRP debonding and rupture
B-6	SCC-R5-45°	1109	194	21.2	CFRP debonding

*Reference (solid beam)

The ultimate load for the (SCC-R3-00) was (635kN) and the mode of failure was diagonal splitting failure as shown in Figure (11), the load level was reduced by (30.6%) compared with the reference beam. The ultimate load of beam specimen (SCC-R5-00) was (735.5kN) and the mode of failure is similar to (SCC-R3-00). The load level of (SCC-R5-00) was reduced by (19.62%) compared with reference beam. It may be noted that, the specimen (SCC-R5-00) has a higher level of load by (15.8%) compared with (SCC-R3-00), this may be due to increasing of the number of internal ribs, which led to increasing in the total volume of concrete; and the position of two internal ribs under the load (at mid span) causes this a higher level.

The influence of CFRP was clear in both, load and mode of failure. For beam specimen (SCC-R0-45º) the ultimate load was (1170 kN) and two mode of failure were take place, the CFRP debonding and rupture as shown in Figure (15). In comparison between the beam specimens (SCC-R0-45º) and (SCC-R0-00), the increasing in load capacity was (27.87%).

The ultimate load of beam specimen (SCC-R3-45º) was (847.5 kN) with combined mode of failure of CFRP debonding and rupture as shown in Figure (16). It may be noted that, the ultimate load of beam specimen (SCC-R3-45º) were decreased by about (7.38%) in comparison with the reference beam. The means the CFRP strengthening reduce the damage of hollow but not reach to the ultimate load of reference beam like the beams of five internal ribs. The gains in ultimate load due to strengthened by CFRP when compared beam specimens (SCC-R3-45º) with (SCC-R3-00) was (33.46%).

The ultimate load of the beam specimen (SCC-R5-45º) was (1109kN) with CFRP debonding failure as shown in Figure (17). The increase in ultimate load of the beam specimens (SCC-R5-45º) was (21.2%) in comparison with the reference beam. The increase of the ultimate load for the beam specimens (SCC-R5-45º) was (50.78%) in comparison with the beam specimen (SCC-R5-00). Clearly, this may be due to the contribution of strengthening by CFRP.

Figure 15. Debonding and Rupture of CFRP for Beam Specimen (SCC-R0-45º)

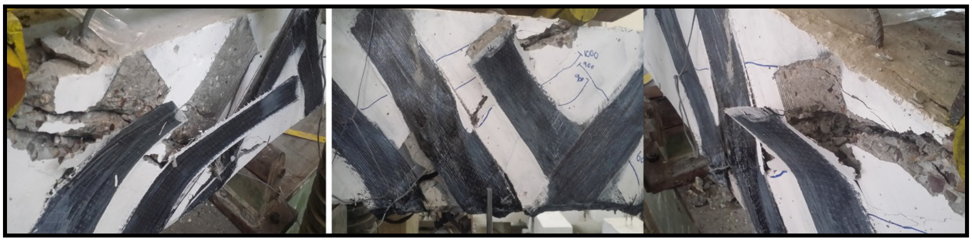


Figure 16. Debonding and Rupture of CFRP for Beam Specimen (SCC-R3-45º)

Figure 17. Debonding of CFRP for Beam Specimen (SCC-R5-45º)

3.4 Load-Deflection Behavior

In all tested beams, the deflection (displacement in vertical direction) were measured in mid span and in quarter span (near the meddle support). Load-displacement curves for the tested beams were plotted and presented in Figure (18).

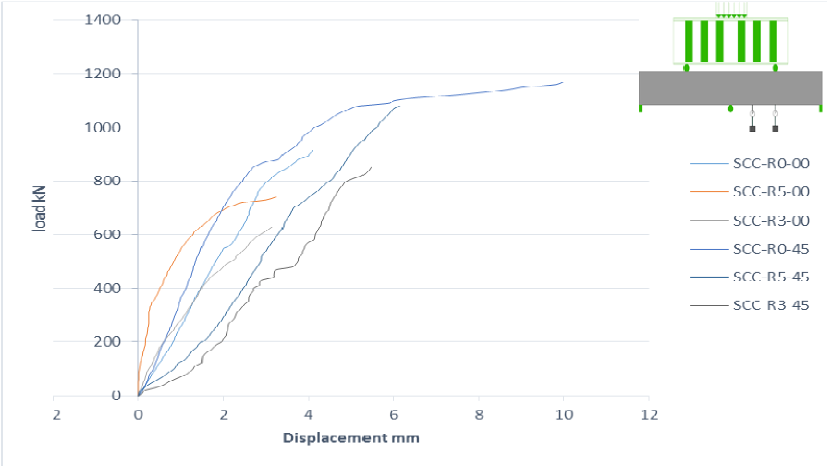


Figure (18) Load-Deflection Relationship at Mid Span

The result show that the hollow effect was observed clearly by reduced the defection, in mid span, for the beam specimen (SCC-R5-00), by (20.73%) and for the beam specimen (SCC-R3-00) by (22.68%) compared with reference beam. The effect CFRP on deflection for the solid beam was (143.9%) for the beam specimen (SCC-R0-45º) compared with reference beam. The results were defers in the hollow section strengthened by CFRP, the deflection increased for beam specimens (SCC-R5-45º) by (49.76%) in comparison with reference beam. For beam specimen that have three internal ribs, the increment was (33.41%) for (SCC-R3-45º) in comparison with reference.

The deflection was so large for the hollow beams strengthened by CFRP. After using of CFRP, the deflection was increased for about (72.55%) for beam specimens (SCC-R3-45º) in comparison with beam specimen (SCC-R3-00), and for beam specimens (SCC-R5-45º) the increasing was (88.92%) compared with beam specimen (SCC-R5-00). The effect of the number of internal ribs was observed when compared the deflection of beam specimens (SCC-R3-00) and (SCC-R3-45º) with (SCC-R5-00) and (SCC-R5-45º) in which the increasing in deflection were for about (2.52%) and (12.24%) respectively.

3.5 Load-Strain Behavior

The instrumentations for strain monitoring were carefully engineered to provide the information and data much needed for the understanding of the shear resistance mechanisms involved in beams retrofitted with CFRP Strips. It must be realized that all the recorded data was subjected to careful examination, analysis, and comparisons.

3-5-1 Concrete Strain

According to ACI-318-14, the maximum compressive strain of concrete at crushing was (0.003) to higher than (0.008) under special conditions. However, the strain at which ultimate moments are developed is usually about (0.003) to (0.004) for members of normal proportions and materials. In the present paper, the value of strain was recorded every (10 kN), Figure (19-a) shows the curves representing the shear force in the lateral direction of concrete at distance of (303mm) from the middle support. For the beam specimen (SCC-R3-00), the mode of failure was a diagonal splitting failure, this means the ultimate load exceeds the ultimate stress and the concrete approaches to peak response. The other three beam specimens (SCC-R0-45º), has CFRP rupture failure which means that the CFRP is look like the jacket working to restrict the concrete, and as a result, the stresses and strains were increased. Before failure of CFRP, the strain in concrete was increase slowly but at the CFRP, the stain was jumped over the strain of concrete. Figure (19-b) show the load-strain curves for concrete at mid span. Maximum bending strain in all beams was less than the ultimate strain of concrete. For solid beams, the strains were closed and the solid beams strengthened by CFRP give the higher values than the solid without strengthening. The increasing in strains for beam specimen (SCC-R0-45º) was (7.62%) compared with (SCC-R0-00).

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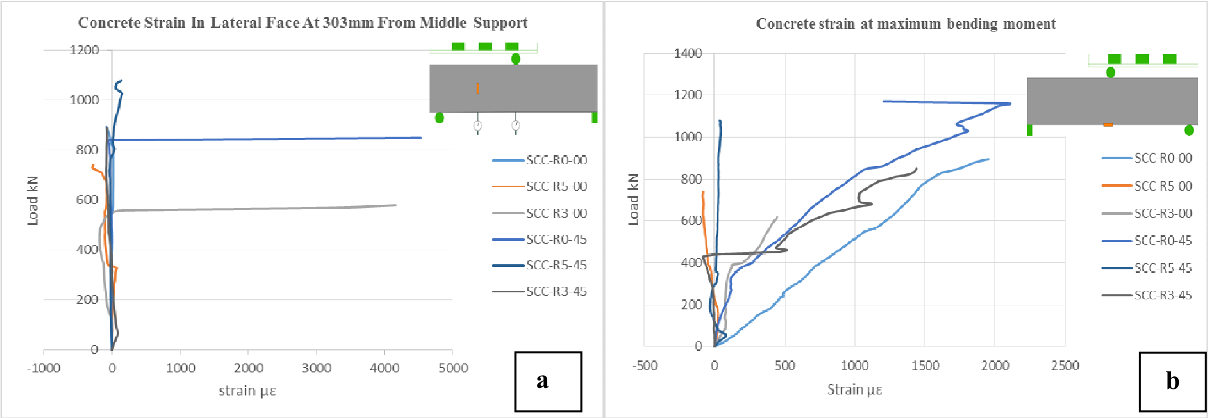

Figure 19. Strain in Concrete at Quarter and mid span (Microstrain)

3-5-2 Steel Reinforcement Strains

The yield and ultimate strains for shear reinforcement (stirrups) were calculated from stresses assuming ($Es=200x10^3$ MPa). The yield and the ultimate strains were (0.0038) and (0.0048) respectively, Figures (20-a) and (20-b). The strain gauges were fixed on stirrups at distance of (d/2) from the middle support and on stirrups at distance of (91mm) from the edge support.

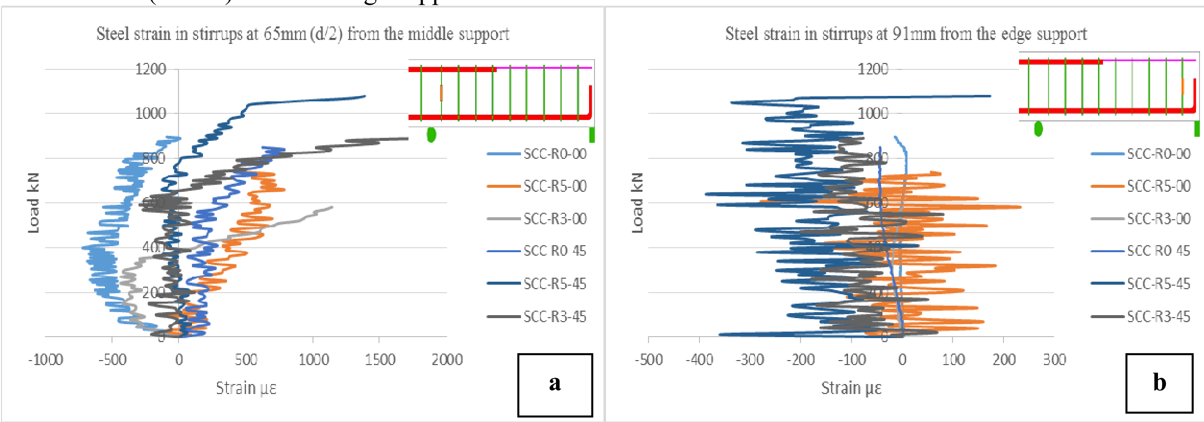

Figure 20. Strain in Steel Reinforcement near Middle and Edge Supports (Microstrain)

Experimental results indicated that the measured strains didn't reach to the yield strain in steel reinforcement. The strain for stirrups at critical section (d/2) from the middle support for all beams dose not reach to yield strain. The strains in beam specimens (SCC-R5-45º) and (SCC-R3-45º) give higher values compared with the other beams. The strains in beam specimen (SCC-R3-45º) were higher than for (SCC-R5-45º). Solid beam specimens without strengthened give less value relative to other beams and the beams with five internal ribs without strengthened give less value than the beams with three internal ribs. The strain in the stirrups at edge was less than the strain at distance of (d/2) form the middle support because the shear value at the edge support was half value of the shear at the middle support. For the top steel reinforcement, the yield strain was (0.00306) and ultimate strain was (0.00365). Figure (21) shows the strains for SCC beams at maximum negative moment. All measured strains didn't reach to the yield strain of steel bar. The solid beam specimens strengthened by CFRP give higher strain value compared with the others. The maximum strain for beam specimen (SSC-R0-45º) occurs at the load of (840 kN) which represents (71.8%) of the ultimate load. For the strengthened beam specimens that failed by debonding of CFRP, the strain values were higher than the values of the beams failed by rapture. CFRP strips reduce the growth of diagonal cracks and reduce their progression into the compression zone. When the debonding takes place, more cracks appeared in the tensile zone of concrete which is exposed to maximum moment.

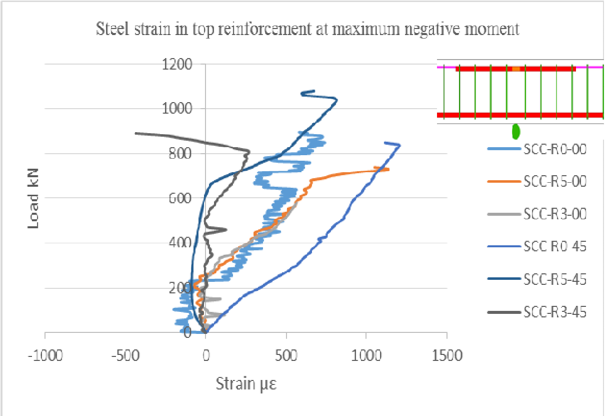

Figure 21. Strain in Steel Reinforcement at Maximum Negative Moment (Microstrain)

3-5-3 CFRP Strain

Figure (22) shows the load-strain curves in the CFRP for strengthened SCC beam specimens. After the first crack, most of stress shift from the concrete to steel reinforcement and CFRP in the advanced stages of loading.

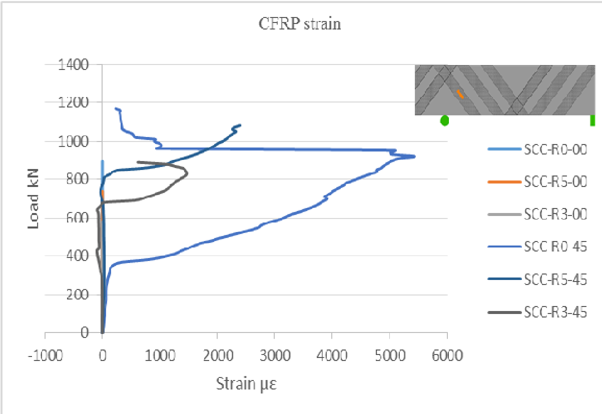

Figure 22. Strain in CFRP at First Strips from Middle Span (Microstrain)

3.6 Effect of Beam Weight

The hollows in the beams means that there is two basic characteristics, the first one is advantage in reduce the weight of the beam and the second one is not advantage because it reduces the failure load of the beam. Therefore the (CFRP) were used to reduce the disadvantage of the hollow. The gain in the dead weight of the beam reduces the ultimate load by about (19.62-30.6%) compared with solid beam without strengthened, while when strengthening with CFRP the ultimate load increased by (21.2%) for (45º) orientation of the CFRP strips. This means the goal was achieved in overcoming on the disadvantage of the hollows by strengthening the beam by CFRP. For beam specimens poured with three ribs and strengthening by CFRP, the goal to reach the ultimate load of the solid beam (reference beam) was not achieved but that not means the strengthening was unsuccessful. The reduction in ultimate load was (7.37%) for (45º) orientation of the CFRP strips. Table (5) shows the effect of hollow to reduce the ultimate load.

Table 5. Load Due to Variation in Weight

Beam Encoding	Ultimate Load (kN)	Weight (kN)	Variation in Weight	Percentage of Hollow
SCC-R0-00	915	4.58	0%	0%
SCC-R0-45º	1170			
SCC-R3-00	635	3.78	17.6%	17.6%
SCC-R3-45º	847.5			
SCC-R5-00	735.5	3.85	16%	16%
SCC-R5-45º	1109			

4. Conclusions

Based on the obtained results, observations and discussion, the following conclusions can be drawn:

1- Shear failure was the dominant failure for all tested beams and three types of cracking pattern were monitored during the tests; a small flexural crack, which does not extend to the neutral axis, shear cracks diagonally extended from the support toward the load point, and cracks appeared at the top of the tested beams that

strengthened with CFRP wrapped at (45º).
2-The ultimate (failure) load for the hollow beams strengthened by five and three internal ribs reduced by about (19.62%) and (30.6%) respectively compared with reference beam. The CFRP effects on failure load by increasing the load capacity for about (27.87%) for solid beams compared with the reference beam.
3- The number and location of internal ribs effects significantly on the ultimate load. The beam specimens who have five internal ribs give (15.8%) higher than the beam specimens who have three internal ribs. This may be due to contribution of the additional internal ribs under the concentrated load.
4- The ultimate load was increased for about (50.7%) for five internal ribs hollow beams strengthened by CFRP strips of (45º), in compared with the hollow beam with five internal ribs without strengthening. The ultimate load was increased (21.2%) for the (45º) CFRP orientation after there has been lost because of hollows by (19.13%) in compared with the reference beam.
5- The ultimate load was increased for about (33.46%) for beam specimen who have three internal ribs with CFRP strips of (45º), in comparison with the hollow beam that have three internal ribs without strengthened; and this led to reduce the losses in load capacity from the (30.6%) to (7.37%) for the (45º) orientation.

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