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Strengthening of RC Shallow T-Beams with Shear Zone Large Openings Using CFRP and BFRP sheets: Experimental Study

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Abstract

Behavior of shallow T-section reinforced concrete beams containing web openings at critical shear zone and subjected to four point bending loads was discussed. Strengthening of such beams is surely required because openings reduce the stiffness and capacity of these beams to a great extent. Nine shallow T-beams with web openings were constructed and tested. All beams had the same reinforcement and dimensions, of which two beams were control, seven beams were with web opening and strengthened. The control beams included one solid beam and one beam with opening without any strengthening. The Carbon Fiber Reinforced Polymer (CFRP) sheets were used to strengthen 6 beams with six schemes. Basalt Fiber Reinforced Polymer (BFRP) sheets were used to strengthen the last beam with the most efficient scheme. Great enhancement in ductility and strength was gained by using CFRP and BFRP. Also the paper highlighted that Scheme of strengthening plays an important factor in achieving a good result.

Keywords: *CFRP, BFRP, T-beams, Web Openings*

1- Introduction

In modern building construction, openings in beams are more often used to provide passage for utility ducts and pipes [5]. These arrangements of building services result in a significant reduction in headroom, minimize the floor height and hence result in major savings in material and construction cost especially in tall building construction [1]. However, inclusion of opening leads to high stress concentration at the opening corners and reduction in the total cross section that changes the simple beam behavior to a more complex one [2-6]. The location of openings has a large effect on stiffness and capacity reduction [7]. Transverse openings in beams may be of different shapes and sizes [8], openings that are circular, square, or nearly square in shape may be considered as small openings provided that the depth (or diameter) of the opening is in a realistic proportion to the beam size, say, about less than 40% of the overall beam depth otherwise the opening is considered to be large opening [1]. Behavior of shallow beams containing web openings was studied by many researchers [2-6, 9-14 and 29].

The application of Fiber Reinforced Polymers FRP as external reinforcement to strengthen RC beams has been widely used [15–18].The well-known types of FRP in concrete strengthening are carbon, aramid or glass fibers [16]. Basalt fibers have strength higher than GFRP and lower than CFRP with very good durability [33] but hasn't the same popularity as CFRP and GFRP. Strengthening of RC shallow Rectangular beams containing web openings in shear zone using External Bonded Reinforcement EBR FRP and Steel plates was discussed by many researchers [3, 15, 19-27, and 30]. Strengthening proved to be effective in increasing beam capacity and limiting cracking at the opening corners. Strengthening of deep beams with transverse square opening using CFRP sheets also was studied [31] and % increase in shear capacity was in the range of 35–73%. An experimental investigation on the performance of RC T-beams with and without small circular opening strengthened in shear using mechanically anchored bi-directional U-wrap GFRP fabrics was introduced by [27,32]. Behavior of RC rectangular beams with large opening under pure torsion moment and strengthened using CFRP sheets was discussed by [28]. Although EBR strengthening technique for the tested beams in the previous literature increased the shear capacity of the beams, the common failure mode of this technique in most studies was debonding without reaching to the FRP ultimate strains. There are many studies on the effect of existence of opening on the rectangular and T-section beams; however, limited work has been conducted on strengthening of T-beams with openings in shear. To date, no literature available for the study of R/C shallow T- beams with large rectangular openings in shear zone just below the

slab and strengthened by complete wrapping BFRP or CFRP.
The main Objectives of study are to investigate experimentally the effectiveness of strengthening using CFRP and BFRP sheets for T-beams containing rectangular transverse opening in shear zone and to discuss the effect of strengthening scheme on efficiency.

2. Experimental Program

2.1 Test specimens

The experimental program included testing of nine reinforced concrete shallow T-beams. Experiments were divided into two main groups. The first group consisted of two beams which included one solid control beam and one beam with non-strengthened opening. The second group included seven beams with web openings at critical shear zone, of which six were strengthened by CFRP sheets and one was strengthened using BFRP sheets. Dimensions and reinforcement details of tested beams are shown in fig. 1 and fig. 2.

Table 1: Test specimens

Specimen designation	***Strengthening scheme***	
B1(Solid beam)	NO	
B-O-Ns	NO	
B-O-S-CFRP-1	**CFRP** sheets	Scheme1
B-O-S-CFRP-2		Scheme2
B-O-S-CFRP-3		Scheme3
B-O-S-CFRP-4		Scheme4
B-O-S-CFRP-5		Scheme5
B-O-S-CFRP-6		Scheme6
B-O-S-BFRP	**BFRP** sheets	Scheme4

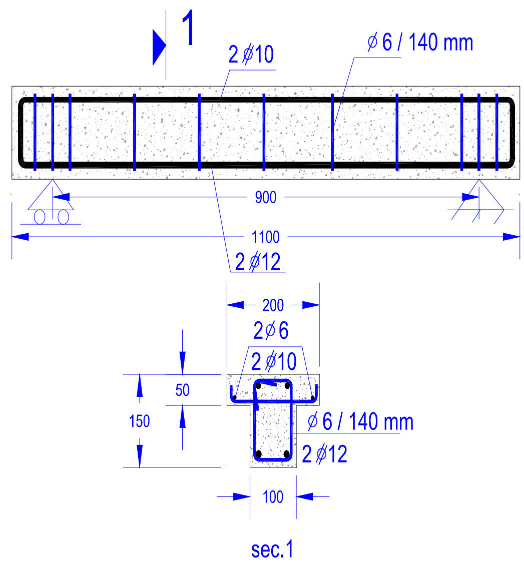

Fig. 1 Reinforcement of solid beam (dimensions are in mm)

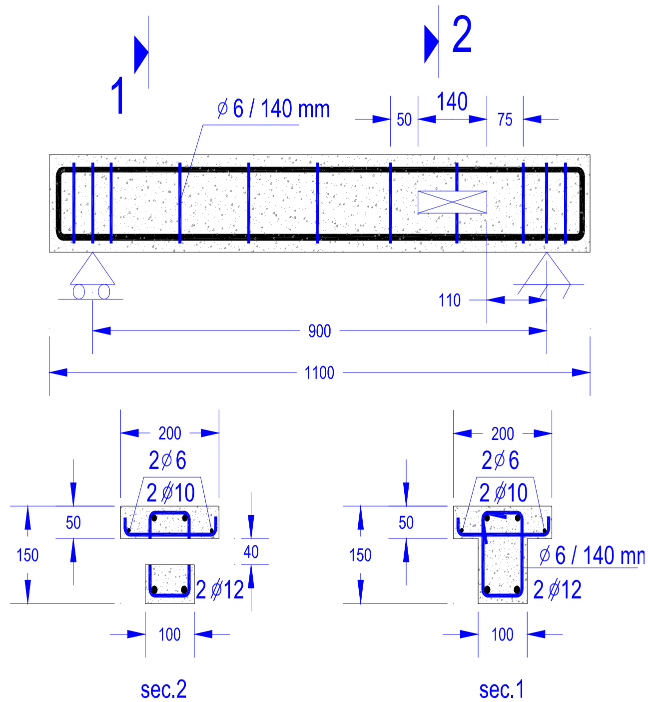

Fig. 2 Reinforcement of Beam with web opening at shear zone (dimensions are in mm)

2.2 Material properties

The concrete mix was designed to achieve cube compressive strength f_{cu} of 45 MPa at 28 days. Trial mixes were carried out to obtain the required strength with good workability. Three standard concrete cubes were taken for each patch mix and cured in water for 28 days. Compressive strength was determined by testing three concrete cubes and average value was considered.

Average compressive strength of concrete cubes was 44 MPa. Average yield stress of steel bars was 550 MPa for 10mm and 12mm bars and 340 MPa for 6mm bars. The carbon fiber sheets CFRP used in this study is unidirectional black carbon fibers (99% of total areal weight) woven by white thermoplastic heat-set fibers (1% of total weight) and used for wet layup application. The commercial name for this carbon fiber is sikawrap-230 from SIKA EGYPT for construction chemicals [34]. The ultimate stress, ultimate strain, and modulus of elasticity for a cured laminate of CFRP sheet were 360 MPa, and 1.1%, 33.5 GPa, respectively from experiment. The commercial name for the basalt fiber is BJ30 from Anjie Company, CHINA. The ultimate stress, ultimate strain, and modulus of elasticity of for cured laminate of this BFRP sheet were 171 MPa, 1.9%, and 9.0 GPa, respectively from experiment.

Epicor-NR from YASMO MISR, Egypt for construction chemicals was used as adhesive and impregnating resin for FRP sheets. It included two parts; resin and hardener mixed together with a filling material.

2.3 Strengthening schemes

Different Strengthening schemes are illustrated in figures (3-8). **B-O-S-CFRP-1** was strengthened by confining the bottom cord using one layer of CFRP sheet (complete wrap). **B-O-S-CFRP-2** was strengthened by applying two horizontal side strips of CFRP, and confining the bottom cord using one layer of CFRP (complete wrap). In addition U-strips were applied to right and left of the opening for the beam stem only (not complete wrap).

B-O-S-CFRP-3 was similar to **B-O-S-CFRP-2** but additional longtudinal CFRP strip with 100 mm width was applied to slab top surface above the opening as a top reinforcement. **B-O-S-CFRP-4** was typically as **B-O-S-CFRP-3** but additional horizontal strip with 100 mm width was applied to the beam soffit under the opening and extended 100 mm right and left. Also the side vertical strips were completely wrapped around the web through slots pre-cut through the slab. **B-O-S-CFRP-5** was typically as **B-O-S-CFRP-4** but the confining CFRP sheet for the bottom cord was replaced by two layers of 50 mm width CFRP strip wrapped around the top cord at the opening mid length through holes that were made in the slab. **B-O-S-CFRP-6** was strengthened by applying two horizontal side strips of CFRP in the bottom cord, Horizontal strip with 100 mm width was applied to slab top surface above the opening In addition completely wrapped strips with 50 mm width were applied to right and left of the opening. **B-O-S-BFRP** was strengthened similar to **B-O-S-CFRP-4** but with **BFRP** instead of **CFRP**.

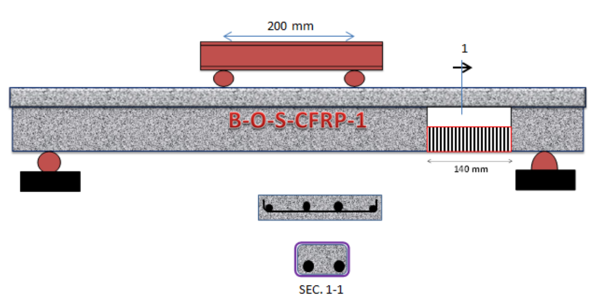

Fig. 3 strengthening scheme (1)

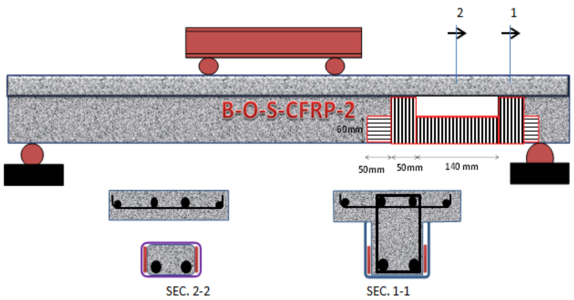

Fig. 4 strengthening scheme (2)

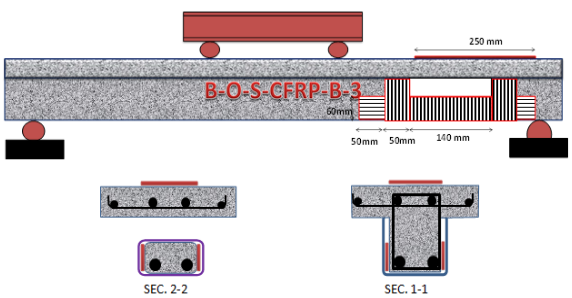

Fig. 5 strengthening scheme (3)

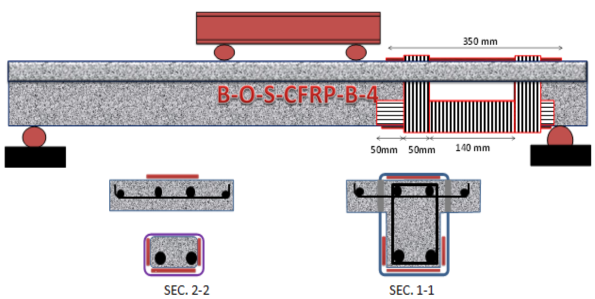

Fig. 6 strengthening scheme (4)

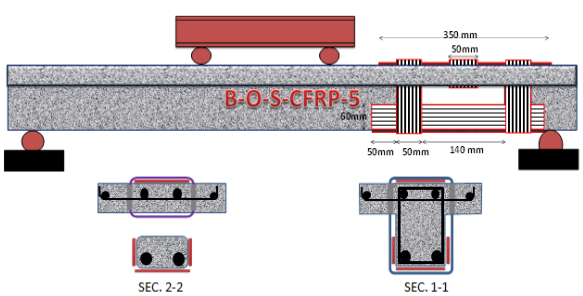

Fig. 7 strengthening scheme (5)

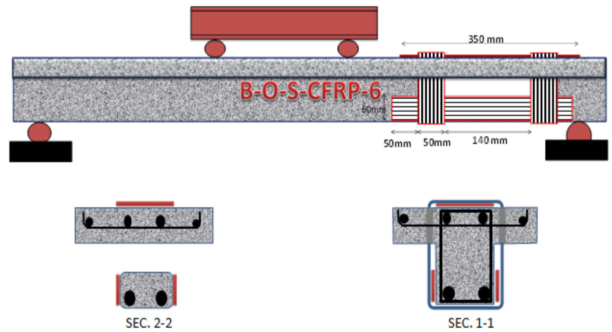

Fig. 8 strengthening scheme (6)

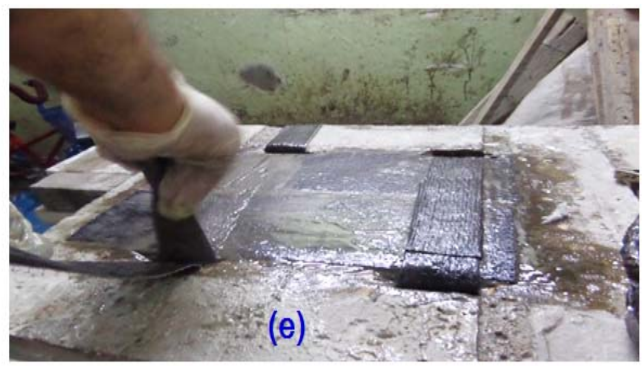

Fig. 9 Wrapping of CFRP sheets

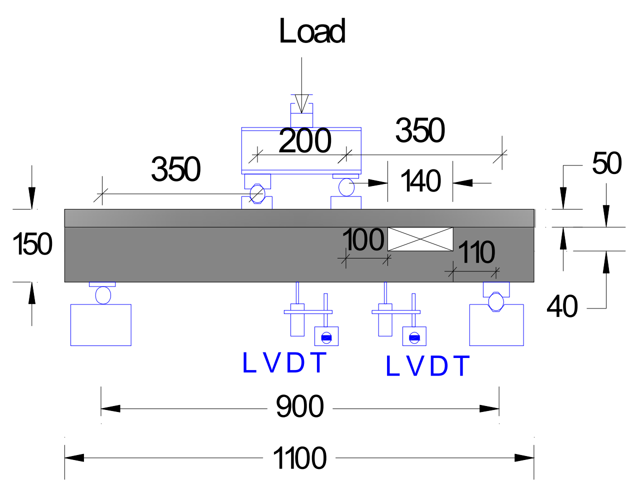

Fig. 10 testing setup (dimensions are in mm).

Fig. 11 Testing machine and instrumentation

2.4 Strengthening process

Group of holes of 8 mm diameter were drilled vertically through the slab from top to bottom beside the opening right and left top corners to make slots with 50 mm length and 8 mm width to the total depth of the slab using an electrical drill. These slots were used after that to pass the complete wrapping FRP strips right and left to the opening. An electrical grinder then was used to grind the top, bottom and side surfaces of the opening at the area where the CFRP strips would be applied. This operation was to get a sound flat surface. The corners were rounded with a fillet radius about 10 mm. After that, an air compressor was used to clean the surface of the holes and the grinded areas to remove fine dust. CFRP sheet was cut to the required sizes on a flat, clean and dry surface using a cutter. Resin and hardener were mixed and the CFRP strips were glued to the concrete surface according to the required scheme; see figure 9.

2.5 Testing setup

After full curing of the strengthening system, the test specimen was placed in the testing machine on the supports. LVDTS, calibrated load cell and steel and FRP Strain gauges were then connected to the data acquisition system. The load was applied using hydraulic jack with an average displacement rate of 0.25 mm/minute.

3. Experimental Results and Discussion

Four modes of failure were observed: Shear failure at solid part, shear failure across the un-strengthened opening, Brittle shear failure across the strengthened opening with debonding of the FRP sheet, and Shear failure by rupture of the complete wrap FRP strip; see (Figures 22 to 30). It was clearly observed That debonding of BFRP and CFRP strips was prevented by complete wrapping. A summary of the test results, ultimate loads, percentage increase in capacity over the control B-O-NS and mode of failure for all tested beams are presented in Table 2. Stiffness after first cracking, absorption energy, and ductility index are summarized in Table 3. Figures (12 to 21) show the load versus deflection curves for all tested beams.

3.1 Failure mechanism

3.1.1 Solid beam

For the solid beam, the failure mechanism was a shear failure with about 60 degrees major shear crack starting from mid height of the beam web extending to the top compression zone and to the bottom tension zone causing partial debonding between bottom steel and the surrounding concrete and ended by crushing failure at the loading points. Failure occurred at 105.5 kN after the bottom steel had been yielded at 96kN showing some ductility.

3.1.2 Un-strengthened beam with opening:

For Opened beam without CFRP strengthening, the failure occurred at 60kN when the bottom cord lost its shear capacity followed by steel/concrete cover separation. At this moment, the shear force was redistributed totally to the compression cord that wasn't shear reinforced causing sudden shear failure and the load dropped to 40kN not to zero. That indicates the participation of tensile steel bars, compressive steel bars and aggregate interlocking in shear capacity of the reinforced concrete elements.

3.1.3. Strengthened beams

The failure mechanism of B-O-S-CFRP-1 started by formation of major diagonal two shear cracks. The first crack started from the right bottom corner of the opening towards the right support and the second started from left top corner of the opening towards the loading point. The failure at the end was by concrete crushing under the right loading point. No debonding or rupture of complete wrap CFRP strips was noted.

B-O-S-CFRP-2 failed by formation of major independent diagonal two shear cracks. The first started from the right top corner of the opening towards the right support and the second started from left top corner of the opening towards the loading point and finally failed by crushing of concrete at the crack tip under right loading point. Debonding of U-CFRP right side strip was seen at 80% of failure load.

B-O-S-CFRP-3 failed by two independent shear cracks as B-O-S-CFRP-2 and concrete cover separation occurred at the top horizontal strip at the right of the opening. B-O-S-CFRP-4 failed by shear failure at the solid part far away from the opening. Only hair cracks were seen at the top left corner and to the right of the opening. Flexural cracks were seen clear at the middle part of the beam. Bottom steel exceeded its yield strain indicating ductile failure.

For B-O-S-CFRP-5, a crack at top left corner between the slab and the web was seen at 30 KN and increased in width and length extending through the CFRP vertical strip. Successive high knocking sounds and pops were heard followed by seeing partial rupture of the left vertical CFRP strip at 63 KN. The strain gauge fixed at this location was cut into two parts after reaching strain limit more than 1.1%. The loading scenario was continued until a sudden shear failure occurred by diagonal major shear crack at the bottom cord followed by shear failure at top cord. The ultimate load was 93.8 KN. Delamination and partial rupture of the side CFRP strips was seen clearly after shear failure. No debonding occurred for the complete wrapping CFRP system or the reinforcing bars.

B-O-S-CFRP-6 failed in the same manner of B-O-S-CFRP-5 but the shear failure occurred by two independent diagonal shear cracks at the top and bottom cords at 88 KN.

For B-O-S-BFRP, The inclined cracks that were started at the two opening corners at 36 KN increased in length rapidly with increasing the load and this was noted by following out the data acquisition results graph for the FRP strains while loading. The strain gauge at the right corner recorded strain of 1.9 % at 88.7 KN and partial rupture for this vertical BFRP strip was noted accompanied by Successive high knocking sounds and pops . The left corner vertical strain gauge didn't record more than 1.1% and no rupture was seen for this strip to the end of loading scenario. The loading was continued until a sudden shear failure occurred by diagonal major shear crack between the web and bottom cord at the right corner of the opening followed by diagonal shear failure for top slab at the opening location. The ultimate load was 93.9 KN then dropped suddenly to 70 KN and by applying more displacement the load reached 28 KN. Rupture of the confining BFRP sheet at the bottom cord was seen clearly after shear failure. No debonding was seen for the two side complete wrapping BFRP systems or the reinforcing bars to the end of the loading scenario.

Table 2: Ultimate loads, bottom steel first yielding loads at mid span, and failure modes tested beams

Beam	P yield (KN)	Pu (KN)	% increase in ultimate load over control un-strengthened B-O-NS	Failure mode
B1 (solid beam)	96	105.5	76%	Shear failure
B-O-Ns	-	60	-	Shear across the opening
B-O-S-CFRP-1	-	76.5	27.5%	Shear across the opening.
B-O-S-CFRP-2	-	93	55%	Shear across the opening
B-O-S-CFRP-3	97	97	61%	Shear across the opening
B-O-S-CFRP-4	96.5	106	76.5%	Shear at solid part
B-O-S-CFRP-5	-	93.8	56.3%	Shear across the opening
B-O-S-CFRP-6	-	88	46.6%	Shear across the opening
B-O-S-BFRP	-	93.9	56.5%	Shear across the opening

Table 3: Stiffness, absorption energy, and ductility index for tested beams

BEAM	Tangent Stiffness after first cracking (kN/mm)	% increase in stiffness / B-O-Ns	Total absorbed energy KN.mm	Ductility index $=\Delta_{failure}/\Delta_{yield}$ (Mid span)
B1 (Solid beam)	22	37.5%	825	10.3/5.7 =1.8
B-O-Ns	16	-	235.2	-
B-O-S-CFRP-1	18.8	17.5%	370.6	-
B-O-S-CFRP-2	20.5	28%	530	-
B-O-S-CFRP-3	23.6	47%	648.5	8.0/8.0 =1.0
B-O-S-CFRP-4	24	50%	822	10.1/5.0 =2.02
B-O-S-CFRP-5	23.9	49.3%	450	-
B-O-S-CFRP-6	22	37.5%	400	-
B-O-S-BFRP	18.5	15.6%	552	-

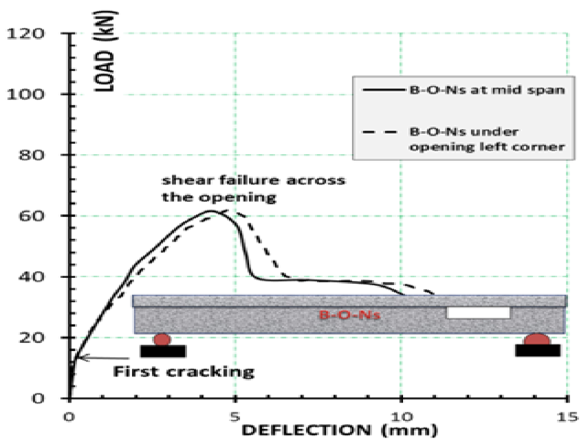

Fig. 12 Load-deflection curves for B-O-NS

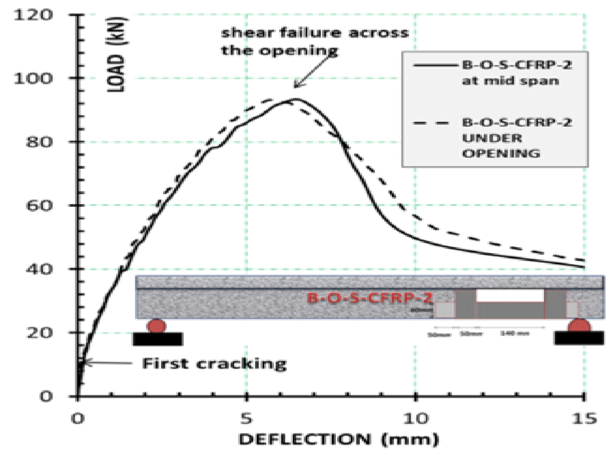

Fig. 15 Load-deflection curves for B-O-S-CFRP-2

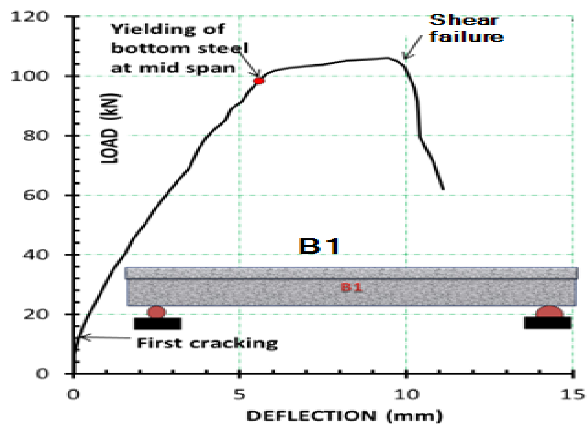

Fig. 13 Load-deflection curves for B1

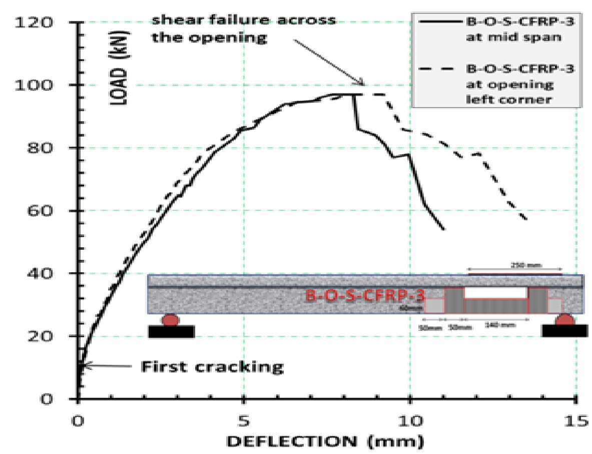

Fig. 16 Load-deflection curves for B-O-S-CFRP-3

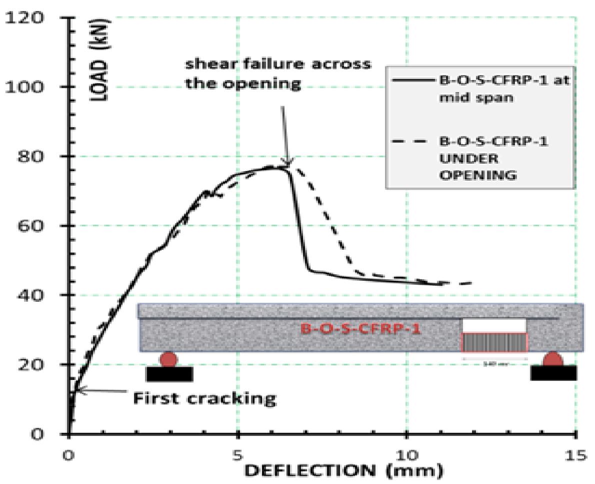

Fig. 14 Load-deflection curves for B-O-S-CFRP-1

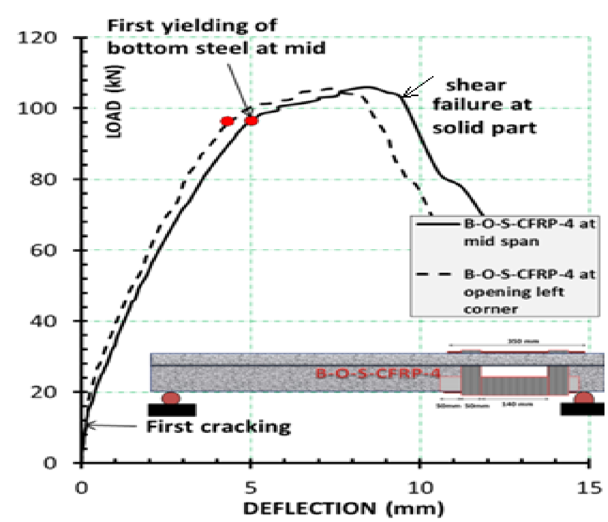

Fig. 17 Load-deflection curves for B-O-S-CFRP-4

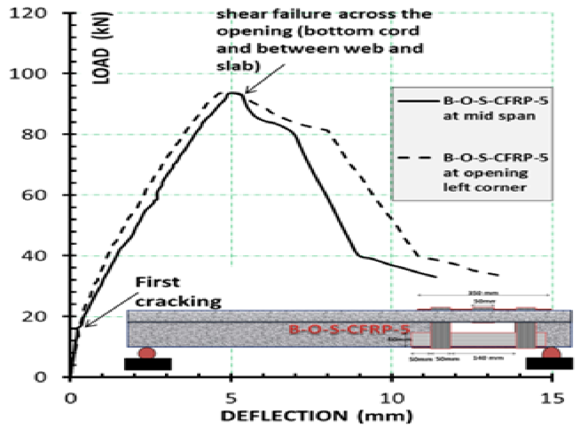

Fig. 18 Load-deflection curves for B-O-S-CFRP-5

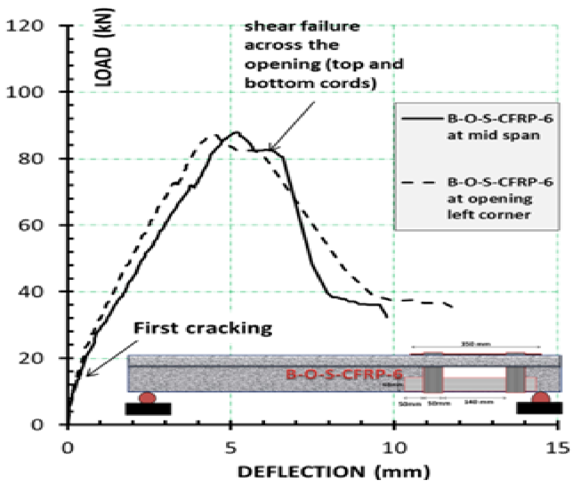

Fig. 19 Load-deflection curves for B-O-S-CFRP-6

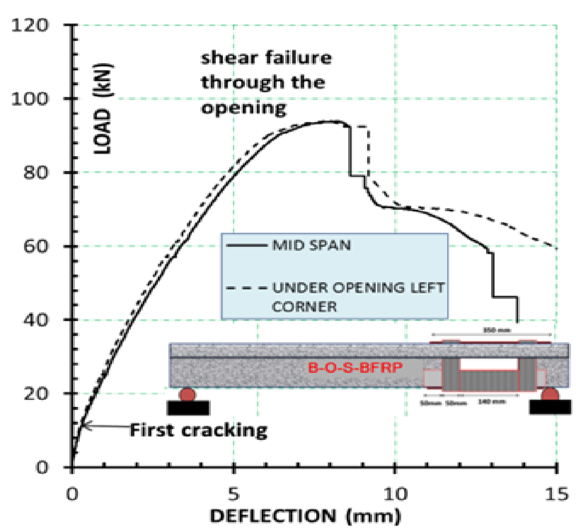

Fig. 20 Load-deflection curves for B-O-S-BFRP

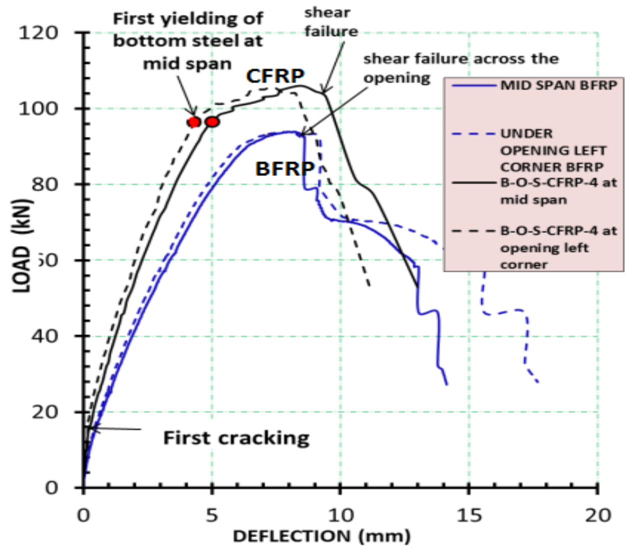

Fig. 21 Comparison between CFRP and BFRP strengthened beams with scheme No.4

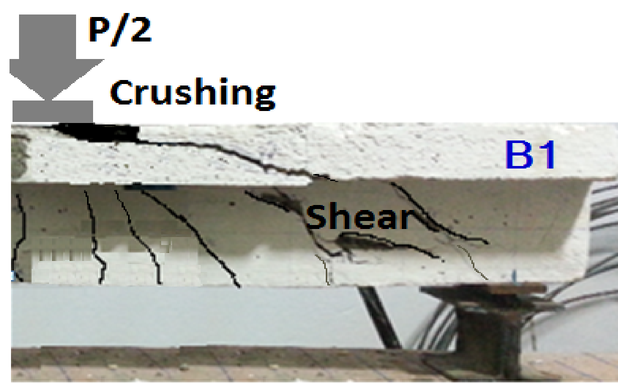

Fig.22 Failure mode for Solid beam (**B1)**

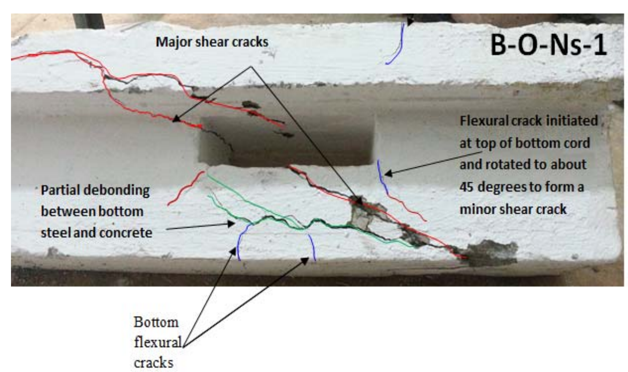

Fig.23 Failure mode for B-O-NS

Fig. 24 Failure mode for**B-O-S-CFRP-1**

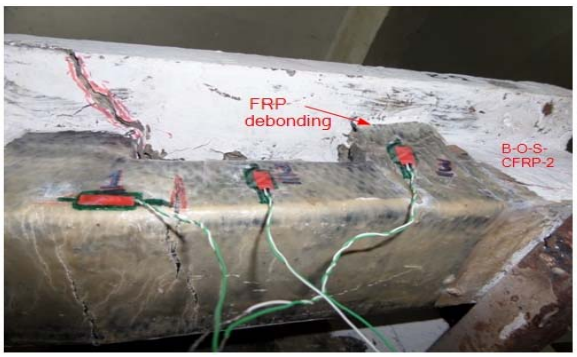

Fig.25 Failure mode for**B-O-S-CFRP-2**

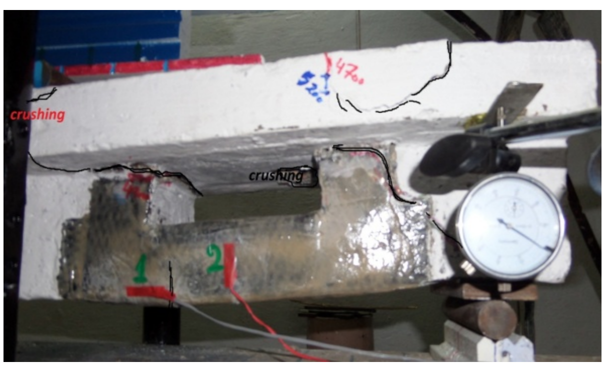

Fig.26 Failure mode for B-O-S-CFRP-3

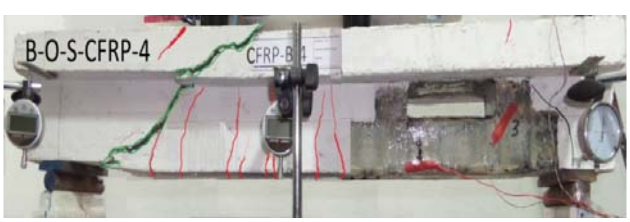

Fig. 27 Failure mode for B-O-S-CFRP-4

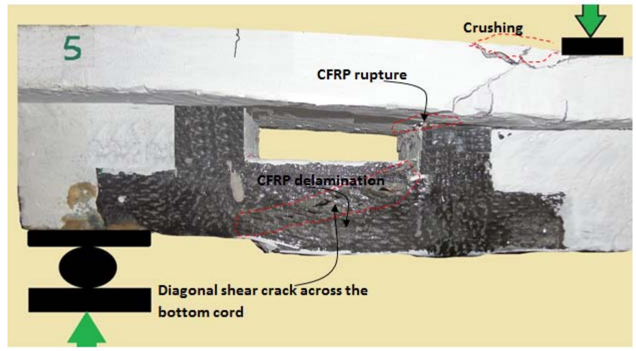

Fig. 28 Failure mode for **B-O-S-CFRP-5**

Fig. 29 Failure mode for **B-O-S-CFRP-6**

Fig. 30 Failure mode for **B-O-S-BFRP**

6 Conclusions

The performance of shallow RC T-beams containing web large opening in shear zone strengthened with CFRP and BFRP sheets, and two not strengthened control specimens, of which one was solid and another one with opening was investigated. The current experimental study highlighted the effectiveness of different strengthening schemes and the benefit from wrapping FRP through the top slab while highlighting areas for future research on BFRP.

Conclusion results are as follows:

1- Existing of large openings in shear zone in shallow RC beams reduced to great extent the load carrying capacity, stiffness, and ductility.

2- Using externally bonded CFRP and BFRP sheets resulted in increase in stiffness, ductility, and load carrying capacity for the strengthened beams.

3- Scheme of the strengthening controlled the efficiency significantly.

4- Beams that were strengthened around the opening using U-CFRP without complete wrapping suffered from debonding.

5- Corner cracks at opening location delayed and were restricted by FRP system for the different schemes and kept tighten up to the failure load; this enhanced the shear strength of the opening cords.

6- Complete wrapping for BFRP also eliminated the debonding and resulted in great enhancement in beam capacity and utilized the BFRP strips to their full capacity.

7- CFRP is more efficient than BFRP due to high modulus of elasticity and tensile strength; max % increase in ultimate load over control beam was 76.5% and 56.5% for CFRP and BFRP strengthened beams respectively.

8- Max % increase in stiffness over control beam was 50% and 15.5% for CFRP and BFRP strengthened beams respectively.

9- Max gain in Total energy absorption was 250% and 135% for CFRP and BFRP strengthened beams respectively with respect to control beam with opening.

10-With proper arrangement of FRP SYSTEM, T-beam with web opening can behave better than a solid beam in terms of ductility and stiffness. The ductility index equals 2.02 and 1.8 for the CFRP strengthened beam with scheme 4 and solid beam respectively.

11- Without complete wrapping, the full shear strength of the beam can't be restored.

Based on the above conclusions, the use of CFRP sheets as external reinforcement is recommended to strengthen RC T-Beams with web openings using the scheme No.4 (complete wrapping in addition to horizontal strips at top, bottom and to the sides). Strengthening using BFRP sheets needs further research. Multiple layers or wider strips of BFRP may restore the full capacity of the beam.

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