



BEHAVIOR OF RC BEAMS WITH STRENGTHENED OPENINGS IN D-REGION

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ABSTRACT: Provision of openings in serviceable reinforced concrete beams may result in a substantial decline in the beam's capacity and integrity; pointing out the necessity of opening strengthening. The present study investigates the response of reinforced concrete T-beams with strengthened openings disposed in shear span. The experimental program consisted of four large-scale beam specimens. An opening in the web of 100-mm x 300-mm was centrally disposed in the shear span. The strengthening of the openings was achieved using mild steel strips of 3.0-mm thick or uni-directional CFRP fabrics. All specimens were tested as simple beams subjected to two-points loading with a shear span to effective depth ratio of 1.7. The load was incrementally applied following a specified displacement history. Test results indicated that the strengthening of openings may offset the anticipated decline in the beam capacity and stiffness due to the existence of the openings. The extent of offset is dependent on the strengthening scheme adopted. The gain in shear capacity of the tested beams ranged from 48% to 100%. In addition, a non-linear finite element analysis; NLFEA was carried out to investigate the ultimate behavior of the beam specimens. The application of NLFEA for the strength prediction of the tested beams yielded adequate results.

INTRODUCTION

Shear strengthening of reinforced concrete beams by the using of CFRP sheets has been examined by many researchers, and it was shown that it is an effective means of strengthening. However, less research has been performed concerning the behavior of RC beams with strengthened openings in D-region using such advanced composite sheets. In this work, a large scale RC T-beams containing openings in D-region are strengthened in shear by applying steel plates or uni-directional external CFRP sheets using epoxy adhesion. A relatively new technique involves the replacement of steel plates by CFRP, or simply composites, in the form of thin laminates or fabrics since they are light-weight, corrosion free, and have a high tensile strength. When compared with conventional methods, this technique provides a low-cost solution due to significant reduction of construction time.

Considerable experimental research has been performed to investigate the ultimate shear strength of beams with openings, and relevant formulae of shear analysis have been presented¹. Elfgren and Taljsten² reported experiences based on experimental work conducted on beams strengthened with externally bonded steel plates to increase bending and shear capacity of the beams. As the presence of opening produced excessive internal stresses around the opening and may lead to a local failure, a special strengthening technique should be used to compensates for

the reduction in shear capacity due to the existence of the opening. Recently, Abu-Amirah *et al.*³ have been attempted to address the various effects of the aspect ratio of the openings, and the CFRP configuration on the shear behavior of rectangular R.C. beams. All specimens were tested as simple beams with a shear span to effective depth ratio (a/d) equal 3.3. They concluded that, the depth of the openings has great influence on the reduction of the shear capacity, while the openings width has insignificant effect. They also recommended that, the opening edge should be at a minimum distance equal to (d) from the support and preferable to be square as much as possible. Shear failure was observed only in two of the strengthened beams. Yet, substantial increase in the load-carrying capacity ranging from 51% to 110% was noticed.

The present study investigates the shear response of RC T-beams with openings centrally disposed in the shear span. The experimental program consisted of four large-scale T-beam specimens. The openings were strengthened using steel plates or uni-directional CFRP fabrics with the objective to lessen the anticipated adverse effect of openings' provision on the beam response. In addition, a non-linear finite element analysis; NLFEA was carried out to investigate the ultimate behavior of the beam specimens. The predictions were compared with the experimental results and a good agreement was obtained.

EXPERIMENTAL PROGRAM

The experimental program was undertaken to study the shear behavior of RC T-beams with strengthened openings centrally disposed in D-region using steel plates or uni-directional CFRP. The main parameters studied in this investigation are the effect of different strengthening material (steel & CFRP) and different strengthening technique to maximize the shear capacity of the strengthened beams.

Test Specimens

Four large scale RC T-beams were tested as simple beam using two points loading with $a/d = 1.7$. All the tested beam specimens had identical dimensions with a clear span of 2500 mm, as shown in Fig. 1. Each of the tested specimen contain an opening of 100x300 mm, nearly centered with the shear span, and reinforced with the same stirrups and longitudinal steel bars. The average concrete cube strength after 28 days was 34 MPa. In order to investigate the shear behavior, the specimens were designed to fail in shear (i.e., the flexural capacity was designed to exceed the shear capacity of the tested beams).

Strengthening Configuration

The beam specimens were identified as BOCT, BOSP, BOF1 and BOF2 depending on the strengthening provisions for the opening. Beam Specimen BOCT was not strengthened representing a control specimen for the strengthened beams. The opening in Beam BOSP was strengthened with horizontal steel strips 3-mm thick. The steel plates were fastened on to the concrete surface using an epoxy resin as well as steel bolts. In Beams BOF1 and BOF2, the opening was externally strengthened all around with individual CFRP strips having uni-directional fibers. In addition, the top and bottom web chords of the opening were strengthened with individual CFRP plies in the form of U-wrap and []-wrap, respectively. The U-wrap was extended by 100-mm which was cemented to the flange intrados, and cautiously riveted to the beam at web-flange intersections using 25x25x5-mm steel angles as shown in Fig. 2. Beam Specimen BOF2 was characterized by supplementary strengthening of the shear spans apart from the opening using U-shape CFRP wraps of 100-mm width at 100-mm clear spacing. The concrete surface beneath the CFRP fabrics, in general, was roughened and then leveled prior to the adhesion using an epoxy

resin. Figure 2 illustrates the applied methods of beam strengthening. Table 1 shows the material Properties.

Table 1: Material Properties

Material	Diameter (Thickness) (mm)	Yield strength (MPa)	Compressive strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)
Concrete	--	--	34.33	3.93	25.7
Steel RFT.	6	240.0	--	360.0	196.2
	12	274.6	--	415.2	196.2
	18	392.4	--	569.0	196.2
CFRP fiber	0.176	--	--	3873.5	244.6

Test Setup and Instrumentation

The main component of the testing facility includes the LVDTs, strain gages, the control station, the hydraulic jack equipment and the testing frame as shown in Figs. 3& 4. All beam specimens were simply supported and tested under monotonic point loading with $a/d=1.70$ (displacement control). The strains in the longitudinal steel bars, stirrups and the CFRP wraps were monitored using electrical strain gages. The load point deflections of the tested beams were measured through LVDTs. The crack development was plotted on the white – washed surface of the beams at regular intervals during the loading stages.

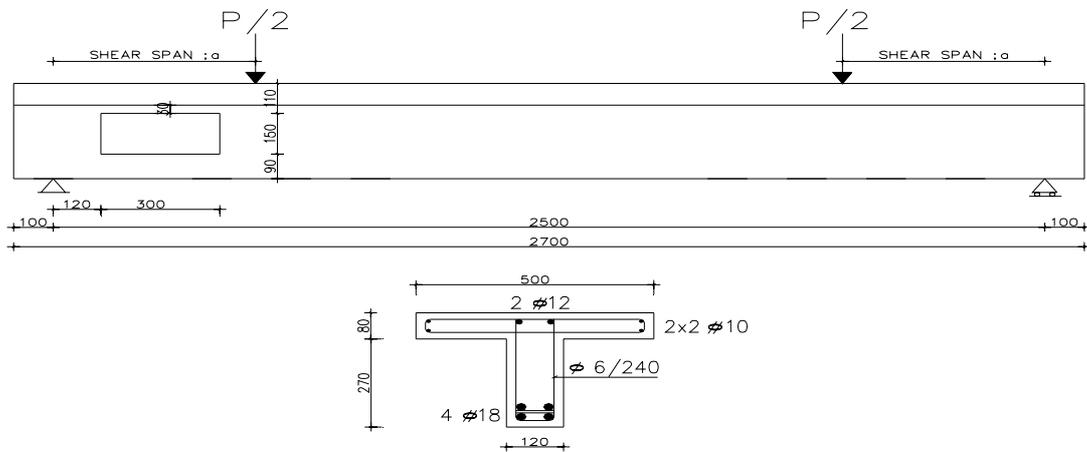


Figure 1. Details of Tested Beams

Test Procedure

All of the beams were tested under monotonic two point loading with $a/d=1.70$. For each test, the load was applied at a constant rate under deflection control following a specified displacement history up to the failure of the beam, Fig.4. Specimens were not loaded nor pre-cracked before strengthening them. This emulates the cases of upgrading/strengthening rather than the cases of repair and retrofitting. Testing is stopped when the maximum load at a given displacement is reduced to about 80% of the ultimate load, i.e more than 20% loss in the vertical load resisting capacity has occurred.

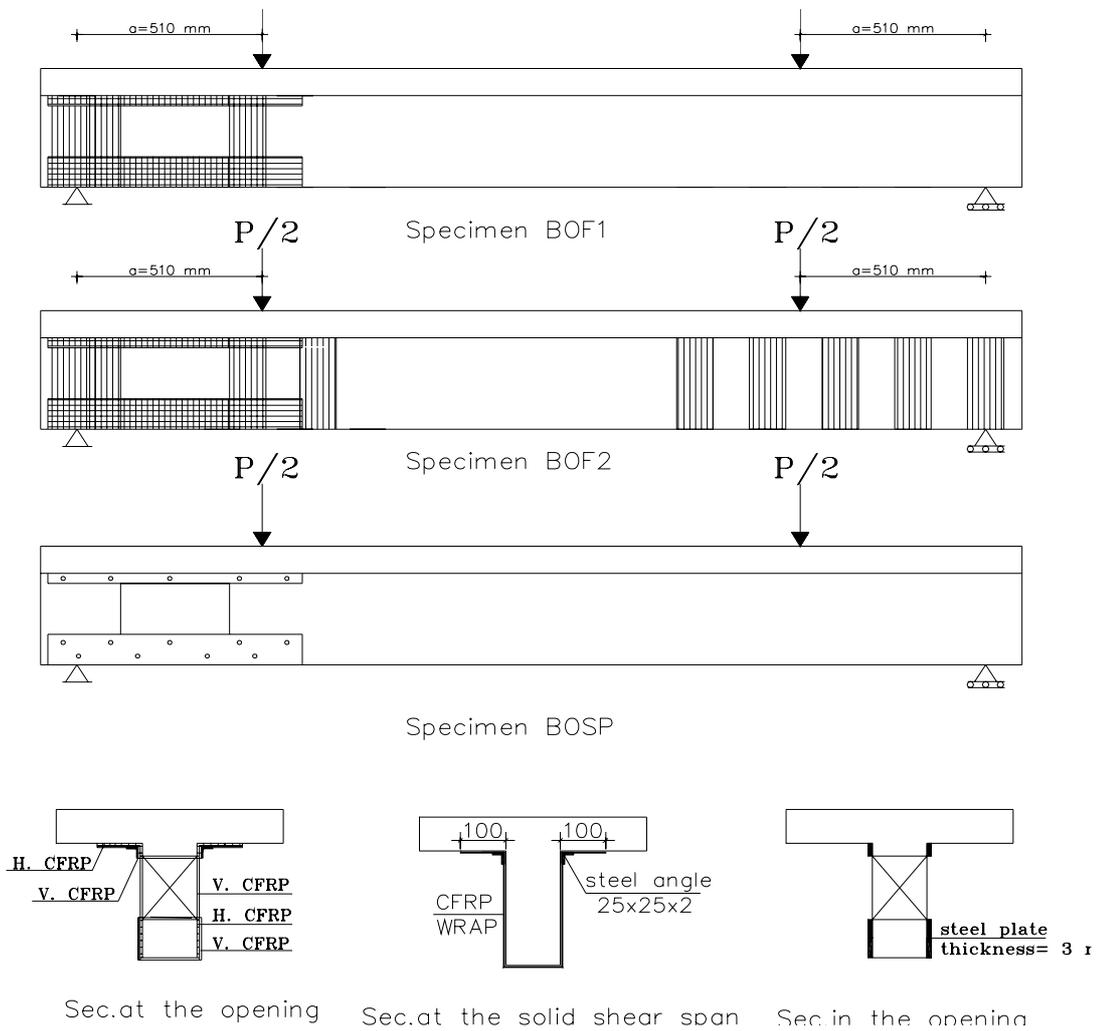


Figure 2. Configuration of the Test Specimens

Test Results and Discussion

A large amount of data was obtained from the tests which clearly can not all be presented here. A summary of the main test results is shown in Table 2. Figures 5 and 6 show details of the typical failure mode of the beams. Curves of load versus strain (in steel bars and steel plates/ or CFRP wraps) are shown in Fig.7-a. The load versus central deflection behavior during testing for the the four specimens is displayed in Fig. 7-b.. To facilitate the presentation of the results, the specimens are categorized in four groups: a) cracking behavior and mode of failure, b) strain, c) deformation, d) ductility

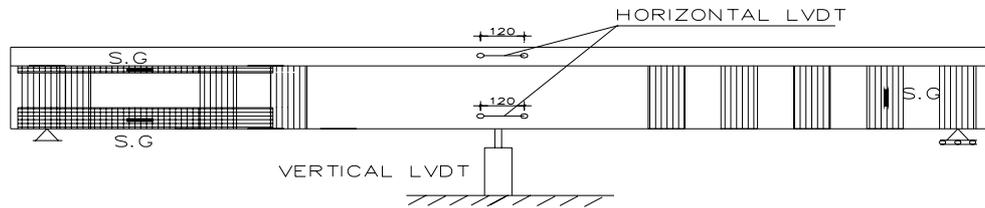


Figure 3. Instrumentation of Test Specimens

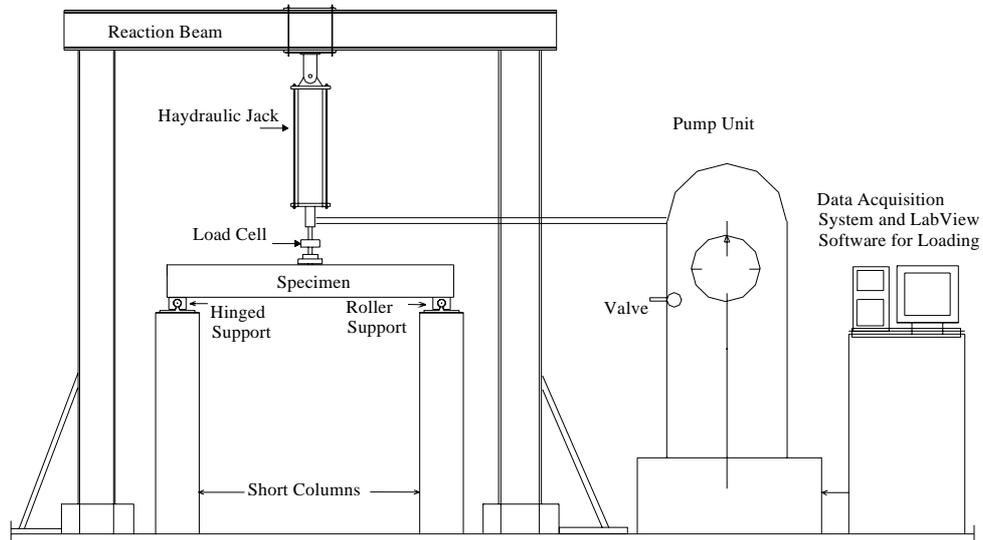


Figure 4. Test Setup

Table 2. Summary of the Test Results

Specimen	Load at				Mode of failure
	Flexure cracking (kN)	Shear cracking at solid shear span (kN)	at opening corner (kN)	Ultimate (kN)	
BOCT	56.90	111.83	54.94	144.2	Shear
BOF1	58.86	115.76	170.7	250.8	Shear
BOF2	58.86	124.59	178.55	288.1	Shear
BOSP	58.86	113.80	54.94	213.6	Shear

Cracking Behavior and Mode of Failure

Unlike the beams without openings⁴, inclined and flexural cracks in the control beam, BOCT, were simultaneously developed at 36% of the ultimate load, P_u . Inclined cracking initiated at the opening corners along the line joining the loading pad and the beam support, and propagated with subsequent increase of the applied load. The onset of shear cracking in the solid shear span was observed at 76% of P_u . At 83% of the ultimate load, an influential crack was created downwards from the opening extending to the support with an inclination angle of about 30° . This was followed by remarkable propagation and widening of the old cracks. Figure 5 depicts the major cracks developed prior to the beam's failure. The ultimate load for the control beam was 144 KN.

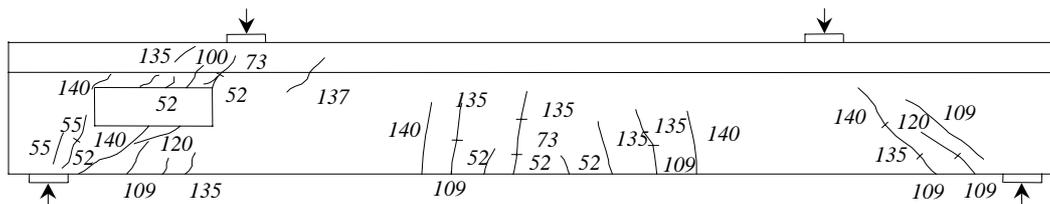


Figure 5. Cracks' pattern for Test Specimen BOCT

For Beam BOSP, inclined cracking initiated close to the opening's corners and in the solid shear span at 26% and 62% of the ultimate load, P_u , respectively; whereas, the flexural cracking developed at a load of 28% of P_u . Formation of new cracks continued up to 82% of P_u . Thereafter, cracks tended to concentrate around the opening, resulting in the beam's failure due to the separation of the steel plates strengthening the opening near the support from the concrete, followed by the concrete crushing at the support. Significant shear deformation at the opening was observed as shown in Fig. 6-a. The failure load was about 214 KN, representing 1.48 times that of the control specimen. A close examination of the beam's performance near failure suggests using the steel plates all around the beam opening.

For Beam Specimen BOF1, flexural cracking initiated at 24% of the ultimate load, P_u , whereas inclined cracking developed in the solid shear span at 46% of P_u . Formation of flexural and shear cracks continued with the subsequent increase of loading and a significant widening of the shear cracks was observed at 56% of P_u .

On the other hand, formation of visible cracks near the strengthened opening commenced at 66% of the ultimate load, and was accompanied by an audible sound. A fracture in the opening's corner near the loading pad was observed. Incidentally, overlaid cracks might be developed under the strengthening fabric at a lesser load. The failure was characterized by vertical rupture and buckling of the CFRP fabric, and an inclined fracture in the concrete between the opening and the supporting pad, see Fig. 6-b. The beam failed at a load of 251 KN revealing a 74% increase in the load-carrying capacity.

As far as beam specimen BOF2 is concerned, the overall response of the beam was comparable to that of the beam BOF1. Contrarily, inclined cracks in the flange above the opening appeared at 62% of the ultimate load, P_u . These cracks rapidly widened as the beam was approaching failure, resulting in a separation of CFRP strips from the flange intrados. At failure, vertical rupture and buckling of the fiber was observed above the beam support where the concrete was deteriorated. Beam BOF2 failed at a load of 288 KN realizing a 100% enhancement in the shear capacity. It is pertinent that the shear deformation of the beam was observed to be less than that of beam BOF1 due to the strengthening of the entire beam.

In conclusion, the anticipated decrease in the load-carrying capacity due to the provision of openings can be substantially recovered following these methods of strengthening, as revealed in

Table (2). Test results show a 38% decline in the ultimate shear capacity of the beam due to the existence of the opening; refer to the results of beams B1 and BOCT. This decline was rather offset for the beam strengthened with horizontal steel strips, beam BOSP, for which the shear capacity was 91% of that of beam B1. The beams strengthened with CFRP fabrics, Beams BOF1 and BOF2, restored the shortage of shear capacity. The ultimate capacity for beams BOF1 and BOF2 was 1.07 and 1.23 of that for beam B1. Furthermore, strengthening of the openings using CFRP fabric is a practical approach as the fabric is a durable material and can be easily arranged, while on the contrary, steel is a material liable to corrosion.

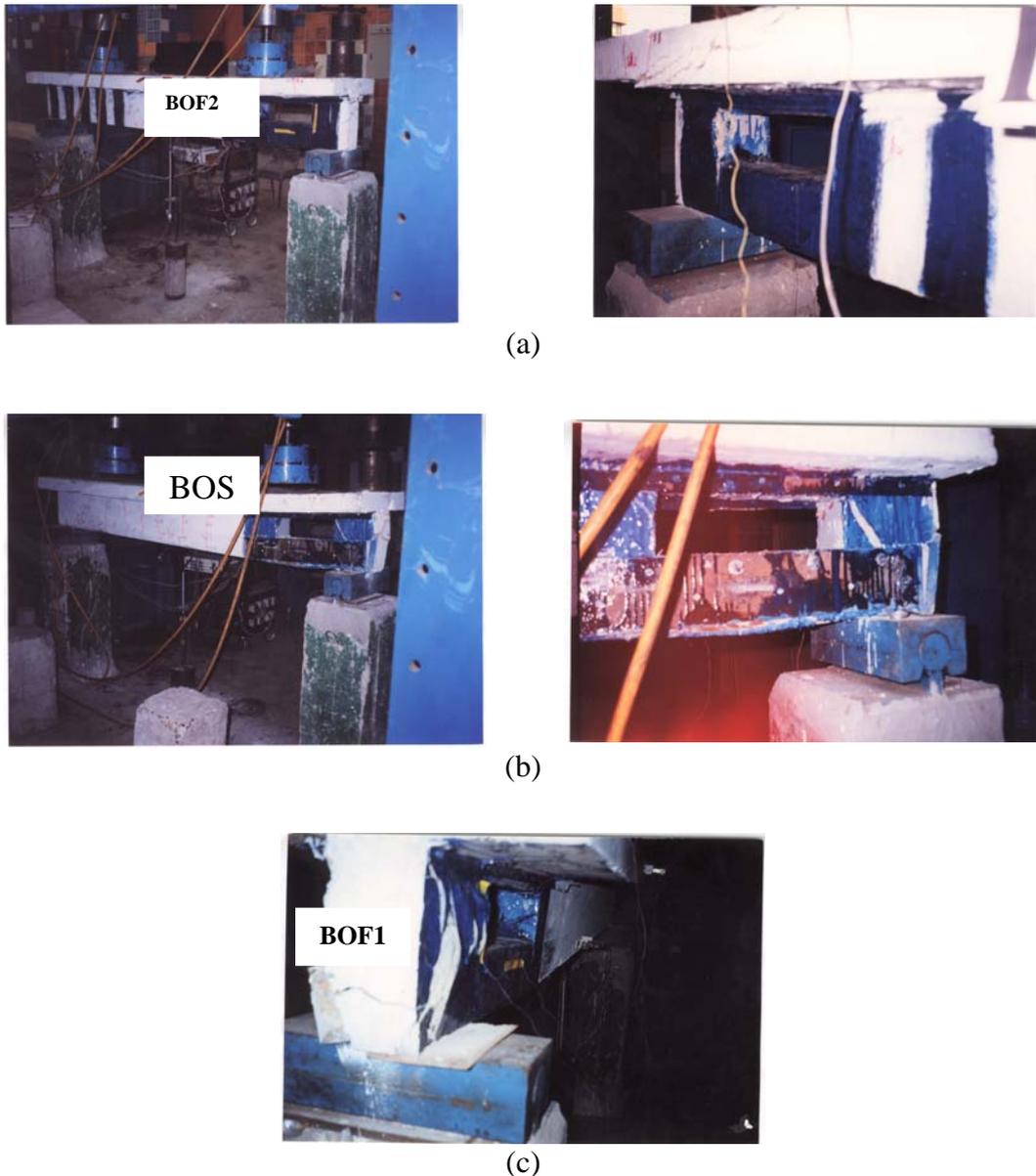


Figure 6. Test Specimens at failure – a) BOF2; b) BOSP; c) BOF1

Strains

The load-carrying capacity of the tested beam specimens was limited by a mode of shear failure. The recorded strains reflected this ultimate response of the specimens. The compressive strain in concrete at midspan was subordinate to the failure strain of concrete. The maximum strain in longitudinal tension bars was less than the yield value. On the contrary, the strain along the vertical strips bounding the opening was far below the ultimate value. The maximum strains measured in the strips were 1.3% and 14% of the ultimate strain for beams BOF1 and BOF2, respectively. These insignificant strains, however, do not oppose the rupture of CFRP fabric observed at failure. Khalifa *et al.*⁵ reported that the failure of CFRP system occurs at an average effective stress level below the nominal strength of the fiber due to the internal stress concentrations. The strains in steel stirrups at the openings are shown in Fig. 7-a to be dependent on the concrete cracking. Lorenzis and Nanni⁶ pointed out that the recorded steel strain is not necessarily a maximum value as it is strictly related to the location of the gauge with respect to the shear cracks. According to Chaallal *et al.*⁷, retrofitting RC beams in shear with CFRP wraps limits the strain and leads to a local decrease in ductility.

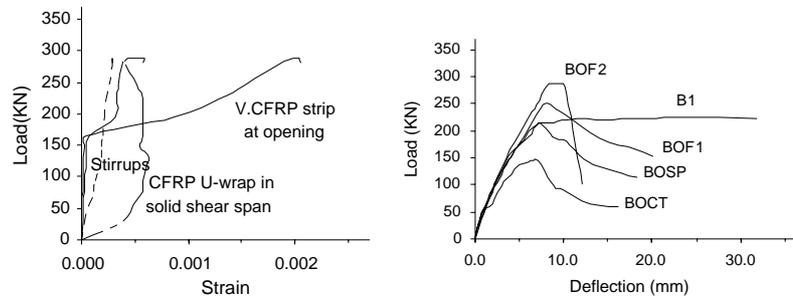


Figure 7. Strains and Deformations
a) strain for Test Specimen BOF2,
b) load versus midspan deflection for test specimens

Load Deflection Curves

The load versus the mid-span deflection curves for all specimens are shown in Fig. 7-b. Table 2, shows the cracking & ultimate loads and mode of failure for all of the tested specimens.

As can be seen from Fig 7-b, the load – deflection curves are similar for all specimens at early stages of loading. As the load increase, the strengthened beams showed larger local stiffness compared to the control specimen. The presence of CFRP or steel plates reduced the specimen mid span deflection compared to the control specimens at its ultimate capacity. The obtained mid span deflection for specimens BOF1, BOF2 and BOSP was about 55%, 55% and 45% of the specimen BOCT at its ultimate capacity. It had to be noted that, the observed deflection under the opening is more than the mid span deflection, this may be attributed to the expected shear deformation that take place of the opening shear strengthening of the tested specimens results in higher ultimate (peak) load and corresponding stiffness. About 70%, 99% and 47% increase in ultimate load are obtained for specimens BOF1, BOF2 and BOSP respectively in terms of 55%, 55% and 45% reduction in the mid span deflection. According to the strengthening technique, the ductility can be decreased relative to the control specimen. It is obvious that, CFRP wraps as strengthening material, in case of opening, is better than using horizontal steel plates. It was also noted that, strengthening of the solid shear span using CFRP wraps (BOF2) increase the ultimate shear capacity and delay the formation of plastic hinges at the opening. The presence of strengthening

reduces the stress concentration around the opening and prevents severe damage. It is obvious that a good technique of strengthening around opening can compensate the reduction in shear capacity due to the presence of the opening (BOF2).

Ductility

In addition to structural strength, ductility is considered to be a major safety consideration in the design of strengthened RC beams. In general, the ductility is characterized by excessive deflection or rotation of structural element while sustaining all its load carrying capacity. A ductile behavior is preferable than the brittle one because it implies the ability of a structure to sustain large deformation without failure.

The ductility factor, is the ratio of the mid-span deflection at the working ultimate load level (which is approximately equal to 80% of the ultimate load) to that at the intersection of 80% P_u of the descending line of the load deflection curve. Figure 8 shows the calculated displacement ductility factors according to the ductility indicators explained above. The shown behavior exhibits a distinct decrease in the ductility of the strengthened beams. The midspan deflection of the strengthened specimens was about 50% of that of the control specimen at its ultimate load. The global ductility of test specimens, characterized by the midspan deflection at failure, however, was rather maintained. Overall, the beam deflection near the opening was noticed to exceed its midspan deflection due to the significance of shear deformations.

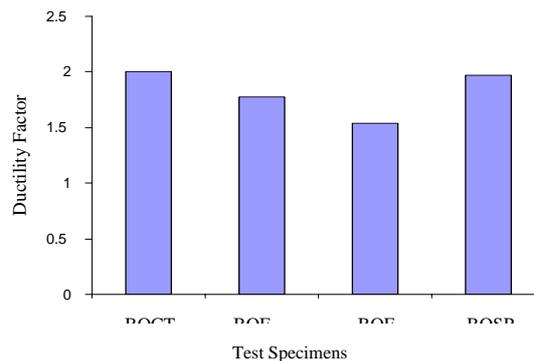


Figure 8. Ductility of the Tested Specimens

NON-LINEAR FINITE ELEMENT ANALYSIS

Finite Element Model

In the present study, a well-correlated computer code for NLFEA of reinforced concrete plates and membranes presented elsewhere [8], was utilized. In the code, the concrete is regarded as an orthotropic linear or non-linear elastic material. The behavior of concrete parallel to the crack direction is modeled in tension as a pure linear-elastic model followed by a linear decay strain-softening model. The softening parameter that relates the ultimate tensile strain to the cracking strain was taken as 10. In compression, the concrete is regarded as non-linear elastic considering the deterioration in concrete stiffness and strength arising from transverse cracking. To account for aggregate interlock and dowel action, the transfer of shear stresses is modeled numerically using a constant fraction shear retention model. The shear retention factor was specified as 0.25 in this analysis. On the other hand, the deformational response of concrete to bi-axial compressive state of stress is described by means of mathematical expressions through the decomposition of the

strain and stress states into hydrostatic and deviatoric components expressed in terms of the octahedral shear and normal strains and stresses.

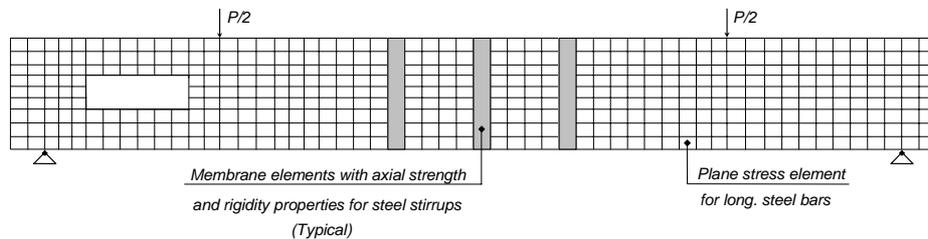


Figure 9. Typical Finite Elements Mesh for Tested Beams

The program was modified to include plane-stress elements of a non-compression feature to simulate the fiber-resistance characteristics. A 4-node quadrilateral membrane element with 8 degrees of freedom was chosen to idealize the beam components including the concrete, CFRP fabric and longitudinal and transverse reinforcing steel bars as shown in Fig. 9. The CFRP fabric and stirrups are represented as smeared elements of equivalent thickness, having uni-axial strength and rigidity properties. The response of the elements is represented at the Gauss integration points, where a 2x2-integration rule was used. Perfect bond between CFRP fabric as well as reinforcing steel bars, and concrete was assumed to avoid local effects inconsistent with the smeared-crack approach adopted here. This assumption agrees with the observed behavior of test specimens as no peeling off or debonding of the CFRP fabric was noticed.

Analysis Procedure

The numerical solution technique used for the analysis of tested beams was an incremental load procedure. For each load increment, the iterative solution performed was a combination of the standard Newton-Raphson and modified Newton-Raphson methods, in which the stiffness was reformulated every so often. The stiffness of CFRP fabric elements that are in compression was reduced to zero. Residual forces were computed at the end of each iteration. The iterative process was carried on until the specified convergence criterion was satisfied. The convergence criterion used was based on the iterative nodal displacements. Euclidian norm of the iterative nodal displacements was compared with the given tolerance. The convergence tolerance varied between 1% and 3%.

Results of NLFEA

A comparison of the experimental with predicted ultimate loads of the tested beam specimens is given in Table 3. As shown, a good agreement between the experimental and analytical results is achieved. The ratios of the predicted to experimental ultimate strength for the beams B1, BOCT, BOSP, BOF1 and BOF2 are 1.07, 0.93, 0.88, 0.88 and 0.76, respectively. Implicitly, the analysis reflects the significance of the strengthening contribution to the load-carrying capacity, except for beam BOF2 that was characterized by additional strengthening of the shear span apart from the opening. The stiffness of the specimens, particularly the post-cracking stiffness were overestimated as noticed in Fig. 10. Yet, the analysis yields the observed mode of failure of the tested beam specimens.

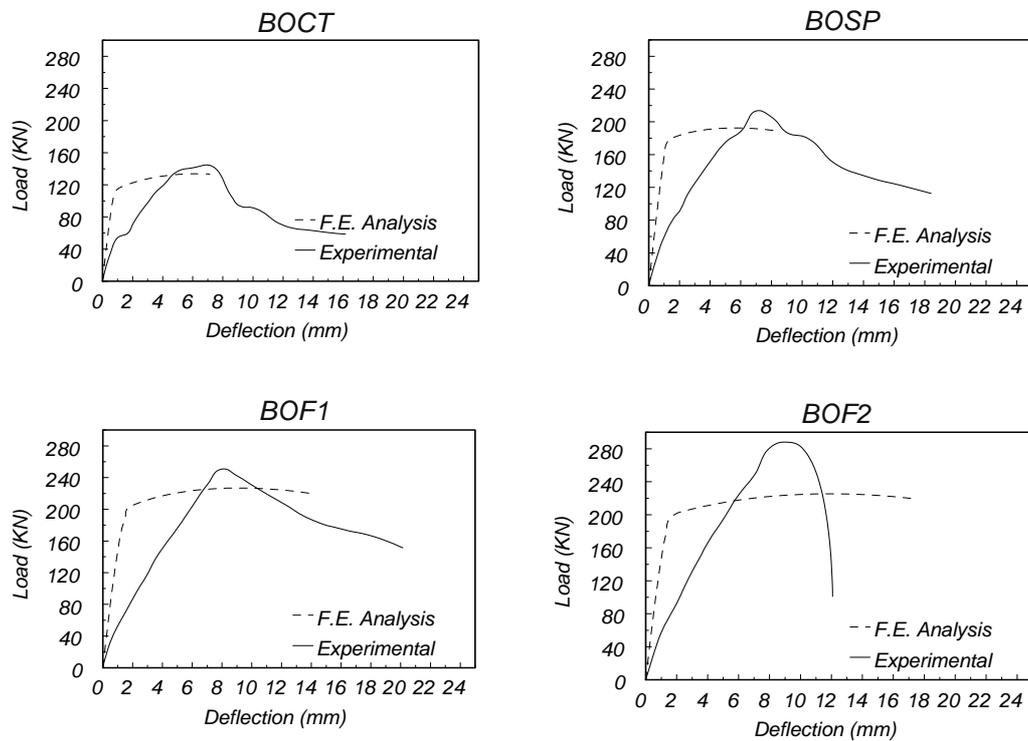


Figure 10. Predicted Response of Test Specimens

Table 3. Experimental and Analytical Test Results

Test Specimen	Ultimate Load, P_u (KN)		Anal. / Exp.
	Exp. Result	F.E. Analysis	
B1	234.4	251.1	1.07
BOCT	144.2	133.4	0.93
BOSP	213.6	188.4	0.88
BOF1	250.8	219.8	0.88
BOF2	288.1	219.8	0.76

CONCLUSIONS

Based on the study presented herein, the following conclusions have been drawn

- (1) Enhancement in the shear capacity of tested RC T-beams with openings may be achieved using the strengthening schemes presented herein. The gain in shear capacity of the tested beams ranged from 48% to 100%. The load-carrying capacities of the beams with strengthened openings were 91%, 107% and 123% of that of the beam without opening.

- (2) Rupture of CFRP fabric occurs at a stress level far below the nominal strength of the fiber. The maximum strains recorded for beams strengthened with CFRP fabric were 1.3% and 14% of the ultimate strains.
- (3) Test results exhibit a distinct decrease in the ductility of the beams with strengthened openings. The global ductility of the test beams, characterized by the midspan deflection at failure, however, was rather maintained.
- (4) Application of non-linear finite element procedures for the strength analysis of reinforced concrete beams with strengthened openings yields acceptable load-carrying capacities. The ratio of the predicted to experimental ultimate strength ranged between 0.76 and 0.93 respectively.

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