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Strengthening of Opening R.C. Beams in Shear Using Bonded External Reinforcements

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Abstract*— Creating opening in existing beam is required to achieve the necessary layout of pipes and ducts, the transverse openings through beams are a source of potential weakness. This paper describes the result of an experimental investigation on the response of creating opening in reinforced concrete beams and the performance of strengthening in shear using either externally epoxy-bonded steel strips plate or FRP strips. The beams were instrumented and tested under three-point bending condition (3PB). The experimental program consisted of testing eight simply supported reinforced rectangular beams. The main parameters of study are the shape and the material used for strengthening. The deflection, failure load, failure mode and ductility of the retrofitted beams are discussed. A nonlinear finite element method NFEM analyses (Ansys program) was used to corroborate the results from the experimental study. The discontinuous web strengthening is failed to prevent the diagonal shear cracks at the bottom and top of the opening. The continuous web reinforcement retrofit succeeded to prevent the diagonal and horizontal cracks due to the existence of opening. The analytical results are compared with the data obtained from beam tests through the linear and nonlinear ranges up to failure. It was found that the FE models can identify the structural behavior of the tested beams and can be an excellent alternative of destructive laboratory test with an acceptable variation of results.

Index Terms—**R C beams, Shear, Repair, Rectangular opening, FRP, Nonlinear, FEA, ANSYS.**

I. INTRODUCTION

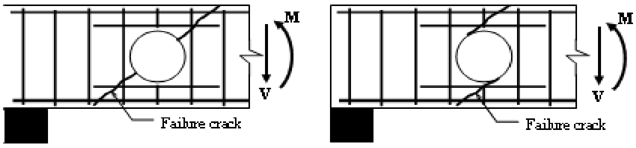
In the construction of modern buildings, a network of pipes and ducts is necessary to accommodate essential services like water supply, air-conditioning, electricity, telephone, and computer network. Usually, these pipes and ducts are placed through transverse openings in the floor beams. The transverse openings through beams are a source of potential weakness. Many researches (1, to 10) have been carried out to guess and understand the behavior of beams with web openings. They recommended rational methods for design of such beams based on both experimental and theoretical investigation, they suggested addition and diagonal bars around the opening to control the cracks width and reduce the beam deflection for beams with large length and depth of opening and undergo bending moment and shear force. These methods are lucratively used for opening beams before casting. For old buildings, the necessary layout of pipes and ducts are decided through providing an opening in an existing beam, the decision of creating opening in existing beam, jeopardizes the existing beam due to the reduction in both strength and stiffness of the beam and excessive cracking at the opening due to high stress concentration. Little researches had been carried out to retrofit the opening in existing solid beam. Okasha (11) has studied experimentally, the availability of providing rectangular web opening in existing solid beams with smallest minus effect on both strength and stiffness by strengthening openings with Carbon Fiber Reinforced Plastic laminates. The use of circular holes in shear zone of beams is preferable and better than other shape (5). In case of circular opening CFRP may be not flexible in repairing. Glass Fiber Sheets may be preferable in such case due to its lightweight, flexibility, and its resistance to weather conditions (12).

II. BEAMS WITH SMALL OPENINGS

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 (10). In such a case, beam action may be assumed to prevail. Therefore, analysis and design of a beam with small openings may follow the similar course of action as that of a solid beam. The provision of openings, however, produces discontinuities or disturbances in the normal flow of stresses, thus leading to stress concentration and early cracking around the opening region. Similar to any discontinuity, special reinforcement, enclosing the opening close to its periphery, should therefore be provided in sufficient quantity to control crack widths and prevent possible premature failure of the beam.

A. *Combined Bending and Shear*

In a beam, shear is always associated with bending moment, except for the section at inflection point. When a small opening is introduced in a region subjected to predominant shear and the opening is enclosed by reinforcement, as shown by solid lines in Figure 1, test data reported by Hanson (15), and Salam (16), indicate that the beam may fail in two distinctly different modes. The first type is typical of the failure commonly observed in solid beams except that the failure plane passes through the center of the opening (Figure 1a). In the second type, formation of two independent diagonal cracks, one in each member bridging the two solid beam segments, leads to the failure (Figure 1b). Labeled respectively as beam-type failure and frame-type failure (Mansur, (17)), these modes of failure require separate treatment.



(a) Beam-type failure (b) Frame-type failure

Fig (1). The two modes of shear failure at small openings

B. *Reinforcement Details*

Consideration of beam-type failure will require long stirrups to be placed on either side of the opening, while that of the frame-type failure will need short stirrups above and below the opening (10). For anchorage of short stirrups, nominal bars must be placed at each corner, if none is available from the design of solid segments. This will ensure adequate strength. For effective crack control, nominal bars should also be placed diagonally on either side. The resulting arrangement of reinforcement around the opening is shown in Figure 2. Under usual circumstances, introduction of a small opening with proper detailing of reinforcement does not seriously affect the service load deflection.

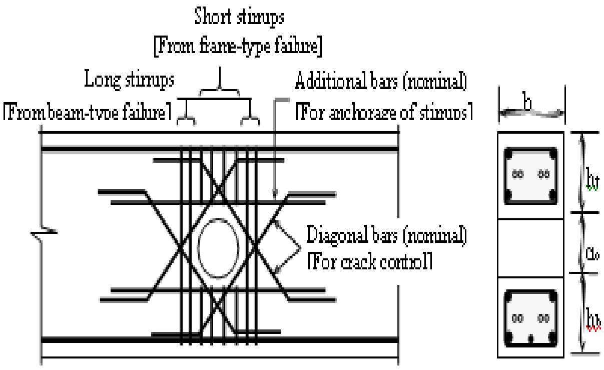


Fig (2). The Reinforcement details around a small opening.

III. BEAMS WITH LARGE RECTANGULAR OPENING

Similar to a beam with small openings, incorporation of a large opening in the pure bending zone of a beam will not affect its moment capacity provided that the depth of the compression chord is greater than or equal to the depth of ultimate compressive stress block, and that instability failure of the compression chord is prevented by limiting the length of the opening (Mansur and Tan, (18)). In practice, openings are located near the supports where shear is predominant. In such a case, tests have shown that a beam with insufficient reinforcement and improper detailing around the opening region fails prematurely in a brittle manner (Siao and Yap, (19)). When a suitable scheme consisting of additional longitudinal bars near the top and bottom faces of the bottom and top chords, and short stirrups in both the chords, as shown in Figure 3, is furnished, then the chord members behave in a manner similar to a Vierendeel panel and failure occurs in a ductile manner. The failure of such a beam is shown in Figure 4. Clearly, the failure mechanism consists of four hinges, one at each end of top and bottom chord.

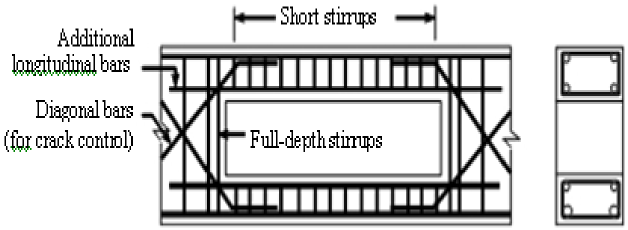


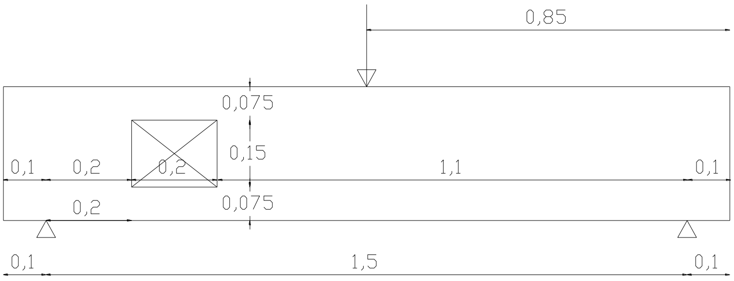
Fig (3). A suitable reinforcement scheme for the opening region.

Fig (4). Ductile failure of a beam under combined bending and shear.

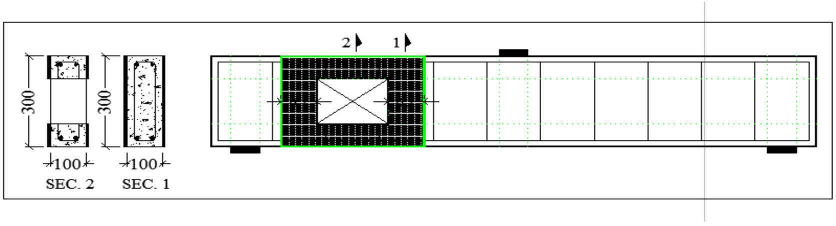
On the basis of the literature review and the above discussion which summarizes the behavior of the opening in R.C beam, taken into account the reinforced details around the opening before construction. Yet the decision of creating opening in existing solid R.C. beam with retrofitting the new opening has not been fully answered by yes or no. There is a necessity of carrying out this study.

IV. EXPERIMENTAL PROGRAM

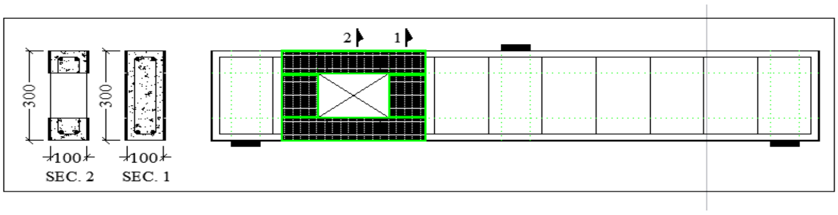
The experimental program of this study was conducted on eight beams. Figure (5) and Table (1) summarize the details, properties and the investigated parameters of the tested beams. All tested beams have the same total length 1.7m and overall cross section 100x300 mm. They simply supported 1.5m apart. The tested beams were designed as under-reinforcement sections with cube strength 27.0 N/mm2, the steel reinforcement of all beams was: two bars 12mm diameter as tension reinforcement, two bars 10mm diameter as compression reinforcements with yielding stress 360 MPa and stirrups 8 mm diameter with 15cm spacing with yielding stress 240MPa . The first beam B1 was a solid one with no openings and was considered as a control beam. The opening of beam B2 represents the control for the new opening in existing beam without any specially reinforcement around the opening, the stirrups at the top and the bottom of opening are deformed as U shape to represent the cutting of stirrups at location of opening. The opening beam B3 was retrofitted using steel plates with 2mm thicknesses, which were bonded around the faces of the beam with dimension as shown in Figure (5). The opening beam B4 was retrofitted similar to B3, but the steel plate at each face of beam are consists of steel strips with the same dimensions for beam B3. The opening beam B5 was retrofitted with steel plate in U shape around the opening as shown in table (1). The opening beam B6 was retrofitted using Carbon Fiber similar to beam B5. The opening beam B7 was retrofitted similar to B4 using Carbon Fiber instead of steel strips. The opening beam B8 was retrofitted similar to B5, (using NSM method) the concrete cover was removed and the steel pates were bonded directly at the face of the concrete and internal stirrups of the beams.



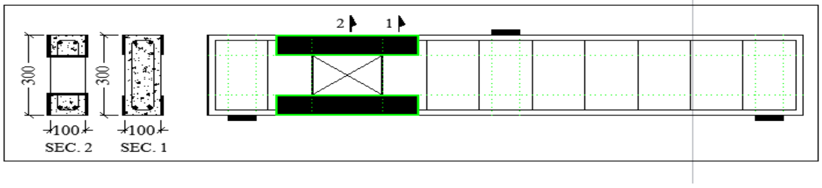
Control Specimen (B2)



Specimen (B3)



Specimens (B4, B7)



Specimens (B5, B6, B8)

Fig (5). Methods of retrofitted tested beams

(i) Table 1: Specimens Details

Specimen	Method of strengthening	strips number	Plate Thick.
B1	Without opening (control Specimen)	-	-
B2	With opening (control Specimen)	-	-
B3	Bonded externally steel plate At each face	One plate for each face	2 mm
B4	Bonded externally steel strips At each face	four Steel strips for each face	2 mm
B5	Bonded externally steel strips With U shape	two Steel strips for opening for top and bottom chord of opening	2 mm
B6	Bonded externally carbon fiber strips With U shape	two carbon fiber strips for opening for top and bottom chord of opening	-
B7	Bonded externally carbon fiber strips at each face	four carbon fiber strips for each face	-
B8	Bonded externally steel strips With U shape (NSM)	two Steel strips for opening for top and bottom chord of opening	2 mm

A. Retrofitting Procedures

For beams B3, B4, and B5, the steel plates were bonded directly at their Side's faces using epoxy-adhesive component (Kemapoxy 165). For beams B6, and B7, the adhesive material used with carbon fiber strips was also Kemapoxy 165. For beam B8 (using NSM method), retrofitting was performed in two operations. First, concrete cover was removed with area similar to steel plate area face; the area of removed cover was cleaned from any fine particles to ensure bonding between the epoxy adhesive and the concrete, the steel plates were bonded directly at the face sides of the opening using epoxy-adhesive component similar to above beams. Second, the concrete surface at the bottom was coated using epoxy adhesive (Kemapoxy 104) to bond the new concrete to the old concrete.

B. *Experimental Setup*

All beams were tested as simply supported beams under three- point bending with a total span of 1500 mm. Using a dial gauge with accuracy of 0.001 mm, to measure the deflections. The beams were loaded in increment of 5 kN, the mid span deflection and deflection cracking pattern, cracking load and ultimate loads were recorded. Figure (6) shows the setup of beam test.

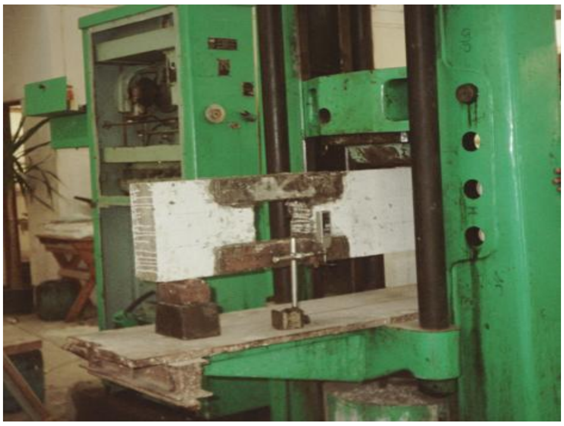


Fig 6: the setup of beam test

V. FINITE ELEMENT MODELING

The present study addresses a three-dimensional nonlinear finite element analysis (FEA) modeling for the prediction of the shear behavior of reinforced concrete (RC) beams, with and without opening, strengthened with externally bonded steel plate and carbon fiber reinforced polymers (EB-CFRP) materials. The nonlinear FEA was performed using the ANSYS program. Eight nodes 3-D space solid elements were used to represent the concrete, and steel plate epoxy. The steel reinforcements were modeled as discrete reinforcing steel bars using two nodes 3-D space link element.

A. *Element type*

Concrete and resin was modeled using 3-D (8-node) solid elements. The main feature of this element is the ability to account for material nonlinearity. This element is capable of considering cracking in three perpendicular directions, plastic deformation and crushing, and creep. The element is defined by eight nodes having three translation degrees of freedom at each node in the x, y and z directions. Steel plate and FRP composite were modeled using SOLID185 element. This element is defined by eight nodes having three degrees of freedom at each node; translations in the nodal x, y, and z directions. The element is capable of plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities. SOLID185 element uses enhanced strain formulation, simplified enhanced strain formulation, or uniform reduced integration. SOLID185 is available in two forms, Homogeneous Structural Solid and Layered Structural Solid which used to model the steel plate and the FRP composites, respectively. A LINK180 element is used to model steel reinforcement. The element is a uniaxial tension-compression element with three degrees of freedom at each node: translations in the nodal x, y, and z directions. This element is also capable of plastic deformation.

B. *Material type*

To perform nonlinear model, a nonlinear properties of material for concrete, steel reinforcement and resin are chosen. Concrete is considered as a quasi-brittle material, that's where the stress decreases gradually after the peak stress, and the properties of concrete in compression and tension are different from each other. The tensile strength of concrete is typically 8-15% of the compressive strength, (20). Complete stress-strain curves of concrete are needed to accurately predict structural behavior to failure and post-failure. Equation 1 and Equation 2 introduced by Desayi and Krishnan, (21), were used along with Equation 3; ECP 203-2007 (22) constructs the simplified uniaxial compressive stress-strain curve, as shown in Figure 7, for concrete used in this finite element model. The value of Ec can be obtained using the Equation 3 with a value of fcu equal to 27 MPa. Poisson's ratio for concrete was assumed to be 0.2 for all four beams as denoted in ECP 203-2007(22). Typical shear transfer coefficients range from (0.0 to 1.0), with 0.0 representing a smooth crack (complete loss of shear transfer) and 1.0 representing a rough crack (no loss of shear transfer). This specification may be made for the closed and open crack, βc and βt. For this analysis both βt and βc were set to 0.6 achieving a good converging problem.

$$f= (Ec\ \ \varepsilon)/(1+(\varepsilon/\varepsilon o)^2) \qquad (1)$$

$$\varepsilon o=(2\ f(c))/Ec \qquad (2)$$

$$Ec=4400\ \sqrt{(fcu)} \qquad (3)$$

When the element is cracked or crushed, a small amount of stiffness is added to the element for numerical stability. The stiffness multiplier CSTIF is used across a cracked face or for a crushed element, and is taken 0.1.

Two type of steel rebar, according to the uniaxial tensile tests on the different bars introduced in experimental work, are used. The reinforcement element was assumed to be a bilinear isotropic elastic-perfectly plastic material and identical in tension and compression as shown in Figure 8. Modulus of elasticity and Poisson's ratio are taken 2 x 10^5 MPa and 0.3 for all types of steel reinforcement. Yield strength for longitudinal and chord stirrups is 400 MPa.

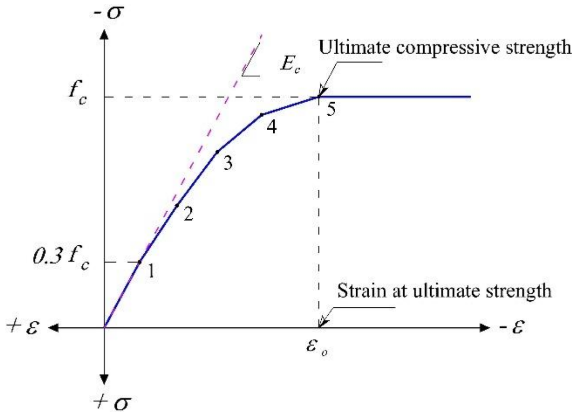


Fig 7: Simplified Compressive Uniaxial Stress-Strain Curve for Concrete

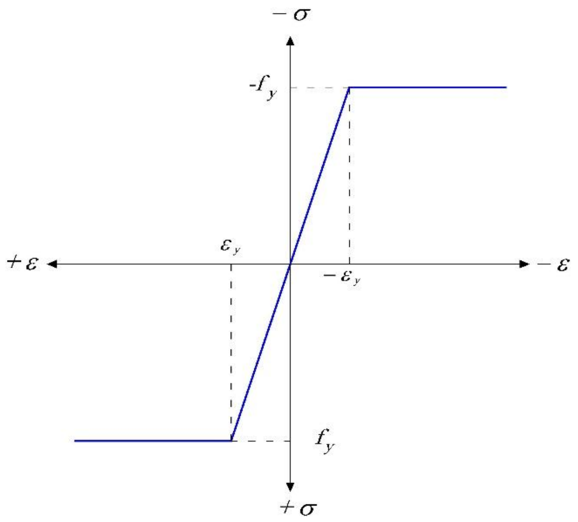


Fig 8: Stress strain relationship of steel rebar

A unidirectional CFRP fabric (SikaWrap-230C) with thickness 0.131 mm per ply was used. The resulted laminate thickness was about 0.35 mm. the tensile elastic modulus and tensile strength based on 1.0 mm of the laminate which have been identified by the manufacturer are 28 GPa and 350 MPa, respectively. FRP laminates have stress-strain relationships that are roughly linear up to failure as shown in Figure 9.In the nonlinear analysis of the full-scale transverse beams, no FRP elements show stresses higher than their ultimate strengths. Consequently, in this study it is assumed that the stress strain relationships for the FRP laminates are linearly elastic.

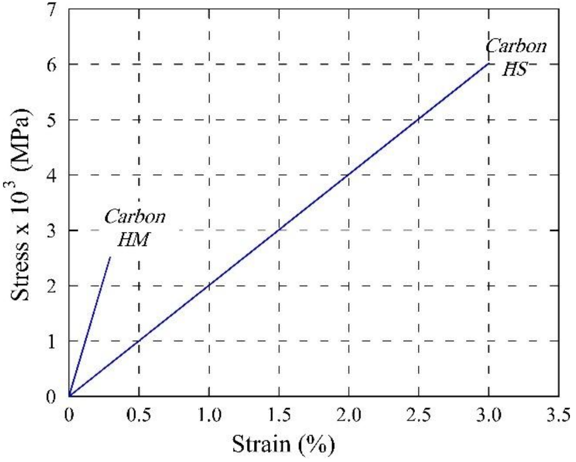


Fig 9: Properties of different fibers Dejke (23).

Table 2 shows a summary of the linear orthotropic properties of the CFRP laminate. The impregnation resin for the used fiber is a two part, thixotropic epoxy based impregnating resin / adhesive (Sikadur-330) with density 1.3 kg/l, tensile elastic modulus 4500 MPa and tensile strength 30 MPa. Poisson ratio and maximum elongation for the resin are taken 0.3 and 0.009, respectively. The open and closed shear transfer coefficients are 0.2 and 0.8, respectively. The crushing capability of the resin is neglected.

Table 2: summary of the linear orthotropic properties of the CFRP laminate.

Elastic modulus Gpa		Major Poisson ration		Shear modulus Mpa	
Ex	28000	Prxy	0.3	Gxy	2145
Ey	4500	Pryz	0.3	Gyz	2050
Ez	4500	Prxz	0.3	Gxz	2145

To ensure that the model acts the same way as the experimental beams, boundary conditions need to be applied at supports which give a better results in convergence solution. The nodal displacement load is used to model the boundary condition in this ANSYS models. The supports were modeled in such a way that a roller is created.

VI. RESULTS AND DISCUSSION

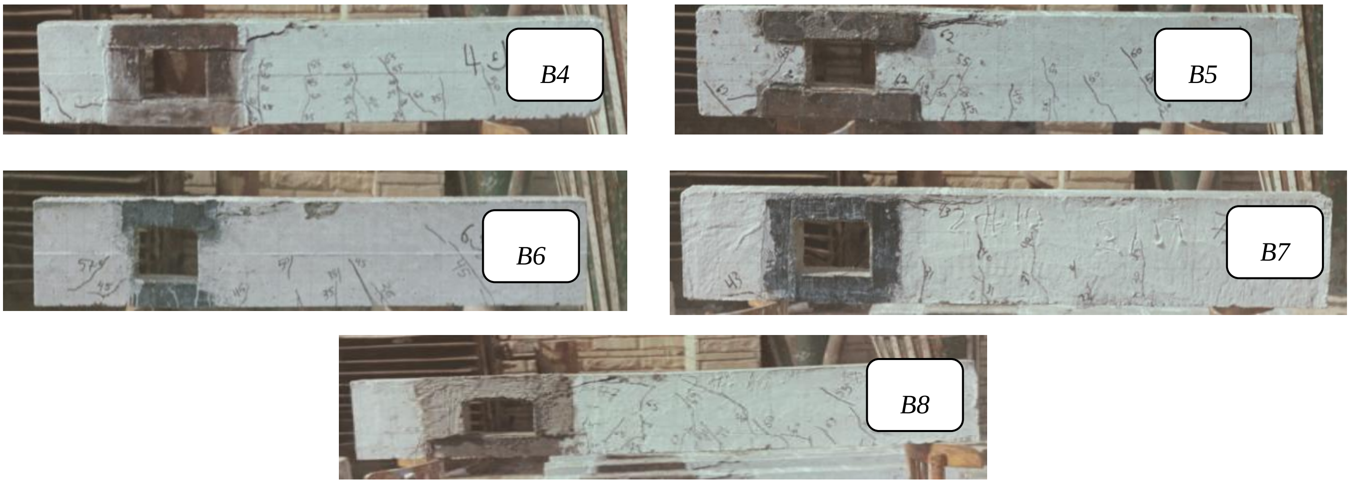
A. CRACKING BEHAVIOR AND FAILURE MODES

The control specimen (B1) was designed to fail in tension failure, so the first crack was observed at mid span in the bottom of the beam at load of 35 kN. The crack extended to the top beam nearly to the point load with several cracks during the increase of load (Figure 10-a). For the control specimen (B2) with opening and without strengthening, the crack appeared at corners of opening for top and bottom chords of the opening at load 25 kN. With sudden failure at ultimate load due to the reduction in the stiffness at the opening, and the top and bottom chords behave as individual cross-sections, the shear stress was significant and the diagonal tensile induced at this corners of opening were larger to cause frame-failure with no special stirrups for the early top and bottom chords of the solid beam (Figure 10-b). For strengthening specimen (B3), the failure mode of the beam is shown in (Figure 10-c); the beam failed by the occurrence the development of a several number of bending cracks at mid span similar to specimen (B1) with first crack load of 41 kN. In all strengthening different for B4 to B8, a several cracks were observed in tension zone until near the ultimate load. The development of shear cracks were developed suddenly, followed by a sudden shear failure in one side of the beam specimens as illustrated in (Figure 10-d), with average ultimate failure load less than the control specimen (B1).

(Fig 10-a).

(Fig 10-b).

(Fig 10-c).



(Fig 10-d).

Fig 10: Mode of failure of tested RC beams with different strengthening around the opening

B. FAILURE LOAD AND DEFLECTION

The mid span deflections of the specimens are plotted against the applied load in Figure (11). Table (3) shows the summary of principal test results. Taking the response of the specimen B1 as the required target, the ultimate capacity of this specimen was 87 kN, the corresponding mid-span deflection at the ultimate load was 46.6 mm. It may be seen that creating an opening in existing specimen (B2) leads to smaller post-cracking stiffness Figure (11), and significantly reduces the load carrying capacity of a specimen (Table 3 and Figure (11)), The predominant failure mode was a shear failure rather than flexural failure and the ultimate capacity of this specimen was 35.8 kN and the corresponding mid-span deflection at the ultimate load was 5.8 mm. This serves as a warning that drilling an opening in an existing specimen might seriously affect the safety and serviceability of the structure. The strengthening by external plates (B3) can completely eliminate the weakness introduced by creating an opening in an already constructed specimen; the ultimate capacity of this repaired specimen reached 89.4 kN., and the corresponding mid-span deflection at the ultimate load was 46 mm. This can be attributed to the fact that the steel plate external reinforcement was continuous and has eliminated the shear cracks. All strengthen specimens bonded with strips either steel strips or FRP strips are failed in virtually the same manner. After cracks occurred at the centre of the specimens in tension zone, the shear cracks propagated with sudden shear failure, the overall performance was far beyond the the solid control (B1). The ultimate capacity of this strengthen specimen (B4) was 66 kN which is about 75% of the the capacity of the solid control specimen (B1), the corresponding mid-span deflection at the ultimate load was 12.65 mm., the reason is due to the discontinuous of the steel plate external reinforcement. For the specimens (B5) and (B6) the bonded externally steel or FRP with U shape respectively were not sufficient to the weakness introduced by creating an opening in an already constructed specimens, almost all the failures were shear failures, however, the presence of U shape delayed the failure giving warning before failure, which is considered as the desired mode of failure by almost all codes. Greater number of cracks is apparent from (Figure 10-d). The ultimate capacity of this strengthen specimen (B5) and (B6) were 62 kN and 57.5 kN respectively, which are about 71% and 66% of the capacity of the solid control specimen (B1) respectively , the corresponding mid-span deflections at the ultimate load were 8.9 and 9.2 mm. respectively. The behavior of specimen (B7) is similar to the specimen (B4), and the ultimate capacity of this strengthen specimen (B7) was 43 kN which is 0.327 times than the capacity of the solid control specimen (B1), the corresponding mid-span deflection at the ultimate load was 6.4 mm., the decrease in the ultimate capacity due to the discontinuous of FRP strips at the top and upper chord of the opening. For the specimen (B8), the ultimate capacity increased up to 77 KN, but is not adequate to restore the original strength, Fig. (11) Shows the stiffness of the specimen is adequate corresponding of the control specimen (B1). The near surface mounted technique (NSM) enhanced the strengthening performance, but was far beyond the target performance of the solid beam due to the discounts of strips.

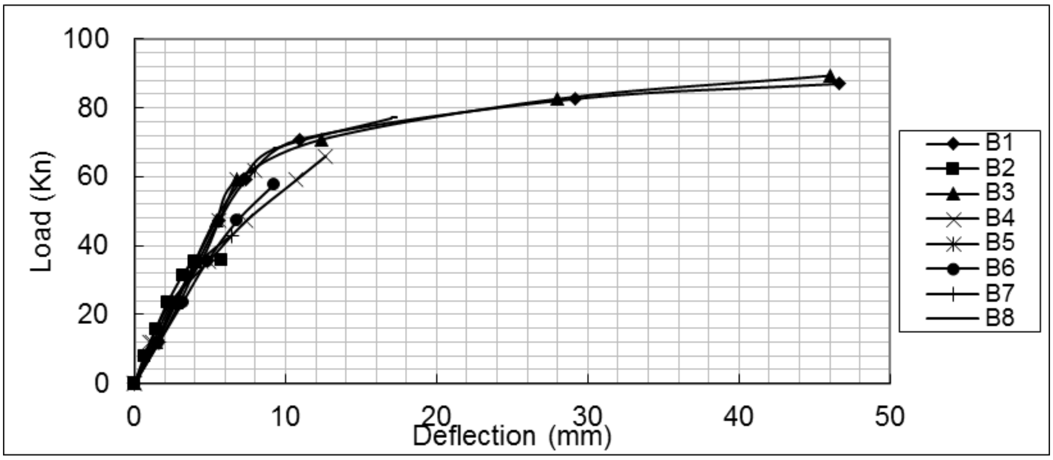


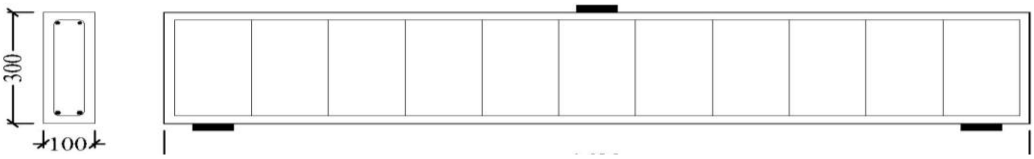
Fig 11: The Load - Mid span Deflection for Strengthened specimens

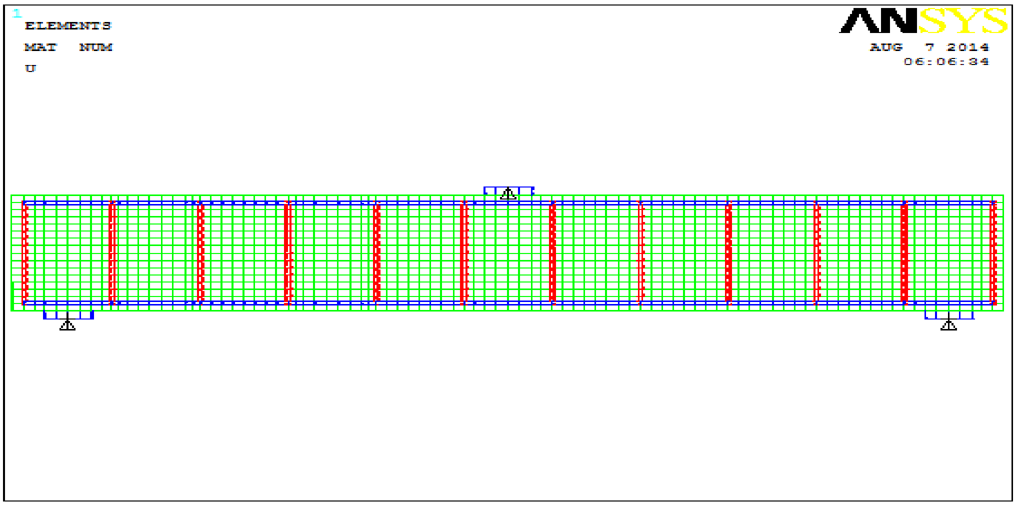
Table 3: measured results at cracking and ultimate load for strengthening methods

Specimen No.	P cracking (Kn)	Maximum Deflection (mm)	Pu (ultimate Load) (Kn)	$\frac{\text{Pu (Ultimate load)}}{\text{Pu of Specimen B1}}$
B1	35	46.6	87	1.00
B2	25	5.8	35.8	0.411
B3	41	46	89.4	1.027
B4	28	12.65	66	0.758
B5	28	8	62	0.712
B6	26	9.2	57.6	0.662
B7	26	6.4	43	0.327
B8	27	17	77	0.885

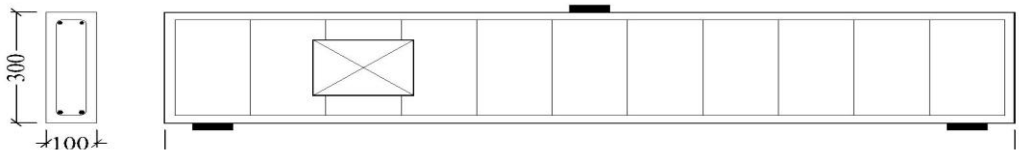
The numerical models were compared with the results obtained from the experimental work. The results were found to be in a good agreement with the experimental results with different not exceed 15%. Figure 12 shows meshing reinforcement arrangement, and boundary condition of solid beam and beam with opening. Figure 13 shows the comparison between the FEA and the experimental results.

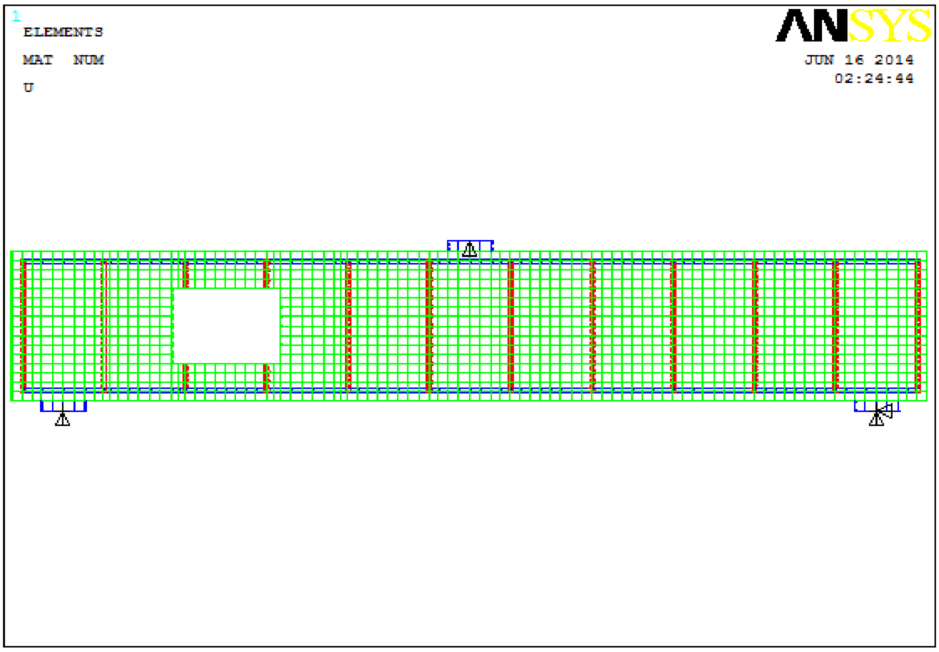
Beam B11





BEAM B22





BEAM B33

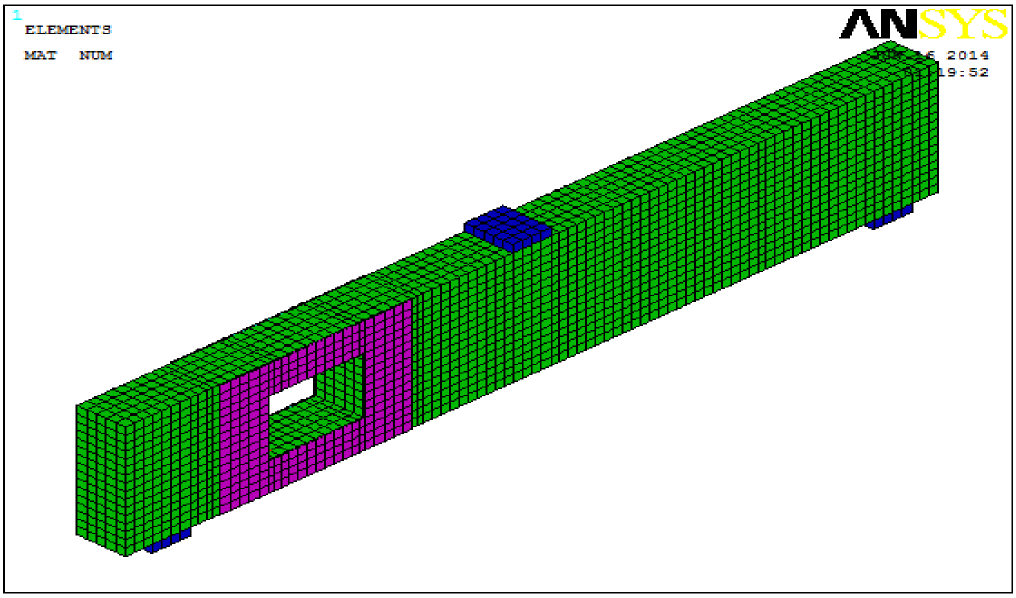


Fig 12: meshing reinforcement arrangement, and boundary condition of solid beam and beam with opening

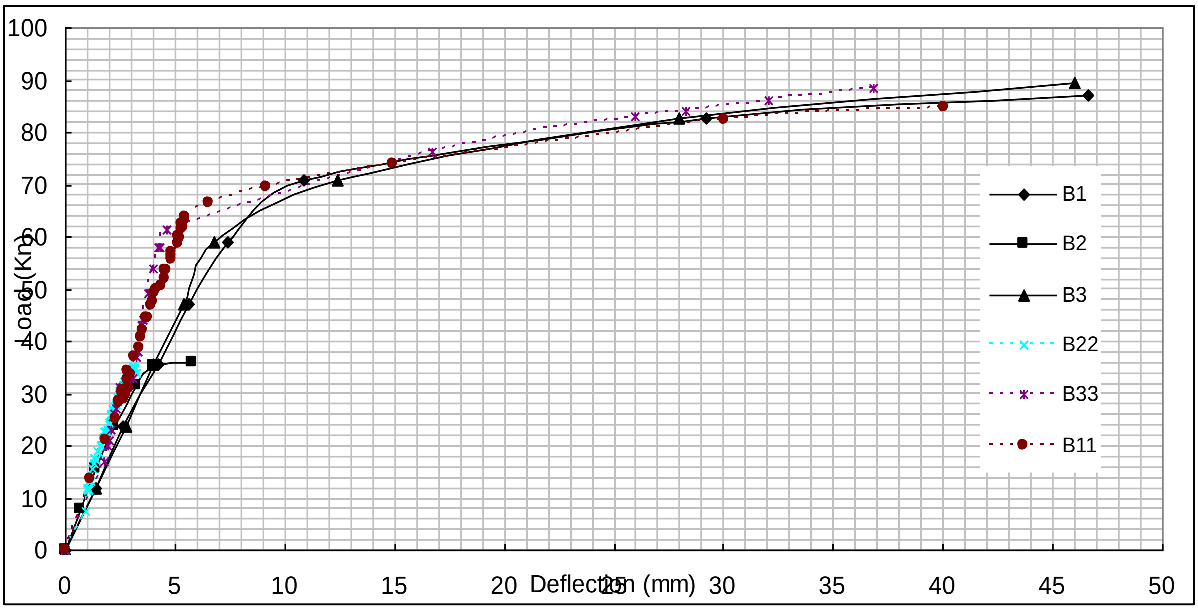


Fig 13: The Load - Mid span Deflection for Strengthened specimens (experimental and FEA)

VII. CONCLUSION

The following conclusions may be drawn from the present experimental study.

1- Drilling an opening of an existing beam may seriously incorporated shear failure at opening zone
2- The strengthened beams around the opening incorporated a flexural failure at mid-span zone, provided that the continuity of strengthening.
3- The continuous steel plate around the opening is more effective than strips FRP
4- The use of near surface mounted (NSM) for continues steel plate is an effective technique to enhance the shear capacity of the opening RC beams.

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