EXPERIMENTAL AND FINITE ELEMENT (FE) STUDIES ON SHEAR BEHAVIORS OF REINFORCED CONCRETE (RC) BEAMS WITH CIRCULAR WEB OPENINGS

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مُسْتَخْلَص

يؤدي انشاء الفتحات في مقاطع عناصر الخرسانة المسلحة إلى تقليل جساءتها وقدرة تحملها. هذا التدهور في القدرة التحملية يعزى إلى تركيز الضغوط والتشققات حول منطقة الفتحات. هذه الورقة تهدف إلى دراسة تأثير الفتحات علي سلوك العارضات الخرسانية المسلحة ضد اجهاد القص. في هذه الدراسة, تم تصنيع واختبار عدد ثلاث عارضات بفتحات بالاضافة الي عارضة واحدة بدون فتحة. كما تم دراسة اثر موقع وحجم الفتحة، ونسبة القص إلى العمق علي سلوك العارضات. تم تحليل العينات باستخدام طريقة العناصر المحددة باستخدام برنامج التحليل ANSYS14.5 لدراسة وتحليل اثر المتغيرات المذكورة أعلاه. كما أظهرت النتائج أن الانهيار المبكر للعارضات حدث عندما تقع الفتحة عند منطقة القص العالية (المنطقة بين الحمل الرأسي والمسند). و من خلال مقارنة نتائج التحليل باستخدام طريقة العناصر المحددة مع نتائج الاختبارات المعملية وجدت ان النتائج كانت متوافقة وبفوارق مقبولة.

ABSTRACT

The introduction of openings into reinforced concrete (RC) elements leads to reductions in the element's overall structural capacity and stiffness. These reductions attributed to stresses concentrations and local cracking at the openings region. This paper presents a study aimed at investigating the influence of web openings at shear span of RC beam on its shear behavior. A total of three beams with circular openings and one beam without opening were fabricated and tested. The opening location and size, and shear span-to-depth ratios, were considered as the main parameters. The FE model using ANSYS14.5 software was calibrated with the experimental results to ensure that the simulation process is correct. Furthermore, the specimens were analyzed using ANSYS14.5 with considering the above mentioned parameters. The results showed that the early collapse of the beam occurred when the openings located in a high shear region. Furthermore, by comparing the non-linear FE analysis results with those from experimental tests, results were showed good agreement.

Keywords: *RC beam, FE analysis, Openings, ANSYS14.5, shear span-to-depth ratios*

1 Introduction

Creating an opening in RC beams usually used for passing water and sewage pipes, air conditioning ducts and electricity wires in the buildings. However, creating an opening in the RC beams resulted to decreasing of load carrying capacity due to stress concentration around the opening. A total of eight RC continuous beams were tested by Mansur (1998) [1], each beam containing a large transverse opening. He found that the opening depth has great effect on load carrying capacity of the beams. Furthermore, the effects of transverse opening on the behavior and strength of RC beams under predominant shear were discussed by Mansur et al (2006) [2], and they stated that opening represents a source of weakness and the failure plane always passes through the opening, except when the opening is very close to the support so as to bypass the potential inclined failure plane [3].

Hanson, et al (1969) [4] tested a regular joist floor i.e. a progression of longitudinally RC T- beams speaking to square and circular openings in the web and found that an opening found adjoining the middle stub (support) created no decrease in strength. The test results conducted by Somes and Corley (1974) [5] showed that when the opening close to 0.25 times the depth of the beam (a small opening) is presented in the unreinforced RC beam in shear, the mode of failure mainly the same as in the solid beam. Salam (1977) [6] tested RC beams with rectangular cross section under two point loads. Siao and Yap (1990) [7] stated that when the beams unreinforced around the openings it will fail suddenly due to development of diagonal cracks in the compression zone. Mansur (1999) [8] studied the effects of web opening on strength behavior of RC beams. Their results showed that the opening represents a source of weakness especially around the unreinforced openings, but it showed little decreasing in the beam capacity when the opening is near to support. Many researchers [9- 11] investigated the RC beams with openings by using Finite element (FE) programs. They were discussed and described the previous researches which are related to the openings in the web of reinforced concrete (RC) beams. Studying of the strength defect in RC beam due to the presence of large square openings located at two different places in shear region was investigated by S.C. Chin,et al (2011) [12].

2 Research program

The study program contains two parts; the first part was the validation of the finite element (FE) method by using ANSYS with the results from experimental tests, and the second part was the parametric study. The effects of opening location and shear span-to-depth ratios on the shear behavior of RC beams with circular openings were investigated in this study. The experimental results were compared with those obtained from FE analysis to ensure more confidence for reinforced concrete beams with openings using FE analysis. Furthermore, it can be used as a guidance for further studies related to this field.

3. Experimental program

For this experimental study, one rectangular RC beams without openings and three beams with openings were designed and tested. The following sections show the details of tested beams.

3.1 Materials properties

In this study, Intensive experimental tests were carried out to obtain the materials properties. All specimens were prepared and cured under same conditions to confirm that the concrete cube has same strength after 28 days. The achieved concrete compressive strength after that time was 33 MPa. Deformed steel bars Grade 350 and 250 were used for longitudinal and web steel reinforcement, respectively.

3.2 Specimen details

A rectangular cross section of 100 mm wide and 280 mm high, with a total length of 2000 mm was considered in all test beams. The effective depth (d) was 260 mm for all beams. Stirrups diameter of 8 mm with spacing of 150 mm were used as shear reinforcement. Two of the 10-mm and two of 12-mm diameter deformed bars were used as top, and bottom steel reinforcement, respectively. A clear cover of 20 mm considered in top and bottom sides of the beam, and cover of 15 mm was used at the vertical sides.

Figure 1 shows the details and geometry of tested beams which divided into two groups according to their shear span to depth ratios (a_v/d) of 2.0 and 2.5. The beams named as B1- B4 and detailed in Table 1. Three beams had two circular openings, one in each shear span, that were placed symmetrically about the mid-point of the beam. The opening size of 105, which equal to height-to-depth ratio of 0.4. The openings distance is varied from 200 mm to 300 mm from the support.

3.3 Test setup

The beams were tested under four-point loading, as shown in Figure 2. As shown in Figure 1, the beam was tested as simple supported with clear span of 1800 mm. A steel spreader beam was used to transfer the load from a 500-kN capacity jack to the beam.

The load was measured by a 500-kN capacity load cell. Load cell machine was used to apply the load in increment of 10 kN. The deflection and crack values corresponding to load increment were recorded and crack pattern was highlighted on the beam sides. Table 1 shows the details of the tested beams.

Linear variable differential transducers (LVDTs) were used to measure the deflection during the test. The deflection during testing was measured using LVDTs located under the two load points and at mid-span as shown in Figure 2

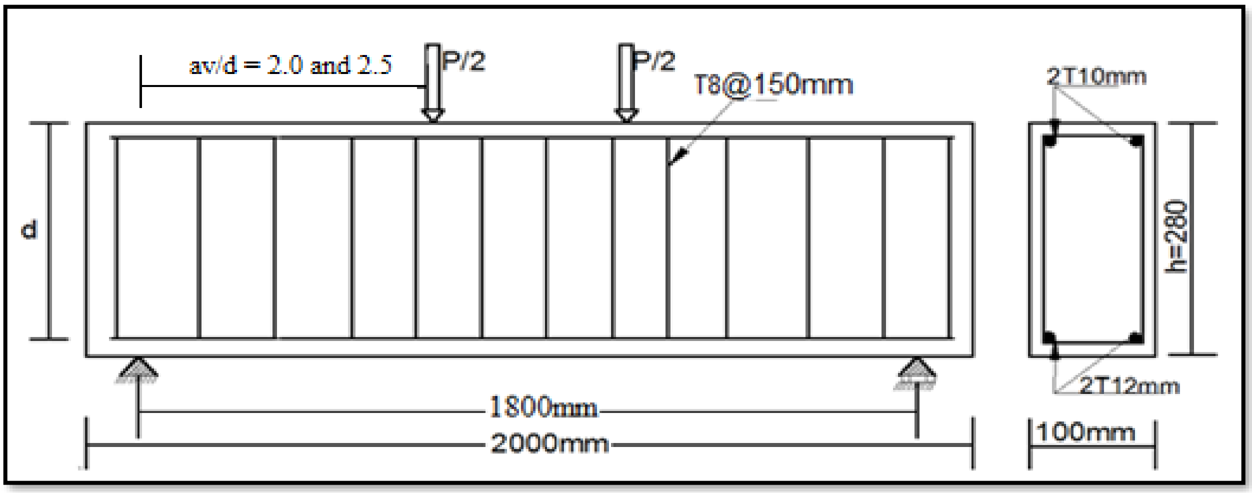

Figure2: Geometry of tested beams

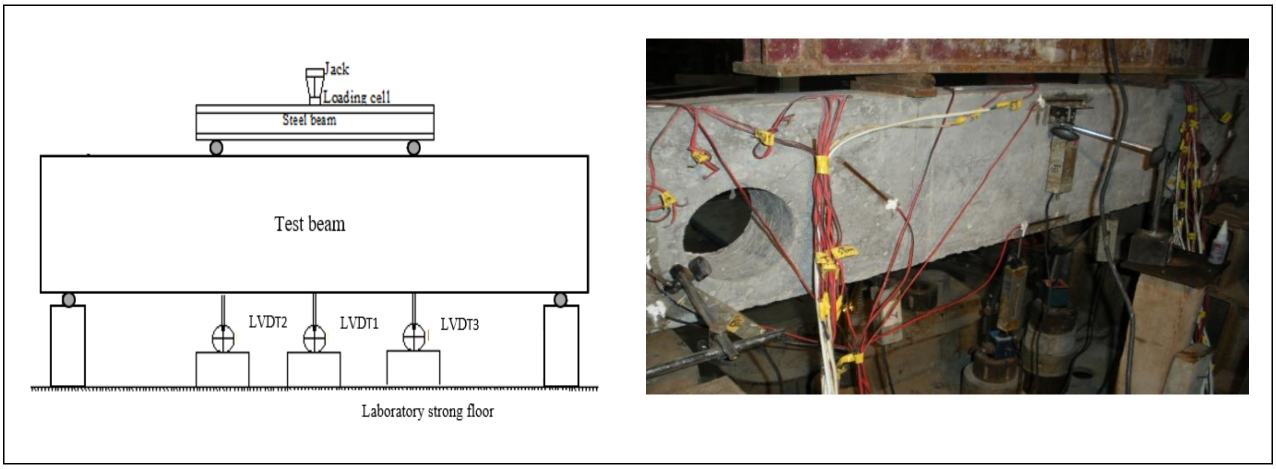

Figure 3: Test setup

Table 1: Details of tested beams

No	specimen	$\frac{a_v}{d}$	Bott. steel	Top steel	Stirrup	Opening size (mm)	Opening location
1	B1	2.0	2 ϕ 12	2 ϕ 10	ϕ8@150	-	-
2	B2	2.0	2 ϕ 12	2 ϕ 10	ϕ 8@150	0.4d	200
3	B3	2.0	2 ϕ 12	2 ϕ 10	ϕ 8@150	0.4d	300
4	B4	2.5	2 ϕ 12	2 ϕ 10	ϕ 8@150	0.4d	300

4 Results and discussion

Table 2 gives a summary of the failure modes and load carrying capacity of the tested beams. The comprehensive discussions and observation of the beam during the tests were presented in the following sections.

4.1 Failure criteria and cracking behaviors

All beams were failed in shear failure mode as designed. The first shear cracks in beam labeled B1 appeared in the region of the support at load about 24 kN, and the first diagonal crack appeared with increasing the load. Furthermore, other flexural and shear cracks were formed at the shear span and the constant moment region. By load increasing, the cracks at flexure zone grew in size and number, but the cracks in shear region still not active. Finally, the beam was failed by shear at load approximately 163 kN. Figures. 3 illustrate the failure mode of the tested beams. First shear and flexural cracks of beam B2 occurred at load of 22 kN and 55 kN,

respectively. By the loading increase, diagonal cracks at the shear span was appeared at load of 90 kN, the cracks widened, and several minor cracks appeared further with load progressing. The beam failed mainly by diagonal shear cracking at load about 140 kN.
Failure load and cracks distribution in beam B3 same as that in Beam B2, but the failure load in this beam is little lower, this due to that the opening is located at the shear bath in beam B3. Failure load of this beam is approximately 133 kN.

In beam B4, at load of 18.5 kN, the first shear crack appeared followed by flexural crack at load of 52 kN in the beam face near the mid-span. With the load increasing, a diagonal crack passing through the opening center was formed at 81 kN. Two other cracks in the beam`s chords near the opening were formed. Finally, the beam failed in the bottom chords of the opening due to this cracking at a load of approximately 123.4 kN. Compared to the equivalent beam B3, the capacity dropped by 11% in this beam.

The load was periodically paused during the test and a magnified glass was used as visual inspection to observe cracks and the load corresponding to each crack was determined. The failure modes for specimens were observed. A special microscope with 0.02-mm accuracy was used to measure the crack width. The recorded cracking width of beam B1 was approximately 0.18 mm at 50 kN. With increasing load, the crack width was approximately 0.63 mm and 1.98 mm at 120 kN and failure load, respectively.

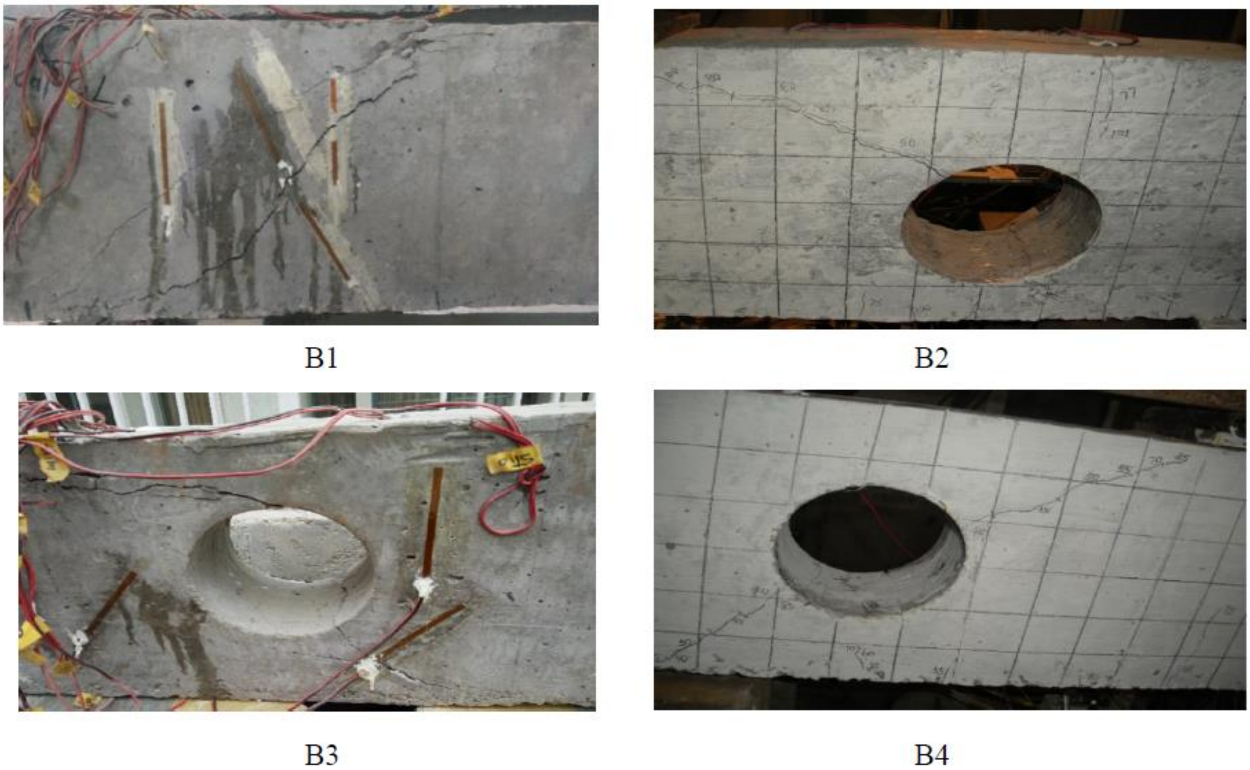

Figure 3: Failure mode of tested beams

Table 2: Maximum shear crack width (mm) at 50 kN, 80 kN, 120 kN, and at ultimate load

Beam	At 50 kN	At 80 kN	At 120 kN	At ultimate
B1	0.18	0.27	0.69	1.38
B2	1.15	3.43	4.15	5.05
B3	1.50	3.86	5.34	6.65
B4	1.93	4.02	5.68	7.11

Table 2 showed the crack width of tested beams. The crack patterns of the beams B2-B4 showed similar crack patterns; but the maximum recorded crack width for beam B1was lower, this revealed that the presence of the openings have an effect on the crack width of RC beams. As shown from the table, shear span also affected the load and crack width.

Based on the experimental test, the results showed clear indicator that the deflection, failure load, and mode of failure were influenced by the beam opening and effective shear span-to-depth ratios ($\frac{a_v}{d}$).

To investigate the deflections and stiffness of the reinforced concrete beams, the load deflection curves were studied. Three LVDTs which located in the bottom face of the beam, were used to measure the displacement as illustrated in Figure 2.

5 Finite Element (FE) using ANSYS [13]

In the FE analysis, the beams which tested experimentally were simulated for verification study. As shown in Table 3, there was good relationship between the FE and experimental load-deflection curves. This confirmed the validity of the settled FE models and reliability of the FE analysis. The attained ultimate loads, failure mode and deflection of tested beams compared with those from FE were illustrated in Table 3.

5.1 Model Construction

The most essential part of the model construction is the selection of the proper elements, followed by defining the material properties, real constant, and creating and meshing the model. A reinforced concrete beam includes different elements type with selected element type can be summarized. 3D reinforced concrete solid (SOLID 65) was used to model the concrete. The solid is capable of cracking in tension and crushing in compression. LINK8 is a spar (or truss) element which may be used in a variety of engineering applications. This element can be used to model trusses, sagging cables, links, springs, etc. SHELL41 is suitable for analyzing thin to moderately-thick shell structures. The element is defined by four nodes with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. SOLID45 is used for the 3-D modeling of solid structures. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions.

Modeling of structural reinforcement concrete elements using FE (ANSYS) prove the ability of modelling and analyzing the reinforced concrete elements in all circumstances including strengthening cases. Since the above verification levels' results had shown a good agreement between FE modelling procedures using ANSYS and the results from published papers. Therefore, the parametric study gets corroboration and consolidation.

5.2 Crack patterns and compressive stresses

Figures 4 and 5 showed sample of the crack patterns predicted numerically using FE analysis for opening diameters of 0.4d and 0.5d, respectively. The failure mode and crack pattern for the finite element support the experimental results. This confirmed that the beams failed mainly in shear. The principal compressive stresses obtained by the FE analysis showed that there was a good matching between the observed and predicted crack patterns. This confirmed the capability of the FE models to predict the crack pattern at the onset of failure. The location of the principal compressive stresses were consistent with the crack pattern. The compressive stresses were a maximum at the opening regions. The concrete failure initiated at the openings regions due to stress concentration.

Table 3: Summary of experimental and ANSYS finite element results with failure mode

Beam	*Cracking load (kN)*		$\frac{Exp.}{FE}$	*Failure load (kN)*		$\frac{Exp.}{FE}$	*Max. Deflection (mm)*		*Failure mode*
	Exp.	FE		Exp.	FE		Exp.	FE	
B1	22	24	0.91	169	198.3	0.85	4.99	5.417	Shear
B2	20	22	0.90	142.2	175	0.81	4.82	5.38	Shear
B3	19	21	0.91	127.3	145	0.88	3.87	4.41	Shear
B4	18.5	20	0.93	89.3	106	0.85	2.89	3.15	Shear & flexure

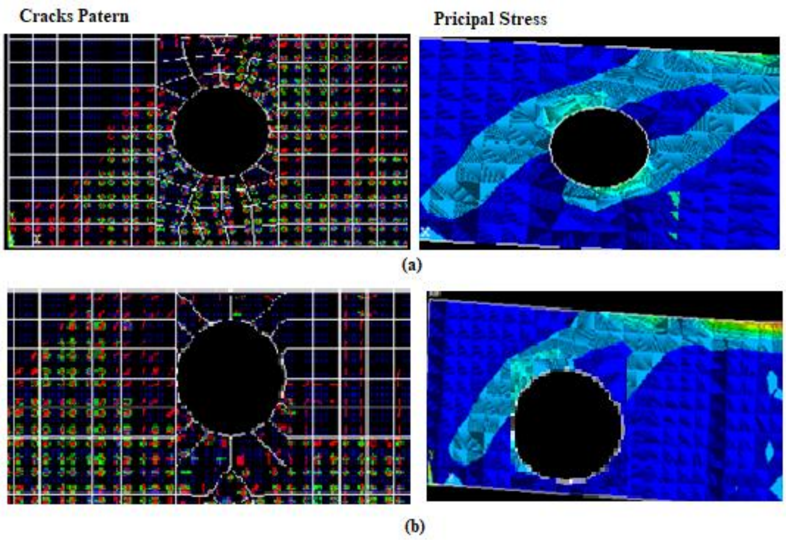

Figure 4: Sample of cracks pattern and principal compressive stresses at failure load for a_v/d = 2.0 and opening size of (a) 200 mm (b) 300 mm.

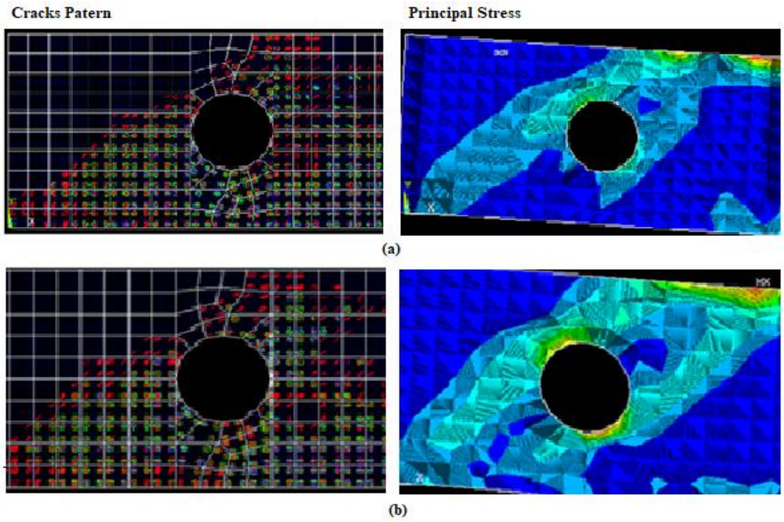

Figure 5: Sample of cracks pattern and principal compressive stresses at failure load for a_v/d = 2.5 and opening size of (a) 200 mm (b) 300 mm.

6 Conclusion

In this paper four reinforced concrete (RC) beams were experimentally tested and 3D nonlinear FE models were developed, to simulate the response of RC beams with openings, and the following conclusions are achieved.
1- As presented from experimental test and confirmed by findings from FE, the results showed that deflection, failure load, and mode of failure were significantly influenced by the effective shear span to depth ratios (a_v/d) and the openings size and location.
2- The crack patterns observed experimentally were in good agreement with those predicted by the FE models with error band not more than 15%.
3- The established FE models which verified in this paper could be used as alternatives to experimental work which costly and consume the time. And it could be used as a numerical platform for prediction of shear strength of RC beams without openings reinforcement.

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