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Investigation of the Oppening Effects on the Behavior of Concrete Beams Without Additional Reinforcement in Opening Region Using Fem Method

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Abstract: In this study a three-dimensional nonlinear finite element method using ANSYS 10.0, a finite element analysis software, has been employed to simulate the simply supported concrete beams consisting of circular openings with varying diameters. The effects of circular opening size on the behavior of such beams were investigated in this research. Two cases were carried out for verification study. Subsequently, numerous models of simply supported reinforced concrete rectangular section beams with circular and square opening were loaded monotonically with two incremental concentrated loads. The beams were simulated to obtain the load-deflection behavior and compared with the solid concrete beam. All beams had an identical cross section of 100 mm × 250 mm and 2000 mm in length with the circular opening in seven diameters: 150 mm, 130 mm, 120 mm, 110 mm, 100 mm, 80 mm and 60 mm and an equivalent square opening with 133 mm in width. The results obtained from this study showed that the performance of the beams with circular openings with diameter less than 0.48D (D is depth of the beam web) has no effect on the ultimate load capacity of the RC rectangular section beams. On the other hand, introducing the circular opening with diameter more than 0.48D reduces the ultimate load capacity of the RC rectangular section beams at least 26%.

Key words: web openings, concrete beams, finite element, modeling, ultimate load

INTRODUCTION

Web openings in the beams occur quite often in practice to provide convenient passage of environmental services. As a result, story heights in buildings can be reduced and slight reduction in concrete beams weight would improve the demand on the supporting frame both under gravity loading and seismic excitation which resulting in major cost savings. These openings may be of different shapes and sizes, and are generally located close to the supports where shear is predominant. In fact, openings should be positioned on the concrete beams to provide chords with sufficient concrete area to develop the ultimate compression block in flexure and adequate depth to provide effective shear reinforcement. Although numerous shapes are possible, circular and rectangular openings are the most common ones.

According to Somes and Corley (1974), a circular opening may be considered as large when its diameter exceeds 0.25 times the depth of the web because introduction of such openings reduces the strength of the beam. The test data reported by Somes and Corley (1974) indicated that when a small opening is introduced in the web of a beam, unreinforced in shear, the mode of failure remains essentially the same as that of a solid beam. However, based on Mansur's (1998) findings, as the opening represents a source of weakness, 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.

Hanson (1969) tested a series of longitudinally reinforced T-beams representing a typical joist floor with square and circular openings in the web and found that an opening located adjacent to the centre stub (support) produced no reduction in strength. Salam (1977) conducted an investigation on perforated beams of rectangular cross section tested under two symmetrical point loads. Moreover, Mansur *et al* (1991) an experimental carried out an investigation on eight reinforced concrete continuous beams, each containing a large transverse opening. Their study showed that an increase in the depth of opening from 140 mm to 220 mm led to a reduction in collapse load from 240 KN to 180 KN.

Mansur (1998) discussed about the effects of introducing a transverse opening on the behavior and strength of reinforced concrete beams under predominant shear. When no additional reinforcement is provided in the

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members above and below the opening (chord members), tests conducted by Siao and Yap (1990) have shown that the beams fail prematurely by sudden formation of a diagonal crack in the compression chord. Abdallaa *et al*. (2003) used bre reinforced polymer (FRP) sheets to strengthen the opening region in an experimental program. Thompson and Pessiki (2006) conducted an experimental study to investigate the precast, prestressed inverted-tee girders with large web openings. Moreover, Hasnat *et al* (1993) tested 17 axially prestressed concrete beams without stirrups containing a transverse circular opening. In their research, beams which had two different opening diameters were subjected to various combinations of torsion and bending.

Many experimental and analytical researches have been carried out on precast and prestressed beams, T-beams, deep beams and rectangular concrete beams with web openings. The researches have provided several practical results. At the present time, many methods for analyzing reinforced concrete members are available. One of the most powerful methods is the finite element technique which spares much time and efforts. Even though many experimental studies have been reported, no research study has been done on RC rectangular beams with circular opening by simulation. In order to verify the finite element model, a solid reinforced concrete beam model without opening and with un-strengthened rectangular openings was provided in Abdalla *et al*'s study (2003).

2. Problem Statement:

A large number of studies have been performed regarding the effects of opening on the T-beams, precast beams and deep beams, but very limited data have been reported on rectangular beams with web opening. Because of the limited depth of the rectangular RC beams, introducing the opening in these beams is very significant. In the case that openings are more than half of the depth of the beam web, their effects on the behavior of the beam become more considerable. Due to unexpected alterations in the sectional configuration, opening corners are subject to high stress concentration that may lead to cracking which is unacceptable from aesthetic and durability viewpoints. The reduced stiffness of the beam may also give rise to excessive deflection under service load and result in a considerable redistribution of internal forces and moments in a continuous beam (Mansur, 2006). The proper provisions of the web openings may be critical on the strength and serviceability of the floor beams and reduce the torsion, bending, and shear capacities of the members. Unless special reinforcement is provided, the strength and serviceability of such a beam may be seriously affected. However, reinforcement of these openings is usually expensive.

3. Objectives and Scope of Study:

The purpose of this study is to investigate the effect of sizing the circular unreinforced opening on the behavior of concrete beams without strengthening of the opening by additional reinforcement. This research study focuses on two different cases:

- The effect of different diameters of circular opening on the behavior of concrete beams.
- Comparison between circular opening (d=150 mm) and equivalent square opening in the area (h=133 mm).

The scope of this research is to simulate simply supported reinforced concrete rectangular beams with circular and square openings loaded monotonically with two incremental concentrated loads via ANSYS 10.0 software package to obtain the load-deflection and compare with the solid concrete beams. All beams have an identical cross section of 100 mm × 250 mm and 2000 mm in length with the circular opening in seven diameters: 150 mm, 130 mm, 120 mm, 110 mm, 100 mm, 80 mm and 60 mm and a square opening with height and depth of 133 mm.

3. Models Specifications:

3.1 Material Properties:

3.1.1 Concrete:

Concrete is a quasi-brittle material and has different behaviors in compression and tension. According to Abdallaa *et al*. (2003), the axial compression strength of concrete for the RC solid beam without opening and RC beam with opening are 49 MPa and 52 MPa respectively. The tensile strength of concrete is typically 8%-15% of the compressive strength (Shah, *et al*, 1995) and Poisson's ratio (v) for concrete was assumed to be 0.2 (Bangash, 1989).

SOLID65, an eight-node solid element, was employed to model the concrete. The solid element has eight nodes with three degrees of freedom at each node. Moreover, SOLID45, an eight-node solid element, was used for the 3-D modeling of the steel plates at the supports and under applied loads in the beam models. The element is defined with eight nodes having three degrees of freedom at each node. LINK8, a three-dimensional spar element with plasticity, was also employed to model the internal reinforcement in the beams. Two nodes are required for this element. In fact, the 3-D spar element is a uniaxial tension-compression element with three degrees of freedom at each node. The element is also capable of plastic deformation.

3.1.2 Reinforcement and Steel Plates:

Element Solid45 utilized for modeling the steel plates was added at support locations and loading points in the finite element models to provide a more even stress distribution over the support and loading areas. An elastic modulus equal to 199,955 MPa (29,000 ksi) and Poisson's ratio of 0.3 were used for the plates (Gere and Timoshenko, 1997). The steel plates were assumed to be linear elastic materials. Therefore, Solid45 element is modeled as a linear isotropic element.

Yield strength of steel stirrups is 240 MPa and area of steel stirrups is 50.27 mm^2. Moreover, yield strength for longitudinal reinforcements is 400 MPa with 78.54 mm^2 area. Link8 element was employed to represent the steel reinforcements. The steel was assumed to be an elastic-plastic material and identical in tension and compression. Therefore, Link8 element is modeled as a bilinear isotropic element with Poisson's ratio of 0.3 (Gere and Timoshenko, 1997).

3.2 Loading and Boundary Conditions:

Boundary conditions are needed to be applied at nodes in the supports to ensure that the model acts the same way as the experimental beam. The supports were modeled in a way that the roller and hinged supports were created. The force, P, is applied on all nodes that exist at the entire centerline of the plates.

3.3 Meshing:

In this research a convergence study was carried out to determine an appropriate mesh density. Various mesh sizes were examined in ANSYS and the ultimate load was obtained for each mesh size as tabulated in Table 1. From this table, it can be observed that the obtained ultimate load for mesh size 40mm (77,925N) is nearest to the ultimate load of experimental beam (83000N). Consequently, the mesh size equal to 40 mm was chosen for this study. Figure 1 shows the load-deflection relationship for different mesh sizes.

Table 1: Different mesh sizes and corresponding ultimate loads.

Mesh size (mm)	mesh 20	mesh 40	mesh 50	mesh 70	mesh 100
Ultimate load (N)	16,971	77,925	76,574	77,175	75,150

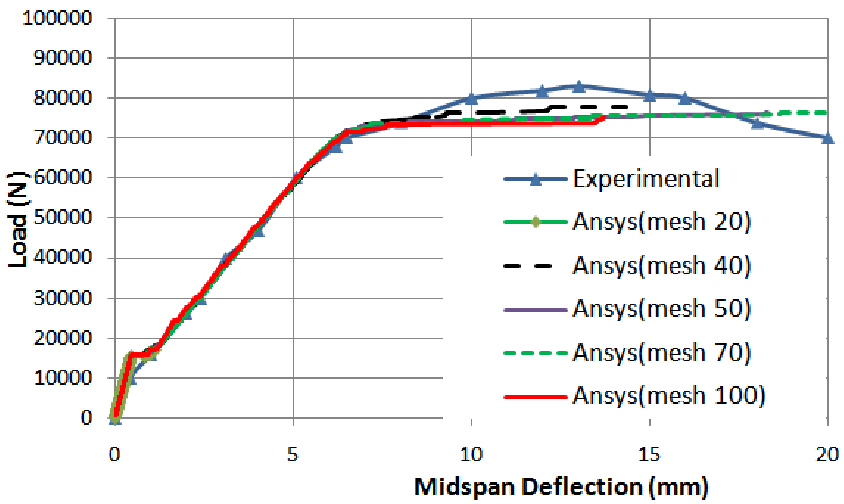

Fig. 1: Load vs. deflection curves for different mesh sizes.

4. Verification Study:

This FEA calibration study includes modeling a concrete beam with the dimensions and properties corresponding to solid beam and beam with rectangular opening of 100 mm× 300 mm tested by Abdalla *et al*. (2003). The dimensions of the full-size beams were 100 mm × 2050 mm×250 mm. The span between the two supports was 2000 mm. Longitudinal reinforcements and shear stirrups are modeled throughout the beam. The goal of the comparison of the FE model and the beam from Abdalla (2003) is to ensure that the elements, material properties and convergence criteria are adequate to model the response of the member and make sure that the simulation process is correct. Therefore, in this research two experimental beams tested by Abdalla *et al*. (2003) were simulated as verification study.

The first beam was RC solid beam without opening that the ultimate load obtained from the experimental test was 83,000N, while the ultimate load extracted from ANSYS analysis outputs is 77,925N. Therefore, the difference is about 6% and it was proven that ANSYS software is an appropriate method to predict the behavior of RC beams. Theoretical calculations of the solid beam based on the equations, can be seen in Appendix B. Figure 2 shows the load-deflection relationships between simulated beam by ANSYS and experimental beam.

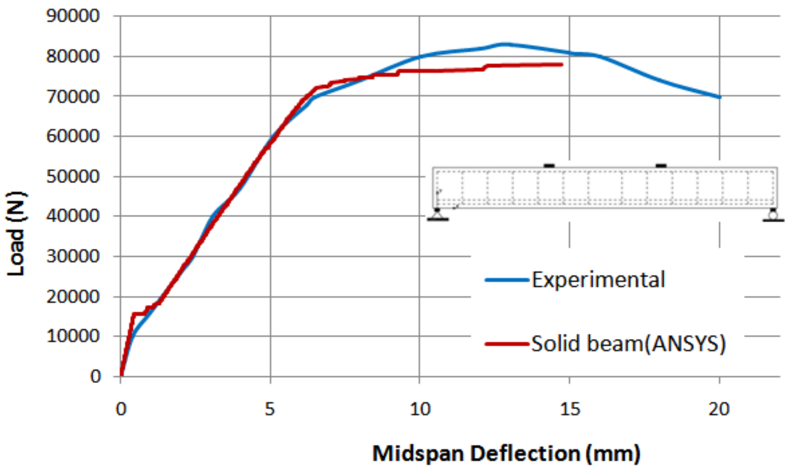

Fig 2: Load vs. deflection curve for solid beam without opening.

The second beam was RC beam with rectangular opening (height of the opening = 100 mm and width of the opening = 300mm). The ultimate load obtained from the experimental test was 41,000N, whilst the ultimate load attained from ANSYS analysis outputs is 47,582N. Therefore, the difference is about 16% and it was acceptable. Figure 3 shows the load-deflection curves for simulated beam (with rectangular openings) by ANSYS and experimental beam.

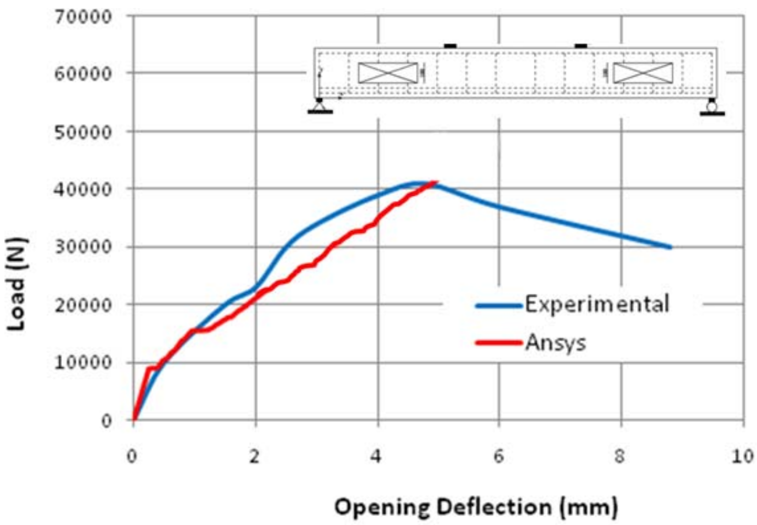

Fig. 3: Load vs. deflection curve for beam with rectangular openings (100×300 mm)

RESULTS AND DISCUSSIONS

Results and discussions can be divided into two sections. In the first section we will discuss the finite element modeling of the reinforced concrete beams with circular opening in varying diameters (150, 130, 120, 110, 100, 80, 60 mm) and in the second section a comparison will be made between circular opening (d=150 mm) and equivalent square opening in the area (h=133 mm). These beams have the same dimensions as the experimental beam tested by Abdalla *et al*. (2003). The longitudinal reinforcements and shear stirrups are included as discussed in the calibration model. The space between the end of the opening and the support is 200 mm along the X direction. The center of the circular opening is situated in 137.5 mm along the Y direction from the origin of coordinate system. Figure 4 shows the location of the circular opening inside the RC beams in this study. These simply supported beams were loaded incrementally to failure by applying two-point loads. All the necessary steps taken to create the model and the analysis used for the RC beams with circular and square openings are explained.

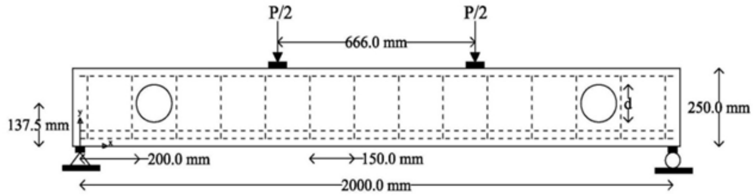

Fig. 4: Location of the circular opening inside the RC beams in the present study.

The obtained load-deflection graphs from the analysis of the beams with different circular openings were compared with RC solid beam without opening. Moreover, a comparison was done between circular and square openings with the equivalent opening areas. This investigation reveals the effects of the size of circular opening on the behavior of the RC beams.

5.1 Effects of Circular Opening Sizes with Varying Diameters:

5.1.1 Model 1:

The effect of different sizes for circular opening in the first model is illustrated by the load-deflection response and ultimate load capacity. Model 1 was analyzed and plotted in Figure 5. It was loaded symmetrically by two-point loading, where the position of the applied load was kept constant and the distance from the support to the end of the opening for both sides of the beam was taken as 200 mm (See Figure 4). The diameter of the circular opening in this beam is 60 mm. The relationship between load and deflection for model 1 is shown in Figure 5. According to this figure, there is a slight difference between solid beam (from ANSYS) and model 1. The load-deflection curve for model 1 approximately coincides to the solid beam curve. Therefore, introducing the circular opening with diameter equal to 24% of the depth of the beam has no effect on the behavior of the beam; in addition, Figure 5 demonstrates this conclusion. As a result, the ultimate strength of the beam will not be affected by the presence of this circular opening because the circular opening with 60 mm in diameter does not reduce the concrete area necessary for the development of the compressive stress block at ultimate.

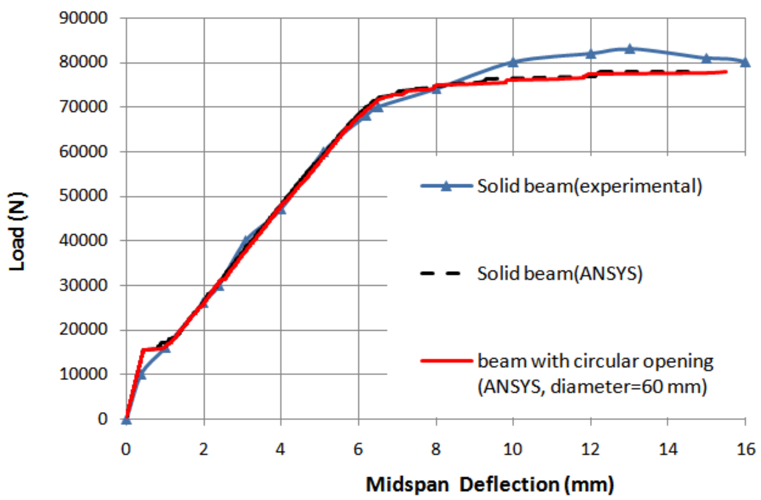

Fig. 5: Load-deflection curves for model 1 and solid beam.

Figure 5 shows crack pattern at the collapse load for model 1. Moreover, the main cracks in this beam appear at the midspan and the failure caused by flexural cracks is quite similar to the solid beam without opening. From the crack propagation shown in Figure 6, it can also be derived that the behavior of the beams with circular opening with diameter less than 24% of the depth of the beam is the same as the solid beams without opening.

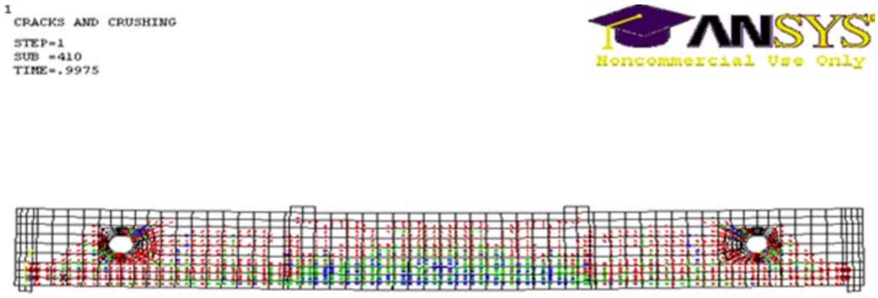

Fig. 6: Crack pattern at the collapse load for model 1.

5.1.2 Models 2, 3, 4 and 5:

All conditions and the situations of the openings are the same as model 1 except the diameter of circular opening. The diameters for circular openings in models 2, 3, 4 and 5 are 80, 100, 110 and 120 mm, respectively. Figure 7 illustrates the load-deflection relationships for the solid beam and the models 2, 3, 4, and 5, simultaneously. The predicted values of ultimate load capacity for models 2, 3, 4 and 5 from ANSYS analysis were 77727, 77142, 76992 and 76713 N, respectively. The corresponding value for the solid beam (without opening) obtained from ANSYS was 77925 N and from experimental test was 83000N; therefore, the difference between the largest opening with 120 mm in diameter and solid beam is around 2% reduction in the ultimate load capacity. This value is negligible. Hence, introducing the circular opening with diameter less than 48% of the depth of the beam has small effect on the behavior of the beam because the depth of the compression chord is greater than the depth of compressive stress block.

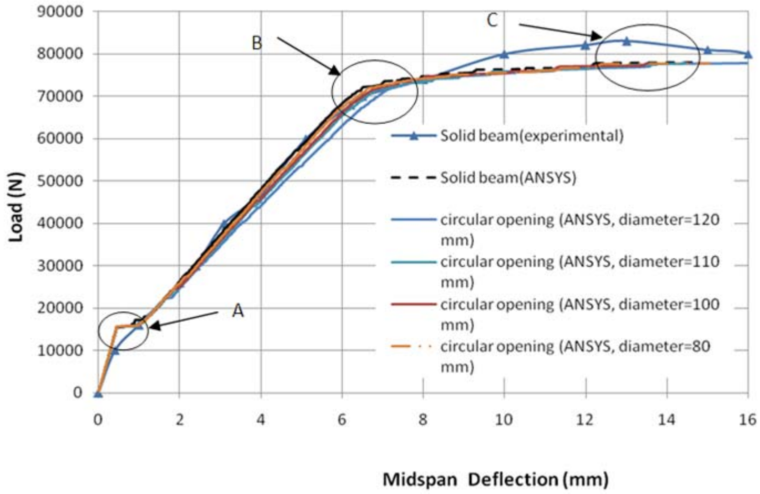

Fig. 7: Load-deflection curves for the solid beam and the models 2, 3, 4, and 5.

As shown in Figure 7, fist cracking occurs in point A; point B indicates the steel yielding and point C is failure point. The vertical displacement for model 5 in point B is about 7.1 mm while for the solid beam is 6.3 mm (from ANSYS output). It is observed that by increasing the diameter of circular opening, the rigidity of the beam decreases.

5.1.3 Model 6:

The effect of diameter size is further increased up to 130 mm diameter and known as model 6. All conditions were kept constant as the same as the models 1 to 5. The load-deflection relationship for the solid beam and the model 6 is shown in Figure 8. The obtained value of the ultimate load capacity from the

ANSYS output for model 6 was 57,915 N, while the corresponding value for solid beam is 77,925 N. Therefore, by introducing the circular opening with 130 mm in diameter in the solid beam reduces 26% capacity of the ultimate load. In other words, by creating the circular opening with diameter equal to 52% of the depth of the beam, capacity of the ultimate load reduces 26%. The main reason of the reduction in ultimate load capacity of this beam is that this opening is placed in such a way that it cuts material from the compression zone and thereby reduces the concrete area required for the development of the full compressive stress block at ultimate.

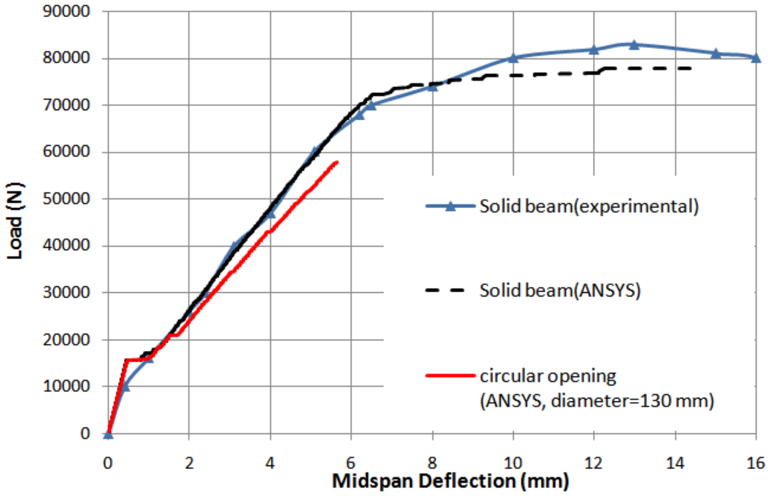

Fig. 8: Load-deflection curves for the solid beam and model 6.

Figure 9 shows the crack pattern at the collapse load for model 6. The main cracks in this beam occur at the bottom and top chord with the angle 45 degrees from loading points to supports as described by Yoo *et al*. From the crack propagation shown in Figure 9, it can be derived that the failure mode is shear at the opening region.

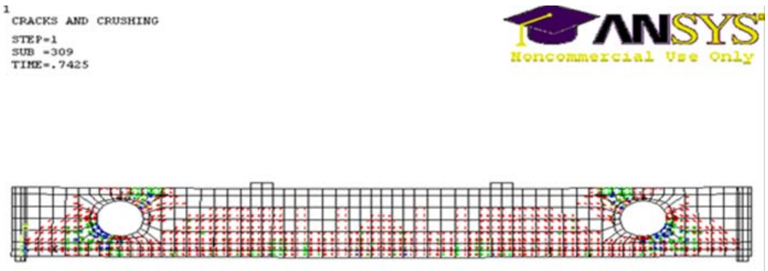

Fig. 9: Crack pattern at the collapse load for model 6.

5.1.4 Model 7:

All conditions and the situations of the openings are the same as all previous models except the diameter of circular opening where the diameter for circular opening in model 7 is 150 mm. The test results of this beam in the form of load-deflection response were compared with the results of the control beam. The load-deflection relationships for the solid beam and model 7 are shown in Figure 10. The obtained value of the ultimate load capacity for model 7 from ANSYS analysis was 55,458N, whereas the corresponding value for the solid beam (without opening) obtained from ANSYS was 77,925 N. Therefore, the reduction about 29% occurs in ultimate load capacity of the solid beam by creating the circular opening with 150 mm diameter. This reduction in the ultimate load capacity of the beam is considerable. In other words, by creating the circular opening with diameter equal to 60% of the depth of the beam, the capacity of the ultimate load reduces 29%.

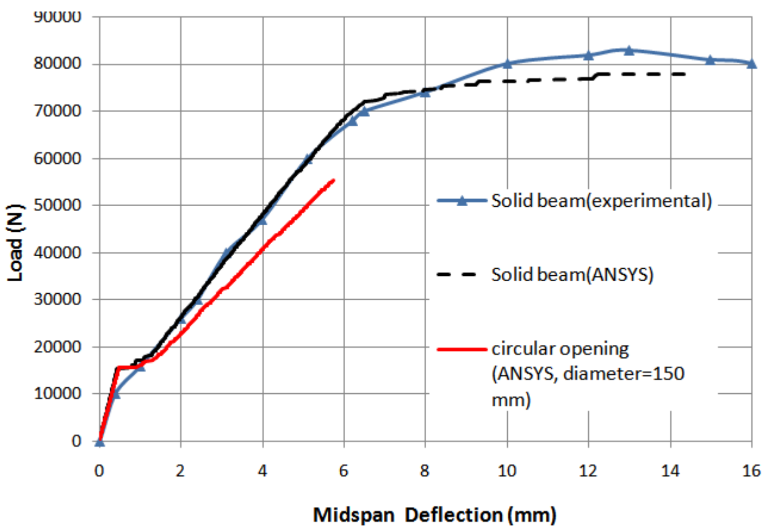

Fig. 10: Load-deflection curves for the solid beam and model 7.

Figure 11 shows the crack pattern through the beam and around the opening for model 7 at the collapse load. As seen in this figure, the main cracks occur at the bottom and top chord; in addition, the crack path led to the failure in the openings extends with 45 degrees from loading points toward supports. From the crack propagation shown in Figure 11, it can be observed that the failure mode is shear at the opening region.

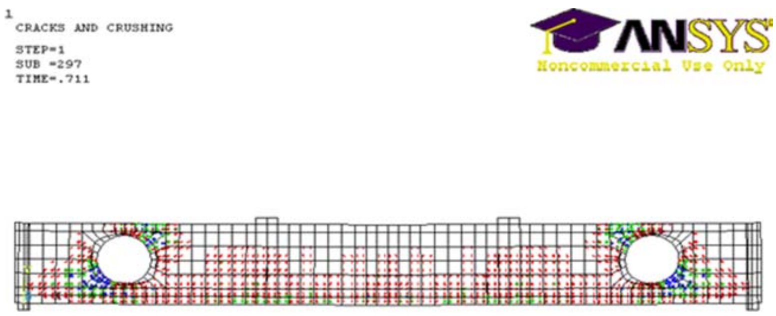

Fig. 11: Crack pattern at the collapse load for model 7.

Table 2 shows the characteristics of the analyzed beams and summary of the results in this study.

Table 2: Characteristics of the analyzed beams and summary of the results

	Type of Opening	Dimension of Opening W(mm)	H(mm)	Concrete Strength (Mpa)	Ultimate load P_u(N)	Percentage different
1	Solid beam(without opening)			49	77,925	--
2	Rectangular	300	100	52	47,582	39
3	Circular	60		49	77,805	0.2
4	Circular	80		49	77,727	0.25
5	Circular	100		49	77,142	1
6	Circular	110		49	76,992	1.2
7	Circular	120		49	76,713	1.6
8	Circular	130		49	57,915	26
9	Circular	150		49	55,458	29

5.2 Effect of Circular Opening Compared to the Equivalent Square Opening:

In this section the RC beam with square opening (width = 133 mm) has been used and the results compared to its equivalent circular opening (diameter = 150 mm). All conditions and the situations of the openings are the same as all previous models. As illustrated in Figure 12, the test results of this beam in the form of load-deflection response were compared with the results of the control beam and equivalent circular opening. The obtained value of the ultimate load capacity for square opening from ANSYS analysis was

50,505N, while the corresponding value for the solid beam (without opening) and equivalent circular opening obtained from ANSYS were 77,925 N and 55,458N, respectively. Therefore, the reduction about 35% occurs in ultimate load capacity of the solid beam by creating the square opening with 133 mm width. On the other hand, the difference in the ultimate load capacity between circular opening (d = 150 mm) and equivalent square opening (w = 133 mm) is about 9%. It shows that circular opening reduces the ultimate load less than the equivalent square opening and the circular opening has more strength than square opening. The main reason for more reduction of the ultimate load capacity in square opening is that the existing orthogonal corners cause to produce the stress concentration at these corners.

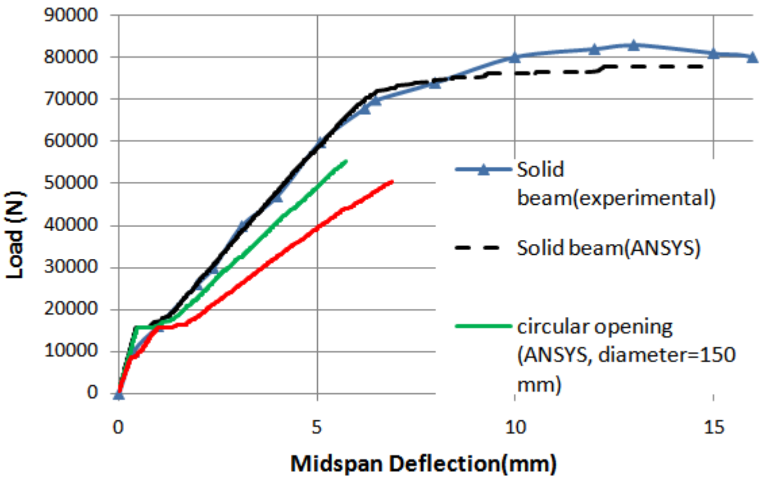

Fig. 12: Load-deflection curves for the solid beam, circular opening and equivalent square opening.

Figure 13 shows the crack pattern along the beam and around the square opening at the collapse load. As seen in this figure, the main cracks occur at the two corners in the bottom chord. From the crack propagation shown in Figure 13, it can be observed that the failure mode is shear at the opening region. This phenomenon occurs due to the reduction of the rigidity and the ultimate moment capacity of the beam. Accordingly, moment of inertia at section of the beam through the opening will be reduced and cracks will be produced in opening and the beam will collapse in the opening region.

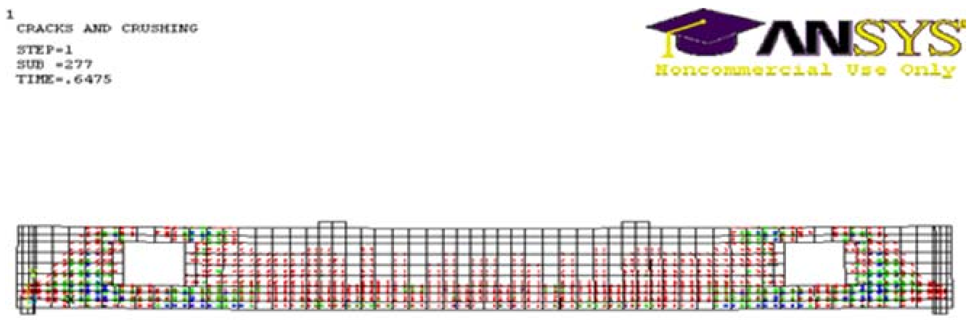

Fig. 13: Crack pattern at the collapse load for square opening.

Figure 14 presents load-deflection curves for the solid beam and all circular openings which were tested simultaneously in this study.

In this study the simulation results of models 1 to 7 were presented and discussed. Each model has been compared with the solid beam and the reduction ratio of the ultimate load capacity of models with respect to the solid beam has been obtained.

6. Conclusions:

Following conclusions can be drawn with respect to the results obtained from the analysis of the solid beam without opening, beams with circular opening with 150 mm, 130 mm, 120 mm, 110 mm, 100 mm, 80

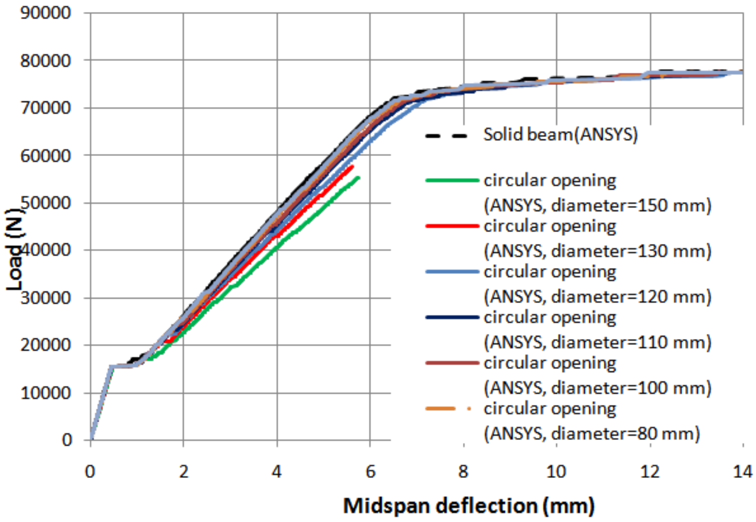

Fig. 14: Load-deflection curves for the solid beam and all circular openings tested in this study.

mm and 60 mm in diameter and beam with equivalent square opening with 133 mm in width. The suggested recommendations for the future works are also presented. This research mainly comprises the load-deflection curves behavior for solid beam and the effect of beams with circular opening and square opening on the ultimate load capacity of the beams. Furthermore, the effect of circular opening compared to the equivalent square opening has been discussed. The following conclusions can be stated based on the evaluation of the analyses of the calibration model and the RC beams with circular and square openings:

1. The ultimate load obtained by ANSYS for the RC beam without opening is very close to the ultimate load measured during experimental testing.
2. Introducing the circular opening with diameter less than 48% of the depth of the beam (without special reinforcement in opening zone) has no effect on the ultimate load capacity of the RC rectangular beams, meaning that these beams behave similar to the beams without opening. This result is clearly observed and shown in Figure 14. Moreover, according to the crack pattern, mode of failure is flexure at midspan in these beams.
3. Introducing the circular opening with diameter more than 48% of the depth of the beam (without special reinforcement in opening zone) reduces the ultimate load capacity of the RC rectangular beams at least 26%. Mode of the failure is shear at the opening at a low load level.
4. The circular opening has more strength than equivalent square opening with difference of 9% in ultimate load capacity.

The following recommendations are suggested for future researches which are not covered in the present study:

Based on the finite element method, future studies can include different types of loading to further test the design method. This comprises studies with continuous beams, multiple load points, and different opening shapes and also includes examining the vertical location of the transverse openings in the RC beams. Moreover, strengthening of the opening in the RC beams with composite sheets and additional steel reinforcement around the opening can be investigated and simulated by finite element computer software.

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