Diyala Journal of Engineering Sciences Vol (17) No 1, 2024: 63-74

Diyala Journal of Engineering Sciences

Journal homepage: https://djes.info/index.php/djes

ISSN: 1999-8716 (Print); 2616-6909 (Online)

Numerical Investigation of Reinforced Concrete Beams with Single and Multi-Longitudinal Hollow Openings

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ARTICLE INFO

Article history:
Received November 11, 2023
Revised February 10, 2024
Accepted February 19, 2024
Available online March 6, 2024

Keywords:
Reinforced concrete beam
Single/multi-longitudinal hollow opening
Circular/rectangular/square opening shape
Deflection
Cracking behavior

ABSTRACT

This numerical study was conducted to evaluate the effect of longitudinal hollow openings in reinforced concrete beams. The study was divided into three groups: The first group: was circular holes of different sizes. The second group: different shaped openings (circular, square, rectangular). The third group: the number of openings (one, two, three). Abaqus software was used to analyze the behavior of reinforced concrete beams with hollow openings. The following effects of hollow openings were studied (effect on bending resistance, effect on beam deformations). The results also showed that the presence of hollow openings leads to increased threshold deformations. The results also show that the aperture size has a significant effect on the threshold deformations. Sills with large openings have a greater negative impact on sill deformations compared to sills with small openings. Concrete beams' longitudinal circular hole provides greater load-bearing than rectangular or square slots. Increasing the number of longitudinal holes provides greater load-bearing, but increasing the number reduces the load-bearing. Concrete with longitudinal slots is cheaper and lighter than hollow concrete openings and is used in buildings on a limited budget. Circular slots (10.46% difference) are better than rectangular (18.60% difference) and square (19.76% difference). One hole (10.46% difference) is better than two holes (18.60% difference) and three holes (19.76% difference).

1. Introduction

In general, the self-weight of the structures represents a very large portion of the existing design weight, thus, implementing a practical technique to reduce such type of weight is required more and more since it is resulting in reducing the accumulated design loads and the size of foundations [1-5]. Using lightweight concrete is considered a general method that can be applied to all types of structural members [6-9]. In addition, many approaches deal with reducing floor self - weight such as bubbled slabs, precast beam and block slabs, hollow core slabs, and waffle slabs [10-14]. Innovation of any technique that can reduce the concrete volume within any structural member other than slabs represents a good step to increase the overall reduction in concrete amount, in this context, the subtraction of concrete within the reinforced concrete beam section can play a considerable role within this area since beams are considered as vital structural members. This role can be attained by using a practical subtraction technique such as installing suitable tubes or pipes along its entire span where the flexural stresses are minimum or in the tension zone to create what is known as a hollow-core concrete beam (HRCB). The hollow-core concrete beam has many advantages over the

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DOI: 10.24237/djes.2024.17106

conventional beam [15,16] which can be summarized as follows:

Reduced quantities of concrete and associated costs. Using pipes or tubes in concrete beams can reduce the quantities of concrete needed by up to 50%. This results in a significant reduction in costs, as concrete is one of the most expensive structural materials. Longitudinal cavities in hollow concrete beams can be used to operate mechanical and electrical equipment. This can result in space savings and improved efficiency. Hollow concrete beams can be cast faster than conventional beams, as dense reinforcement is not required. This can result in reduced construction time, which can save money. Reducing the amount of concrete needed reduces carbon dioxide emissions. This makes hollow concrete beams a sustainable technology. Because hollow concrete beams contain cavities, it is important to carefully monitor the quality of the concrete to ensure there are no cracks or other defects. Hollow concrete beams cannot be used when the loads are concentrated at a particular point within the span of the beam. This is because cavities can impair the beam's ability to withstand concentrated loads. In general, hollow concrete beams have many advantages over traditional beams. However, it is important to be aware of the potential drawbacks before choosing this type of beam.

Much research in the field of hollow-core beams and using lightweight material in tension zones has been presented in recent years. Alshimmeri and Al-Maliki [17] investigated the structural behavior of concrete beams with a rectangular hollow under a partially uniformly distributed load. Varghese and Joseph [18] presented an experimental and numerical study for investigating the flexural behavior of concrete hollow-core sandwich beams, in that work, the concrete in the tension zone was partially replaced by expanded polystyrene and polyurethane foam as a lightweight material. Manikandan et al. [19] studied the influence of hollow-core shapes on the flexural behavior of sandwich beams. Varghese and Joy [20] presented a study on the flexural behavior of hollow-core sandwich concrete beams with different core depths. Parthiban and Neelamegam [21] have studied the effect of the presence of different pipe numbers in the shear section on the flexural behavior of reinforced concrete beams. Dhinesh and Satheesh [22] studied the effect of different hollow-core depths on the flexural behavior of reinforced concrete beams. Satheesh and Nyodu [23]. There are several reasons why openings are necessary for RC packages: Basic amenities: Basic amenities, such as water and sanitation, provide basic daily living for residents. In some cases, these facilities may be necessary for the operation of the structure itself, such as vents in bridges. Additional amenities: Additional facilities, such as electricity, telephone, and air conditioning, provide comfort and convenience. In many cases, these facilities have become essential in modern life [24]. An experimental study was conducted on prestressed convex concrete beams supported by several holes of different shapes under constant monotonic loads. The results show that insertion holes in such a beam lead to a concentration of stresses at the corners of these holes. As a result, an extensive cracking appears. The results of the experimental study were compared with the results of numerical models. These results showed that the numerical models can actively simulate the behavior of prestressed convex concrete beams reinforced with multiple openings [25]. The importance of the study section is to clarify what is new that this study offers compared to previous studies on reinforced concrete beams with longitudinal openings. The following are the highlights of this study: Conducting a comprehensive experimental and analytical study of reinforced concrete beams with longitudinal openings, using a variety of modern methods and techniques. Studying the effect of a group of factors on the behavior of these beams, including the type of concrete used, the resistance of the concrete, dimensions of openings, method of reinforcement, and method of construction. Most previous studies were analytical only, and no practical experiments were conducted on sills. Some previous studies were limited to study the effect of only some factors on the behavior of sills, such as concrete resistance or dimensions of openings. Previous studies have practical recommendations for effectively designing and implementing reinforced concrete sills with longitudinal openings. Therefore, this study provides a new and interesting contribution to the field of design and implementation of reinforced concrete lintels with longitudinal openings. Providing practical recommendations for the effective design and implementation of sills, as recommendations have been made about the type of concrete used Concrete resistance, opening dimensions, reinforcement method, and construction method. The objective of this research is to present a numerical investigation of the flexural behavior of hollow RC beams using the Abaqus program. The investigation includes three variables that are: the diameter of the hollows, the shape of the hollows, and the number of holes.

2. Software Program used in the study

The software program of this study contains two stages: the first stage involves a validation study to check the validity and accuracy of the finite element models with a previous study, while in the second the most important variables are studied represented by the diameter of hollows, the shape of the hollows and several hollowes.

To check the validity and accuracy of the finite element models of reinforced concrete hollow beams, a verification study is done. Nonlinear finite element analysis on three of the available experimental HCRCBs in the previous study is performed by using the ABAQUS software program and then a comparison between the numerical and experimental results is presented in this section. The experimental beam specimens have identical dimensions (1000 mm length, 150 mm height, and 100 mm width). Two of these specimens have longitudinal voids created by using recycled plastic pipes with outer diameters of 32 mm and 36 mm to eliminate the concrete with percentages of 5.4% and 6.8% respectively, from the volume of the beam, as well as a solid beam (without longitudinal voids) used as a reference. The layout, cross-sections of the beams, and side view in one of the hollow-core beams are shown in Figure 1 and Table 1.

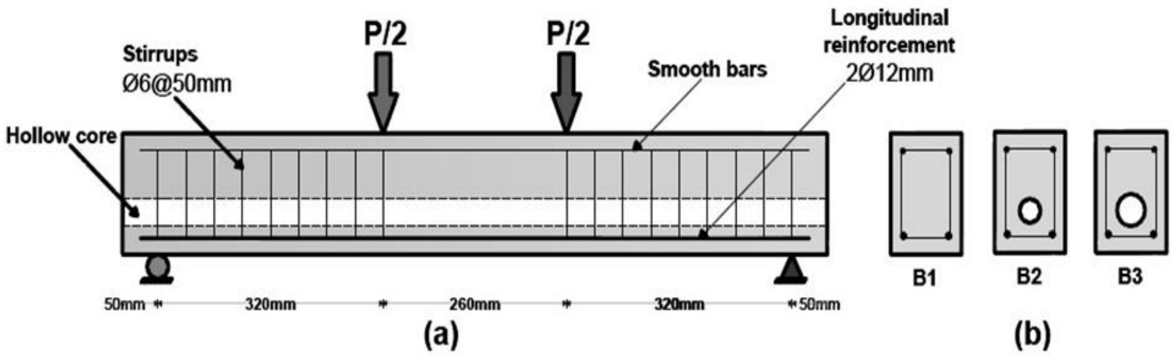


Figure 1. (a) Layout of the hollow-core concrete beams (b) Cross-sections of the solid beam (B1) and hollow-core concrete beams (B2 and B3)

Table 1: Beam details of the experimental test [24]

Beam code	Compressive strength fc' (MPa)	Beam kind	Hollow-core diameter (mm)	Concrete elimination (%)
B1	30.3	Solid	-	-
B2	30.1	Hollow-core beam	32	5.4
B3	30.9	Hollow-core beam	36	6.8

In this study, shear reinforcement (stirrups) and deformed steel bars with a diameter of 210 mm and a yield stress of 492 MPa were used to strengthen the tested beams in the tension zone. To further secure passengers, Smooth steel rods with a diameter of 2.5 mm were inserted into the compression area (Figure 1).

The SOLID element was used to represent the sill concrete, while the spar element was used to simulate all the rebar. The steel element C3D8R was used to model the concrete. Figure 2 depicts the element geometry and node locations. In this study, the spar element T3D2 was used to model the rebar.

Figure 3 shows the geometry of spar element T3D2 in Abaqus software. There were several stages in which the load was applied. A representation of the beams' finite element mesh. A tolerance of (5%) was applied to the models that were developed, and the entire Newton-Raphson method was utilized as a nonlinear solution methodology. The models were implemented utilizing the force convergence criterion. The reinforcement is assumed to be capable of transmitting axial forces only, and a perfect bond is assumed to exist between the concrete and the reinforcing bars. To provide the perfect bond, the element of the steel reinforcing bar is connected between nodes of each adjacent concrete solid element, so the two materials share the same nodes.

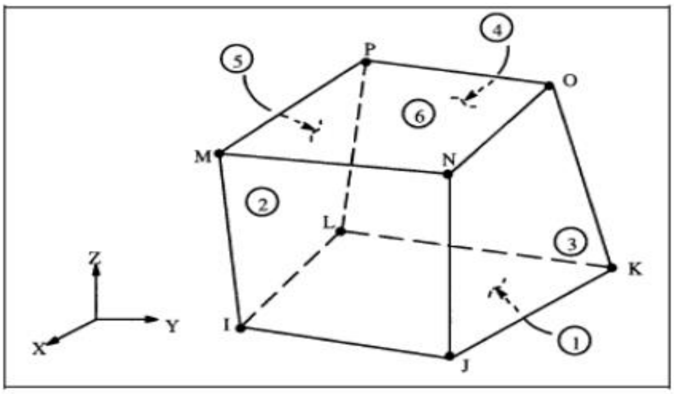


Figure 2. Solid -3D reinforced solid element C3D8R

Figure 3. Spar element T3D2

3. Results of comparison between experimental and numerical investigations

Table 2 and Figure 4. show that the computed ultimate load from the finite element analysis is slightly less than the actual experimental ultimate load of reinforced concrete solid beam B1 and hollow core beams B 2 and B 3.

It can be seen that the ratio of the numerical to experimental ranges between 89.6%-98.8%. The reasons for differences between the experimental and the numerical results belong to the approximate FEM due to many factors, which are mainly:

1. Approximation in the material modeling of concrete and steel.
2. Approximation inherent in the finite element technique.
3. Approximation in the integration function used in this numerical analysis.

4. Approximation is introduced due to the type of procedure used to solve the nonlinear system of equations.

Figure 4 shows a comparison between numerical results (Abaqus) and experimental results of maximum load under different models of beams. According to Figure 4, it was found insignificant differences between the experimental and numerical results.

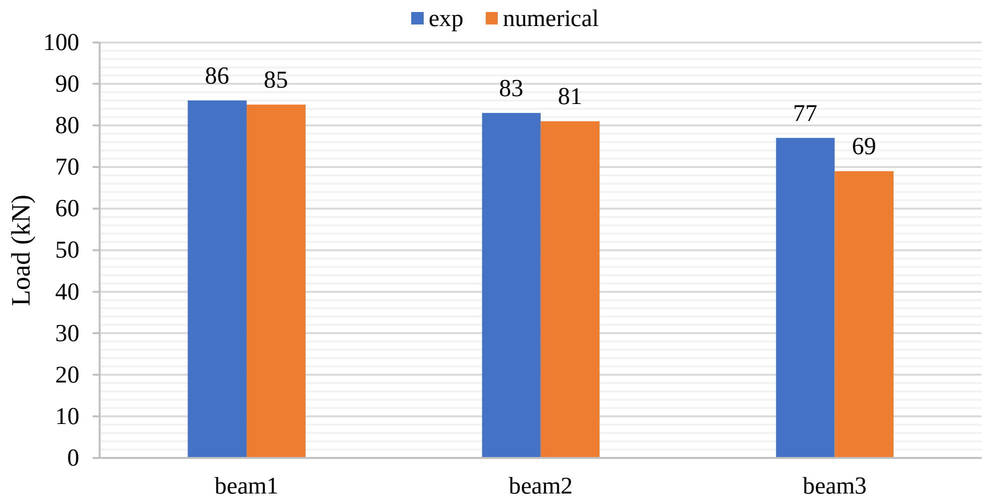


Figure 4. Comparison of the maximum load for different models according to beam (Abaqus) and beam (EXP.)

Table 2: Comparison of ultimate loads

Beam	Ultimate Loads in kN Experimental	Ultimate Loads in kN Numerical (Abaqus)	Numerical/Experimental (%)
Beam1	86	85	98.8
Beam2	83	81	97.6
Beam3	77	69	89.6

4. Parametric study

4.1 Diameter of hollows

Openings in reinforced concrete sills are an important part of their design and installation.

Openings can be necessary for the passage of pipes, cables, or other items, or they can simply be a design feature. The diameter of openings in reinforced concrete sills depends on several factors, including:

Diameter of pipes or cables to be passed through the openings: The diameter of the opening must not exceed the diameter of the pipes or cables.

- Load acting on the sill: The diameter of the opening must be sufficient to bear the load acting on the sill.
- Openings in reinforced concrete beams can be divided into two main types:
- Longitudinal hollow openings: These are openings that extend along the length of the threshold.
- Transverse hollow openings: These are openings that extend the width of the threshold.

In our research, hollow longitudinal openings were used, and they were in three groups:

4.1.1 The first group has circular diameters of different sizes

The first group consists of reinforced concrete beams with circular openings of different sizes. The hole sizes in this group range between 52 and 32 mm, as shown in Figure 5.

Different-sized circular holes can have different effects on the threshold resistance. In general, the larger the diameter of the opening, the greater the surface area of the sill that is subjected to the load. This means that a sill with a larger opening will have less resistance to deformation.

4.1.2 The second group: The shape of the openings varies (circular, square, and rectangular)

The second group consists of reinforced concrete lintels with openings of different shapes. This group includes circular, square, and rectangular openings. Moreover, the different shapes of the openings are the same size, as in Figure 6. The shape of the opening can have different effects on the threshold resistance. In general, circular openings have greater resistance to deformation than square or rectangular openings.

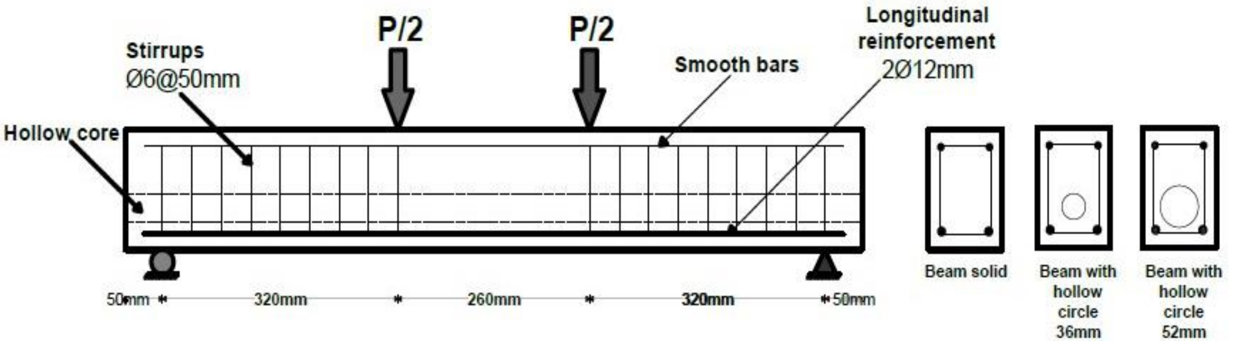


Figure 5. Group 1

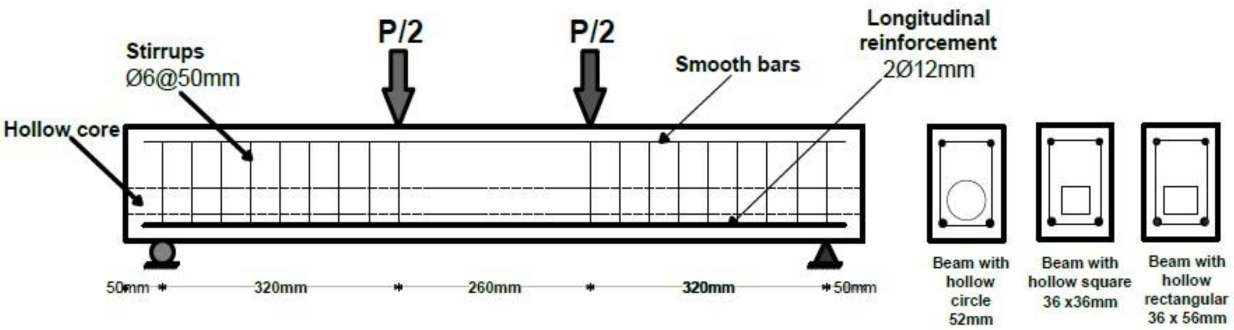


Figure 6. Group 2

4.1.3 The third group: The number of openings varies (one, two, or three)

The third group consists of reinforced concrete beams with a different number of openings. This group includes one, two, and three slots. Moreover, the different number of openings have the same size, as in Figure 7. The number of slots can have different effects on the threshold resistance. In general, the greater the number of openings, the greater the surface area of the sill that is subjected to the load. This means that a sill with multiple slots will have less resistance to deformation.

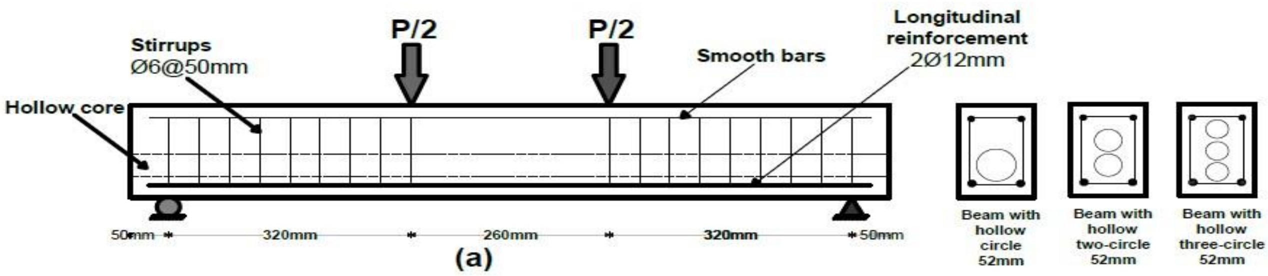


Figure 7. Group 3

5. The effect of the hole shape on the beam

The shape of the openings in reinforced concrete beams greatly affects their bearing, as the openings cause a reduction in the area of the reinforced concrete, thus reducing its ability to bear loads. In general, circular openings have less negative impact on the bearing of reinforced concrete beams than square or rectangular openings, because circular openings cause less reinforced concrete area reduction than square or rectangular openings. In an experimental study conducted on reinforced concrete beams with openings, it was found that beams with circular openings had a durability strength of 1.42% higher than beams with square openings, and 10.38% higher than beams with rectangular openings. This is because circular openings cause less reduction in the reinforced concrete area than square or rectangular openings, and thus cause a reduced effect of the openings on the durability strength of the beam. In addition to the shape of the openings, the size of the openings also affects the tolerance of reinforced concrete sills. The larger the opening, the lower the load bearing of the reinforced concrete sill. An experimental study conducted on reinforced concrete beams with openings found that beams with smaller openings had higher durability strength than beams with larger openings. This is because larger openings cause a greater reduction in the reinforced concrete area than smaller openings, and thus cause a reduced effect of the openings on the shear strength of the beam. The following steps can be followed to increase the durability of reinforced concrete beams with openings: Use circular openings instead of square or rectangular ones. Reduce the size of the openings as much as possible. Use additional reinforcement for the threshold, such as rebar or reinforced concrete. The results are shown in Table 3 in Figure 8.

Figure 9 shows a sectional view of the hollow central area ratio of 14.2%. Furthermore, both the B (46 x 46mm) square-hollow beam model and the B (36 x 56mm) rectangular-hollow beam

Table 3: Beams with the different shapes in hollow-core

Beam	Compressive strength FC (MPa)	First crack load(Kn)	Decreasing percentage (%)	Ultimate load (kg)	Decreasing percentage (%)
B1	30.3	20.05	-	86	-
B(36x56mm) Rectangle-hollow	30.3	17.95	10.47	77	10.46
B(46x46mm) square-hollow	30.3	17.95	10.47	70	18.60
B3circle	30.3	16.08	19.80	69	19.76

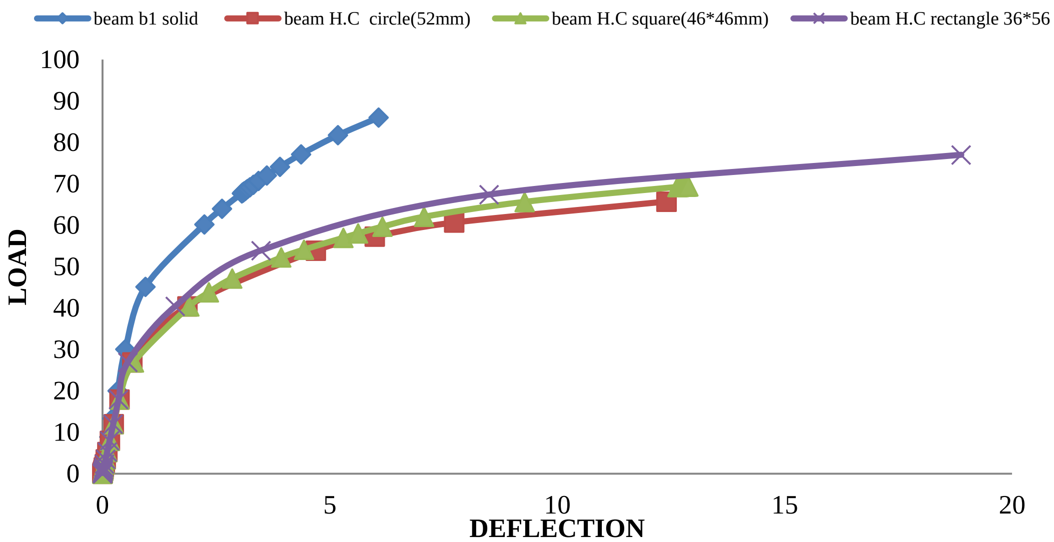
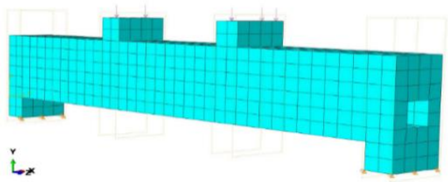
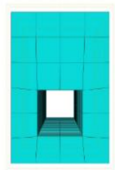


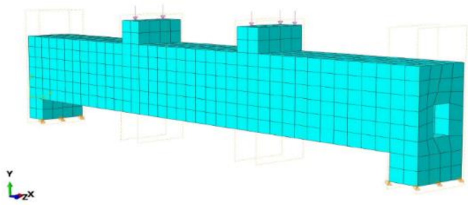
Figure 8. Load-deflection curve for beams with different shapes H.C.



(a) Finite element beam model mesh B(46X46)square



(b)Section view of beam



(a) Finite element beam model mesh B(36X56)rectangle

(b)Section view of beam

Figure 9. Sectional a view from within the beam model B (46X46) square, B (36X56) rectangle, and a The beam model seen in three dimensions B (46X46) square, B (36X56) rectangle with a hollow core area ratio of 14.2%

6.The effect of the number of holes

The number of circular openings in reinforced concrete beams greatly affects the durability, as increasing the number of openings leads to a further reduction in the area of reinforced concrete, thus reducing its ability to bear loads.

In general, the greater the number of circular openings, the lower the tolerance of the reinforced concrete beam.

An experimental study conducted on reinforced concrete beams with openings found that beams with one opening had a 1.4% higher durability strength than beams with two holes, and 10.4% higher than beams with three holes.

This is because single-slot beams cause less reduction in the reinforced concrete area than beams with two or three holes, and thus cause a reduced effect of the openings on the durability strength of the beam.

To increase the durability of reinforced concrete beams with circular openings, the following steps can be followed:

- Reduce the number of openings as much as possible.
- Use smaller diameter holes.
- Use additional reinforcement for the threshold, such as rebar or reinforced concrete.

Table 4 and Figure 10 show the effect of the number of circular openings on the durability of reinforced concrete beams. we split a 52 mm hole into two 36 mm holes on one embodiment and three 30 mm holes for a circle on another embodiment, all of which are the same size and have a hollow center area ratio of 14.2 percent. Figure 11 illustrates the hollow core area ratio of 14.2% in a 3D view of beam models

Table 4: Beams with the different numbers in hollow-core

Decreasing percentage(%)	Compressive strength fc	First crack load(Kn)	Decreasing percentage(%)	Ultimate load (kg)	Decreasing percentage(%)
B1	30.3	20.05	-	86	-
B3(3circle)	30.3	17.95	10.47	77	10.46
B3(2circle)	30.3	16.32	18.60	70	18.60
B3(circle)	30.3	16.08	19.80	69	19.76

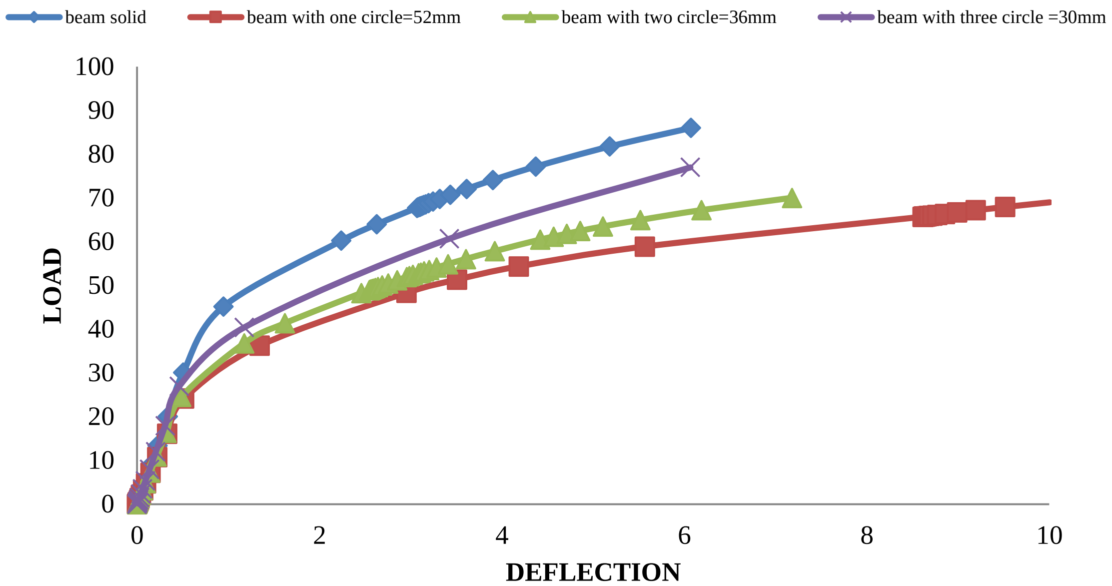
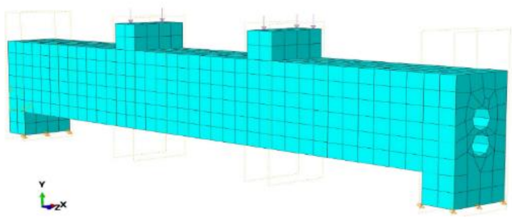
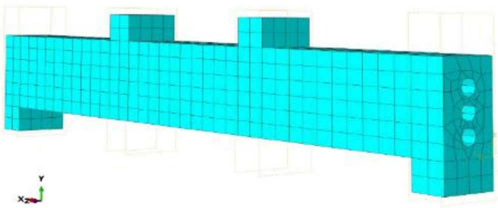


Figure 10. Load-deflection curve for beams with different numbers H.C

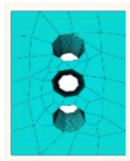


(a) Finite element beam model mesh B(36mm two circles)

(b)Section view of beam model



(a) Finite element mesh of beam model B(30mm three circles)



(b)Section view of beam

Figure 11. The hollow core area ratio of 14.2% in a 3D view of beam models B (36mm two circles), B(30mm three circles), and a section view of beam models B (36mm two circles), B(30mm three circles).

7. Shape of cracks for experimental and numerical beams

In general, cracks in reinforced concrete sills that have hollow openings along the length of the sill tend to form along the openings, as the openings cause a reduction in the tensile strength of the concrete.

However, the shape of the cracks varies depending on the shape of the openings, the number of openings, their location, and their distribution along the sill.

- Hole shape

Circular openings: Circular openings tend to cause fewer cracks than square or rectangular openings because circular openings cause less area reduction in reinforced concrete than square or rectangular openings. Square or rectangular openings: Square or rectangular openings tend to cause more cracks than circular openings because square or rectangular openings cause a greater reduction in the area of reinforced concrete than circular openings.

- Number of slots

Few openings: Beams with few openings tend to cause fewer cracks than beams with many openings, because beams with few openings cause less reduction in the reinforced concrete area than beams with many openings. Many openings: Beams with many openings tend to cause more cracks than beams with few openings because beams with many openings cause a greater reduction in the area of reinforced concrete than beams with few openings.

- Location of openings

Openings in the shear zone: Openings in the shear zone tend to cause more cracks than openings in the bending zone because holes in the shear zone cause a greater reduction in the tensile strength of concrete than holes in the bending zone. Openings in the bending zone: Openings in the bending zone tend to cause fewer cracks than openings in the shear zone because openings in the bending zone cause less tensile strength in concrete than openings in the shear zone.

- Distribution of slots

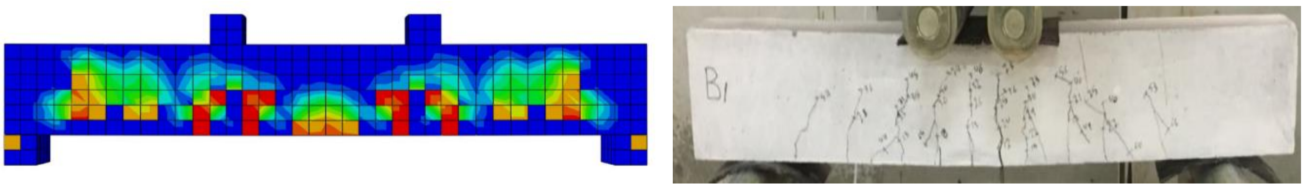
Evenly Distributed Slots: Sills with evenly distributed slots tend to cause fewer cracks than sills with unevenly distributed slots because sills with evenly distributed slots cause stress to be distributed more uniformly on the concrete. Unevenly distributed slots: Sills with unevenly distributed slots tend to cause more cracks than sills with evenly distributed slots because sills with unevenly distributed slots cause stress to be distributed less uniformly on the concrete.

- Cracking effect

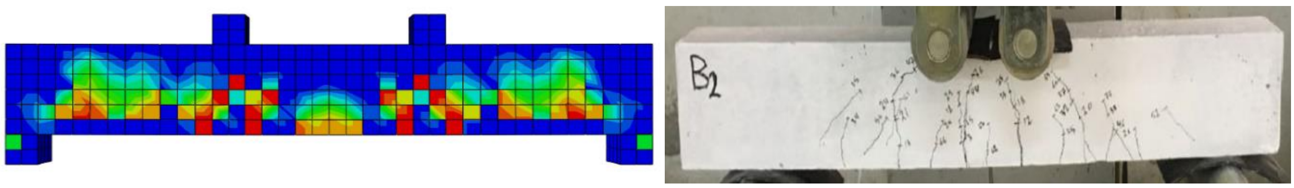
Small cracks: Small cracks may not have any effect on the integrity of the threshold, but they may cause aesthetic blemishes. Large cracks: Large cracks may weaken the integrity of the threshold and may lead to its collapse. To prevent cracks in reinforced concrete sills that contain hollow openings along the sill, the following steps can be followed:

Use smaller openings.

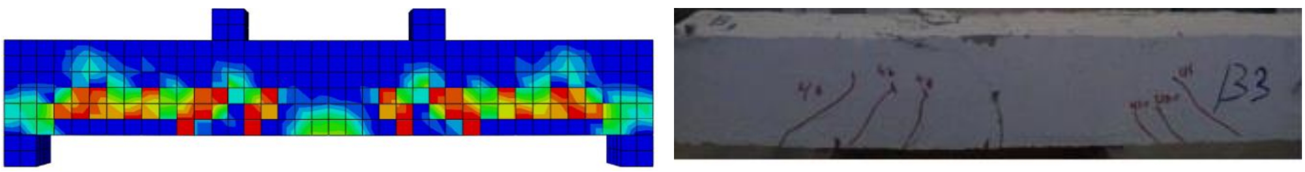
Distribute the openings evenly along the threshold. Use additional reinforcement for the threshold, such as rebar or reinforced concrete. The crack patterns of the beam models are displayed in Figure 12. According to Figure 12, the results revealed remarkably similar cracking patterns seen in the experimental tests [14].



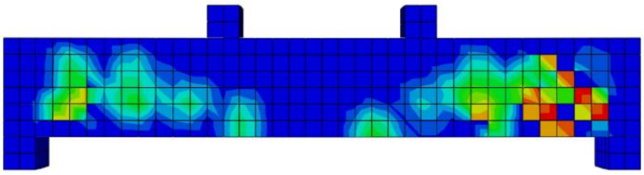
Beam B 1



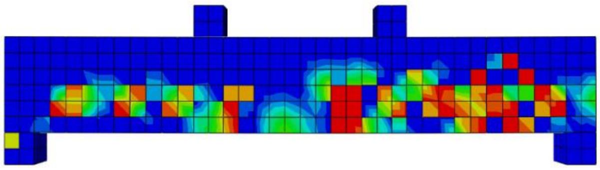
Beam B 2



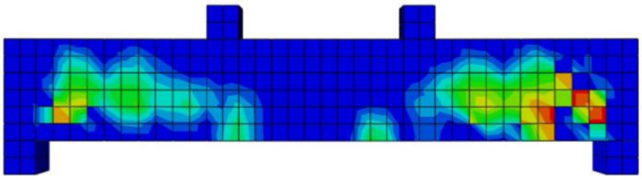
Beam B 3



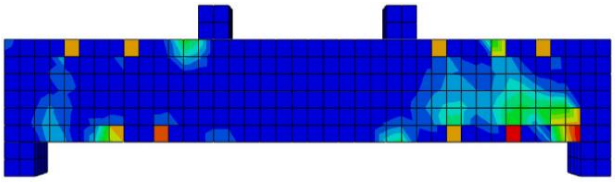
B(36X56) rectangle



B(46X46)square



B(36mm two circles)



B(30mm three circles)

Figure 12. Studies contrasting the modes of failure and the cracking patterns observed in experiments with those predicted by numerical simulations [14]

8. Conclusions

1. Effect of the presence of hollow holes

The presence of hollows reduces the bending resistance of the beam. The shape and size of the opening have a significant impact on the threshold resistance.

2. Effect of hole shape

Circular openings have less negative impact on bending resistance than square and rectangular openings. Increasing the dimensions of square and rectangular openings increases their negative effect on bending resistance.

3. Effect of the number of slots

Single-slot beams have higher strength than two- or three-slot sills. Increasing the number of holes leads to decreased durability.

4. Effect of concrete removal of hollow cores

Removing concrete from hollow cores using longitudinal voids maintains the initial crack load and bearing capacity. The concrete removal rate from hollow cores reaches 14.2%.

5. Comparing slotted lintels with solid lintels:

Beams with circular openings maintain 80.1% of the initial crack load and 96.5% of the bearing capacity compared to solid beams. Beams with square and rectangular openings maintain 80.1% of the initial crack load and 80.2% of the bearing capacity compared to solid beams. Single-slot sills maintain 89.5% of the initial crack load and 80.2% of the bearing capacity compared to solid beams. Double-slot sills maintain 80.1% of the initial crack load and 89.5% of the bearing capacity compared to solid beams. Three-slot sills maintain 80.1% of the initial crack load and 89.5% of the bearing capacity compared to solid beams.

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