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Natural frequencies of RC concrete slab with opening

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ABSTRACT

Vibration analysis of plates with openings represents an important issue in civil, aerospace, and mechanical engineering applications. It has been familiar that the opening or cut-out may be considered as a defect in most cases, which generally leads to a decrease in the stiffness of the member, according to the opening's size, shape as well as location. Hence, it affects the dynamic properties, for instance, the natural frequencies and the mode shapes. In this work, numerical modal analysis of fixed ends supported RC concrete slabs with three different aspect ratios as well as two different central square and circular openings has been investigated. The study is based on evaluating the natural frequency of these cases, as a global parameter. A simulation process for the modal analysis using ANSYS software is done to compare the results. The natural frequencies of RC concrete slab with openings have been evaluated and compared with each other as well as with the intact slab, as control ones. The results showed that both two shapes of central openings have an impact on the natural frequencies of the slab depending on sizes and aspect ratios.

KEYWORDS: Vibration, modal analysis, natural frequency, openings, RC slab.

1. INTRODUCTION

The Slab is the main structural element in the construction of buildings. The slab's thickness is small compared to its length and width. Therefore, it is called a thin planar surface part which transmits the transverse loads to its supports, beams, columns, and walls (Park and Gamble, 2000). Slabs can be made in-situ using formwork or may be prefabricated off-site. In-situ concrete slabs can be categorized based on; the nature and type of the support (for example, simply supported; or continuous/fixed), direction/ method of spanning (for instance, one-way spanning; or two-way spanning), and category of section, such as solid and ribbed with permanent blocks; ribbed without blocks, (Bhatt et al., 2013).

Reinforced Concrete (RC) solid slab has been widely used for multi-story buildings. Some multi-stories buildings have openings through all floor slabs. Openings in slabs have many advantages such as improved air circulation, improved lighting, being lightweight, and aesthetics. In addition to these advantages of opening in slabs, opening with a small size is frequently essential in the slab to accommodate essential services, for instance, electricity, computer network, heating, plumbing, water supply, sewerage, and ventilating risers. While substantial size openings that could amount to the elimination of a large area within a slab panel are sometimes required for stairways and lifts (Mota and Kamara, 2005 Ravindra et al, 2017 Mahlis et al, 2018; and Ravindra et al, 2017).

Despite the advantages of using openings in RC slabs, they have some adverse effects. The effect of a small opening on structural performance is frequently not considered significant. This is because the ability of the structure to redistribute stresses is anticipated (Mohammed et al, 2009 and Cheng et al, 2009). In the case of large openings, however, this is not the case. These types of openings pose a break in the continuity of both concrete and steel of the slab. As a result, the structure's ability to withstand or redistribute the imposed loads may be compromised.

In the last decades, some research on the structural behavior of slabs with various openings under static loads has been published. The published studies give a clear understanding of the behavior and failure mechanisms of slabs with openings. In addition, they give many different approaches to strengthening such slabs to rebuild a specific system to regain its serviceability and strength. A review article on the strengthening of Reinforced Concrete (RC) Slabs with openings is presented by EL-Khouly et al, 2020.

Generally, RC slab is excreted to heavy loads due to Heating, Ventilation, Air Conditioning (HVAC) and generator, or any mechanical equipment. The RC slabs are subjected to dynamic loads as a result of such equipment. When slabs are subjected to static load, their response will undoubtedly be different. The stiffness of opening RC slabs decreases when they are subjected to dynamic loads. When the stiffness of the slabs is changed, the dynamic characteristics of the slabs are also changed. Openings in RC slabs are not generally prescribed in standard codes. Even when they are in some ways, they raise concerns regards to the location of the applied loads as well as the size of the openings. (Aman et al, 2020). Therefore, special attention is required to be paid to the analysis and design of RC slabs with an opening under loadings.

Because of the complex geometry of the slab in the presence of the hole, using analytical modal analysis of RC slabs with openings is monotonous or impossible. For modal analysis of slabs, the available theoretical (analytical) solution is limited to solid, homogeneous, isotropic plates. Relying on the experimental concept to find the response of RC slab with an opening under dynamic loading using the full-scale experimental test is hugely expensive. This is related to the difficulty in locating appropriate equipment and materials. Due of the aforementioned challenges, the usage of finite element methods is becoming more prevalent. To sum up all of the above, the Lack of sufficient information about the slabs with openings under dynamic loading and performance is another concern. Therefore, this research addresses the effect of reinforced concrete slabs with different shapes and sizes of openings on natural frequencies

2. METHODOLOGY

An analytical attempt was made to predict the natural frequencies of the solid slab. However, a numerical approach was utilized to determine the natural frequencies of slabs with and without openings. Two different shapes and three different sizes of opening were located in the center of the slab, with fixed ends boundary conditions were taken into consideration

2.1 Analytical formulas for frequencies

The following analytic closed-form formula is used for calculating the angular natural frequencies of a prismatic plate under different boundary conditions. The expression of the natural frequency of the plate is widely available in the literature (Blevins, 2001) which is denoted by the followings. It is worth mentioning that the slab is assumed as homogenous and isotropic while the analysis is carried out based on the linear behavior. Using an analytical approach for intact cases in this study is important to establish the accuracy and applicability of the current simulation and to emphasize the fact that the numerical modeling is correctly achieved and dependable.

$$\omega_n = \frac{\lambda^2}{l \cdot b}\sqrt{\frac{D}{\mu}} \tag{1}$$

$$f_n = \frac{\lambda^2}{2\pi \cdot l \cdot b}\sqrt{\frac{D}{\mu}} \tag{2}$$

$$D = \frac{Eh^3}{12(1-\nu^2)} \tag{3}$$

Where,
l is the length of the slab.
b is the width of the slab
h is the thickness of the slab
υ is the Poisson ratio, 0.24
$\mu = \rho h$ is the mass density per unit area of the slab
λ is the natural frequency factor, dimensionless
ωn is natural circular frequency for n mode, in rad/sec
fn is natural frequency for n mode, in Hz
D is the Flexural rigidity of slab
E is the dynamic modulus of elasticity

2.2 Numerical Investigation

To get a better understanding of the behavior of concrete slabs with an opening under fixed ends vibration, modal analysis was developed in this study using ANSYS software. The software is suitable for modelling the behavior of the RC slabs in terms of free and forced vibration under different loads. It is also capable of highly linear and nonlinear problems (Ansys manual, 2015; and Madenci and Guven 2015).

To illustrate the effect of opening size on the slab's dynamic characteristics, the overall analysis is carried out for various levels of stiffness and mass reduction. Besides the effects of the size of the opening, the effect of changing shapes, for example, rectangular and circular shapes were also taken into consideration during this study. All the above-mentioned cases under fixed end conditions were studied.

2.3 Provision of openings in slabs.

Under different expected static loads with the condition of performing full structural analysis to assure the fundamental requirements for slab such as safety, strength, and serviceability, the ACI 318-14 code permits the RC slabs to have openings. For design and analysis, two-way slab systems are mainly divided into two strips, for instance, column and middle strips. The column strip is located on each side of the column centerline. Its width on each side is equal to one-fourth of the length of the shorter span in the two perpendicular directions. The width of the middle strip is 1/2 of the shorter span's length, which is surrounded by two-column strips. It is worth mentioning that in the middle strip part, ACI 318 allows openings of any size in any new slab system, as shown in Fig. 1.

Nowadays, creating openings in slabs is becoming more popular, due to space-saving, left and stairs as aforementioned in the literature. Most of the reported work was related to the behavior of slab with an opening with different locations under static loads and the ways of strengthening to satisfy the fundamental requirements.

When slabs are subjected to in-plane/earthquake loads, the presence of openings might decrease their in-plane capacity and stiffness (Shehab et al, 2017). Unfortunately, free vibration has been mainly limited to slabs with openings. As a consequence, the main aim of this study is to investigate the behavior of RC two-way slabs with central openings of different sizes and shapes under fixed end conditions. The openings were modelled in slabs and simulated which represents slabs under free vibration. The data generated in this paper from modelling and simulating the slabs under various key parameters (by using finite element (FE) modelling) utilizing ANSYS software.

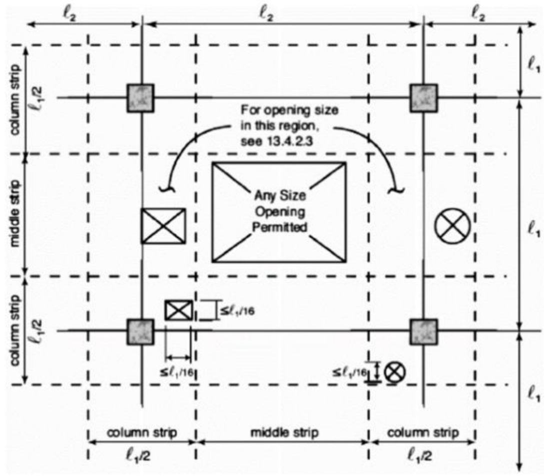


Fig. 1. Opening sizes and locations in flat plates (ACI 318-14).

3. RESULTS AND DISCUSSIONS

In the present study, a FE modelling by using ANSYS software was utilized to investigate the dynamic behavior of fixed ends RC slabs with and without openings of three different aspect ratios under free vibration, as shown in Table (1). The analytical natural frequencies of the control case (intact case with aspect ratios L/b=1) were also calculated and presented in Table 2.

TABLE 1
First six natural frequencies of slabs of different aspect ratios

(b/a)	Opening sizes (m^2)	First six natural frequencies (Hz)					
		1	**2**	**3**	**4**	**5**	**6**
1	intact	48.0	97.8	97.8	143.9	175.2	176.1
	0.6 × 0.6	48.4	96.4	96.4	140.5	171	181.1
	1.5 × 1.5	63.1	89	89	133.6	149.8	203.1
	2.0 × 2.0	88.2	103.9	104	142.2	145	197.7
	D=0.677	48.6	96.8	96.8	141	170.7	181.6
	D=1.693	64.1	92.3	92.3	133.1	161.3	209.8
	D=2.257	90.6	108	108.1	136.2	173.9	214.4
1.25	intact	39.9	70	91.2	118.7	119	165
	0.6 × 0.6	40	69.5	90.2	116.7	118.6	164
	1.5 × 1.5	48.5	63.9	83.1	111	123.7	157.3
	2.0 × 2.0	60.1	65.7	94.1	114.3	124.1	155.1
	D=0.677	40.2	69.6	90.5	117	118.8	164
	D=1.693	49	65.3	86.1	111.3	127.5	160.5
	D=2.257	61.6	68.5	95.9	110.6	140.7	170.1
1.5	intact	36	55.5	87.9	88.6	106	134.5
	0.6 × 0.6	36.1	55.4	87.1	88.4	104.8	132.5
	1.5 × 1.5	41.7	52	80.6	98.6	100.5	127.3
	2.0 × 2.0	48.1	51.4	89.2	101.5	112.6	135
	D=0.677	36.2	55.4	87.4	88.6	104.9	133.1
	D=1.693	42	52.5	83.4	100	101	130.3
	D=2.257	48.9	52.8	90.3	99.5	118.7	142.5

b = longer side of slabs 4 m, 5m, 6m, a = shorter side of slabs, 4m, thickness is constant 12 cm, and concrete compressive strength= 24MPa.

TABLE 2
The first six analytical natural frequencies of slabs fixed ends supports.

(b/a)	Slab's Case	First six natural frequencies (Hz)					
		1	2	3	4	5	6
1	intact	48.1	98.1	98.1	144.7	175.2	176.2

Then, the analytical natural frequencies are compared with their counterpart which was numerically determined to emphasize the prediction of the reliability of the numerical modelling, as shown in Fig. 2. There is a good agreement between all the six analytical and numerical natural frequencies.

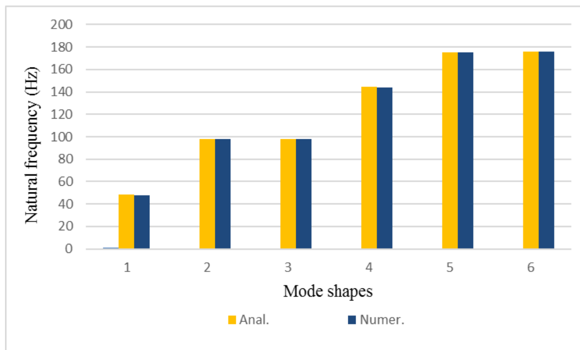
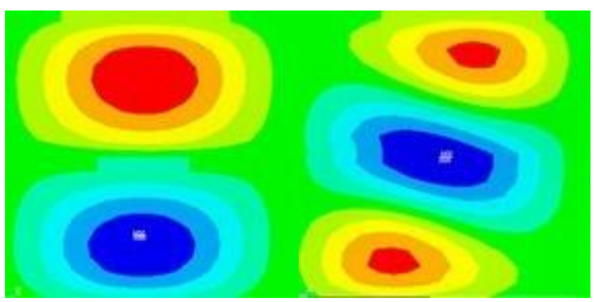
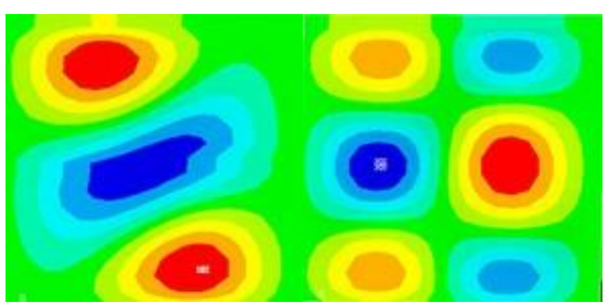


Fig. 2. Comparison between analytical and numerical natural frequencies of the intact case with an aspect ratio (b/a=1).

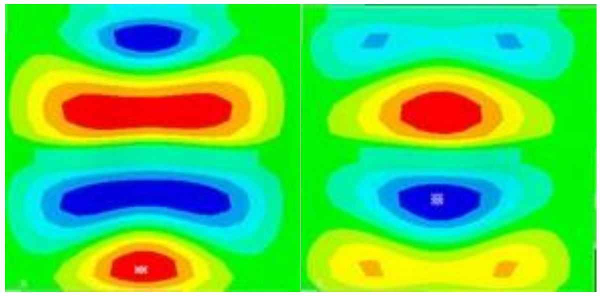
In addition to numerical natural frequencies, the first six mode shapes of the intact slab which were numerically determined are shown in Fig. 3. The colors of graphs correspond to the areas where the response is highest (red) and lowest (blue).



Mode 1 Mode 2



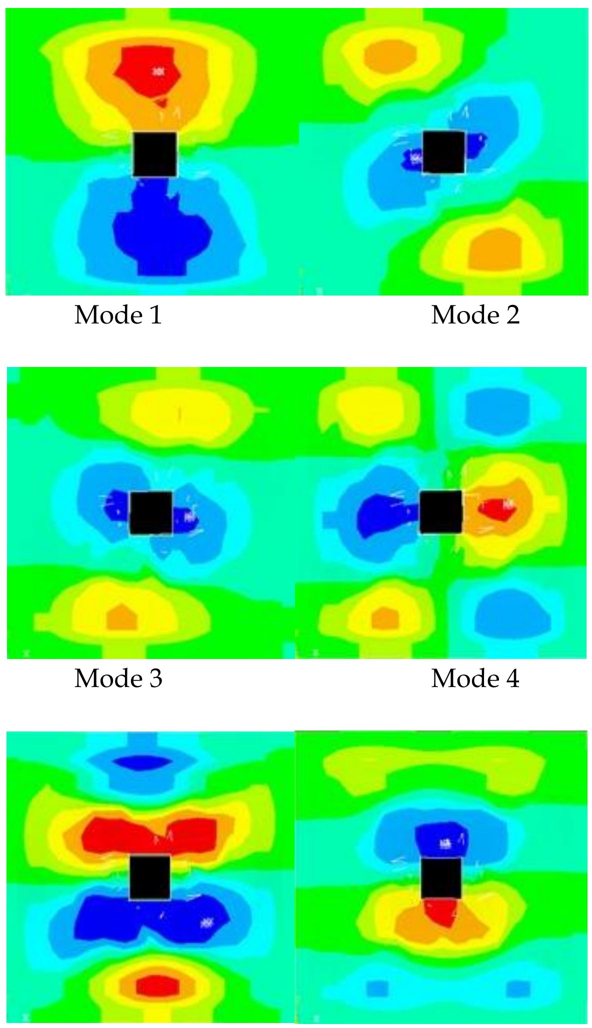
Mode 3 Mode 4



Mode 5 Mode 6

Fig. 3. Numerical natural frequencies of intact case.

However, the first six mode shapes of the square (0.6x0.6 m^2) and circular (D=0.677 m) slab opening of aspect ratio 1 are shown in Figs. 4 and 5 respectively.



Mode 1 Mode 2

Mode 3 Mode 4

Mode 5 Mode 6

Fig. 4. Numerical natural frequencies of square opening.

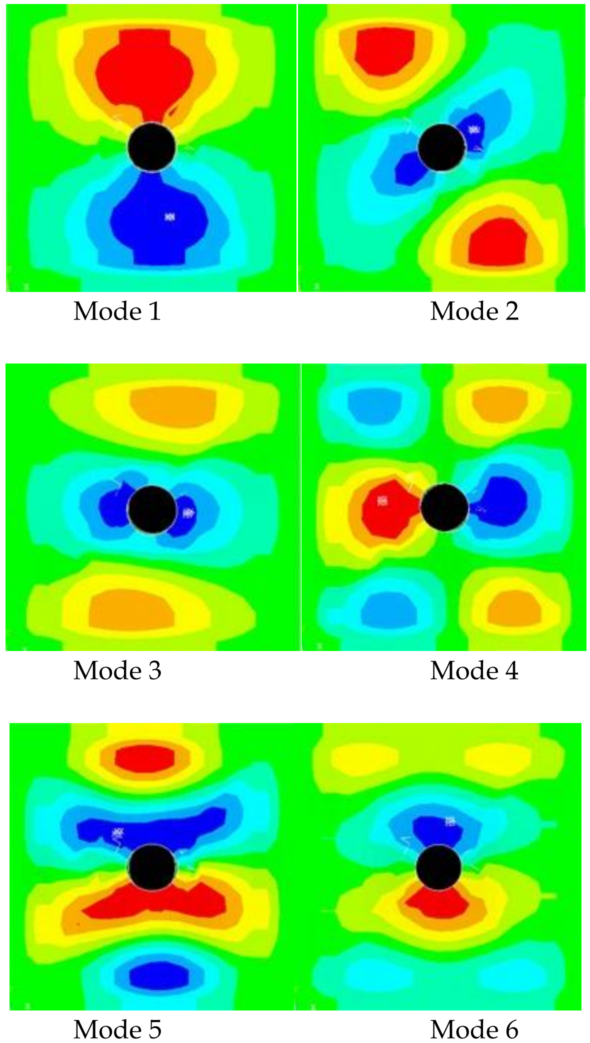


Fig. 5. Numerical natural frequencies of circular opening.

Subsequently, the effects of openings of slabs on natural frequencies have been numerically determined, analyzed, and compared with the intact (without opening) cases. Several parameters such as the effect of sizes and shapes of central openings on natural frequencies of three different rectangularity of the slabs under fixed end conditions have also been considered during this study, as tabulated in Table 1. The results are expressed in terms of the following parameters:

3.1 Effect of rectangularity

The natural frequencies for three aspect ratios (b/a = 1, 1.25, and 1.5) of concrete slabs investigated with and without central openings are presented in Table 1. Figure 6 depicts the natural frequency of slabs with three different aspect ratios.

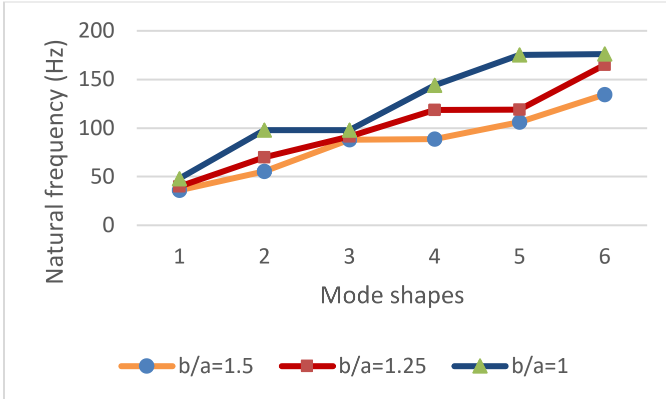


Fig. 6. Numerical natural frequencies of intact case for three aspect ratios, b/a=1, 1.25, and 1.5.

It is clear that with an increase in aspect ratio from 1 to 1.25 and 1.5, the natural frequencies decrease due to an enlargement of the mass of the slab. The same trend is found for slabs with and without openings. It is interesting to note that for the slab with square and circular openings, the natural frequencies are decreased for increasing the aspect ratios, as tabulated in Table 1. It is observed that the natural frequencies decrease as the aspect ratio increases for all types of shapes as well as sizes of openings conditions.

3.2 Effect of size of openings

To study the effect of different sizes of central openings of slabs on the natural frequencies, three sizes were considered and investigate their effect on the natural frequencies for three different aspect ratios under fixed ends supporting conditions. The natural frequencies of central openings for all different sizes were shown in Table 1. The influence of natural frequencies for all different sizes for square and circular are shown in Figs. 7 and 8 respectively.

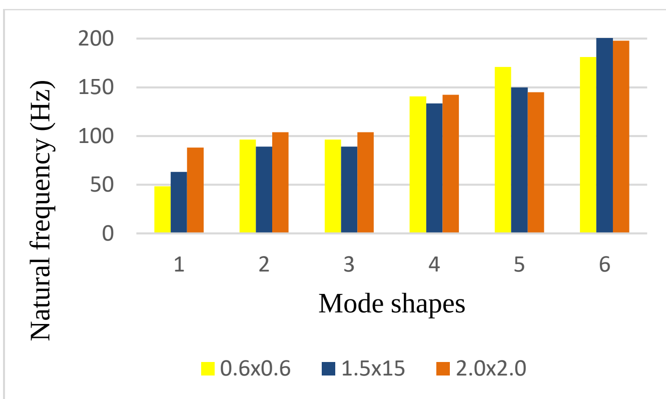


Fig. 7. Numerical natural frequencies of slab with square openings of three different sizes (0.6x0.6, 1.5x1.5, and 2.0x2.0).

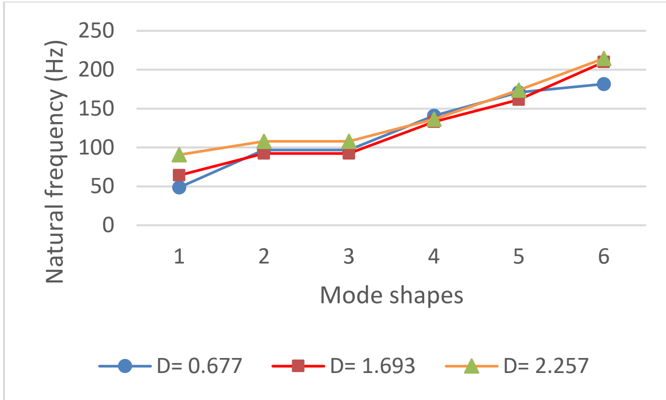


Fig. 8. Numerical natural frequencies of slab with square openings of three different sizes (D=0.677, D=1.693, and D=2.257).

For both shapes, it is revealed that the natural frequencies almost decrease with the increase in percentage reduction in the area of openings from 0.6x0.6 to 1.5x1.5. However, they have increased again with the increase in percentage reduction in the area of openings to 2.0x2.0. It can be concluded that the effect of the opening size on the natural frequencies (small and medium sizes) is more effective to decrease the natural frequencies than the large sizes. This may be because for the large opening the effect of changing stiffness is higher than the effect of changing the mass.

3.3 Effect of shape of openings

To find out how changing the shapes of openings (square and circular) will affect the fundamental natural frequencies for the fixed ends boundary conditions. The opening areas will be maintained constant as (0.36 m^2, 2.25 m^2, and 4 m^2) for both shapes.

The natural frequencies of the control slabs with the slab of circular and square shapes for different aspect ratios and percentages of area reduction are shown in Table 1.

The comparison between the numerical natural frequencies of intact slabs with different opening sizes and shapes is made, as shown in Figs 9, 10, and 11.

From these figures, it is clear that the difference between natural frequencies of slabs with square and circular openings has a little effect on fifth and sixth mode shapes for aspect ratio 1, but this effect became significant on the same modes for the other aspect ratio, 1.25 and 1.5.

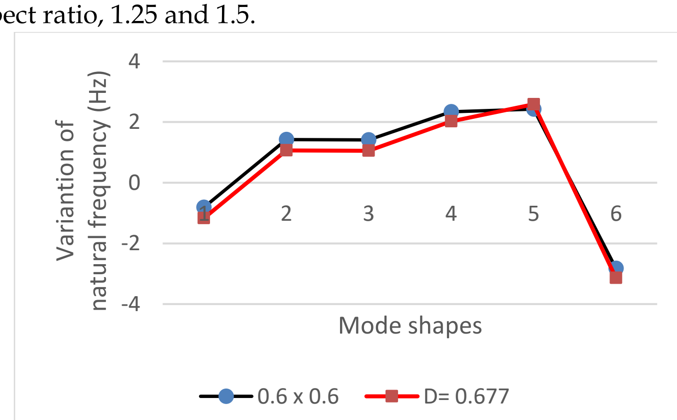


Fig. 9. Numerical natural frequencies of slab aspect ratio 1 with square and circular openings (0.6x0.6 and D=0.677m).

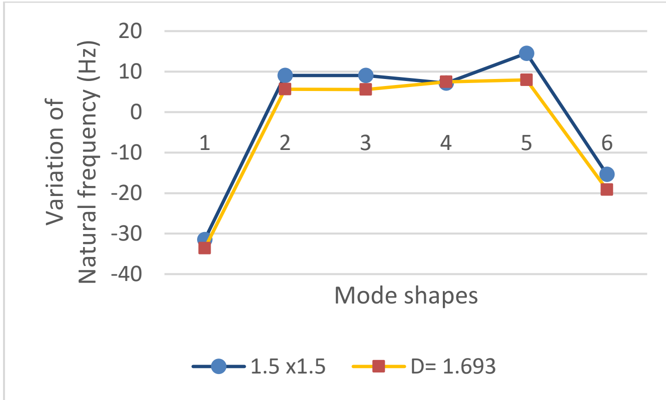


Fig. 10. Numerical natural frequencies of slab aspect ratio 1 with square and circular openings (1.5x1.5 and D=1.693m).

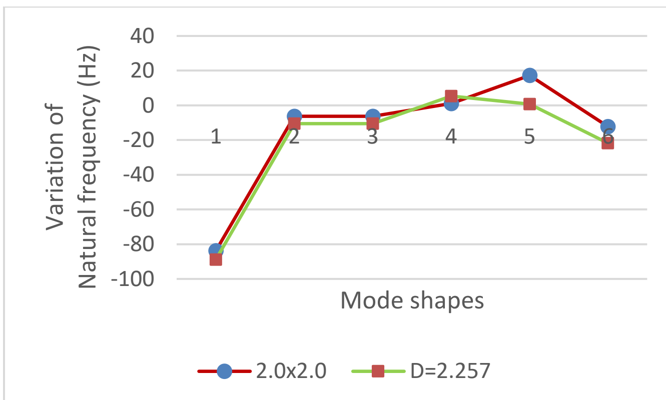


Fig. 11. Numerical natural frequencies of RC slab aspect ratio 1 with square and circular openings (2.0x2.0 and D=2.257m).

It can be concluded that slabs with square openings exhibited a higher reduction in almost natural frequencies concerning the circular openings for all different aspect ratios, which could be attributed to reduced stiffness after creating the opening.

4. CONCLUSION

The current work presented a finite element modelling by using ANSYS software to investigate the dynamic behavior of fixed ends slabs under free vibration. In the studied models, central square and circular opening shapes with three different rectangularity of slab were selected for investigations. For that purpose, a series of numerical analyses were executed studying the effect of some parameters on natural frequencies of the slab with the opening. Predicting the natural frequencies of the slabs with the opening is important because openings are commonly used as access ports for civil, electrical, and mechanical systems. The undesirable vibrations may cause sudden failures due to resonance in the presence of cutouts. For careful investigation, six natural frequencies of the slab with openings for different shapes are compared with the natural frequency of the control ones.

Based on the comparison results, tabulated data, and graphs the following inferences from this study have been summarized as follows:

1. It is concluded that by increasing the value of the aspect ratio (1.0, 1.25, and 1.5) of the slab, the natural frequencies in almost the modes for different parameters are decreased.

2. The natural frequencies of slabs decrease for small and medium sizes for both square and circular shapes, but they increase again for a large opening. This may be because the ratio of decreasing mass is higher than for decreasing the stiffness.

3. The worst-case regarding natural frequencies reduction when the openings (regardless of their shapes) are created in slabs of aspect ratio 1.
4. Central opening size should be cautiously selected based on the aspect ratio of the slab. Increasing the opening size in slab with rectangularity 1 results in more adverse behavior than increasing the opening size with a slabs aspect ratio of 1.5.
5. In the case of creating openings in slabs with all aspect ratios, natural frequencies decrease significantly in cases of square openings compared to circular openings. This indicates that the natural frequencies of slabs are less affected by circular openings when it is compared with the natural frequencies of square opening of slabs.
6. In general, circular openings show better behavior compared to square ones of the same sizes. Slabs with square openings exhibited a higher reduction in almost all natural frequencies compared to circular openings. This could be attributed to the reduced stiffness of the square shapes.

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