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Numerical modeling of dynamic behavior in a bi-axial hollow slab

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Abstract. Bi-axial hollow slab is a technology that reduces the amount of concrete by replacing it with plastic spheres with voids on their inside in areas where it does not perform substantial structural function. This technique leads to material economy and self-weight saving, without considerable inertial loss. As a result, this method is increasingly becoming more present in the matrix of Brazilian construction methods, due to its efficiency in technical, economic and environmental aspects. One of the main loads that a structure is subjected to is dynamic excitation caused by human interaction, such as walking, jumping and running, which are characterized by being periodic and low frequency. With that, the spread of this technology depends on a reliable numerical modeling that describes these behaviors, so that structural designers can have confidence in their work. As a relatively new technology in Brazil's business, the lack of commercial software that has computational models of cross sections with spherical voids makes it difficult to popularize this constructive method. In this context, this work aims to develop a mathematical model that describes the structural dynamic behavior of the hollow slab. To that end, four finite element models were created, and their dynamic properties of vibration modes and natural frequencies were compared to an experimentally tested hollow slab specimen. The models I, II, III and IV were elaborated with frame, shell-thin, shell-layered and solid element, respectively. The results presented in this paper show that the vibration modes were similar, but with different values of natural frequencies compared with the specimen. The lowest variation was obtained by the model IV, with a 0,60% difference for a 6,7 Hz frequency relative to the first mode of the experimental hollow slab. Models I, II and III varied by 8,92%, 1,34% and 43%, respectively. Therefore, it can be concluded that, among the numerical models analyzed in this work, the one that best describes the modal behavior of a bi-axial hollow slab it's the model IV, with finite shell-layered elements, although model II presents good precision too. This opens up a possibility for reliable modeling of the dynamic behavior of this type of slab.

Keywords: Dynamic behavior, Bi-axial hollow slabs, Numerical modeling

1 Introduction

The bi-axial hollow slab concept emerged more than 100 years ago. Nowadays, there are dozens of manufacturers holding patents of this system, each one with their own particularities, but with the same principle: the incorporation of an inert element on the center of the slab.

One of the main consequences of this feature is the reduction of inertia of approximately 35% against the 12% of the massive slabs with the same thickness. In the case of the manufacturer *Bubbledeck* [1], this allows larger spans, since the self-weight overload is greater than the inertia reduction (stiffness) of the element. In this paper, this system will be called as hollow slabs.

Despite its advantages, the slab with voids is still not widespread in Brazilian constructive matrix. One of the reasons for this is the lack of commercial software that facilitates the modeling of cross sections with spherical voids, becoming a bottleneck to its popularization.

Among the actions that the structure undergoes throughout its lifespan, we highlight the dynamic excitation caused by human activity, such as walking, running, jumping, and others that are characterized by being periodic with low frequency. These actions can cause noticeable oscillations, which exceed the allowed limits causing discomfort and, in extreme cases, can lead to the destruction of the structure. Therefore, it is necessary that the structural designers have knowledge about the characteristics of the dynamic behavior of the structure and also have appropriate tools for this analysis.

This work aims to propose a reliable numerical modeling that describes the modal behavior of a stab with voids. Four models were developed by using a software of finite elements *SAP2000 V23* and choosing the appropriate modeling by comparing with experimental results of Sabah and Mohammed [2].

2 Related Work

There is a lot of research on static design parameters of hollow slabs. The relevance of this technology is a well highlighted theme for several researches, such as Churakov [3], Terec [4] and Bubbledeck Brasil [1]. Other authors have also dedicated themselves to understanding the behavior of the flexion of hollow slabs, like Gudmand-Høyer [5], Lay [6], and Silva [7]. Regarding the reactions to shear stresses and punching, we can cite: Marais and R. [8], Lima [9], and Ceballos [10], among others.

When talking about studies on dynamic field, the gap is evident: there are few works about hollow slabs. In this quick numerical research, Lay [6] analyzed and compared dynamic characteristics of hollow slabs. The most promising research was carried out by Liu [11], who addressed numerical and experimental analysis and explored the structure's response to dynamic actions, such as humans walking and the impact of hammers. However, his research is limited to unidirectional slabs.

Regarding the bi-axial hollow slabs, object of study of this paper, Sabah and Mohammed [2] evaluated, through numerical and experimental approaches, the influence of the distribution of plastic spheres in a slab with voids under the effect of a harmonic load. The authors concluded that there were significant changes in the behavior of the structural slab, simply by changing the positions of the plastic spheres. This experiment is more detailed in the next section.

Given the context presented, this work aims to contribute to the field of research field of behavior of bi-axial hollow slabs, proposing a numerical-mathematical model that represents the physical behavior of structural dynamic.

3 Numerical Analysis

To obtain a finite element model that can reliably represent the dynamic behavior of a bi-axial slab with voids, this work uses an experimental specimen obtained by Sabah and Mohammed [2] as reference. This specimen consists on a $250cmx250cmx20cm$ slab with plastic spheres of $12cm$ in diameter, spaced by $16cm$, as shown in Figure 1, made by the same authors.

Table 1 shows the natural frequencies for the first 3 blending vibration modes for the specimen.

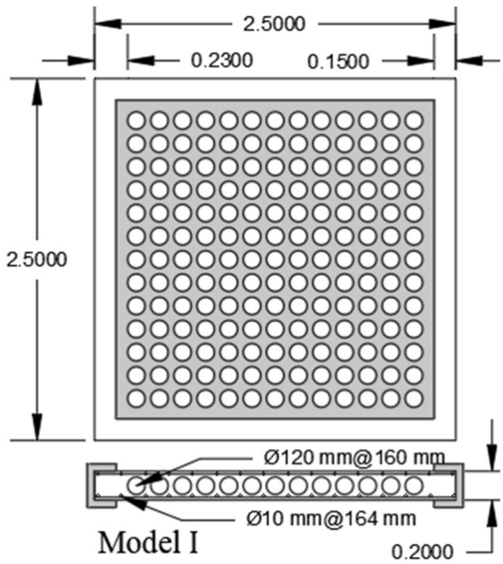

Figure 1. Verification model (Sabah and Mohammed [2])

The construction of the numeric model proposed in this work was done by 4 numerical approaches in the software SAP2000, in which each modeling was done with one type of finite element, from the simplest to the most complex. In all models, the characteristics of the material of the slab used (reinforced concrete) were considered as uniform, as described in Table 2:

Table 1. Dynamic properties of the specimen (Sabah and Mohammed [2])

Vibration modes	Natural frequencies (Hz)
1	6,7
2	12,6
3	18,38

Table 2. Physic Properties of the reinforced concrete

Concrete properties:	
Compressive strength (MPa)	25
Elastic Modulus (GPa)	22
Density (kN/m³)	23,53

Model 1 was made with linear frame, creating a grid composed by beams to simulate the behavior of the specimen. The elements were constructed with $20cm$ of height and $16cm$ of weight, as well as the spacing of the spheres of the specimen being compared. The three-dimensional representation of this model can be seen in Figure 2.

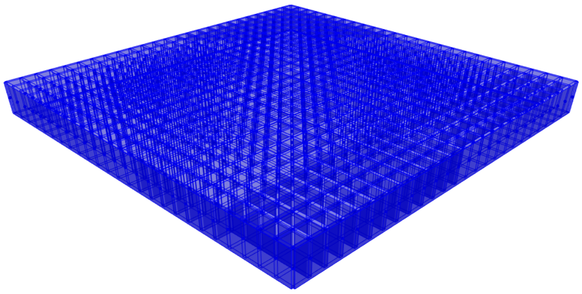

Figure 2. Model 1 - Linear Element Frame

Model 2 (Figure 3) was made by using a finite element of area of 4 nodes, called *shell thin* by the software, simulating a solid and homogeneous slab. This model uses the technique of changing the element height, to equalize the slab inertia with the experimental hollow slabs. A reduction coefficient was applied, decreasing the inertia by 10%, as proposed by Schnellenbach-held [12].

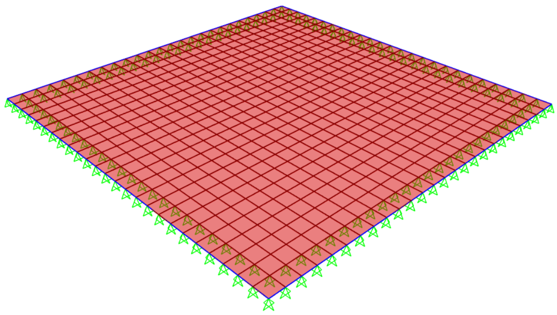

Figure 3. Model 2 - Element plan Shell

Model 3 proposal follows a variant of element of shell area, titled *Shell Layers*, in which is possible to split a planar section into layers and assign individual properties to each of them. Using the same approach as Lay [6], the layer that represents the HDPE part (*high-density polyethylene*) is surrounded by other two concrete layers: an upper and a lower one. This material is used in the manufacture of the inner spheres of $12cm$, surrounded by layers of concrete of $4cm$ each.

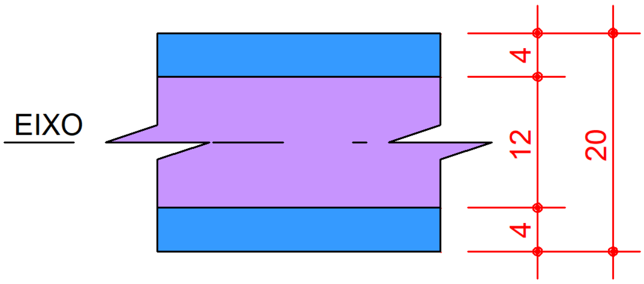

Figure 4. Cross section of the shell-layered slab, in centimeters.

Table 3. Physic properties of the HDPE.

HDPE Properties:	
Compressive strength (MPa)	20
Elastic Modulus (GPa)	0,827
Density (kN/m³)	11,67

Model 4 was made with a cubic finite element (solid) with 8 vertices, each one with 6 degrees of freedom, 3 of translation and 3 of rotation. The hollow slab was designed by using solid cubic units with three edges with $1cm$, so that the area representing the voids of the sphere has no solid unit, as shown by Figure 5. After designing one module, the arrangement was duplicated multiple times to the sides to obtain the same dimensions of the specimen.

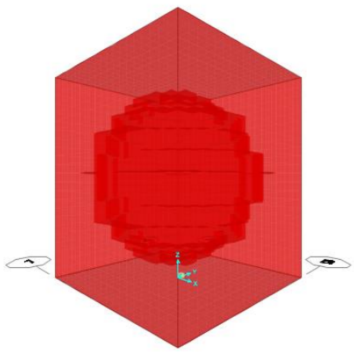

Figure 5. Solid cubic unit of Model 4

4 Results

The results presented below are comparisons between natural frequencies and vertical displacements with the specimen, with absolute and relative values. Except for model 1, all of the mathematical models obtained similar results, but model 3 achieved the best results, as shown in Table 4.

Table 4. Natural frequencies obtained experimentally and with numerical analysis

Modes	Experimental Result	Model 1	Variation (%)	Model 2	Variation (%)	Model 3	Variation (%)	Model 4	Variation(%)
Mode 1	6,7	9,58	43	6,79	1,34	6,74	0,6	6,83	1,94
Mode 2	12,6	21,16	68	13,86	10	13,55	7,54	14,05	11,50
Mode 3	18,38	31,43	71	20,39	10,93	19,60	6,63	19,98	8,70

The high variations in model 1 can be explained with the fact that it is composed of a frame element that simulates beam, which has a rigid degree greater than the real, making the modeled grid less deformable and less flexible, which increase the natural frequencies.

Models 2 and 3 are easy to build, require less computing power and are closer to the behavior of the specimen, as we see in Table 4. However, model 3, built with shell layered element, obtained the best result, with only 0,6% of variation for the first vibration mode.

Regarding Model 4, it is noticeable that making a single module with voids in the sphere (Figure 5), demands stacking 6.188 solid units with $1cm$ of edges in each dimension; This considerably increases the computational cost of simulation of a slab with dimensions similar to those used in practices.

The results also show that the numerical model simulated in this paper was similar to the vibration modes, as shown in Figure 6, where the first three vibration vertical modes obtained numerically can be seen. When compared with the experimental results in Figure 7, the similarity between the format of the first three modes are significant.

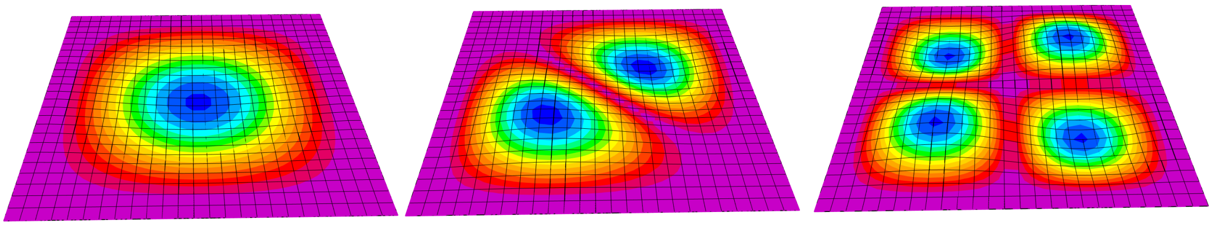

Figure 6. First three vibration modes obtained numerically (Model 3)

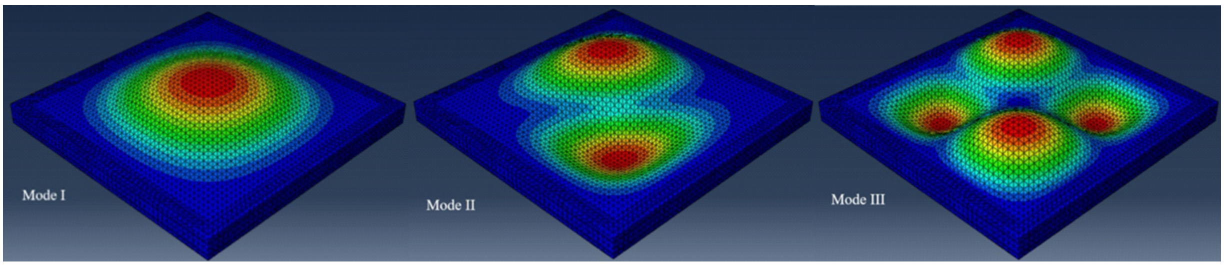

Figure 7. First three vibration modes obtained experimentally (Sabah and Mohammed [2])

With the results obtained, it is clear that model 3 is the most satisfactory for using in dynamic analysis. This is satisfied both in quantitatively, comparing natural frequencies, and qualitatively, comparing the similarity between the deformation of the first three numerical and experimental vibration modes (Figures 6 and 7). Another benefit of choosing Model 3 is the lower computing power demand.

5 Conclusion

In this work, four possibilities of numerical modeling for hollow slabs were presented. The results demonstrate that model 1 is not a good approach, varying 43% of the natural frequency when compared to the first vibration mode. Models 2 and 3 were satisfactorily close to the specimen used as a reference, varying 1,34% and

0,60%, respectively, when compared with the same vibration mode as model 1. Model 4 also had good results, varying only 1,94% for the first mode, but its demand for large computational power is a limiting factor.

This way, among the numerical proposals discussed in this paper, the model 3, built with shell layered finite element and requiring less computational power, was the best approach to the experimental results. The next steps of this research are to use the results obtained here for the analysis of hollow slabs subjected to dynamic loads cause by human actions, like walk, run a jump.

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