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ORIGINAL ARTICLE

Dynamic analysis in a bi-axial hollow slab submitted to human actions

Análise dinâmica de uma laje aliviada biaxial submetida a ações humanas

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Abstract: The bi-axial hollow slab is the result of applying a technology that removes concrete from the least useful region and replaces it with hollow plastic spheres. This technique leads to material economy and self-weight saving, without considerable inertial loss, enabling larger and more flexible spans. Consequently, these spans are vulnerable to unwanted vibrations and dynamic acceleration caused by external actions, such as movements produced by human activity. This way, understanding the dynamic behavior of this technology and confronting it with normative limits on the project phase is essential for a good performance in the serviceability limit state, bringing comfort to the user. This paper studies the dynamic behavior of a bi-axial hollow slab submitted to human actions, such as jumping, dancing, clapping, moving the body, and moving and clapping at the same time. For that, this work made a numerical model of the structure and applied dynamic actions to it. The numerical results show that, for most of the actions, normative limits are satisfied, but the slab presents excessive accelerations in the case of jumping and dancing.

Keywords: dynamic analysis, hollow slab, human actions, vibrations.

Resumo: Laje bidirecional oca resulta da aplicação de uma tecnologia que remove concreto de regiões em que ele é pouco útil e coloca esferas plásticas ocas no seu interior. Essa característica gera economia de material e redução de peso próprio, sem perder considerável inércia, possibilitando vãos maiores e mais flexíveis, que, consequentemente, são suscetíveis a vibrações e acelerações dinâmicas indesejáveis causadas por ações externas, como os movimentos produzidos pela atividade humana. Dessa forma, entender o comportamento dinâmico desta tecnologia e confrontar com limites normativos, ainda na fase de projeto, é fundamental para um bom desempenho no estado limite de serviço, trazendo conforto ao usuário. A presente pesquisa visa estudar o comportamento dinâmico de uma laje bidirecional aliviada submetida às ações humanas de pular, dançar, bater palmas, balançar o corpo e bater palmas balançando o corpo. É realizada a modelagem numérica da estrutura e nela são aplicadas as ações dinâmicas. Os resultados numéricos mostram que, para a maioria das ações (bater palmas, balançar o corpo e bater palmas balançando o corpo) os serviços limites normativos são atendidos, entretanto, a laje bidirecional aliviada apresenta acelerações excessivas para as ações de pular e dançar.

Palavras-chave: análise dinâmica, laje aliviada, ações humanas, vibrações.

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1. INTRODUCTION

Bi-axial hollow slabs are obtained by the inclusion of plastic spheres inside a conventional slab, allowing the removal of concrete that does not have enough structural function. This results in a 35% reduction in self-weight overload while the inertia of the slab is 12% less when compared to a solid slab of the same thickness.

Over a century ago, the concept of a hollow slab emerged as a solution for big spans in situations where the height of the floor did not allow for tall beams. Nowadays, there are a lot of manufacturers such as Bubbledeck™, U-Boot™, AirDeck™, and Cobiax™. They all adopt the same principle: the incorporation of a voided and inert element in the center of a reinforced concrete slab.

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The Danish engineer Jorgen Breuning patented the Bubbledeck™ technology in 1980. Its advantage is that it physically behaves like a solid slab in all directions, following the same rules as the conventional slabs, according to the manufacturer [1]. Adenan et al. [2] discussed the advantages and properties of the bi-axial hollow slab in comparison with conventional reinforced concrete slabs based on studies and research carried out.

Experiments realized by Schnellenbach-Held and Pfeffer [3] show that the flexural stiffness of BubbleDeck slabs varies between 87% and 93% of the stiffness of a solid slab with the same thickness, recommending a value of 90% for correct designing. In our research, the terminology “hollow slab” was adopted to refer to Bubbledeck™ slabs.

Aziz and Heng [4] provided a comprehensive analysis of bi-axial hollow slab, consolidating research carried out between 2010 and 2020. The systematic literature review was conducted by consulting relevant databases.

Gajewski et al. [5] proposed a numerical method to optimize the determination of the stiffness of a bi-axial hollow slab, where the bending stiffness is variable in the cross sections. They applied numerical homogenization and sequential quadratic programming with constraints to simulate the reduction in the self-weight of the slab due to hollow spheres, automatically adjusting the geometric parameters. This process resulted in a reduction of approximately 23% in the weight of the slab's concrete.

Teja et al. [6] compared the results of displacements and stresses with a solid slab of the same thickness. It was found that solid slabs present smaller vertical displacements (around 5.88% less compared to slabs relieved with hollow spheres), while the stresses are greater (6.05% increase for bending moment, 10.29% for shear and 6.43% for maximum stresses compared to slabs relieved with hollow spheres).

Hollow slabs allow for larger spans in more slender and flexible structures, but on the other hand, this can also make them more susceptible to vibrations. If these vibrations exceed regulatory limits, they can cause discomfort to users and even cause the structure to collapse.

During the lifetime of a structure, it is subject to various actions, including external excitations caused by human activity such as walking, running, jumping, and dancing. These actions are periodic and of low frequency, requiring special attention. When the frequency of these actions coincides with the natural frequency of the structure, the phenomenon of resonance can occur, amplifying vibrations and increasing stresses, which can lead to significant damage and, in extreme cases, structural failure.

When designing a structure, it is critical to consider dynamic excitations to avoid resonance. For this, it is necessary to evaluate and identify the critical natural frequencies of the slab and, if necessary, adjust the characteristics of the structure to avoid coincidence with the frequencies of dynamic loads. These adjustments may include increasing the slab stiffness or adding vibration dampers.

Lai [7] studied static and dynamic characteristics of bi-axial hollow slabs on an office floor using finite element numerical modeling. Regarding dynamic behavior, Lai [7] found that the natural frequency characteristics and vibration modes of a bi-axial hollow slab are slightly higher than a solid slab of the same thickness, confirming the similarity of behavior between bi-axial hollow and solid slabs.

Liu et al. [8] developed promising research on the dynamic behavior of precast hollow slabs. The doctoral thesis is based on a compilation of five papers, including numerical and experimental analysis to explore the structure's response to dynamic actions, such as people walking and the impact of hammers on slabs. However, the research was limited to unidirectional hollow slabs.

According to Liu et al. [9], the modeling of hollow slabs with orthotropic shell finite element generates accurate results when compared to experimental tests. Besides that, it is also a viable alternative when looking from the point of view of required computational processing power. However, it is necessary to model all the elements surrounding structures such as beams and columns and, if there is sealing masonry, the authors recommend adding their corresponding masses to the model as well.

In another paper, Liu et al. [10] numerically simulated four dynamic loading models of a walking pedestrian. The results showed that the four types of loads give numerical results that were significantly different from each other and that the modeling of a simple pedestrian walking is not an easy task, since small changes in the dynamic properties of the slab, such as natural frequencies, generate very different dynamic responses.

Varghese and George [11] compared the dynamic behavior of hollow and solid slabs under seismic actions. From the analysis of the generated stresses, they concluded that the spherical voids do not significantly affect the load capacity when seismic events are registered, whereas they can considerably reduce the amount of materials used. This also reinforces the similarity of physical behavior between hollow and solid slabs.

Regarding the bi-axial hollow slabs, the object of study of this paper, Mahdi and Mohammed [12] 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 paper uses the experimental specimen obtained by Mahdi and Mohammed [12] to calibrate our finite element numerical model.

This work aims to analyze the dynamic behavior of a bi-axial hollow slab, subjected to human excitations of jumping, dancing, clapping with the body stopped and moving, and rocking the body. The analyzed parameters are displacements, velocities, and accelerations caused by human excitations.

2. HUMAN-INDUCED VIBRATION

Over the years, researchers continuously developed works on the vibrations induced by human activity in building slabs. One of the known conclusions is that slabs with low natural frequencies and close to the frequencies of human actions can result in excessive vibrations.

When moving, people generate actions that vary in time and space in both directions: vertical and horizontal (lateral and longitudinal). However, in pavements with high in-plane stiffness, the focus of this work, the vertical variation is the most relevant, while the others can be considered negligible.

Through experimental tests, Faisca et al. [13] characterized the dynamic actions generated by human activities, such as jumps with and without stimulation, aerobic gymnastics, soccer fans, and concert audiences. Based on the obtained results, it was possible to generate an analytical model of a characteristic signal and observe that the activities studied presented the same signal form. Thus, it was possible to describe them using a semi-sinusoidal function, presented in Equation 1.

$$F(t) = \sin(\pi f t),\ \forall\, \mathrm{t} \leq \mathrm{Tc} \tag{1}$$

$$F(t) = 0, \forall\, \mathrm{Tc} < \mathrm{t} \leq \mathrm{T}$$

Where$t$ = time of the load, T_c = Time of contact with the structure, T = period. In Bachmann's work [14], human actions were characterized as periodic, and mathematical models were presented for different types of loading, such as jumping, dancing, and moving the body. The author stated that it is possible to assign a standardized dynamic force to each representative activity and to mathematically describe the function that models the rhythmic movements of the body through a Fourier series (Equation 2):

$$F_p(t) = G + \sum_{i=1}^{n} G \cdot \alpha_i \cdot \sin(2 \cdot \pi \cdot i f_p \cdot t - \Phi_i) \tag{2}$$

where G = person's weight ("fictional pedestrian" of G = 800 N), α_i = Fourier coefficient of the i-th harmonic, $G \cdot \alpha_i$ = strength amplitude of the i-th harmonic, f_p = activity rate (Hz), Φ_i= phase offset between the i-th harmonic and the 1st harmonic, i = number of the i-th harmonic, n = total number of contributing harmonics.

The Fourier coefficients α_i and, partially, the phase angles Φ_i were determined by an experimental study for human activities. In Table 1, it is possible to check the relevant values to the coefficients assigned to each representation type of activity. Furthermore, Table 1 provides the density of people commonly related to the activity [14].

Table 1. Fourier coefficients for dynamic actions [14].

Representative type of activity	Activity rate (Hz)		Fourier coefficient and phase angle					Density of the project (People/m^2)
			α_1	α_2	Φ_2	α_3	Φ_3	
Jumping	Normal	2	1.8	1.3	*)	0.7	*)	Fitness training~ 0.25 (in extreme cases up to 0.5)
		3	1.7	1.1	*)	0.5	*)	
	High	2	1.9	1.6	*)	1.1	*)	*) $\Phi_2 = \Phi_3 = \pi(1\text{-}f_pT_p)$
		3	1.8	1.3	*)	0.8	*)	
Dancing		2 to 3	0.5	0.15		0.1		~ 4 (in extreme cases up to 6)
Hand clapping with body bouncing while standing		1.6	0.17	0.1		0.04		No fixed seating ~ 4 (in extreme cases up to 6)
		2.4	0.38	0.12		0.02		Fixed seating ~ 2 to 3
Hand Clapping	Normal	1.6	0.024	0.01		0.009		~ 2 to 3
		2.4	0.047	0.024		0.015		
	Intensive	2	0.017	0.047		0.037		
Lateral body swaying	Seated	0.6	$\alpha_1/2 = 0.4$	-		-		~ 3 to 4
	Standing	0.6	$\alpha_1/2 = 0,5$	-		-		

2.1. Comfort limits

In general, Comfort limits for slab structures subjected to dynamic loads are established based on technical norms and international standards, such as the ISO 2631 norm and the American ASCE 7 norm. These standards establish limits for amplitude (displacement), speed, and acceleration experienced by the structure, in order to guarantee the comfort and safety of the users.

Bachmann and Ammann [15] did a general review of international vibrational comfort standards and recommended acceptable vibration levels for slab structures, according to ISO 2631 and 2631-1, DIN 4150, and BS 6472 standards. These standards establish comfort limits to vibrations at specific frequencies, taking human activity on the structure into account. Table 2 summarizes acceptable levels of vibrations for different types of use.

Table 2. Acceptable levels of vibrations for various uses [15].

Structure	Acceptable levels	Comments
Pedestrian structures	$a \leq$ 5 to 10% of g	Lower values usually do not produce discomfort.
Commercial buildings	$a \leq$ 2% de g	DIN 4150 and BS 6472 have values different from these
Gyms and sport	$a \leq$ 5 to 10% of g	
Dance and concert halls	$a \leq$ 5 to 10% of g	The same for the gym
Industrial floors	$v \leq \pm$ 10mm/s	For conventional industries; high-intensity industries need tighter limits

The French guide Sétra/AFGG:2006 – Technical Guide. Footbridges. Assessment of vibration behavior of footbridges under pedestrian loading [16], evaluates the level of comfort achieved in relation to the acceleration suffered by the structure, which, because of the subjective nature of the concept of comfort, it was judged preferable to define it in terms of tracks, rather than of limits. Although this is not a standard for floors but for walkways, considering that the usual external actions on walkways are the same as those for floors, the recommended limits can be used as a reference.

Table 3 defines four ranges of values, all for vertical accelerations. In ascending order, the first three levels correspond to the maximum, medium, and minimum comfort levels. The 4th level corresponds to uncomfortable and unacceptable levels of acceleration.

To ensure satisfactory behavior of structures subject to vibrations, ABNT NBR 6118:2014 [17] recommends the natural frequency of the structure (f) should be distanced as much as possible from the critical frequency (f_{crit}). The rule imposes that the condition of Equation 3 must be satisfied:

$$f > 1.2\, f_{crit} \tag{3}$$

where: f = natural frequency of the structure, f_{crit} = critical frequency for vertical vibrations caused by the action of people.

Table 3. Value ranges for vertical accelerations Sétra /AFGG [16].

Acceleration levels	0(m/s^2)	0.5 (m/s^2)	1 (m/s^2)	2.5 (m/s^2)
Level 1	Maximum			
Level 2		Medium		
Level 3			Minimum	
Level 4				Unacceptable

Regarding the displacements, ABNT NBR 6118:2014 [17] gives limit values of displacements that aim to provide adequate behavior of the structure in service. The standard also determines that the vertical displacement limit for vibrations felt on the floor, due to accidental loads, must satisfy the condition of Equation 4.

$$D \leq \frac{l}{350} \tag{4}$$

Where D = displacement and l = distance between the external and internal columns.

Besides the amplitude, velocity, and acceleration, it is also important to evaluate the frequency of vibrations. Identifying and avoiding the slab's critical natural frequencies minimizes the risk of resonance. The comfort limits for slab structures subjected to dynamic loads are important to ensure the comfort and safety of occupants.

In line with the parameters outlined in Bachmann and Ammann [15], the Steel Design Guide 11 - Vibrations of Steel-Framed Structural Systems Due to Human Activity, published by AISC [18], provides guidelines pertaining to acceleration limits in relation to rhythmic activities, which constitute the focus of this research. This guide establishes a correlation between acceleration limit values and the gravitational acceleration constant, as documented in Table 4. According to the recommendations presented, the acceptable tolerance range for accelerations perceived on the pavement varies from 4% to 7% of the acceleration of gravity, which, in absolute values, corresponds to a range of 0.39 m/s^2 to 0.69 m/s^2.

Table 4. Recommended tolerance acceleration limits for rhythmic activities in buildings [18].

Affected Occupancy	Tolerance Acceleration Limit, a, %g
Office or residential	0.5
Dining	1.5-2.5
Weightlifting	1.5-2.5
Rhythmic activity only	4-7

3. ANALYZED SLABS

This work presents a case study of a rigid reinforced concrete pavement, whose longest span is 12 m between supports, as shown in Figure 1. The design and dimensioning of the structure followed the recommendations of ABNT NBR 6118:2014 for static parameters.

The construction of the pavement under study adopted the Bubbledeck™ bi-axial hollow slab system. The choice of slab thickness followed the manufacturer's recommendation [1]. For the external span of 12 meters, the decision was to use a slab with a total height of 45 cm, which contains spheres of 36 cm in diameter, as illustrated in the detail in a generic section in Figure 2. In addition, Table 5 presents its physical properties, where HDPE (high-density polyethylene) is the material that represents the hollow part used in the research by Lay [7] and Teja et al. [6].

It is possible to notice the presence of internal holes in the slab in question, indicated by the "X" symbols in Figure 1. These holes were created to meet specific architectural needs. The black rectangles correspond to the pillars, which measure 30 x 100 cm. Most of these pillars directly support the slabs, dispensing with the need for beams. It is important to point out that slabs L1, L2, L3 and L4 are Bubbledeck™ hollow slabs.

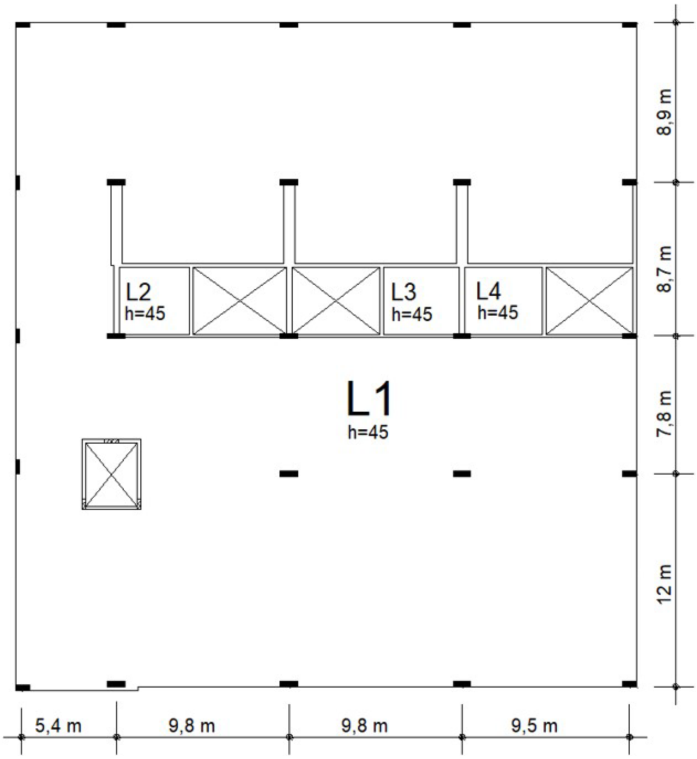


Figure 1. Floor plan of the analyzed floor.

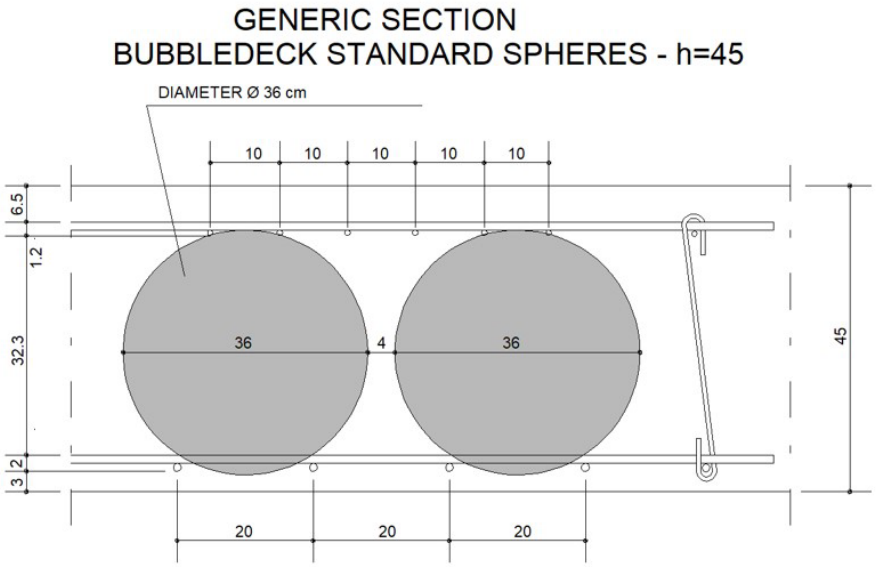


Figure 2. Detail of a generic section of the analyzed pavement, in centimeters.

Table 5. Physical properties of the materials used.

Physical properties	Concrete	HDPE (high-density polyethylene)
Compression strength (MPa)	30	20
Elastic Modulus (GPa)	24	0.827
Density (kN/m^3)	24	11.67

3.1. Numerical modeling of a hollow slab

Among a wide variety of software available and enabled to perform finite element analysis and capable of modeling dynamic characteristics and responses, this work chose the computational tool SAP2000 version 23. Both the academy and the labor market use this software due to its notorious versatility of use and reliable results [19].

Initially, four models were created to describe the dynamic behavior of a bi-axial hollow slab [19]. To evaluate which model would be more appropriate, the experimental study by Mahdi and Mohammed [12] is a reference in this work, since it analyzes a relieved slab with dimensions of (250 x 250 x 20) cm.

Model 1 was built with a linear bar element (frame), in order to create a grid, composed of beams to simulate the behavior of the specimen. The elements were built with dimensions of 20cm in height and 16cm in width, according to the spacing of the spheres of the compared specimen. The three-dimensional representation of the model can be seen in Figure 3a.

For model 2, a finite area element with 4 nodes was used, called Thin Shell by the software used, in order to simulate a massive and homogeneous slab, as illustrated in Figure 3b. In this model, we used the trick of reducing the slab's moment of inertia by 10%, as proposed by Schnellenbach-Held and Pfeffer [3], in order to cause the same effect as reducing stiffness due to the presence of spherical voids in the slab. interior of a slab relieved with hollow spheres. It is important to mention that the loading due to self-weight was entered manually.

For model 3, a variant of the Shell area element called Shell Layers was used, which allows separating a flat section into layers with different properties. This approach was adopted by Lai [7] and Teja et al. [6]. The idea was to represent the properties of the cross-section using an upper and lower layer of concrete surrounding a layer of HDPE (high-density polyethylene), which is the material used to manufacture the internal spheres. The volumetric model 3 is illustrated in Figure 3c.

Model 4 was developed using a cubic solid finite element with 8 vertices, each with six degrees of freedom, that is, three of translation and three of rotation. To represent the void of the slab relieved with hollow spheres, cubic solid units with 1 cm edges were used, allowing the hollow region of the sphere to be formed by the absence of these solid units, as shown in Figure 3d. After constructing a module, the array was duplicated repeatedly in all directions to obtain the same dimensions as the tested specimen.

The first observation that can be made is that the construction of a single module with the void of the spheres requires the stacking of 5,380 solid units with an edge of 1cm. Taking into account that hundreds of spheres are needed to model a single slab, it can be concluded that computational processing capacity is a factor that can be limiting for slabs with large spans.

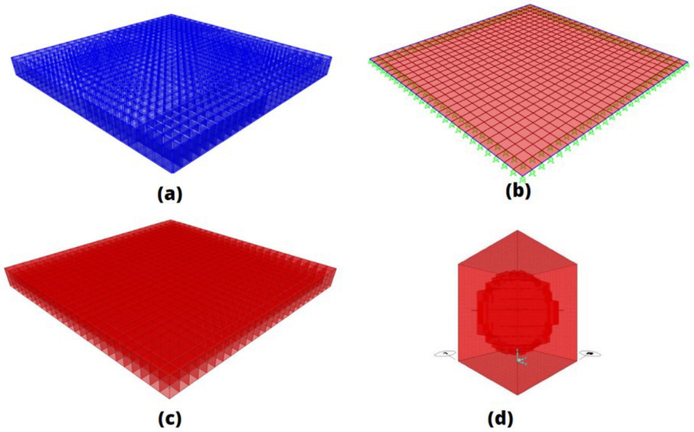

(a) (b) (c) (d)

Figure 3. (a) Model 1 – Linear Element Frame. (b) Model 2 – Element plan Shell-Thin. (c) Model 3 – Element plan Shell-Layered. (d) Model 4 – Unit of a solid element.

Table 6 shows the results of the vibration modes and natural frequencies obtained in this experiment compared with the results of the four models. This approach allowed reliably finding and calibrating a numerical model that best describes the dynamic behavior of a hollow slab with spheres inside.

The comparison of the results with the experimental model proposed in the work of Mahdi and Mohammed [12] showed that model 1 did not approach satisfactorily, deviating 43% from the natural frequency referring to the first mode of vibration. Models 2 and 3 satisfactorily approximate the specimen tested experimentally, varying by 1.34% and 0.60%, respectively, in relation to the natural frequency of the first mode of vibration. Although model 4 deviated only 1.94% from the natural frequency of the first mode, it demands a large computational processing power, which, in practice, is a limiting factor. Table 6 presents the summary of the results.

Table 6. 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	1.32	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

Thus, among the numerical approximations proposed, model 3, built with a shell-layered finite element, was the one that best approached the experimental results, in addition to not requiring a high processing power. In this model, it is possible to separate a flat section into layers and assign individual properties to each of them, so that the layer that represents the part of the material of the hollow spheres, called HDPE (high-density polyethylene), is surrounded by two layers of concrete. Figure 4 represents the cross-section of a *shell-layered* element. The blue layer represents reinforced concrete and the purple layer represents HDPE, with physical characteristics described in Table 5. In Figure 5, it is possible to observe the complete modeling of the rigid pavement, using a Shell Layered finite element.

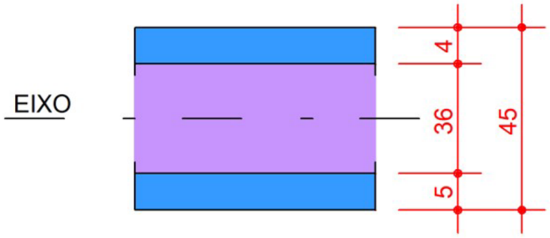


Figure 4. Cross section of the *shell-layered* slab, in centimeters.

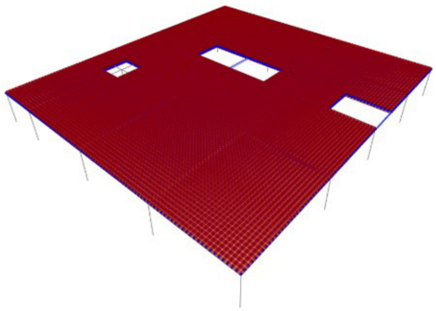


Figure 5. Three-dimensional representation of the studied rigid pavement model, using a Shell Layered finite element.

3.2. Considered loads

In this study, the load functions proposed by Bachmann [14] were employed, in accordance with Equation 1, to simulate human excitations and were applied under the slab. The loads were applied at 0.001-s intervals over 5 seconds, leading to 5.000 increments of load application across the entire surface of the slab.

Although walking is the most common activity in everyday life, this research focused on a study that encompassed a diverse range of environments, ranging from office floors to spaces dedicated to dance and physical exercise activities. This choice is justified by the need to explore situations that involve more intense and challenging rhythmic excitement. The diversity of contexts analyzed will allow for a more comprehensive and in-depth understanding of the biomechanical demands imposed on the slab in response to such actions.

Following the recommendations of the author, the considered density of people per square meter for jumping, dancing, clapping hands, and body moving cases are respectively 0.25; 4; 3; 2 and 3. The loads applied to the entire surface of the slab considered that each person weighs 800 N. This approach considers all actions produced by people in phase with each other (in sync), which represents an unfavorable situation and corresponds to the worst possible case.

Damping properties govern energy dissipation in a structure under dynamic excitation. The damping properties in reinforced concrete structures depend on the state of stress and, consequently, the level of cracking of the analyzed element. This property is defined by the damping coefficient (ζ). Table 7 shows that in a structural member with low-stress intensity (non-cracked state), the damping coefficient is small and tends to increase as the member begins to crack. When the element is fully cracked, the damping coefficient drastically decreases and stabilizes at a value lower than the non-cracked configuration.

Table 7. Damping coefficient [14]

MATERIAL	ζ
Non-cracked reinforced concrete with low-stress level	0.007 to 0.010
Reinforced concrete completely cracked, with a medium stress level	0.010 to 0.040
Completely cracked reinforced concrete, with a high level of tension, but without steel yielding.	0.005 to 0.008
Non-cracked prestressed concrete	0.004 to 0.007
Concrete with limited prestressing, slightly cracked	0.008 to 0.012
Composite materials	0.002 to 0.003
Steel	0.001 to 0.002

Due to the internal efforts observed in the slab, the material was considered as completely cracked reinforced concrete with a medium level of stress, adopting a coefficient of 0.025, which corresponds to the average of the interval between 0.010 and 0.040. To consider non-structural elements, an increase in mass due to non-structural walls was added to the system, with a specific weight of 2.3 kN/m^2.

Four nodes were chosen, called nodes 1, 2, 3 and 4, to monitor the acceleration histories, located at strategic points that correspond to the places of greatest displacements of the first mode of vibration. In Figure 6 it is possible to observe the location of the nodes. The responses to the accelerations were analyzed during the 8-second interval, as will be shown in the analysis item of this work.

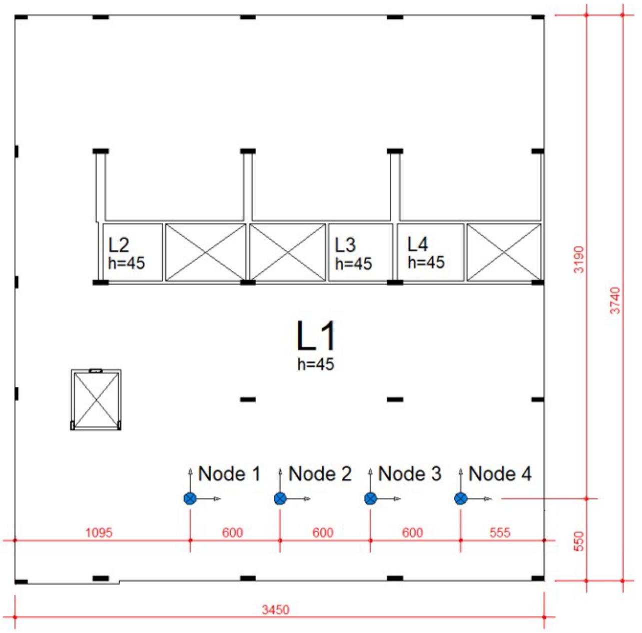


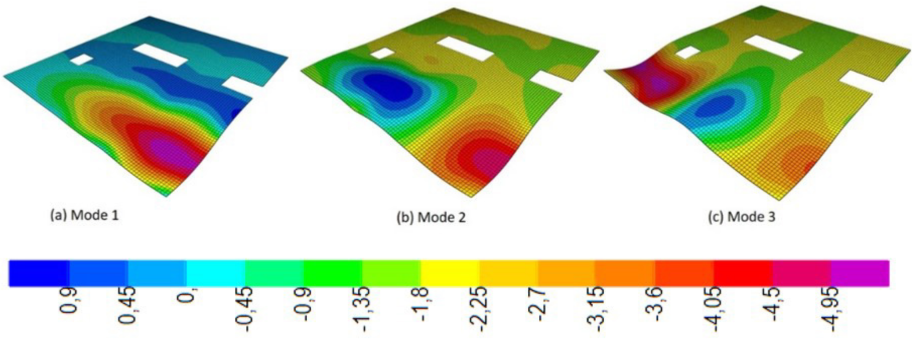
Figure 6. Location of the nodes analyzed in this work (dimensions in cm).

4. DEVELOPED ANALYSIS

4.1. Modal Analysis

Figure 7 presents the dynamic characteristics of the first three vibration modes of the analyzed pavement. Negative and positive displacements are indicated by red and blue colors, respectively. The natural frequencies corresponding to the first three bending modes are in Table 8.

According to the NBR 6118:2014 [17], the critical frequency for vertical vibrations on floors intended for offices is 4.0 Hz. In order to ensure satisfactory dynamic behavior, the natural frequency should be at least 4.8 Hz. Table 8 shows that the natural frequency relative to the first mode is only 2.37 Hz, which characterizes it as a flexible slab, subject to unwanted vibrations.


(a) Mode 1

(b) Mode 2

(c) Mode 3

Figure 7. Representation of the first three vibration modes of the analyzed pavement.

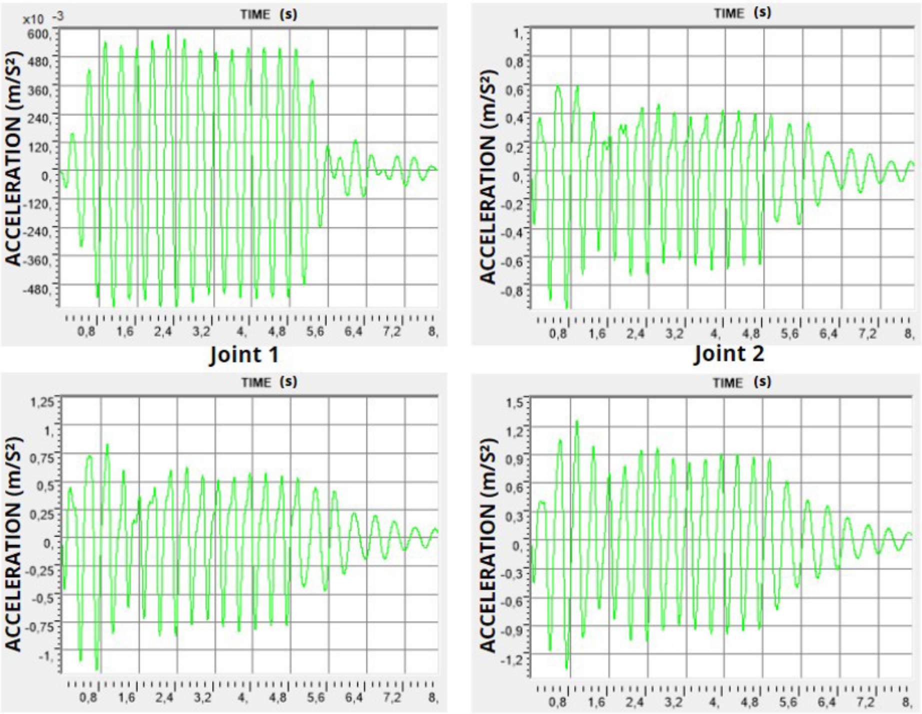
Table 8. Modal characteristics of the analyzed pavement.

Vibration modes	Natural frequency (*f*)	Period
Mode 1	2.37 Hz	0.42 s
Mode 2	2.77 Hz	0.36 s
Mode 3	3.29 Hz	0.30 s

4.2. Dynamic behavior of the hollow slab

For each node indicated above, the history of displacements, velocities, and accelerations were obtained for the actions of jumping, dancing, clapping, swinging the body, and clapping while swinging the body, with excitation frequencies of 3Hz, 2.5Hz, 1.6Hz, 0.6Hz, and 1.6Hz respectively. Figure 8 presents the variation of accelerations in time when the slab is subjected to jumping action. Table 9 to Table 13 show the maximum values found.

When analyzing the vertical displacements for the loading cases reported in Tables 9 to 13, it is observed that, in all cases, they are below 1.3 cm. Considering that ANBT NBR 6118:2014 [17] admits vertical displacements of up to 3.42 cm for spans with typologies of 12 m, it is noted that the displacements experienced meet the normative criteria. This Brazilian standard does not mention any limit for speeds or accelerations of pavements.



Joint 1

Joint 2

Joint 3

Joint 4

Figure 8. Acceleration response obtained for the 4 nodes analyzed for the jumping action.

Table 9. Maximum dynamic responses to skipping loading.

Jumping			
Node	**Displacement (m)**	**Velocity (m/s)**	**Acceleration (m/s^2)**
1	-0.00177	0.0305	0.55
2	-0.00306	0.0456	0.85
3	-0.0038	0.0598	1.16
4	-0.00456	0.0764	1.26

Table 10. Maximum dynamic responses to dancing loading.

Dancing			
Node	**Displacement (m)**	**Velocity (m/s)**	**Acceleration (m/s^2)**
1	-0.0008	0.011	0.17
2	-0.00238	0.027	0.44
3	-0.00311	0.036	0.59
4	-0.00387	0.0465	0.75

Table 11. Maximum dynamic responses to loading from clapping.

Clapping Hands			
Node	**Displacement (m)**	**Velocity (m/s)**	**Acceleration (m/s^2)**
1	0.00026	0.0025	0.04
2	0.00125	0.0088	0.134
3	0.00159	0.011	0.172
4	0.00176	0.012	0.185

Table 12. Maximum dynamic responses to loading from body swaying.

Body swaying			
Node	**Displacement (m)**	**Velocity (m/s)**	**Acceleration (m/s^2)**
1	-0.085	0.025	0.15
2	-0.0111	0.028	0.21
3	-0.0116	0.03	0.31
4	-0.0125	0.037	0.32

Table 13. Maximum dynamic responses to loading from hand clapping with body bouncing while standing.

Hand clapping with body bouncing while standing			
Node	**Displacement (m)**	**Velocity (m/s)**	**Acceleration (m/s^2)**
1	0.00026	0.0025	0.04
2	0.00125	0.0088	0.134
3	0.00159	0.011	0.172
4	0.00176	0.012	0.185

Research carried out by Bachmann [14] indicates that the maximum tolerable acceleration for floors where dancing and physical activities occur is between 5% and 10% of the acceleration of gravity "g". The author states that the maximum admissible acceleration should be limited to 5% of g. Thus, considering "g" as 9.81 m/s^2, the maximum acceleration must not exceed 0.49 m/s^2.

According to Bachmann limits [14] and the numerical results obtained in this work (Table 9 to Table 13) jumping and dancing activities exceeded the limit of 5% of g, as can be seen in a reorganized way in Table 14.

Table 14. Dynamic responses from jumping and dancing activities.

Activity	Node	Maximum Acceleration (m/s^2)	Bachman Limit (m/s^2)	Comfort level Sétra/AFGG	Steel Design Guide 11
14Jumping	1	0.55	Out of limit	Between medium and minimum	within the limit
	2	0.85			**Out of limit**
	3	1.16		**Between minimal and unacceptable**	**Out of limit**
	4	1.26			**Out of limit**
Dancing	1	0.17	within the limit	Between maximum and average.	within the limit
	2	0.44	within the limit		within the limit
	3	0.59	out of limit	Between medium and minimum	within the limit
	4	0.75	out of limit		**Out of limit**

The other cases of clapping, rocking the body, and clapping while swaying the body did not exceed the acceleration limits adopted by Bachmann [14]. The case of "jumping" is the most critical, exceeding the acceleration limit for the most critical node by 257%.

When comparing the results with the guide Sétra/AFGG [16], except for the action of jumping, it is observed that the responses indicate at least a minimum level of comfort. As evidenced by Table 13, in nodes 3 and 4 of the jumping activity, values between the minimum and unacceptable levels are observed in relation to user comfort. An effective way to reduce the sensation of acceleration felt by the user without changing external actions, such as dynamic loading produced by people, is through stiffening the slab. This can be achieved by increasing the thickness of the floor or by reducing large gaps between columns. By doing so, the natural frequencies increase, making the slab less flexible and improving its dynamic performance in the service limit state.

When comparing the maximum accelerations obtained with Steel Design Guide 11 – Vibrations of Steel-Framed Structural Systems Due to Human Activity [18], the results indicate that in the case of jumping activity, all maximum accelerations collected except those from node 1 do not meet the criteria for comfort. A similar situation is observed when analyzing dancing activity in relation to node 4.

5. CONCLUSION

This study presents the numerical modeling of a floor in a bi-axial hollow slab with long spans. Although the static criteria and deflection limit were met, dynamic comfort criteria were not satisfactory. In addition, the analysis of natural frequencies indicated that the pavement is highly flexible, which makes it more susceptible to unwanted vibrations, despite having a thickness of 45 cm.

The results obtained show that the action of jumping and dancing on the pavement causes perceptible accelerations to the users, being considered unwanted vibrations. According to the guide Sétra/AFGG [16] the nodes of the slab are located in minimum to unacceptable comfort ranges for such actions. In the worst case, jump action, there was a 275% increase in acceleration over the baseline acceleration proposed by Bachmann [14]. When comparing the results with the Steel Design Guide 11 - Vibrations of Steel-Framed Structural Systems Due to Human Activity [18] it can be seen that the accelerations recorded at node 1 corresponding to the jumping activity and those at nodes 1, 2 and 3 when considering people dancing, they satisfy the comfort criteria, remaining below 0.69 m/s^2. However, the other nodes analyzed present accelerations outside the stipulated limits, resulting in certain points in which both the jumping and dancing activities carried out by people induce responses that do not meet the established comfort standard. Thus, we can conclude that, although static parameters are met, it does not guarantee that dynamic parameters are satisfactory. This highlights the need to understand and control the dynamic parameters even in the design phase, either by increasing the thickness of the slab or by reducing the size of the spans to increase the stiffness, and consequently, the characteristics of natural modes and vibrations of the slab. This way, it is possible to make it less flexible and therefore less susceptible to unwanted vibrations.

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