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EXPERIMENTAL AND NUMERICAL DYNAMIC EVALUATION OF PROFILED STEEL DECKING SLAB IN A CONTAINER HOUSE USING MEMS

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Abstract.
The reuse of shipping containers is common in civil construction, not only for ecological reasons but also for speeding up the construction time, thus favoring the decrease in the payback time of the applied financial investment. Consequently, technological developments guarantee this trend with lighter structural elements, thus occurring natural frequencies closer to the frequency ranges of dynamic excitations associated with human activities. Therefore, a direct consequence of this new design trend is a considerable increase in problems related to unwanted vibrations in steel and concrete composite slabs, which arise from rhythmic actions, and external vibrations arising from earthquakes, which must be analysed to meet the comfort and safety of residents. Thus, this study aims to present a vibration analysis in a composite floor slab, built in steel deck 59S, of a residence built with reuse maritime containers in the municipality of Gravatá in Pernambuco, Brazil. The structure consists of three floors, with the cantilever slab analysed with dimensions of 8.24 m wide and 4.00 m long. In the experimental phase, vibration analysis was carried out through the heel impact test to obtain the natural frequencies, which had average values of 7.0 Hz, and average values of 7.14% for the damping ratio of the slab, a MicroElectroMechanical System (MEMS) was used, which are accelerometers of signals present in smartphone devices. Subsequently, using the software SCIA Engineer, the numerical analysis of the model was carried out, where usual discretization techniques were used through the Finite Element Method (FEM) to evaluate the structural behavior against dynamic actions, thus obtaining the results of natural frequencies, average values of 6.46 Hz, and modal shapes. With this, it was possible to verify the results regarding the natural frequencies of vibration, analysing the usability, comfort, and health of the structure according to the current normative codes. Finally, this study presents a comparison of modal parameters in numerical and experimental simulations against the dynamic actions that must be considered in the design of steel deck slabs when in a cantilever situation for the type of structure studied to validate comfort and building safety caused by dynamic effects developed by human behavior.

Keywords: reuse of maritime containers, vibratory system, modal analysis, natural frequency, damping.

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1 INTRODUCTION

It is notorious that construction processes are becoming increasingly modern, with the objectives of reducing costs, efficiency in construction, reducing execution time and being an ecologically friendly approach. With these topics in focus, some characteristics of new constructions became more evident, such as the overall weight reduction of the structure, due to the implementation of more modern and lighter materials in constructions, modularity, which allowed the industrialization of construction, the possibility increase in the height of buildings and the possibility of long free spans in bridges and given the proportions, in buildings [1].

With these mass reduction factors and increased supported structural lengths, it is common for structures to present lower natural frequencies, being more susceptible to excitations by dynamic loads and perceptible to human use, since human beings have high sensitivity to dynamic movements [2, 3, 4].

Structural dynamics involve the study of vibrational forces and the properties of any type of structure, with dynamic amplification as the phenomenon caused when the frequencies of this vibration have values close to the natural frequency of the structure, which should be avoided. Therefore, the participation of the mass of the building must be analyzed in relation to the degrees of freedom of the structure [5].

The processes of evaluating the dynamics of the structures, using sensors, allowed the development and optimization of the structures against the use of computational processes, which even allowed structural health monitoring (SHM)[6].

With the advancement of miniaturization of microchips, the emergence of Electro-Mechanical Systems allowed accelerometers to be miniaturized and inserted into cell phones for various purposes. Thus, it is possible to use telephone devices equipped with these systems for dynamic monitoring of structures. With this, it is possible to carry out dynamic monitoring with a smaller financial investment, when compared to traditional commercial accelerometer systems [6, 7].

Therefore, this work has the objective of verifying the dynamic behavior of the cantilevered slab of the structure using an experimental and numerical approach to obtain dynamic behavior data of the building, verifying the applicability of the reuse of maritime containers in civil construction works.

2 METHODOLOGY

This work sought to analyse the vibration characteristics of the cantilevered slab, with dimensions of $8.24\ m$ in longitudinal length and $4.00\ m$ in cantilever, composing a portion of the structure of the building, which has $313.02\ m^2$ in total area built, distributed in three floors, one semiunderground, ground floor and an upper floor, as illustrated in accordance with Figure 1a. Figure 1b illustrates the rear of the building during the construction process, likewise Figure 1c shows the east façade and Figure 1d shows us the façade west, illustrating the completion of the structural elements.

The cantilevered slab structures of a single-family residence built with the reuse of shipping containers, Figura 1, in the city of Gravatá, in the Agreste region of the state of Pernambuco, Brazil, are described as the object of study. The structure of the cantilevered slabs presents their composition according to Figure 1e, responsible as a linking element between the two upper containers, as shown in Figure 1f.

Thus, it is possible to perceive that the structure of this slab is composed partly by the floor structure of the maritime container and the other part by a composite structure, with steel deck plates supported on cold-formed profiles, connected to each other through welded connections,

(a) North facade.

(c) East facade.

(d) West facade.

(e) Structural cantilever of composite slabs.

(f) Containers locations.

Figure 1: Container house.

considered the title of this work to be rigid links.

Table 1 presents the materials used to compose the slab floors present in the building's cantilever, a portion that also connects the structure between the two upper containers.

Element	Specification	Material	Norm
Slab Beam	U-150x50x3	Cold-Formed Steel - CFS	ABNT NBR6355 [8]
Steel deck	Polydeck 59S	Profiled Steel	ABNT NBR16421 [9]
Concrete topping	$25MPa$	Reinforced concrete	ABNT NBR6118 [10]

Table 1: Slab structural specifications.

Therefore, based on the characteristics of the materials that make up the structure of the cantilevered slab, it was possible to define the mechanical properties of these elements in the elaboration of the numerical model of the analysed structure.

The methodology was constituted by two main phases of analysis of the dynamic behavior of the slabs of the structure, being an experimental phase, with local analysis to obtain the vibrations with the aid of a smartphone device using the software *MyFrequency* [11], and another numerical phase, using the commercial software *SCIA Engineer V21.1* [12], to carry out the modelling. The study was carried out on the floor structure present in the cantilevered region of the building, located on the upper floor, built with steel deck slabs supported on cold-formed profiles and another portion of the slab, made with the reuse of the floor structure of the container.

Figure 2 presents the flowchart proposed for the development of the research and obtaining the vibrational parameters of the analysed structure to obtain the results and compare them with the methodologies employed. Therefore, the structure analysis process was defined to obtain the vibrational modes of the studied slabs to identify the points of the structure that meets or does not meet the frequency characteristics available in Annex L of NBR8800:2008 [13].

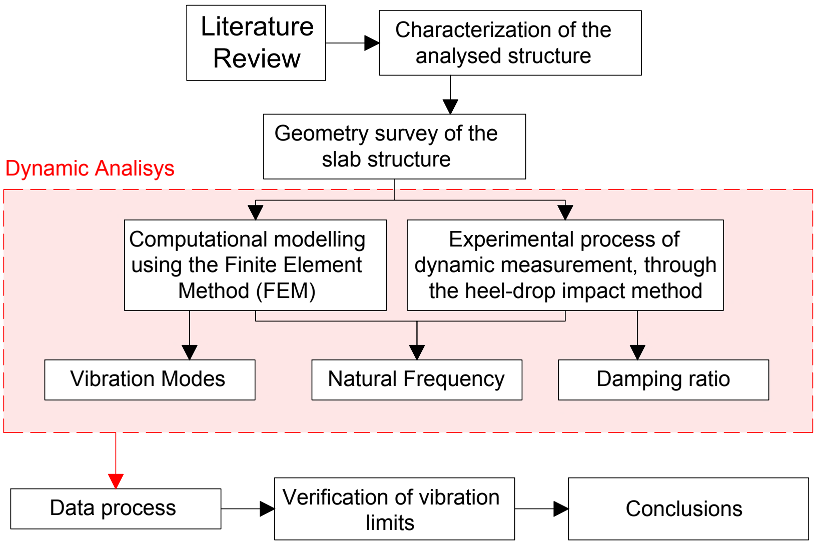


Figure 2: Metodology fluxogram.

Although there are vibration considerations in the Brazilian current, the subject is treated with simplicity and undergoes a review process; therefore it is also necessary to consider other standards and procedures of international relevance that become important for verifying the vibration parameters, such as AISC Design Guide 11 - Vibrations of steel-framed structural systems due to human activity:2016 [14] and PCI Design Handbook - precast and prestressed concrete:2004 [15].

2.1 Experimental Phase

To carry out the procedure, the flowchart defined by Figure 3 illustrates the execution process of this step. The experimental part of the work consisted of carrying out the heel impact test on the cantilevered region of the structure, at the points numbered from P1 to P5, defined in the cantilevered region, according to Figure 4, and at the points P6, P7, P8, P9, P10, P11, P12 and P13, located in other regions of building, with dimensions in mm, to excite the structure and obtain the vibrational parameters of the slab[16, 17].

Data were captured using a smartphone, model S21 Ultra from Samsung, equipped with a microelectromechanical system (MEMS) model LSM6DSO, manufactured by STMicroelectronics, with a maximum sample resolution rate of $500\ Hz$.

Therefore, with the points for carrying out the procedures defined, the region where the smartphone device would be fixed to the floor was cleaned. To perform the fixation, a double-sided acrylic tape with a resistive capacity of 180 g per meter, according to the manufacturer, was applied directly to the posterior region of the device, without the use of protective covers to reduce interference by elements in the collection of the data. Points P1 and P2 are covered with ceramic tiles, point P3 is laminated with wood and points P4 and P5 are finished with carpet.

To observe the dynamic behavior of other regions of the building, with different structural characteristics, the study regions described in points P6, P7, P8, P9, P10, P11, P12 and P13, according to Figure 5 presented other provisions of structural design. The characteristics of

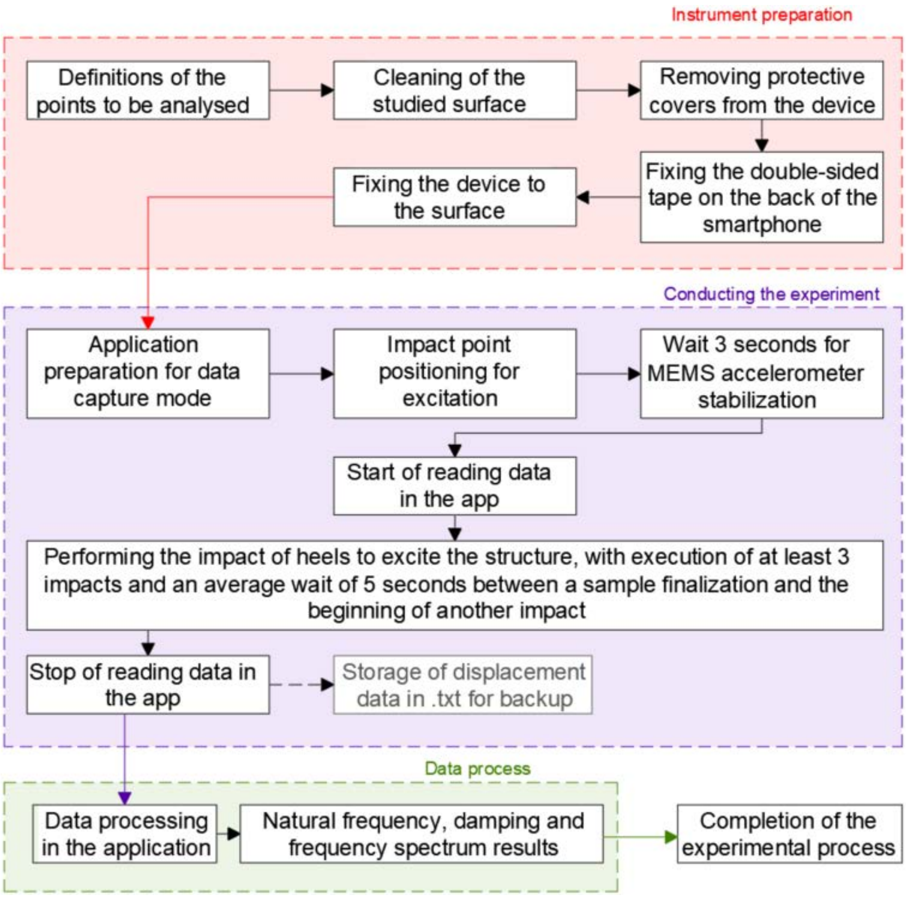


Figure 3: Experimental phase flowchart.

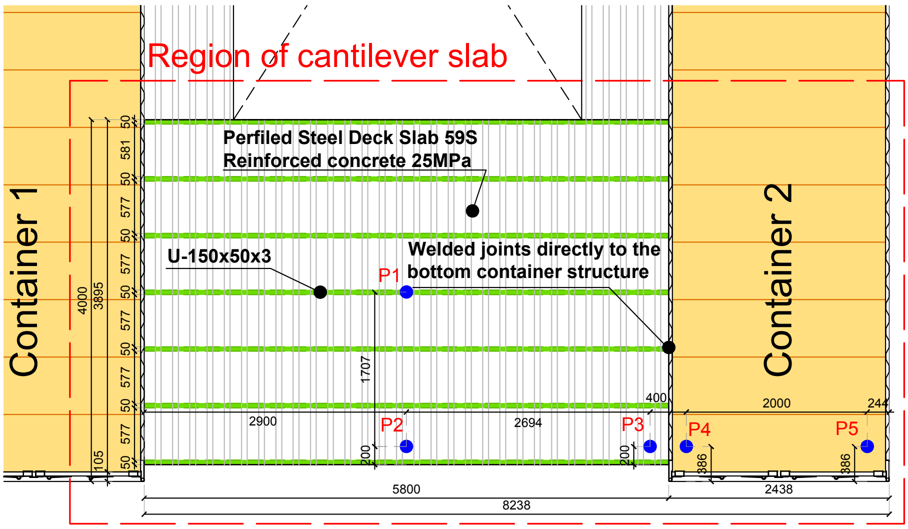
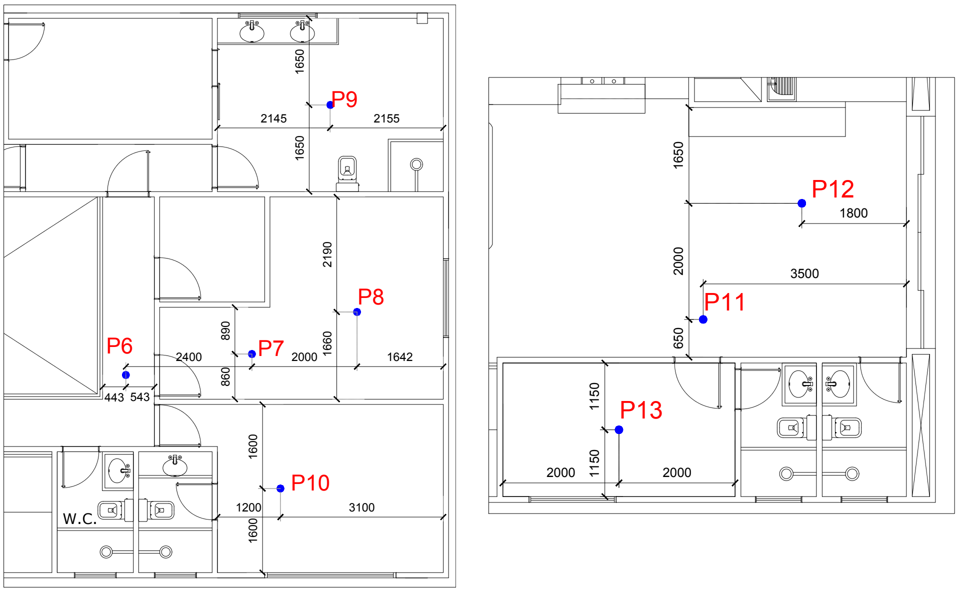


Figure 4: Analysed region of the cantilever slab.

the structural conditions of the slabs at these points are defined by different means of design, regarding the type of slab element, the type of horizontal elements and supporting conditions with support, according to Table 2.



(a) 2^{nd} floor. (b) 1^{st} floor.

Figure 5: Container house regions.

Point of analysis	Slab type	Support horizontal element	Region
P6	Steel deck	Truss - CFS	Hall
P7	Steel deck	Truss - CFS	Office
P8	Steel deck	Truss - CFS	Office
P9	Steel deck	Truss - CFS	Bathroom
P10	Steel deck	Truss - CFS	Suite 1
P11	Steel deck	I profile - laminated steel	Playroom
P12	Steel deck	I profile - laminated steel	Playroom
P13	Concrete on container floor	Container floor structure	Suite 2

Table 2: Description of the structural typology in other parts of the building.

The processing of the experimental data was performed using software developed for the Android operating system, which allowed us to calculate the damping and obtain the frequency spectrum through the fast Fourier transform (FFT).

The software used was MyFrequency, which has the ability to obtain displacement values according to the axis possibilities present in the MEMS sensor available on the device. In this case, the sensor used has the ability to evaluate three axes; however, the analysed data were restricted to the vertical displacement of the structure.

The accelerometer sensitivity was $200\ Hz$ to reduce the capture of external signals due to bad weather, local traffic and other activity dynamics present at the site that could generate excessive noise in the collected samples.

After attaching the smartphone to the point under analysis, a few seconds were waited for the calibration of the MEMS accelerometer signal, and the heel impact was performed at average intervals of 3 seconds, after returning to the resting state of the previous impact. The impact was made by a person measuring $1.65\ m$ tall and weighing 79 kg.

Through the application, during the experiment, it was possible to obtain the natural frequency in Hz, and the percentage damping values, displayed according to the variable D in the application.

The frequency spectrum was obtained through the use of the FFT, using the application, and it is possible to observe in the spectrum the variation of the frequency data obtained in the test, with values in Hz and in acceleration values, in m/s^2. With the frequency spectrum, the variation of the dynamic values in the evaluated range can be evaluated.

The measurements of the practical heel impact test underwent statistical control according to the precision intervals described by [18], in which test precision values are presented according to the coefficient of variation (D.V.C.) present in Table 3.

D.V.C.	D.V.C. Evaluation	Precision
$< 10\%$	Low	Very High
10% to 20%	Medium	High
20% to 30%	High	Low
$> 30\%$	Very High	Very Low

Table 3: Data variation coefficients.

2.2 Numerical Model

Numerical analysis was performed using the Scia Engineer V21.1 software, which uses the usual discretization techniques through the Finite Element Method (FEM). With this software, it is possible to model, analyse, dimension and optimize a three-dimensional model, regardless of the structural system and material adopted, due to the different analysis options, using Brazilian, American or European regulations. Plus, it plugs into a BIM workflow with a logical and intuitive CAD-like interface.

Based on the measurements carried out in loco, it was possible to perform preprocessing, processing and postprocessing of the structure of the container house, as shown in Figure 6.

In the pre-processing stage, the finite elements were defined for each structural component to simulate the real behavior of the structure; definition of the type (steel and concrete) and characteristics of the materials (modulus of elasticity, Poisson coefficient, characteristic compressive strength of concrete, yield strength and ultimate strength of steel, etc.); cross sections, in the case of bar elements, (e.g., C profile, W profile, angle and others); and thickness of two-dimensional components. To facilitate the visualization and distinction of each structural element in the modelling phase, layers were used, a functionality that allows the variation of colors between the modelled elements, as seen in Figure 7.

Still in the preprocessing stage, the linkages of the structural components (columns, beams and trusses) were defined; restrictions on the base supports, with clamping at the bases of the columns and other elements in contact with the ground; connections of elements and nodes, that is, interconnection between one-dimensional and two-dimensional elements that are in contact;

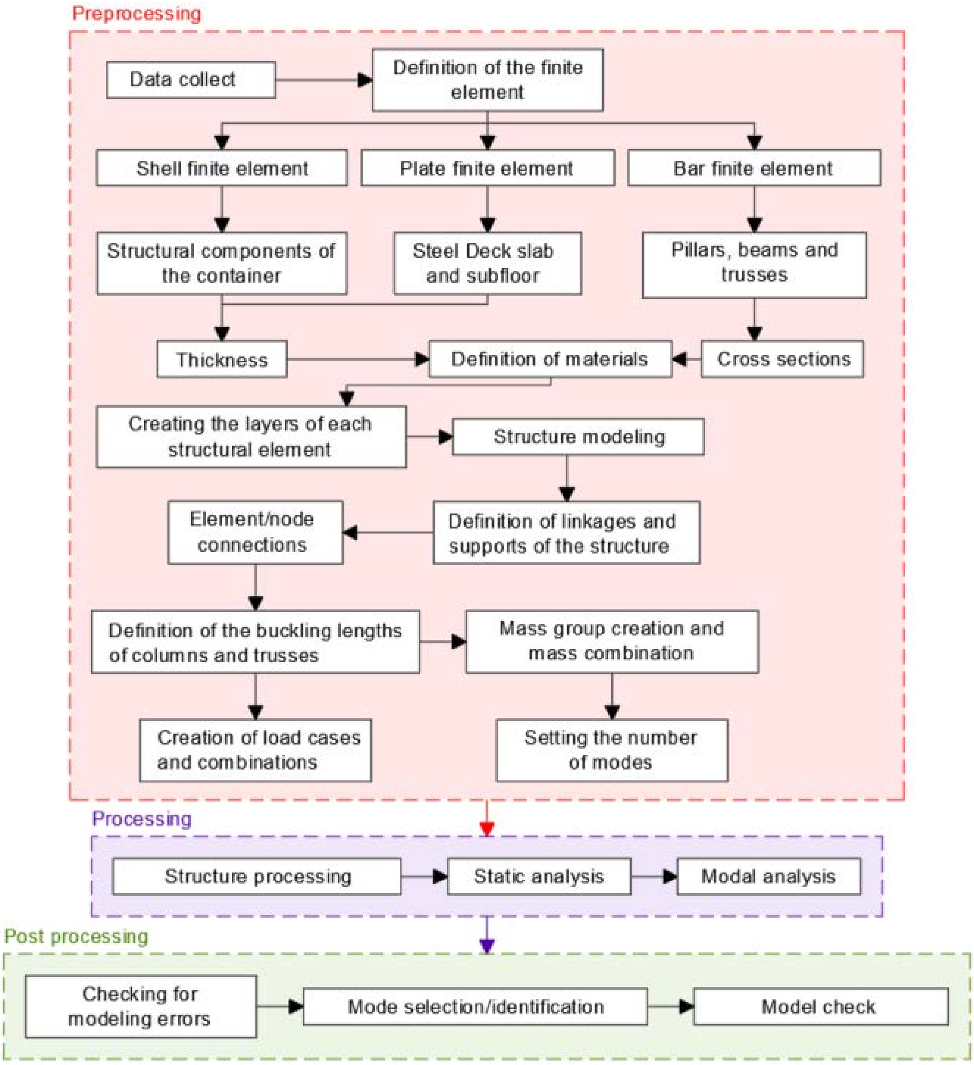
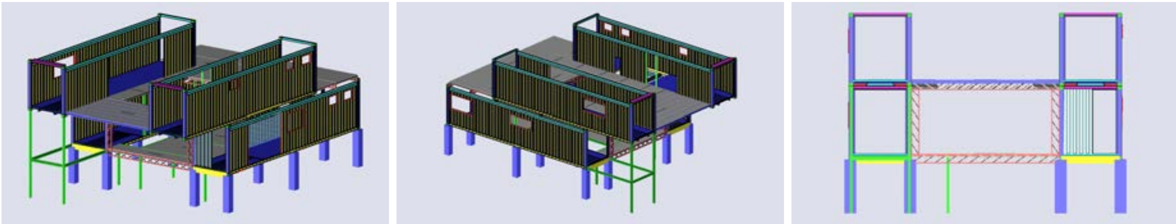


Figure 6: Numerical model flowchart.

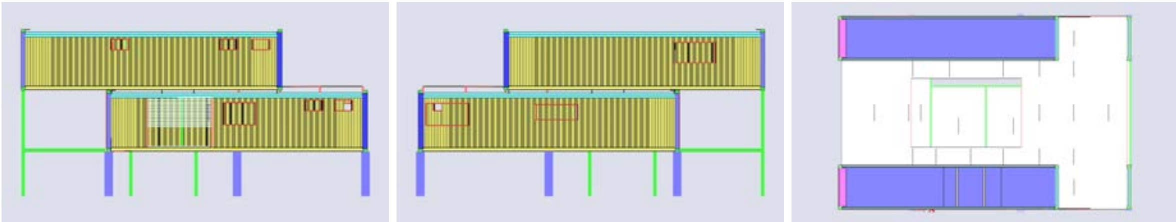
configuration of the buckling coefficients of columns and trusses. Cases of loads and combinations were also created for the static analysis phase, and groups of mass and mass combinations were created for the modal analysis phase. The last definition was the number of natural modes, which at first were processed in six ways to understand the movement of the system, and soon after, the structure was processed with thirty modes.

In the processing and postprocessing stage, the model was processed, and then a static and modal analysis was carried out. The first analysis was carried out with the objective of verifying the modelling errors and guaranteeing the functioning of the structure in accordance with the real one. In the modal analysis, the identification and selection of the important vibration modes for the analysis were performed. To obtain the results of the analysis, 80423 two-dimensional elements, 2810 one-dimensional elements and 65257 nodes were used.

It is worth mentioning that in view of the analyses carried out, it can be seen that the Steel Deck slabs, modelled on the ground and upper floors outside the perimeter of the containers, were not following the movement of the support elements, which was found that the assigned plate element behaved like a rigid diaphragm, so a modification was made to the FEM model.



(a) Isometric model 1. (b) Isometric model 2. (c) Front view.



(d) West view. (e) East view. (f) Upper view.

Figure 7: Container house FEM model.

3 RESULTS AND DISCUSSION

After carrying out the processes proposed by this work, this section will present the results and their respective discussions of the numerical and experimental models to compare the results obtained between the two methodologies and verify the usability conditions of the studied structure.

3.1 Experimental Dynamic Results

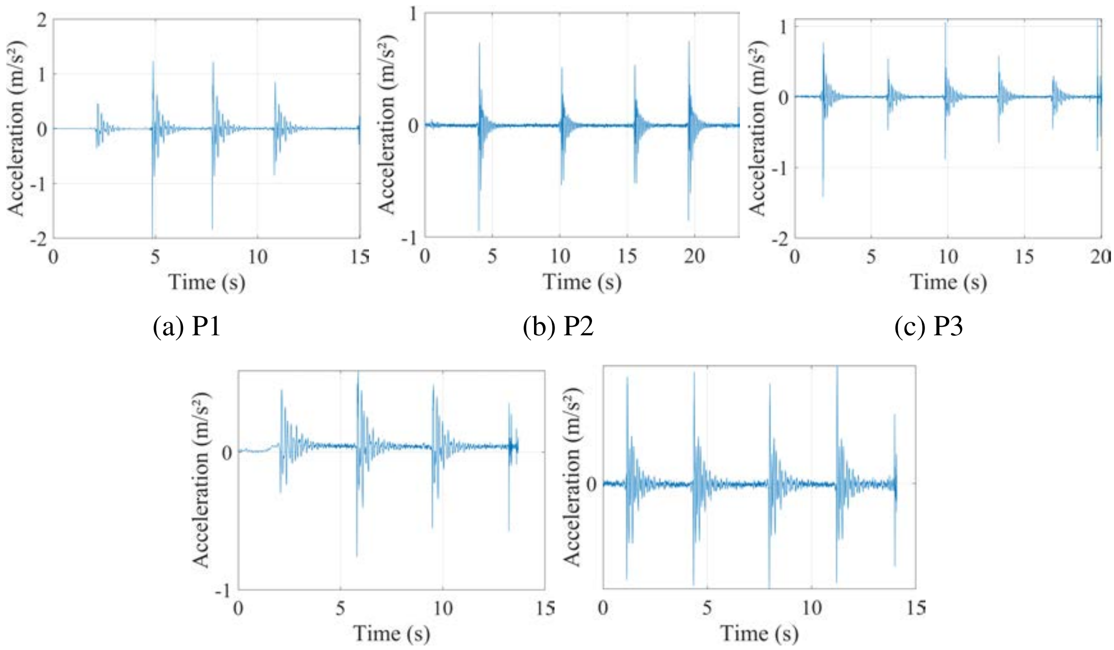
The experimental phase obtained displacement data after the heel impact test, which were recorded and processed at points distributed throughout the building. Figure 8 shows the values obtained for the analysis of points P1, P2, P3, P4 e P5, showing the accelerations in m/s^2 caused by each impact as a function of time.

Table 4 presents the data obtained for each of the analysed points on the cantilevered floor slab, presenting the frequency values and the damping rate of the floor. Additionally, the average values were calculated, as well as the standard deviation of the collected samples.

The acceleration results presented in the graphs shown in Figure 9, correspond to the analysed points on the upper floor of the building, outside the cantilever region, located in previously described rooms.

The processing of data from points P2, P3, P6, P7, P8, P9 and P10 showed average frequency and damping values according to Table 5. Some of these points, P6 in particular, showed high damping values, obtained through the average of the samples. Some factors internal to the structure can influence the data obtained, such as movements between structural elements, internal material dissipation, and supports. Other external, nonstructural factors may also have had an influence, such as furniture and the drywalls[19]. The energy dissipation is caused by material damping which basically depends on three factors: amplitude of stress, number of cycles and geometry. In the case of nonhomogeneous stress distribution the geometry of the structure influences the vibration damping [21, 20].

Figure 10 shows the displacement points recorded on the ground floor of the building. The processing of data from points P11, P12 and P13 showed average frequency and damping values



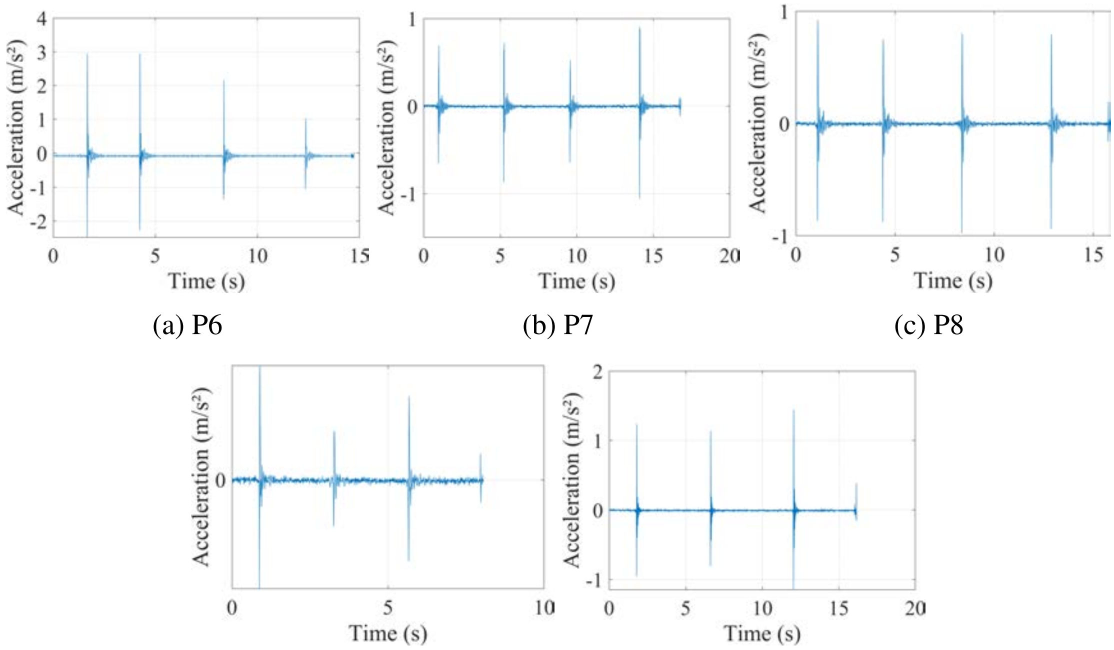
(a) P1 (b) P2 (c) P3

(d) P4 (e) P5

Figure 8: Accelerations recorded on the cantilevered slab in the heel impact test.

Analysed Point	Sample	Frequency (Hz)	Damping Ratio $(\%)$	Average Frequency (Hz)	Average Damping Ratio $(\%)$
	1	10.8	3.53		
P1	2	10.8	3.52	10.77	3.48
	3	10.7	3.4		
	1	7.1	9.25		
P2	2	7.2	7.32	7.10	8.29
	3	7.1	7.99		
	4	7.0	8.61		
	1	7.1	9.25		
P3	2	7.2	7.32	7.10	8.29
	3	7.1	7.99		
	4	7.0	8.61		
	5	7.0	8.61		
	1	7.2	4.21		
P4	2	7.2	4.38	7.10	3.99
	3	6.9	3.39		
	1	11.1	3.18		
P5	2	11.1	2.73	10.95	2.88
	3	11.0	2.49		
	4	10.6	3.12		

Table 4: Frequency and damping values of the analysed points of the cantilevered slab.



(a) P6 (b) P7 (c) P8

(d) P9 (e) P10

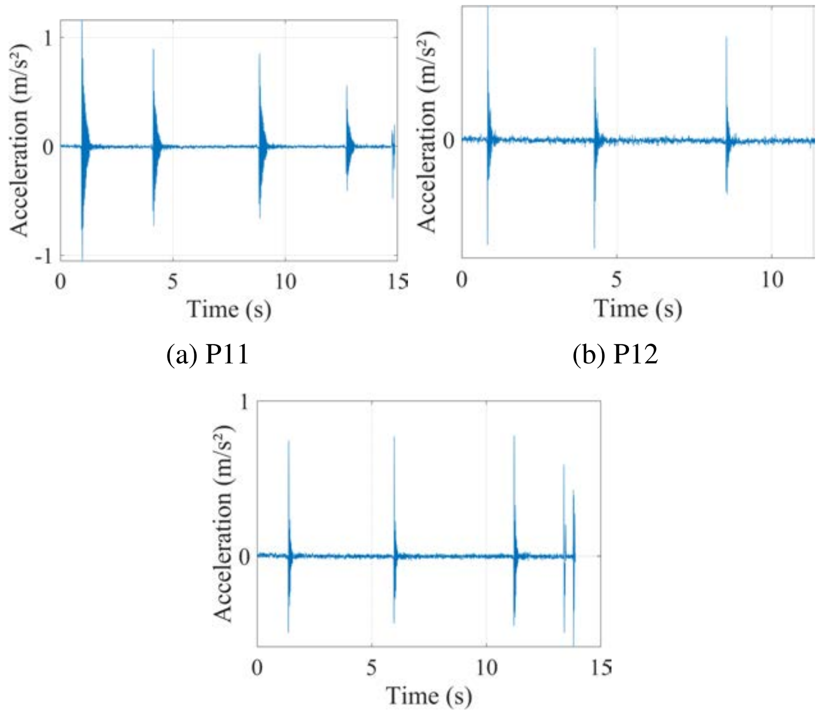
Figure 9: Accelerations on the posterior part of the 2^{nd} floor in the heel impact test.

Analysed Point	Sample	Frequency (Hz)	Damping Ratio $(\%)$	Average Frequency (Hz)	Average Damping Ratio $(\%)$
	1	11.0	25.5		
P6	2	10.6	27.56	10.80	23.94
	3	10.3	17.91		
	4	11.3	24.79		
	1	11.4	8.06		
P7	2	11.5	8.76	10.98	9.22
	3	10.4	9.84		
	4	10.6	10.23		
	1	14.4	8.08		
P8	2	14.2	7.18	14.25	7.82
	3	14.3	8.34		
	4	14.1	7.67		
	1	17.1	7.44		
P9	2	17.3	8.09	17.30	7.36
	3	17.5	6.55		
	1	23.7	10.58		
P10	2	23.4	13.19	22.83	11.53
	3	21.4	10.81		

Table 5: Frequency and damping values of the points in the posterior region of the 2^{nd} floor.

according to Table 6.

To verify the precision of the sample results, Table 7 presents the evaluation of data precision



(a) P11 (b) P12

(c) P13

Figure 10: Accelerations on the 1^{st} floor in the heel impact test.

Analysed Point	Sample	Frequency (Hz)	Damping Ratio ($\%$)	Average Frequency (Hz)	Average Damping Ratio ($\%$)
	1	28.6	4.61		
P11	2	29.4	4.69	29.15	4.58
	3	28.8	4.35		
	4	29.8	4.68		
	1	35,0	4.64		
P12	2	35.8	4.74	35.37	4.53
	3	35.3	4.22		
	1	37.8	5.51		
P13	2	38.1	6.77	38.40	6.29
	3	39.3	6.59		

Table 6: Frequency and damping values of the points in the posterior region of the 1^{st} floor.

according to the coefficients of variation of the data.

The results obtained in the experimental model showed similar values in all observed regions of the floor made of steel deck and cold-formed profiles, consisting of points P1, P2 and P3, and in point P4, which already presents an analysis inside the container in balance. Point P5 presented a sampling frequency above 10 Hz, indicating greater rigidity in this studied point of the structure.

Therefore, after summarizing the experimental results, it is possible to identify some important points in the analysed regions:

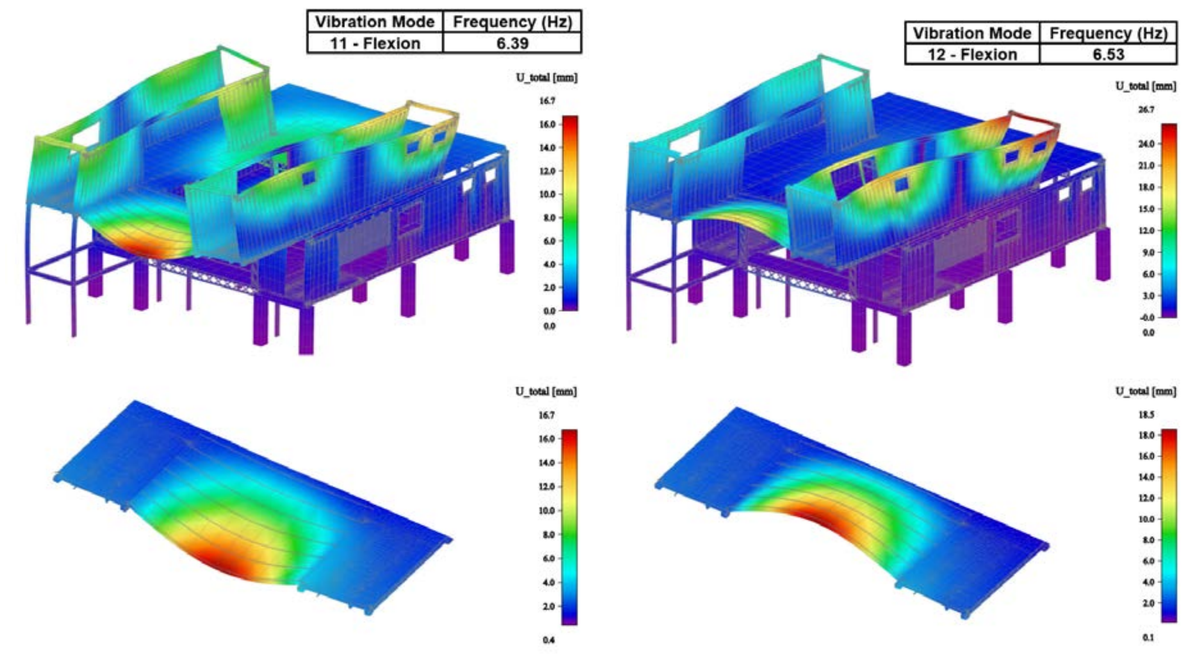
Analysed Point	Average Frequency (Hz)	Average Damping (%)	D.V.C Frequency	Ratio Damping
P1	10.77	3.48	0,54%	1,70%
P2	7.10	8.29	1.15%	8.64%
P3	7.16	6.88	4.14%	9.29%
P4	7.10	3.99	2.44%	10.82%
P5	10.95	2.88	2.17%	9.85%
P6	10.80	23.94	4.07%	15.15%
P7	10.98	9.22	5.07%	9.33%
P8	14.25	7.82	0.91%	5.61%
P9	17.30	7.36	1.16%	8.58%
P10	22.83	11.53	5.48%	10.24%
P11	29.15	4.58	1.89%	3.01%
P12	35.37	4.53	1.14%	4.97%
P13	38.40	6.29	2.07%	8.85%

Table 7: Results and accuracy rate.

- The points described by the cantilever region showed low frequency in the edge regions, with an increase in the natural frequency when approaching the support of the slab, described by point P1;
- The cantilevered region of the container structure has a lower frequency in the connection region with the cold-formed profile slab composition, point P4, showing an increase in the frequency obtained in the corner region, described by point P5. This phenomenon may indicate a possible influence of the cantilevered slab made with a cold-formed profile on the shell element with container;
- The rear region of the property on the second floor, described by points P6, P7, P8, P9 and P10, presented frequencies above 10 Hz, which may indicate increased rigidity in the region. However, high values were also noticed in the damping data, which may indicate that the structure has a complex design, due to the wide variety of materials used in the structure, in floor coverings and their interactions with each other. Loads of use, such as furniture, can also be a factor that influenced these results, as well as the disposition of the nonstructural closing elements, the drywall panels, made with aluminum profiles, drywall boards and internal filling with foam of expanded polypropylene;
- The rear region of the property on the first floor, described by points P11, P12 and P13, also showed frequencies above 10 Hz, indicating high rigidity. The structural configuration of this region was elaborated with laminated steel profiles between the union of the containers, indicated according to points P11 and P12, with a significant increase in the central region of the floor, point P12. Point P13 determines the floor region where the container structure was used, without changing the original shape, presenting a high degree of rigidity, due to the high frequencies.

3.2 Numerical Model Results

After defining, modelling and dimensioning the numerical model of the structure, it was observed that within the possibilities of floor bending, in the range of thirty modes obtained, two modal conditions presented deformation behavior according to the deformations induced by the experiment, displayed in Figure 11.



(a) Mode 11 - Flexion

(b) Mode 12 - Flexion

Figure 11: Slab deformation modes through the numerical model.

The deformation of the floor occurs in the vertical axis of the structure, as evaluated in the experimental phase of the study. It is also possible to identify that the model presented a greater deformation of the steel deck slab element with cold formed profiles.

The observed vibration modes also exhibited a response regarding the deformation of the structure panels; however, experimental verifications of this behavior were not carried out.

The biggest challenge found in numerical solutions in dynamic behavior is the difficulty of obtaining and inserting real data from the analysed structure. Several factors can influence the dynamic results of a structure, such as the actual mass installed in the structure, contemplating precise loads of coatings, walls and furniture. It is also worth noting that special factors may vary in real situations, such as the wear and tear of the building due to redox over the years since its conception.

3.3 Comparison

The results obtained through the two approaches used in this article for points P1, P2, P3, P4 and P5 can be found in Table 8.

Due to the amount of modal analyses carried out in the numerical model, it was not possible to identify the behavior of vertical bending in floor slabs for the regions delimited by points P6, P7, P8, P9 and P10, on the 2^{nd} floor, and the same goes for points P11, P12 and P13, present on the 1^{st} floor of the building, which have experimental data of very high frequencies, characterizing themselves as rigid elements. However, it is perceived that the numerical and experimental models coincide in the observed points with a lower frequency, that is, in the points where the greater deformation of the structure was presented.

Analysed Point	Experimental Frequency	Numerical Frequency Mode 11	Mode 12	Percentage Similarity Mode 11	Mode 12
P1	10,77			59%	61%
P2	7,10			90%	92%
P3	7,16	6,39	6,53	89%	91%
P4	7,10			90%	92%
P5	10,95			58%	60%

Table 8: Comparison of frequencies between numerical and experimental models.

4 CONCLUSIONS

The adoption of structures in maritime containers can be a satisfactory alternative for use in civil construction; however, it is important to observe some dynamic requirements on the floor to comply with current regulatory standards.

The dynamic characteristics on the floor have already been studied by several authors who contributed their research to the study of the area [22, 23, 24]. Among the possible conclusions in this study, it is possible to highlight the following:

- The experimental model presented results similar to those dimensioned in the numerical model through the finite element method (FEM). By observing vibration modes 11 and 12, it was possible to excite the structure to collect data in the experimental phase, including following the frequency variation curve studied between points P1 and P5;
- The cutouts made in the panels that make up the container enclosures can affect their performance in terms of use as a structural element in buildings. Therefore, static and dynamic behavioral studies are pertinent to verify the resistive alterations of these elements;
- Annex L of ABNT NBR8800:2008 considers limits for the natural frequencies on floors depending on the use of the floor region, which may affect activity restrictions on the slab in a free bludger, as the standard does not recommend intense rhythmic activity for slabs with a natural frequency below $8\ Hz$, for maximum vertical displacements of $5mm$ in the support structures, in accordance with the conditions provided in topic 4.7.7.3.3 of this same standard. Therefore, considering that some human activities, such as walking, rhythmic and aerobic activities may not be recommended due to the natural frequency of some slabs;
- According to Steel Design Guide Series n°11 and its approach parameters regarding the flexion of the floors, it is possible to assume that the cantilevered floor presents itself as flexible, since it has sample values below $9\ Hz$ in some regions;
- The structure of the container floor itself showed satisfactory rigidity for use with residential purposes; however, the floor structures and connection between the modules of the containers can influence the structural behavior of the containers, presenting considerable flexibility;
- It is recommended for future work to consider the roof structure to analyse the influence of this element on the conditions of vibration modes of the structure, with details of the model currently built;

- It is proposed for future studies to increase the analysis of structure vibration modes to investigate the structure flexion modes for higher frequencies that may coexist with the frequencies of other regions of the building analysed in the experimental phase;

- The damping factors obtained with the experimental phase showed great variety along the points analysed through the global structure, and the factors that can influence the damping rates are numerous and varied, being linked or not to the components of structural design. Therefore, it is suggested for future work a more in-depth analysis of the structural elements used to make the structure of the property, the methodology of connections between laminated, cold-formed elements and the structure of the container, as well as loads due to furniture and coatings present in these regions.

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