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Human Comfort Assessment of Buildings Considering the Effect of the Masonry Infills and the Soil-Structure Interaction

J.C. Mota Silva[1], L. de Souza Bastos[1], J.G. Santos da Silva[2]*

1 D.Sc., Student, Civil Engineering Postgraduate Programme (PGECIV), State University of Rio de Janeiro (UERJ), Rio de Janeiro/RJ, Brazil
2 Full Professor, Civil Engineering Postgraduate Programme (PGECIV), State University of Rio de Janeiro (UERJ), Rio de Janeiro/RJ, Brazil

Corresponding author: *jgsantosdasilva@hotmail.com*
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ABSTRACT

The increase in slenderness of building projects has been crucial for reducing the natural frequency values, causing excessive vibration problems. Two other important aspects, generally disregarded in the current design practice are related to the effects of the masonry infills and the soil-structure interaction. This research work aims to develop an analysis methodology to evaluate the human comfort of buildings subjected to the wind nondeterministic dynamic actions. This way, the dynamic behavior of a 16-storey reinforced concrete building, 48 m high and dimensions of 15.0 m by 14.2 m is investigated. Numerical models with different characteristics were developed to obtain a more realistic representation of the system, based on the Finite Element Method (FEM), through the use of the ANSYS program. The results have indicated relevant quantitative differences when the dynamic structural response of the building was analysed, such as the significant reduction on the horizontal translational displacements and peak acceleration values, when the effects of the masonry infills and the soil-structure interaction were considered.

1. Introduction

Technological advances linked to a favourable economic scenario have in recent years promoted the construction of tall buildings in several countries, such as the United States, and more

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recently, some of the Asian countries, like China, Malaysia and the United Arab Emirates. This architectural trend with the use of slender structural systems results in buildings with very low natural frequency values and thus more susceptible to problems of excessive vibration and human discomfort [1–3].

In this context, two factors that exert a great influence in conjunction with a random wind action on tall buildings are: the consideration of the effect of stiffness masonry infills and the consideration of the effect of soil-structure interaction [2,3].

Masonries are structural elements that compose buildings and other constructions, filling most of the empty areas inside the porches. The common practice of calculation offices is the adoption of their loads as static, thus disregarding the influence that their arrangement on the building promotes the stiffness of the structure. "The masonry-filled frames have much higher stiffness to horizontal loads compared to empty frames [4]".

Over the past few years, several research works have been developed aiming to show the importance of masonry infills in the overall behavior of the buildings [5–8]. Based on dynamic monitoring investigations, it is possible to verify that the consideration of masonry infill has a considerable influence on buildings dynamic behaviour as its mass and stiffness change characteristics as natural frequencies, mode of vibrations and damping ratios of the building. The non-consideration of masonry infills in numeric models may result in incorrect analyzes due to poor fidelity with the real model. Another important aspect to consider is associated to the increase in lateral stiffness of the building structural frame with the masonry infill [5–8].

The soil has great complexity due to the varied characteristics such as heterogeneity, anisotropy, nonlinear behavior between force and displacement and property change with varying amount of water in its constitution. Consideration of soil-structure interaction over foundations can promote to considerable differences in building calculations. Hence, due to the dependence between these elements (soil and structure), the importance of obtaining through the numerical analysis the effects of this interaction is observed [2,9].

The studies by [10,11] address the effect of considering soil-structure interaction on the seismic response of structures, regarding the importance of its analysis and consideration in projects. According to [10], the effect of soil-structure interaction has conventionally been beneficial on a structure's seismic response, and design codes allow a reduction in the seismic coefficient due to its consideration or suggest that it be ignored. The usual reasoning given in this regard is to consider that the structure becomes more flexible, increasing its natural period and improving its effective damping rate. Design conditions are found where necessary and others where the effects of soil-structure interaction can be suppressed.

According to [11], the evaluation of the effect of soil-structure interaction on seismic risk is performed by calculating the probability distribution of seismic loss for fixed and flexible base structures. The analyzes find the probabilities for which soil-structure interaction is beneficial, uninfluenced or detrimental to various structures. In short, the results for buildings on very soft soils are aligned with the common belief that soil-structure interaction is a favourable effect.

However, results for buildings on moderately soft soils reveal a considerable likelihood, up to 0.4, that this effect will have adverse structure reactions and increase seismic losses.

Wind loads generally applied to structural designs are of purely static nature. As these loads represent a typically dynamic excitation, this consideration needs further investigation. Having in mind that the wind dynamic actions are associated with nondeterministic or random loadings, a statistical treatment that adequately represents wind actions on buildings has to be performed [2].

A reliable human comfort assessment depends on the correct description of the wind dynamic loads when compared with studies of natural wind. Currently the construction of tall and slender buildings to meet the demand of population growth and the reduction of free spaces in urban areas has resulted in relevant structural problems related to excessive vibrations and human discomfort caused by the dynamic characteristics of the wind. Because of that, it became imperative to study the interaction between wind and tall buildings, in order to improve structural designs avoiding possible future service limit state problems [12–16].

Although vibrations caused by the wind in most current design situations do not present risks related to the structural collapse, this kind of dynamic action can cause human discomfort. According to occupant surveys and motion simulators, it is well known that people can develop the sensation of tiredness, low motivation, distraction from work activities and low mood, when subject to wind-induced vibrations [12–16].

This research work approaches the study of the dynamic structural response of buildings, when subjected to nondeterministic wind action, considering the effect of masonry infills. Thereby, throughout the dynamic analysis, it will be used as a base the design of a reinforced concrete building, with a height of 48 m, consisting of 16 floors and plant dimensions of 15.0 m by 14.2 m. The numerical modelling of the building will be done using the Finite Element Method (FEM), on the program [17]. The dynamic structural response (natural frequencies, displacements and accelerations) will be evaluated and compared with the limit values observed in standards and technical design recommendations, aiming to verify the service limit states and the human comfort of the building.

2. Nondeterministic wind mathematical modelling

Wind properties are unstable, have a random variation and therefore their deterministic consideration becomes inadequate. However, for generation of nondeterministic dynamic load time series, it is assumed that the wind flow is unidirectional, stationary and homogeneous. This implies that the direction of the main flow is constant in time and space and that the statistical characteristics of wind do not change during the simulation period is performed [18].

In this investigation, dynamic wind loads are calculated by the sum of two parcels: one turbulent parcel (nondeterministic dynamic load) and another static parcel (mean wind force). The turbulent part of the wind is decomposed into a finite number of harmonic functions with randomly determined phase angles. The amplitude of each harmonic is obtained based on the use of a Kaimal Power Spectrum function, as illustrated in Figure 1.

This works adopts the Kaimal Power Spectrum because it considers the influence of the height of the building in the formulation [19]. The energy spectrum is calculated using equations (1) and (2), where f is the frequency in Hz, S^V is the spectral density of the wind turbulent longitudinal part in m²/s, x is a dimensionless frequency, Vz is the mean wind velocity relative to the height in m/s and z is the height in meters. The friction velocity $u*$, in m/s, is obtained using equation (3), with Karmán k constant. The turbulent part of wind velocity is simulated based on a random process obtained from a sum of a finite number of harmonics, equation (4), where N corresponds the number of power spectrum divisions, f is the frequency in Hz, Δf is the frequency increment and θ is the random phase angle uniformly distributed in the range of [0-2π].

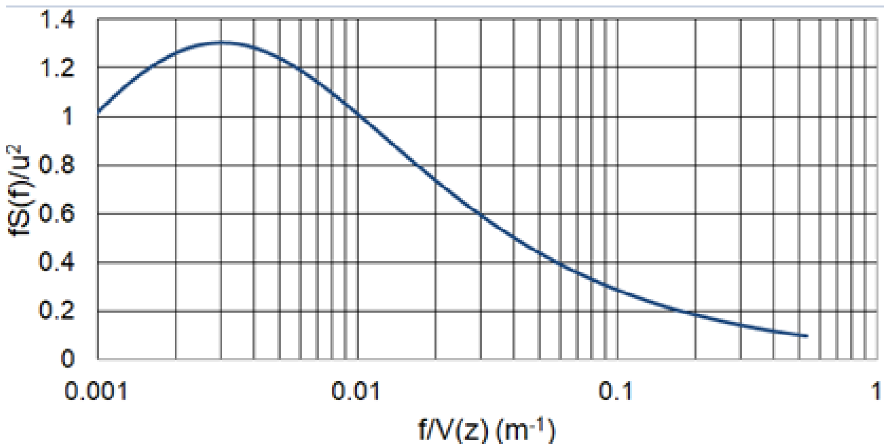


Fig. 1. Kaimal Power Spectral Density.

$$\frac{f\,S^V(f,z)}{{u_*}^2} = \frac{200x}{(1+50x)^{5/3}} \tag{1}$$

$$x(f,z) = \frac{fz}{V_s} \tag{2}$$

$$u_* = \frac{k\overline{V}_Z}{\ln(z/z_0)} \tag{3}$$

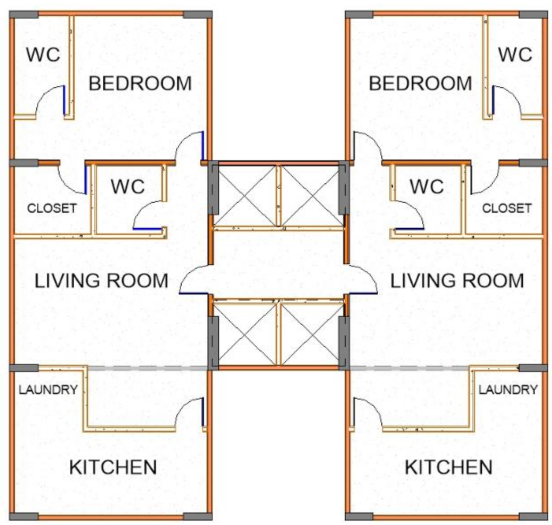
$$v(\mathrm{t}) = \sum_{i=1}^{N} \sqrt{2S^V(f_i)\Delta f}\,\cos(2\pi f_i t + \theta_i) \tag{4}$$

3. Reinforced concrete building: design and structural model

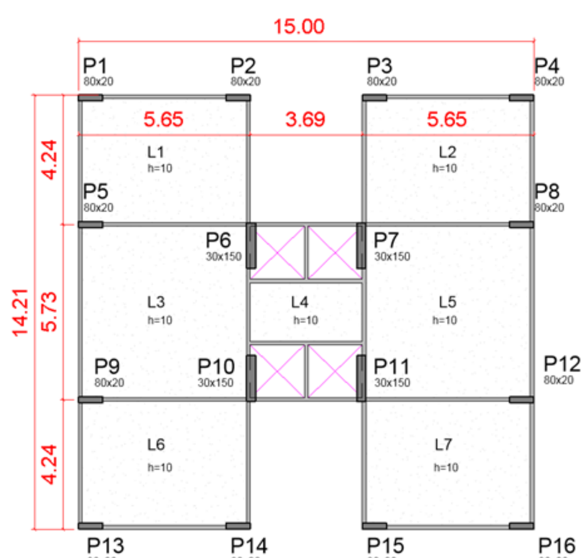
The building investigated in this research work presents rectangular dimensions of 15.0 m by 14.2 m, 16 floors, with a height of 3.0 m, with a total height of 48 m, as shown in Figure 2. The reinforced concrete structure of the building consists of massive slabs with a thickness equal to 10 cm, beams with 12 by 50 cm sections and columns with section dimensions: 20 by 80 cm and 30 by 150 cm. The building is residential, with two apartments per floor, four elevators, located in the city of Rio de Janeiro/RJ, Brazil [2].

The architectural design of the building shown in Figure 2 used 14.5 cm thick walls, 2.5 m high for beamed walls and 2.90 m for slab-supported walls. The masonry used is of infill type, ceramic and laid with cement and sand mortar. The longitudinal modulus of elasticity of the masonry was obtained through experimental tests performed by [20], with a value of 5.82 GPa. The concrete has a compressive strength (fck) equal to 25 MPa, a Young's modulus (E) equal to 23.8 GPa and Poisson's ratio (v) equal to 0.2.

Two structural models were developed in this work, see in Figure 3. Model 1 (M1) consists only of the basic system of the building's reinforced concrete structure (beams, slabs and columns) with the foundations (blocks on piles), considering the soil-structure interaction effect. On the other hand, the Model 2 (M2) presents the same structural system as Model M1, but the masonry infills were considered in the modelling, aiming to evaluate the global stiffness of the building.



a) Building floor architecture.



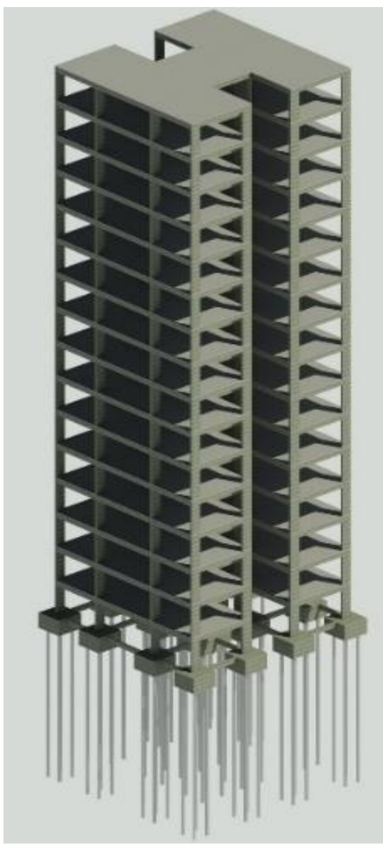
b) Floor structural plan (units in meters).

Fig. 2. Investigated reinforced concrete building.

4. Finite element numerical modelling

The proposed numerical model, developed for the dynamic analysis of buildings, adopted the usual mesh refinement techniques present in the Finite Element Method (FEM) simulations, implemented in the ANSYS program [17], see Figure 4. In both models the foundations are modelled by means of blocks supported by concrete piles.

In the numerical models M1 and M2, the beams, columns and piles were simulated based on the use of BEAM44 three-dimensional finite elements, in which the bending and torsion effects are considered. Concrete slabs and masonry infills were represented based on the use of the SHELL63 finite element. The foundation blocks were discretized based on the use of the SOLID45 element.



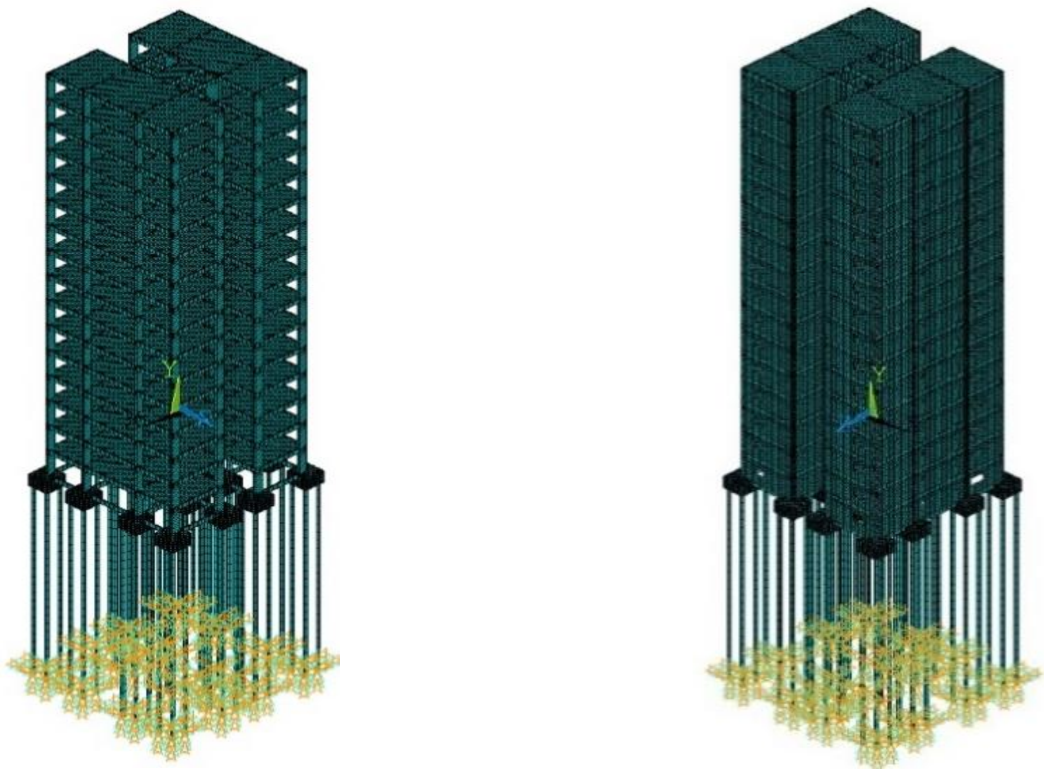
a) Model M1: without masonry infills.

b) Model M2: with masonry infills.

Fig. 3. Structural models of the building consisting of sixteen floors: Models M1 e M2.

It must be emphasized that to simulate the horizontal resistance of the soil imposed on the concrete piles, the BEAM44 element was utilised, considering the calculated horizontal stiffness for the soil. The soil representation was based on Winkler's theory [21]. This theory simulates the soil behaviour as a group of independent springs governed by a linear-elastic model. In Winkler's model, soil stiffness is considered to be the required pressure to produce a unit displacement [21].

It is relevant to note that the Model M1 considers only the soil-structure interaction effect and the Model M2 was developed to consider the masonry infill and soil-structure interaction effects, see Figures 3 and 4. It is important to emphasize that the numerical model M2 considers the decoupling of the upper face of the masonry (gap between the masonry infill and beams). At the bottom and on the sides of the panel the masonry-structure connections were considered as rigid.



a) Model M1: without masonry infills. b) Model M2: with masonry infills.

Fig. 4. Finite element model of the investigated reinforced concrete building: M1 e M2.

5. Global structural stiffness

According to [22], the global effective stiffness coefficient, $K_{x,y,z}$, associated at each direction X, Y, Z, can be given by equation (5). The parameter $\Delta_{x,y,z}$ represents generalized absolute displacement at the top of the building induced by unitary loads, as illustrated in Figure 5. Table 1 presents the values obtained for the two structural models for the X and Z directions.

$$K_{x,y,z} = \frac{1}{\Delta_{x,y,z}} \quad (5)$$

Table 1
Effective global stiffness obtained for each FEM M1 and M2 - Units in N/m.

Structural Stiffness	Model M1		Model M2	
	K_Z	K_X	K_Z	K_X
	5,376	5,291	20,534	21,413

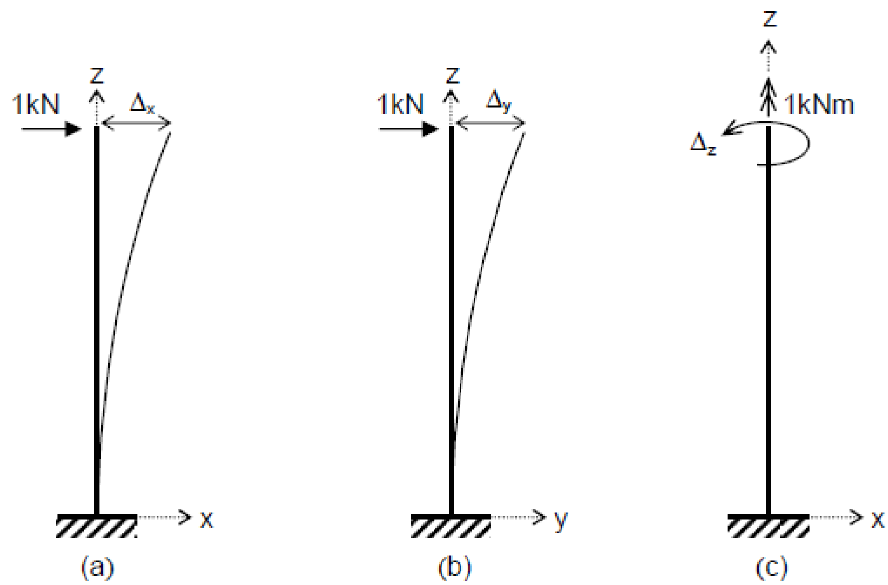
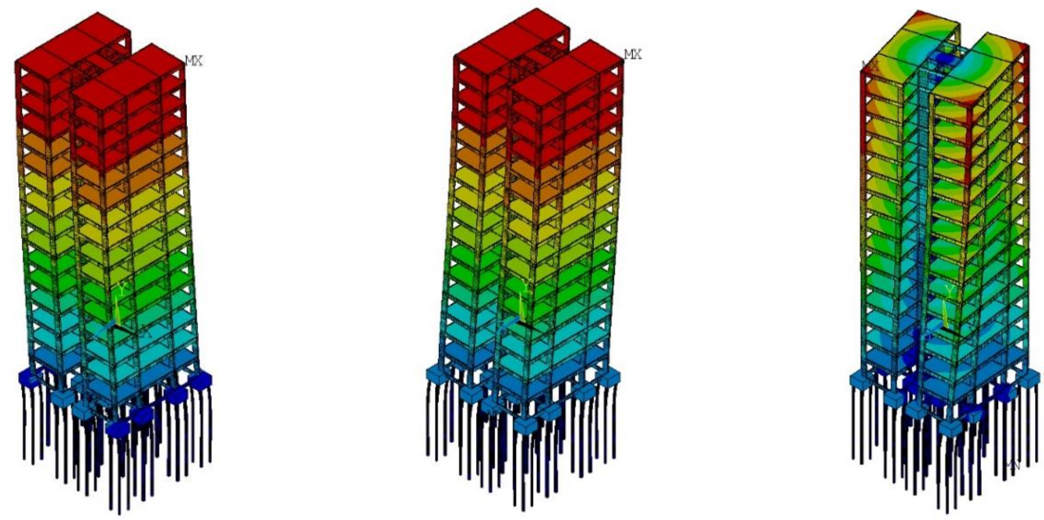


Fig. 5. Illustration of the global effective stiffness coefficients.

According to the results of Table 1 it is possible to conclude that the consideration of masonry infills in the numerical modelling of models M1 and M2 directly influences the results regarding global stiffness and horizontal translational displacements values, due to the application of the unit load. Model 2 presents a global stiffness 587% higher in the X direction and 778% higher in the Z direction. The results found in this investigation agree very well with the results found in several research works [5–8]. It must be emphasized that experimental tests developed by several authors have shown that the lateral storey stiffness of infilled frame buildings can be until 7 times greater that of the bare frame buildings [5–8]. These experimental tests also have shown that the infill walls significantly affected the natural frequency values of the investigated buildings.

6. Modal analysis: eigenvalues and eigenvectors

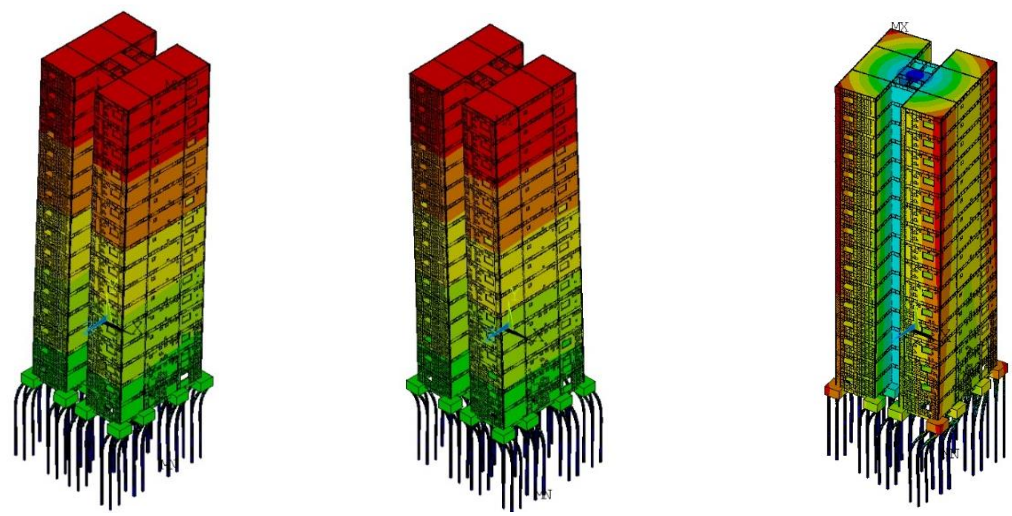
The natural frequencies (eigenvalues) and vibration modes (eigenvectors) of the building were obtained based on numerical methods of extraction (modal analysis), through a free vibration analysis using the ANSYS program [17]. The results obtained in the modal analysis (natural frequencies and time periods) are presented in Table 2. Figure 6 illustrates the vibration modes for the investigated structural models (M1e M2: see Figures 2 to 4), aiming to illustrate the tendency of the structure's vibration. The colour "red" indicates the maximum modal amplitude and the "blue" the minimum. Analysing the results presented in Table 2, in quantitative terms, it can be seen that Model 2 (with masonry infills) presents higher natural frequency values compared to Model 1, because the structural stiffness of the model M2 is about four times larger than the M1 model. In qualitative terms, an inversion of the first two modes of structure vibration (bending effects) can be verified, as a function of the masonry modelling, see Figure 6.



M1 - 1st vibration mode: bending around X (f_{01}= 0.48Hz).

M1 - 2nd vibration mode: bending around Z (f_{02}= 0.48 Hz).

M1 - 3rd vibration mode: torsion around Y (f_{03}= 0.55 Hz).



M2 - 1st vibration mode: bending around Z (f01= 0.67Hz).

M2 - 2nd vibration mode: bending around X (f02= 0.68Hz).

M2 - 3rd vibration mode: torsion around Y (f03= 0.83Hz).

Fig. 6. Vibration modes of the building: Models M1 e M2.

Table 2
Natural frequencies (f) and periods (T) of the FEM M1 and M2.

Vibration Mode	Model M1		Model M2	
	f (Hz)	T (s)	f (Hz)	T (s)
1	0.48	2.08	0.67	1.49
2	0.48	2.06	0.68	1.48
3	0.55	1.81	0.83	1.21

7. Nondeterministic dynamic analysis

It is noteworthy that for the analysis of the dynamic structural response of the building, besides the usual vertical design loads, the nondeterministic dynamic wind action was applied over the building facade (X and Z directions of the numerical models: see Figure 4). The basic wind speed was determined considering a recurrence time of 10 years. The results of the analysis dynamic for the maximum horizontal translational displacement values are obtained at the top structural sections of the building (H = 48m), and for the maximum accelerations these values are calculated at the floor of the last building storey (H = 45m). In this research work 30 nondeterministic wind series were generated, and the parameters used to generate the nondeterministic wind series are shown in Table 3.

Table 3
Parameters used to generate the nondeterministic wind series.

NBR 6123 design parameters [23]	Parameters used in the analysis
Wind Basic Velocity (V_0)	35 m/s
Terrain Category	II
Topographic Factor (S1)	1
Parameters for Roughness Factor (S2)	b = 1 e p = 0.15
Probability Factor (S3)	0.51
Time Duration	600 seconds
Time increment	0.03 seconds

Since the dynamic wind actions considered in this research work have nondeterministic characteristics, it is not possible to predict the response of the structure at a certain instant of time. A reliable response can be obtained through an appropriate statistical treatment using equation (6). According to [24], considering that the dynamic structural response presents a normal distribution, and based on the calculation of the mean (μ) and also the standard deviation (σ), it is possible to obtain the characteristic value ($U_{z95\%}$), that corresponds to a reliability 95%, which means that only 5% of the sampled values will exceed this value.

$$U_{Z95\%} = 1.65\,\sigma + \mu \qquad (6)$$

Concerning the convergence of the numerical results of the dynamic structural analysis, Figure 7 illustrates the mean maximum translational displacement values determined at the top of the building for the Model M2 [M2 (H = 48 m): see Figure 4)], which presents a more representative behaviour regarding the current design practice. These values were calculated for each of the 30 loading series, pointing to the importance of using an adequate number of nondeterministic wind series to obtain consistent results. The numeric convergence study was performed for both models, and the results have presented the same behaviour for the dynamic structural response.

In sequence, the maximum translational horizontal displacements calculated at the top of the investigated building (H = 48 m) and the peak accelerations at the floor of the last building storey (H = 45m) are presented in Figures 8 to 11, considering each nondeterministic wind loading series. On the other hand, the mean maximum displacements and peak accelerations values (characteristic values) of the building structural response are presented in Table 4, based on the statistical treatment of the 30 nondeterministic wind loading series.

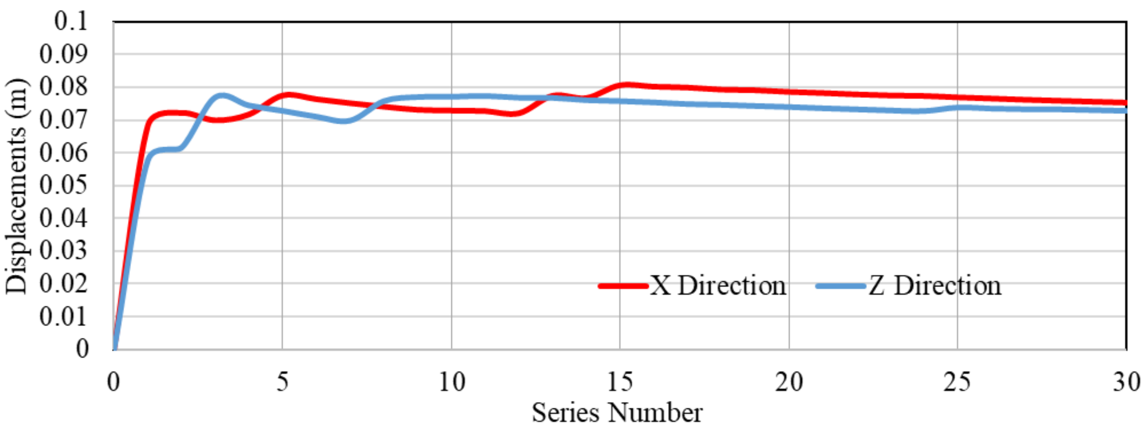


Fig. 7. Convergence of the horizontal displacements: Model M2 (X and Z directions).

Thereby, based on the use of a more realistic numerical modelling strategy developed for the studied building (Model M2: see Figure 4), considering the effect of masonry infills and also the soil-structure interaction, it must be emphasized that the values of the horizontal translational displacements and peak accelerations are substantially reduced, see Figures 8 to 11, and also the mean maximum values presented in Table 4. This fact clearly shows that the building dynamic response was directly influenced by the structural stiffness provided by masonry infills in Model M2. In this situation, the relevance of incorporating the effect of masonry infills and the soil-structure interaction (modelling of the foundations) should be emphasized aiming to develop numerical models of buildings more realistically representative and consistent with the current design practice.

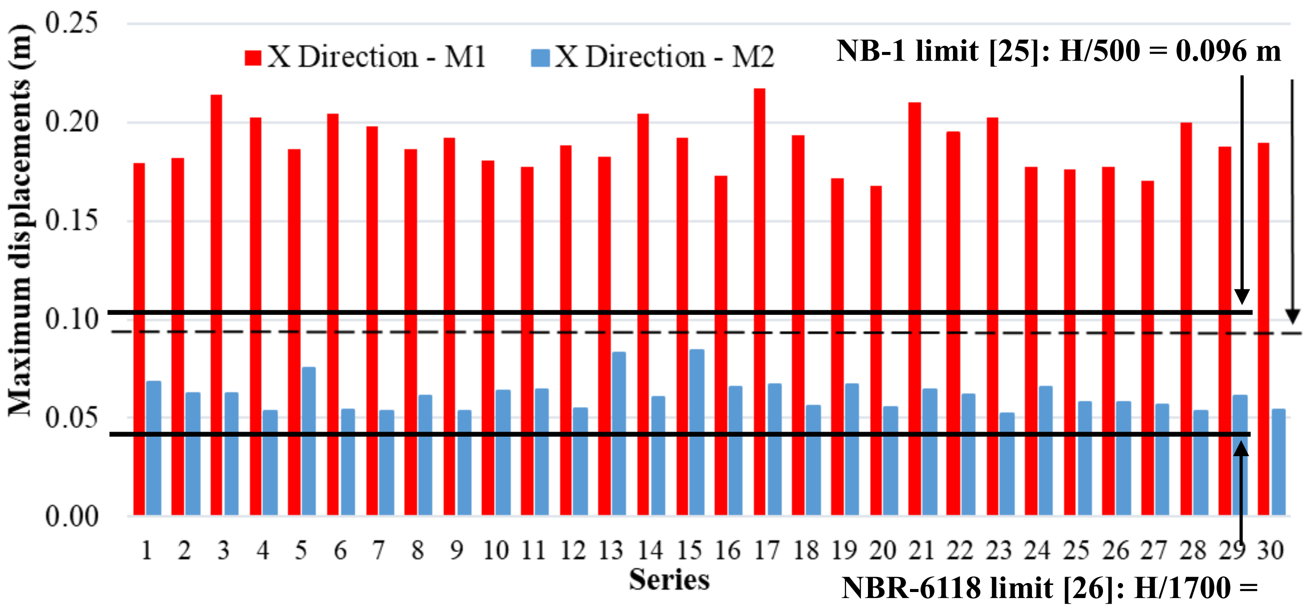


Fig. 8. Maximum horizontal translational displacements in X direction (H = 48 m): M1 and M2

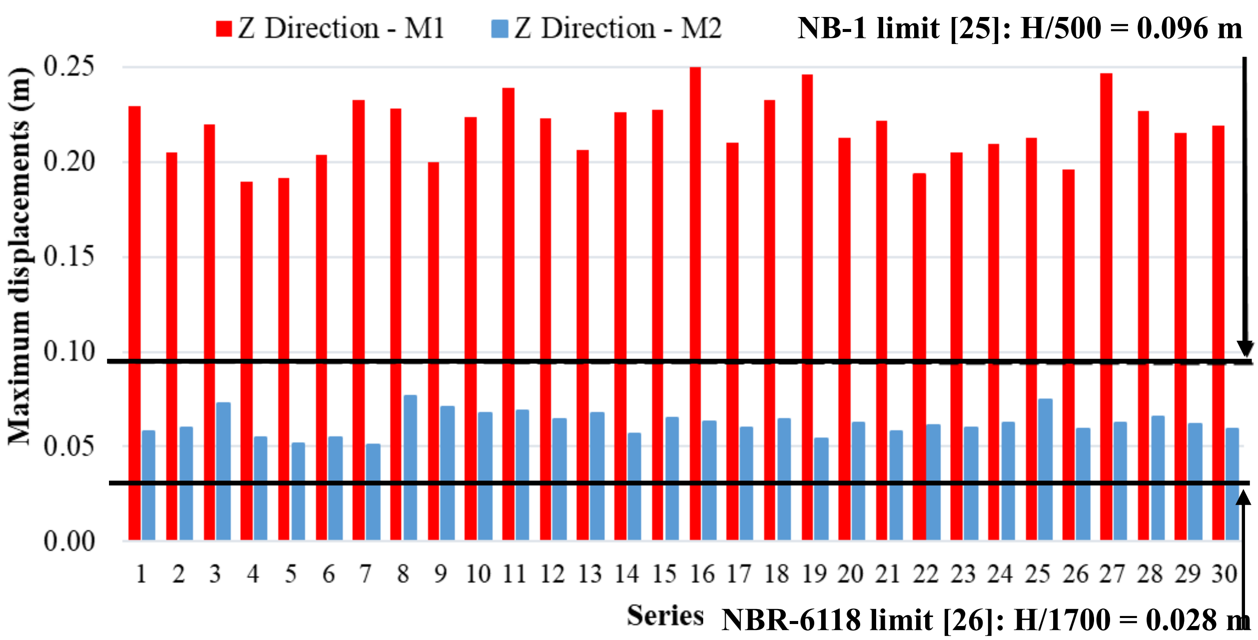


Fig. 9. Maximum horizontal translational displacements in Z direction (H = 48 m): M1 and M2

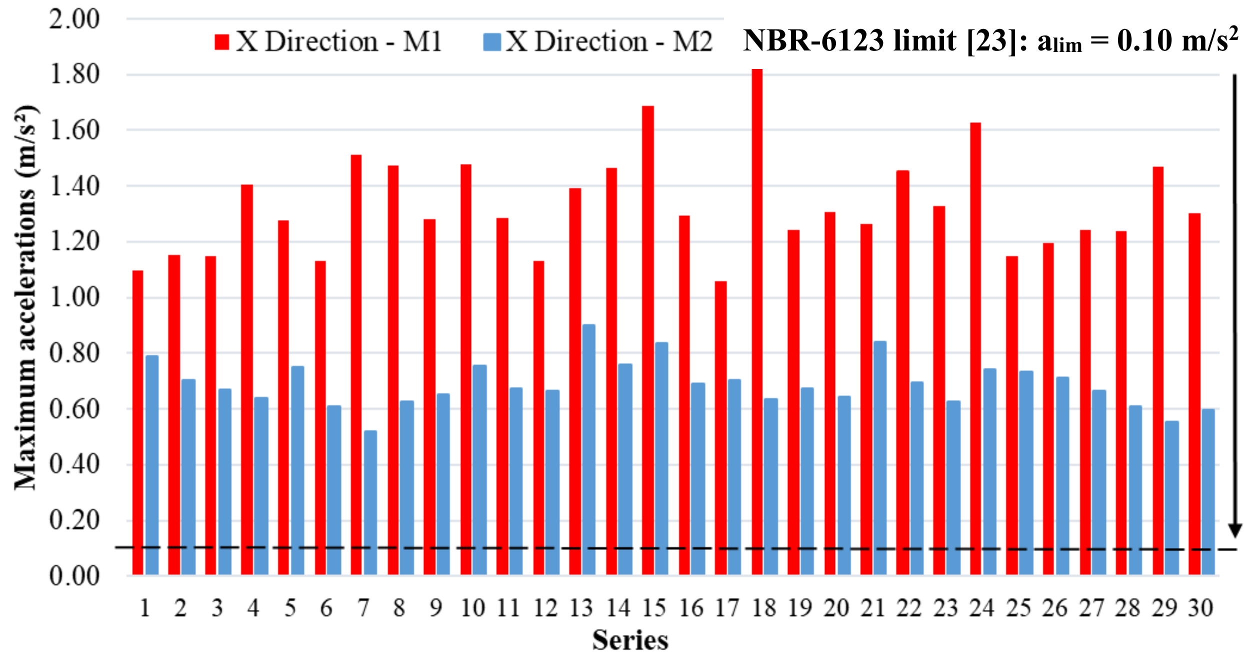


Fig. 10. Maximum accelerations (peak accelerations) in X direction (H = 45 m): M1 and M2

It must be emphasized that despite the significant reduction on the horizontal translational displacements and peak acceleration values when Models M1 and M2 are compared (see Figures 8 to 11 and Table 5), the mean displacements values exceeded the recommended limits equal to H/500 = 9.60 cm (NB-1: 100% of wind action [25]) and H/1700 = 2.83 cm (NBR-6118: 30% of wind action) [26]), see Figures 8 and 9 and Table 5. With reference to the peak acceleration values (mean maximum values), the design limit value recommended by the Brazilian standard (NBR-6123: alim= 0.10 m/s2 [23]) is not met. Based on the criterion of human comfort proposed by [27] the building would fall into the category “intolerable” (Model M1) and “very uncomfortable” (Model M2).

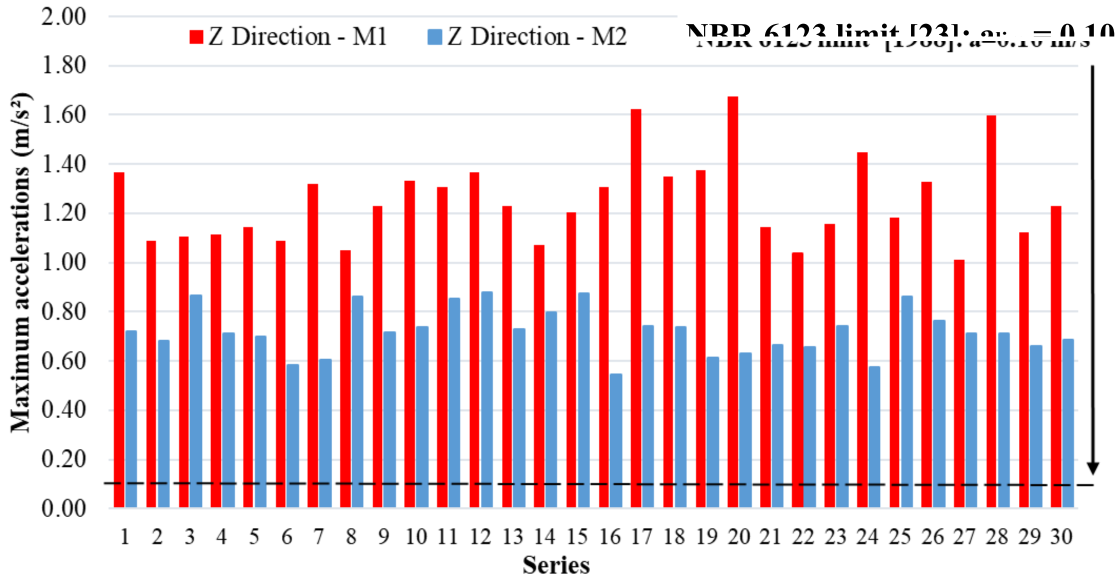


Fig. 11. Maximum accelerations (peak accelerations) in Z direction (H = 45 m): M1 and M2.

Table 4
Mean maximum values (30 nondeterministic wind series): displacements and accelerations.

Wind Loads Direction	Structural Model	Displacements (cm) H = 48 m	Accelerations (m/s²) H = 45 m
X	M1	21.14	1.63
	M2	7.53	0.83
Z	M1	24.73	1.54
	M2	7.29	0.88

It must be emphasized that despite the significant reduction on the horizontal translational displacements and peak acceleration values when Models M1 and M2 are compared (see Figures 8 to 11 and Table 4), the mean displacements values exceeded the recommended limits equal to H/500 = 9.60 cm (NB-1: 100% of wind action [25]) and H/1700 = 2.83 cm (NBR-6118: 30% of wind action) [26]), see Figures 8 and 9 and Table 4. With reference to the peak acceleration values (mean maximum values), the design limit value recommended by the Brazilian standard (NBR-6123: a_{lim}= 0.10 m/s^2 [23]) is not met. Based on the criterion of human comfort proposed by [27] the building would fall into the category “intolerable” (Model M1) and “very uncomfortable” (Model M2).

It is noteworthy that the investigated building presents natural frequencies with very low values, below 1 Hz; and even with the significant increase in structural stiffness from consideration of the effect of masonry infills, causing a reduction of the building dynamic structural response, the structural system needs significant modifications in the original project aiming to attend the serviceability limit states related to excessive vibrations and human comfort.

8. Conclusions

This research work aims the analysis of the dynamic structural response and evaluation of the human comfort of buildings, through the numerical representation of the effect of the masonry infills and also the soil-structure interaction (modelling of the foundations). The investigation was performed based on the use of a 48m height reinforced concrete residential building, consisting of 16 floors, and global dimensions of 15.0m by 14.2m. The main conclusions of the present investigation are as follows:

- Structural stiffness: The presence of masonry infills, incorporated into the finite element model of the building, substantially increased the global lateral stiffness of the structure in both analysed global directions (X and Z directions). However, as might be expected, consideration of the effect of soil-structure interaction (foundation modelling) reduced global stiffness but made the numerical model more realistic when compared to the hypothesis of rigid supports.
- Dynamic structural response: The presence of the masonry infills in the modelling has caused an increase in the building's natural frequency values (free vibration analysis: modal analysis). Due to this fact, based on the nondeterministic dynamic analysis (forced vibration analysis), it was possible to verify a very significant decrease of the maximum displacements and accelerations values, in both directions (X and Z directions), at the top of the building.
- Human comfort assessment: It is noteworthy that even considering a more realistic numerical modelling of the investigated structural system (Model M2), with substantial reduction of the dynamic response of the structure, the users of the analysed residential building will certainly feel the vibrations arising from the wind actions, according to Brazilian design standard [23], as well as the design criterion [27], which classified the building as "very uncomfortable".

The consideration of the effects of masonry infills and the modelling of the foundations has produced relevant changes (qualitative and quantitative) on the dynamic response of the building (natural frequencies, displacements and the peak accelerations). This conclusion is relevant to the fluctuating response of wind actions, because when the resonance effects related to wind acting on buildings are considered, these differences can be decisive and deserve the attention of the structural designers, especially for buildings with fundamental frequency value below 1 Hz.

Acknowledgments

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