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Human comfort assessment of buildings considering the modelling of masonry infills and the soil-structure effect

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Abstract. In the last decades, the urban verticalization in Brazil has been remarkable, and even in medium-sized cities, the project and construction of high buildings is growing exponentially. However, the architectural dareness and also the increasing in the building project's slenderness have been crucial to reducing the natural frequency values of these structures, and in some situations, these facts could induce excessive vibration problems. On the other hand, important aspects, generally disregarded in the current design practice are related to the effects of the masonry infills and the soil-structure interaction. This way, this research work aims to develop an analysis methodology aiming to evaluate the structural behaviour and assess the human comfort of buildings subjected to the wind nondeterministic dynamic actions, including in the analysis the effects of the masonry infills and the soil-structure interaction. This way, the dynamic structural behaviour of a 16-storey reinforced concrete building, 48 m high and dimensions of 15.0 m by 14.2 m is investigated. Thus, numerical models 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 obtained along this investigation have indicated relevant quantitative differences when the dynamic structural response of the building was analysed, such as the reduction of the horizontal translational displacements and peak acceleration values, when the effects of the masonry infills and the soil-structure interaction were considered.

Keywords: High buildings; Modelling of masonry infills; Soil-structure effect.

1 Introduction

In recent years, technological advances linked to a favourable economic scenario have promoted the construction of tall buildings in several countries, such as the United States, and more recently, in some of the Asian countries such as: 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, according to Blessmann; Silva; Barboza [1,2,3].

A building assessment of reliable human comfort according to Ferrareto; Rist; Lamb *et at*. [4,5,6], depends on the correct description of the wind dynamic loads when compared with studies of natural wind. For this reason, it became imperative to study the interaction between the wind and tall buildings in order to improve structural designs avoiding possible future state service limit problems. In this context, the two factors that exert a great influence in conjunction with a random wind action on tall buildings are: the effect of stiffness masonry infills and the effect of soil-structure interaction.

Masonries are structural elements that compose buildings and other constructions, filling most of the empty areas inside the porches. As reported by Araujo [7], 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. Based on dynamic monitoring investigations by Timuragaoglu *et al.*; Zahir and Garg; Komur *et al.* [8,9,10], it is possible to verify that the consideration of masonry infill has a major 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 analyses due to poor fidelity with the real model.

The soil has great complexity attributable to the varied characteristics such as heterogeneity, anisotropy, nonlinear behaviour between force and displacement and property change with varying amount of water in its constitution. Consideration of soil-structure interaction over foundations can provide significant differences in building calculations. Hence, due to the dependence between these elements (soil and structure), the importance of obtaining numerical analysis and the effects of this interaction is observed by Silva; Borges [2,11]. According to Anand and Satish Kumar [12], 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.

As reported by Silva [2], 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. Taking into account 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.

This work approaches the study of the dynamic response of buildings when subjected to nondeterministic wind action, considering the effect of masonry infills. Thereby, throughout the dynamic analysis, the design of a reinforced concrete building will be used as a base, 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 performed using the Finite Element Method (FEM), on the ANSYS program [13]. The dynamic response (natural frequencies, displacements and accelerations) will be evaluated and compared with the limit values observed within the standards and technical recommendations, aiming to verify the service limit states and the human comfort of the building.

2 Nondeterministic Wind Mathematical Modelling

Wind properties are unstable, possess a random variation and as a consequence, their deterministic consideration becomes inadequate. However, to generate 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 the wind do not change when the simulation period is performed according to Obata [14].

In this investigation, dynamic wind loads are calculated by the sum of two parcels: one, turbulent parcel (nondeterministic dynamic load) and the other, 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 Fig. 1.

This work adopts the Kaimal Power Spectrum because it considers the influence of the building height in the formulation as maintained by Drummond [15]. The energy spectrum is calculated using eqs. (1) and (2), where f is the frequency in Hz, SV is the spectral density of the wind turbulent longitudinal part in m^2/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 eq. (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, eq. (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 $[0\text{-}2\pi]$.

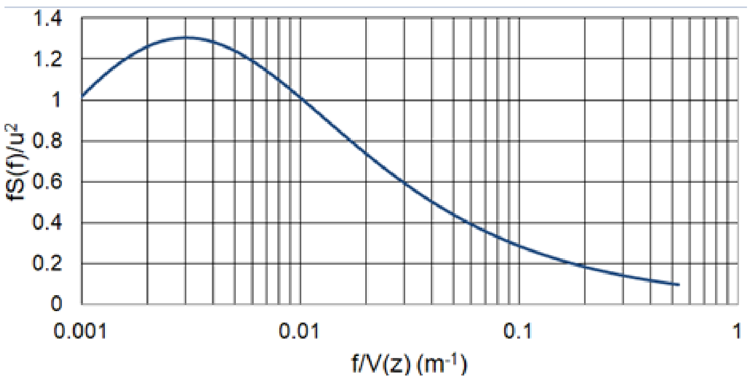


Figure 1. Kaimal Power Spectral Density

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

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

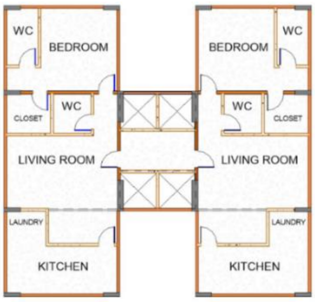
$$u^* = \frac{k\overline{V}_Z}{ln(z/z_0)}. \tag{3}$$

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

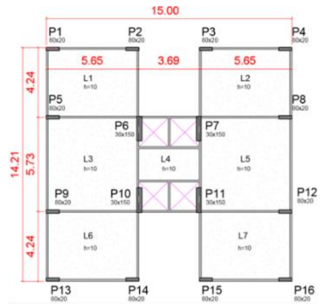
3 Investigated Reinforced Concrete Building

The investigated building in this research work presents rectangular dimensions of 15.0 m by 14.2 m, 16 floors, with a height of 3.0 m, and total height of 48 m, as shown in Fig. 2. The reinforced concrete structure of the building consists of massive slabs whose thickness is 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, as approached by Silva [2].

The architectural design of the building shown in Fig. 2 used 14.5 cm of 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 Pinheiro [16], with a value of 5.82 GPa. The concrete has a compressive strength (*fck*) and is equal to 25 MPa, a Young's modulus (E) is equal to 23.8 GPa and Poisson's ratio (ν) is equal to 0.2.



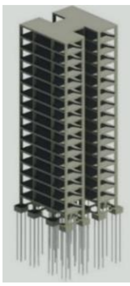
a) Building floor architecture



b) Floor structural plan (units in meters)

Figure 2. Investigated reinforced concrete building

Two structural models were developed in this work, see in Fig. 3. On the one hand, Model 1 (M1) consists only of the basic system of the building's reinforced concrete structure (beams, slabs and columns) with its 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) Model M1: without masonry infills

b) Model M2: with masonry infills

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

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 [13], see Fig. 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

Figure 4. Finite element model of the investigated reinforced concrete building: 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, [17] that simulates the soil behaviour as a group of independent springs governed by a linear-elastic model.

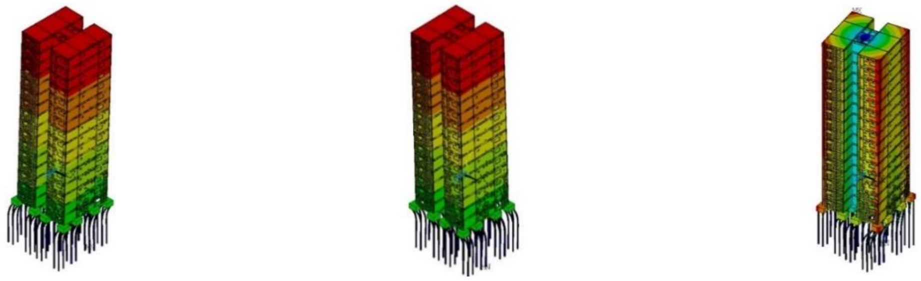
It is relevant to note that the Model M1 only considers the soil-structure interaction effect and the Model M2 was developed to consider the masonry infill and soil-structure interaction effects, see Figs. 3 and 4. It is important to emphasize that the numerical model M2 considers the decoupling of the 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.

5 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 [13]. The results obtained in the modal analysis (natural frequencies and time periods) are presented in Tab. 1. Figures 5 and 6 illustrates the vibration modes for the investigated structural models, aiming to illustrate the tendency of the structure's vibration. The color red indicates the maximum modal amplitude and blue the minimum.

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)

Figure 5. Vibration modes of the building: Model M1



M2 - 1st vibration mode: bending around Z (f_{01}= 0.67Hz) | M2 - 2nd vibration mode: bending around X (f_{02}= 0.68Hz) | M2 - 3rd vibration mode: torsion around Y (f_{03}= 0.83Hz)

Figure 6. Vibration modes of the building: Model M2

Table 1. 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

6 Nondeterministic Dynamic Analysis

It is important to note 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 Fig. (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 of the building's structural sections (H = 48m), and for the maximum accelerations these values are calculated at the floor of the last building storey (H = 45m). In this research, 30 nondeterministic wind series were generated, and the parameters are shown in Tab. 2.

Table 2. Parameters used to generate the nondeterministic wind series

NBR 6123 design parameters [18]	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 eq. (5). According to Chávez [19], 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 ($Uz_{95\%}$), that corresponds to a reliability of 95%, which means that only 5% of the sampled values will exceed this value.

$$U_{Z95\%} = 1.65\,\sigma + \mu \tag{5}$$

Concerning the convergence of the numerical results of the dynamic structural analysis, Fig. 7 illustrates the mean maximum translational displacement values determined at the top of the building for the Model M2 [(H = 48 m): see Fig. 3)], 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. The mean maximum displacements (calculated at the top of the building) and peak acceleration values (at the floor of the last building storey) of the building structural response are presented in Tab. 3, based on the statistical treatment of the 30 nondeterministic wind loading series.

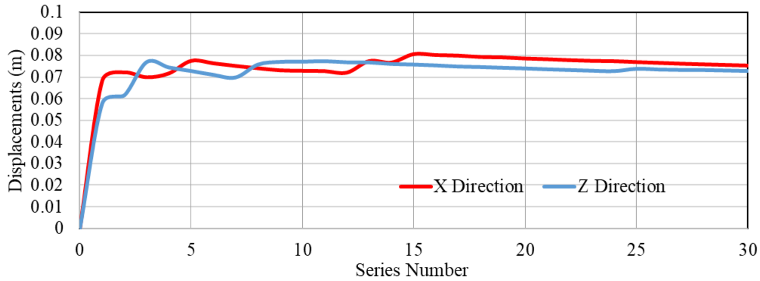


Figure 7. Convergence of the horizontal displacements: Model M2 (X and Z directions)

Table 3. 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 Tab. 3), the mean displacements values exceeded the recommended limits which is equal to H/500 = 9.60 cm (NB-1: 100% of wind action [20]) and H/1700 = 2.83 cm (NBR-6118: 30% of wind action) [21]), see Tab. 3. With reference to the peak acceleration values (mean maximum values), failing to achieve the design limit value recommended by the Brazilian standard (NBR-6123: a_{lim}= 0.10 m/s^2 [18]). Based on the human comfort criteria proposed by Bachmann *et al.* [22] the building would fall into the category of "intolerable" (Model M1) and "very uncomfortable" (Model M2).

It is important to consider that the investigated building presents natural frequencies with very low values, below 1 Hz; and even with the significant increase in structural stiffness taking into account 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.

7 Conclusions

The main conclusions of this investigation focused on alerting structural engineers to the possible variations, associated to the reinforced concrete building dynamic response, subjected to dynamic wind actions, due to the effect of the masonry infills and also the soil-structure interaction (modelling of the foundations) in the analysis. Thus, the following conclusions can be drawn from the results presented in this study:

1. 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) [39.6% increase]. 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 displacement and acceleration values, in both directions [reduction of 64.3% when the wind is applied in the X direction and 70.5% when the wind is applied in the Z direction], at the top of the building.

2. The presence of the masonry infills in the modelling has caused a decrease of the dynamic response of the structure to acceleration [reduction of 49.1% when the wind is applied in the X direction and 42.9% when the wind is applied in the Z direction]. However, the users of the analysed residential building will certainly feel the

vibrations arising from the wind actions, according to Brazilian NBR 6123 Design Standard [18] [a_x=0.83 m/s² e a_z=0.88m/s² are greater than a_{NBR}=0.1 m/s²], as well as the design criterion by Bachmann *et al.* [22], which classified the building as "very uncomfortable".

3. The consideration of the effects of masonry infills and the modelling of the foundations has produced relevant changes 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 below 1Hz.

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