Investigation on the nondeterministic dynamic structural response of tall buildings

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Abstract. Based on the last few decades, the Brazilian cities have presented a relevant increasing when the design and construction of tall and slender buildings is considered. It must be emphasized that this architectural trend produced very flexible structures, with low natural frequency values and more susceptible to excessive vibrations problems, especially when subjected to wind dynamic loads. Having these ideas in mind, this investigation aims the study of tall buildings non deterministic dynamic structural response, considering the soil-structure interaction effect. This way, the developed analysis methodology considers the wind pressure coefficients on the building's facade determined based on the use of CFD (Computational Fluid Dynamics) techniques that nowadays represents an increasingly important role in high-rise buildings projects, utilised as a sophisticated analysis method to predict the airflow on the building's structural system. This way, the nondeterministic dynamic structural behaviour of a 40-storey reinforced concrete building, 140 m high and floor dimensions of 9 m by 29.05 m was investigated. The building numerical model was developed to obtain a realistic representation of the structure, based on the Finite Element Method (MEF), using the ANSYS program. It must be emphasized that the results obtained throughout this research work, considering the wind pressure coefficients calculated based on CFD techniques and those determined by the Brazilian design standard NBR 6123 have indicated important quantitative differences, when the dynamic structural response (displacements and peak accelerations) and the building human comfort were investigated.

Keywords: high-rise buildings, dynamic structural analysis, human comfort assessment.

1 Introduction

The construction of high-rise buildings has emerged as a constructive trend worldwide, which is due to several factors, such as population growth, urbanization of large centres, reducing the useful areas of construction, the technological evolution of construction materials and calculation methods adopted in recent years, enabling the construction of buildings with increasingly slender elements, among others. In connection with this trend, structural problems due to excessive vibrations are becoming more frequent, as well as human discomfort caused by various dynamic actions, among which wind action stands out as one of the most important [1-3].

The construction projects currently carried out in Brazil are based on the Brazilian standard NBR 6123 [4] recommendations for the consideration of wind action on structures. In the formulation, the wind action is transmitted through the application of pressure coefficients along the facades of the building, and it is assumed that the wind loads are purely static. However, wind actions have a nondeterministic dynamic character, that causes a zone of high energy transfer associated with low natural frequencies, which are often present in buildings, and maximize the effects of the wind loads on structures [1-3].

Based on these considerations, this research work aims to investigate the nondeterministic dynamic behaviour of a high-rise building considering the soil-structure interaction effect. In this way, the developed analysis methodology takes into account the wind pressure coefficients on the building facades, which are determined based on the Brazilian standard NBR 6123 recommendations [4] and based on the use of CFD (Computational Fluid

Dynamics) techniques [5], which nowadays play an increasingly important role in high-rise building projects and are used as a sophisticated analysis method to predict the airflow on the structural system of the building. In this way, the nondeterministic dynamic structural behaviour of a 40-storey reinforced concrete building, with a height of 140 m and floor dimensions of 9 m by 29.81 m was studied.

2 Investigated structural model

In this research work, a 140 m high reinforced concrete building with 40 floors and floor dimensions of 9 m by 29.81 m is investigated [2]. The structural system consists of reinforced concrete columns, beams, and slabs. The concrete has a modulus of elasticity of 32 GPa, a Poisson's ratio of 0.2, a damping ratio of 0.02, and a specific weight of 25 kN/m³. The reinforced concrete columns (P) and beams (V) of the building have the geometrical characteristics shown in Figure 1, and the reinforced concrete slabs are 20 cm thick. It should be emphasized that the studied building project complies with the ultimate and serviceability limits recommended in the Brazilian design standard NBR 6118 [7].

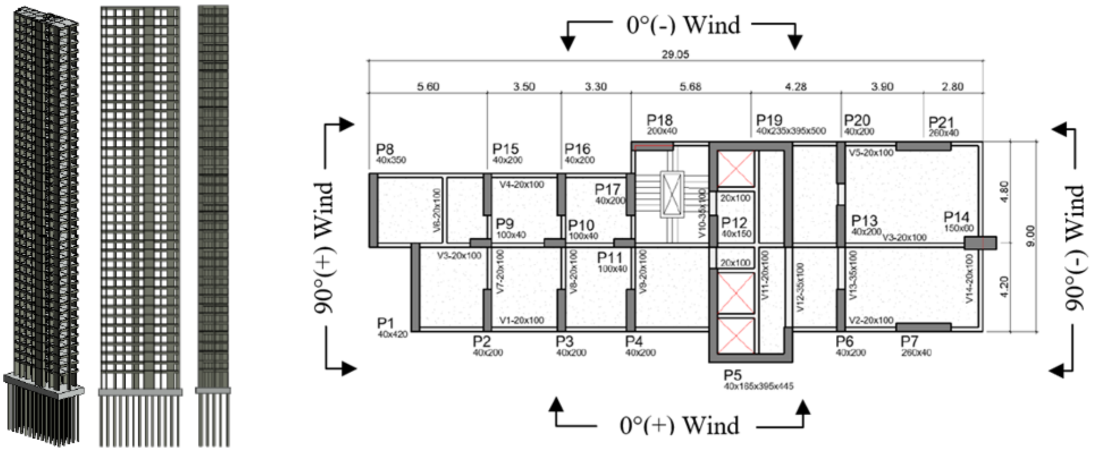


Figure 1. Investigated reinforced concrete building [2]

3 Finite element modelling of the building

The reinforced concrete building finite element model developed for the nondeterministic analysis uses the usual mesh refinement techniques used in simulations with the finite element method in the ANSYS program [6]. The reinforced concrete beams and columns were represented by three-dimensional BEAM44 finite elements, where the effects of bending and torsion are considered, and the concrete slabs were simulated using SHELL63 finite elements (see Figure 2).

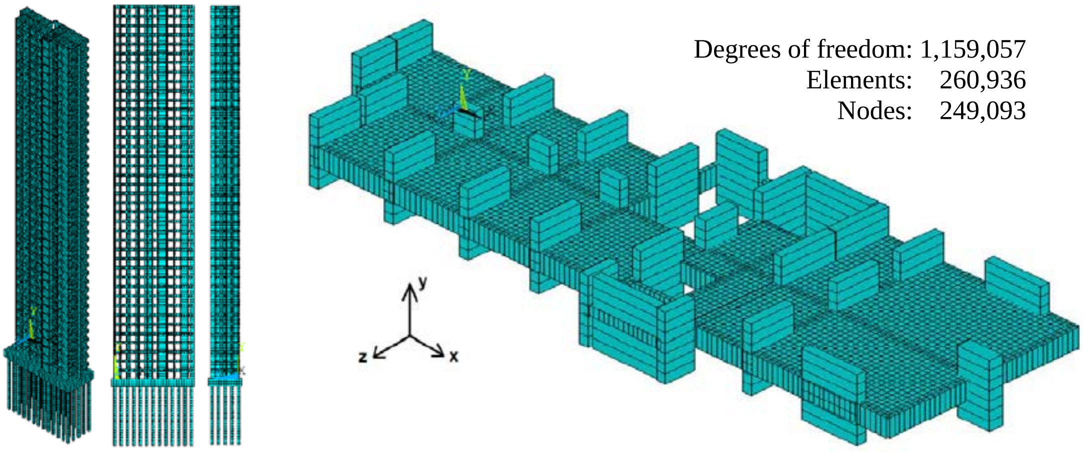
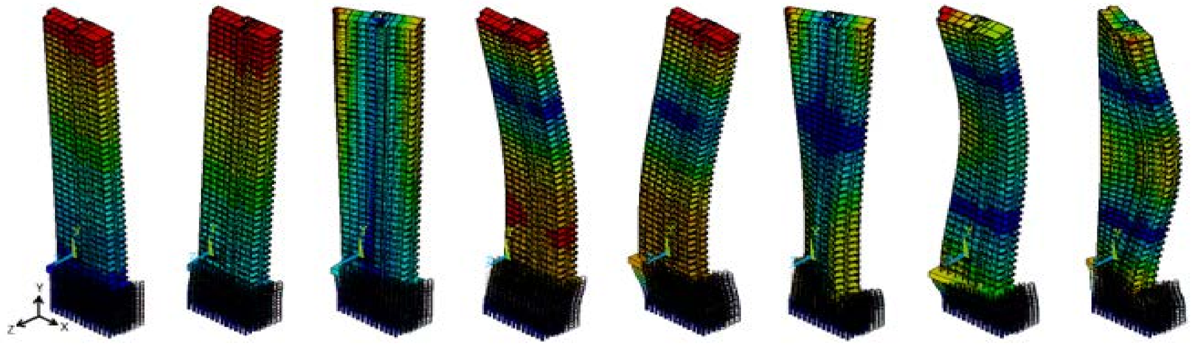


Figure 2. Developed building finite element model

The element size considered in this finite element modelling has dimensions of 50 cm for columns and 25 cm for beams and slabs. The numerical model was subjected to convergence tests to determine an appropriate level of refinement that allows a good representation of the nondeterministic dynamic response of the building. The building supports constrain only the translational vertical and horizontal displacements on the pile foundations, but the rotational displacements are free.

4 Modal analysis: eigenvalues and eigenvectors

The studied natural frequencies (eigenvalues) and vibration modes (eigenvectors) of the building were obtained based on numerical extraction methods (modal analysis) through a free vibration analysis using the ANSYS program [6]. The vibration modes and the natural frequencies of the building are shown in Figure 3.



f_{01} 0.216 Hz Bending around X

f_{02} 0.363 Hz Bending around Z

f_{03} 0.436 Hz Bending around Y

f_{04} 0.876 Hz Bending around X

f_{05} 1.055 Hz Bending around Z

f_{06} 1.219 Hz Bending around Y

f_{07} 1.951 Hz Bending around X

f_{08} 2.095 Hz Bending around Y

Figure 3. Frequency values and vibration modes of the structure

5 Mathematical modelling of the dynamic wind actions

First, it must be emphasized that, in this study, the recommendations of the Brazilian standard NBR 6123 [4] and the CFD techniques [5] are used only in the first step related to the calculation of the wind pressure coefficients. Then, the nondeterministic dynamic wind loads acting on the facade of the studied building are generated based on the developed analysis methodology.

The CFD (Computational Fluid Dynamics) simulation [5] uses the Navier-Stokes equations (momentum equation) and the first law of thermodynamics (energy equation). In general, this mathematical formulation can be described by equation (1), where ρ is the density (kg/m³), t is the time (s), u is the velocity component in the X-direction, v is the velocity component in the Y-direction, and w is the velocity component in the Z-direction (m/s).

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \tag{1}$$

The recommendations of the Brazilian standard NBR 6123 [4] aim to establish the necessary conditions to determine the static and dynamic forces due to wind action on building facades, based on the use of a characteristic wind velocity represented by equation (2), where $\overline{V}(z)$ is the characteristic wind velocity (static part - m/s), V_0 is the basic wind velocity (m/s), S_1 is a topographic factor, S_2 is the factor that takes into account the roughness of the terrain, the dimensions of the structure, and the height above the terrain, S_3 is the statistical factor, b is the meteorological factor, F_r is the gust factor, and p is the exponent of the potential law (see Table 1).

$$\overline{V}(z) = V_0\, S_1\, S_2\, S_3 \;\; ; \;\; S_2 = b\;\; F_r \left(\frac{z}{10}\right)^{p} \tag{2}$$

The authors intend to compare the wind pressure coefficients calculated based on the previously described methods and use these results to generate the nondeterministic dynamic wind loads. Because the wind properties are unstable and random, a second-order nondeterministic ergodic process with stationary properties was adopted in this work for the mathematical modelling of the wind loads.

In this research, the Spectral Representation Method (SRM) was applied to generate the nondeterministic dynamic wind loads [2-3] as shown in equation (3), where f represents the frequency (Hz), Sv(f) refers to the increment of wind power spectral density, f_i is the frequency related to the harmonic i (Hz), Δf is the frequency increment (Hz), and θ_i is the random phase angle normally distributed in the interval (0-2π).

$$\hat{V}(z,t) = \sum_{i=1}^{N} \sqrt{2S^{v}(f_i)\Delta f}\,\cos(2\pi f_i t + \theta_i) \tag{3}$$

The fluctuating part of the wind velocity $\hat{V}(t)$ is generated with random phase angles, and the amplitude of each harmonic is calculated based on the spectral density determined by using the Kaimal spectrum, see equation (4). In this equation, fS(f) corresponds to the spectral density associated with the longitudinal component of the turbulence with frequency f, u_* is the friction velocity (m/s), X is the dimensionless frequency, $\overline{V}(z)$ is the wind velocity (m/s) at height z, and K is the Kármán constant.

$$\frac{fS(f,z)}{{u_*}^2} = \frac{200X}{(1+50X)^{5/3}} \quad ; \quad X(f,z) = \frac{fz}{\overline{V}(z)} \quad ; \quad u_* = \frac{K\overline{V}(z)}{\ln\left(\frac{z}{z_0}\right)} \tag{4}$$

It should be emphasized that, according to the Kaimal power density spectrum, the fundamental frequency of the building (f_{01}= 0.216 Hz) determined by the modal analysis, is in the range of higher energy transfer associated with low natural frequencies (see Figure 4). Therefore, a dynamic structural analysis (forced vibration) is required aiming to evaluate the ultimate and serviceability limit states.

Finally, based on the developed mathematical formulation [1-3], the nondeterministic wind-induced response of the building can be calculated by the sum of a static part and a dynamic part (random vibration) of the wind. Then, the dynamic forces acting on the building facades are calculated at several different points around the structure considering the air density ρ ($\rho = 1.225\ \mathrm{kg/m^3}$), the wind pressure coefficient C_p, the area of influence A_i (m²) and the nondeterministic wind velocity $V_i(z,t)$ (m/s), see equation (5). The expanded formulation of the wind force is shown in equation (6). Figure 5 shows a general example of the nondeterministic wind load used in the dynamic analysis, for a particular section of the building facade.

$$V(z,t) = \overline{V}(z) + \hat{V}(z,t) \quad ; \quad q(z,t) = 0{,}613\ V(z,t)^2 \quad ; \quad C_p = \frac{2(p - p_\infty)}{\rho_\infty {V_\infty}^2} \quad ; \quad F(z,t) = q(z,t)\ A\ C_p \tag{5}$$

$$F(z,t) = 0{,}613\ C_p\ A \left\{ \left[\overline{V}_0 \left(\frac{z}{z_0}\right)^{p}\right]_{\substack{static\\part}} + \left[\sum_{i=1}^{n} \sqrt{2S^{v}(f_i)\Delta f}\,\cos\,(2\pi f_i t + \theta_i)\right]_{\substack{floating\\part}} \right\}^2 \tag{6}$$

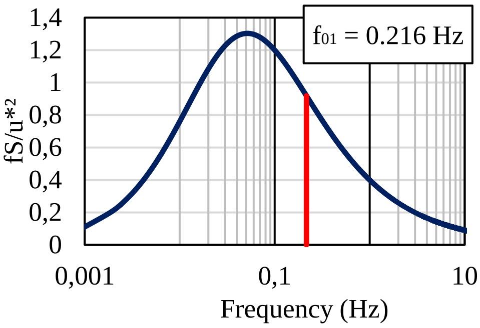


Figure 4. Kaimal power density spectrum

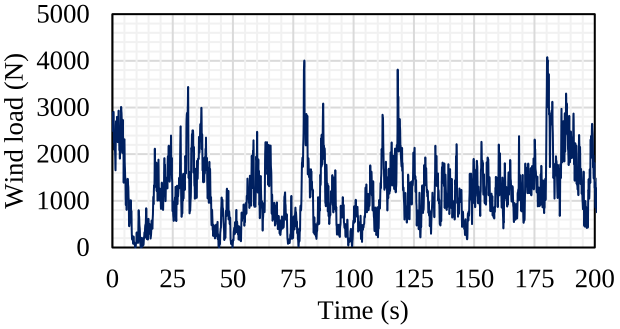


Figure 5. Nondeterministic wind loading

In this study, the wind pressure coefficients were evaluated based on the previously described methodologies (CFD simulation [5] and Brazilian standard NBR 6123 recommendations [4]) and used to determine the nondeterministic wind actions on the investigated structural model. It should be mentioned that the Brazilian design standard NBR 6118 [7] specifies that accidental loads must be multiplied by a coefficient ψ_1 of 0.3 in serviceability verifications.

6 Analysis and results discussion

Regarding the characteristics of the wind loads acting on the reinforced concrete building according to the Brazilian standard NBR 6123 [4], the basic wind velocity of 45 m/s and the normative parameters used to calculate the wind loads are described in Table 1. It is also highlighted that the structural damping was calculated based on the Rayleigh damping matrix and a structural damping ratio of 2.0% ($\xi = 0.02$) was assumed.

Based on the parameters described in Table 1, and considering the developed analysis methodology for the nondeterministic dynamic wind loads based on the use of the wind pressure coefficients previously determined by the CFD simulation [5] and the recommendations of the Brazilian standard NBR 6123 [4], 10 series of nondeterministic dynamic loads were generated and applied to each facade of the building according to the X and Z-directions. Figure 6 shows the velocity profile along the height calculated based on equation (5). Then, it is possible to calculate the pressure coefficients C_p, which are dimensionless numbers that describe the relative pressures in a flow field in fluid dynamics, see equation (5), where p is the static pressure at the point where the pressure coefficient is calculated (Pa), p_∞ is the static pressure in the free flow (Pa), ρ_∞ is the density of the free flow ($\rho_\infty = 1.225$ kg/m³) , and V_∞ is the velocity of the free flow, or the velocity of the body through the fluid (m/s).

Due to the asymmetry of the building, four simulations were performed, each with a different wind incidence: 0°(+) wind, 90°(+) wind, 0°(-) wind and 90°(-) wind (Figure 1). The turbulence profiles and the contour plot showing the pressure throughout the building for the four different simulations are shown in Figure 7.

For clarification, it is worth mentioning here that the Brazilian standard NBR 6123 [4] considers only a single wind pressure coefficient on the building facades in the analysis. In contrast, the CFD simulation [5] generates several different pressure coefficients (3400 for this particular building), which corresponds to what occurs in reality in high-rise building projects. This fact is likely to have a significant impact on the final dynamic response of the building (displacements and accelerations).

Table 1. Parameters following the Brazilian standard NBR 6123 [4]

Type	Value	Description
Basic wind velocity	45 m/s	Isopleths: Balneário Camboriú/SC
Ground	IV	Urban Region
Class	C	Dimension higher than 50 m
S_1 factor	1.00	Flat ground
S_3 factor	1.00	63% for 10 years
F_r factor	0.95	Gust factor
b parameter	0.85	Meteorological parameter
p parameter	0.125	The exponent of the potential law
Analysis period	600 s	Standard time interval

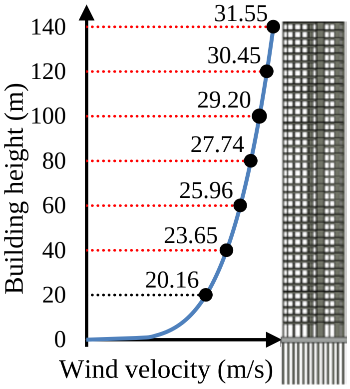


Figure 6. Velocity profile

Regarding the acceleration results (see Table 2), according to the recommendations of NBR 6123 [4], the amplitude of acceleration for human comfort checks must not exceed 0.1 m/s². The accelerations in the X-direction are very far from this limit, but in the Z-direction the limit is exceeded, with peak values in the order of 0.155 m/s² in the analyses with the pressure coefficients according to NBR 6123 [4] and 0.137 in the analyses with the pressure coefficients according to the CFD simulation [5].

As for the displacement results, concerning the serviceability limit states, the Brazilian design standard NBR 6118 [7] requires that the maximum displacements at the top of the building must not exceed the limit value H/1700. Thus, for a 140 m high building, the limit displacement is 0.082 m. As it happened with the accelerations, the displacement in the X-direction is quite far from this limit, but the limit is exceeded by the displacements of both analyses in the Z-direction, with displacements in the order of 0.135 m for the analyses with pressure coefficients according to NBR 6123 and 0.102 m for the analyses with pressure coefficients according to the CFD simulation [5]. These results show the importance of considering the nondeterministic dynamic structural response in the design of high-rise buildings.

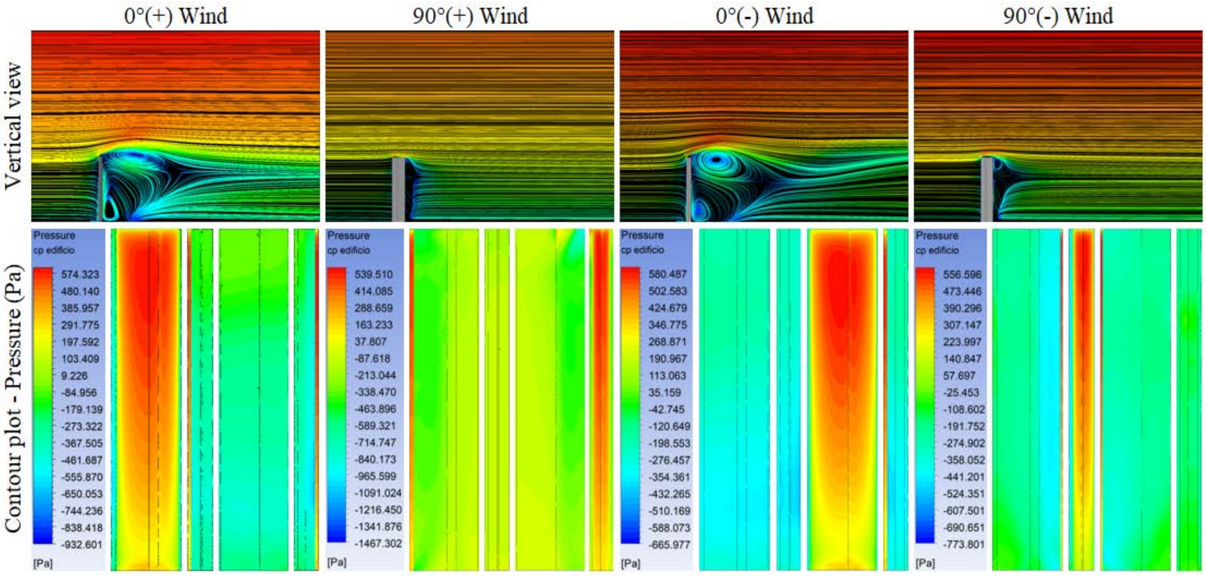


Figure 7. CFD results: Turbulence profile and pressure contour plots

Table 2. Accelerations [m/s²]: NBR 6123 [4] and CFD [5]

	X-direction				Z-direction			
Series	Peak		RMS		Peak		RMS	
	NBR 6123	CFD	NBR 6123	CFD	NBR 6123	CFD	NBR 6123	CFD
1	0.045	0.027	0.013	0.0079	0.16	0.12	0.044	0.033
2	0.059	0.029	0.014	0.0081	0.13	0.14	0.038	0.035
3	0.050	0.029	0.014	0.0083	0.15	0.14	0.045	0.034
4	0.047	0.027	0.014	0.0078	0.15	0.12	0.047	0.034
5	0.047	0.029	0.014	0.0081	0.19	0.17	0.047	0.033
6	0.055	0.028	0.014	0.0082	0.18	0.10	0.044	0.034
7	0.053	0.036	0.013	0.0079	0.13	0.14	0.044	0.034
8	0.073	0.026	0.016	0.0072	0.17	0.15	0.043	0.033
9	0.075	0.029	0.015	0.0076	0.12	0.15	0.042	0.034
10	0.052	0.036	0.014	0.0081	0.15	0.13	0.046	0.034
Standard deviation (σ)	0.0106	0.0036	0.0007	0.0003	0.0220	0.0187	0.0025	0.0006
Mean (μ)	0.056	0.029	0.014	0.008	0.155	0.137	0.044	0.034
	NBR 93.1% higher		NBR 75% higher		NBR 13.1% higher		NBR 29.4% higher	
μ + 2σ	0.077	0.037	0.016	0.009	0.199	0.175	0.049	0.035
	NBR 108% higher		NBR 77.6% higher		NBR 13.7% higher		NBR 40% higher	

Concerning the differences between the two analyses, the analyses using the pressure coefficients according to NBR 6123 [4] showed higher values of accelerations in both directions, with a peak acceleration difference of about 13.1% in the Z-direction and up to 93.1% in the X-direction. The displacements were also in line with this pattern in the Z-direction, with a difference of 32.3% in average peak values. Those results show that, in general, the analyses using the pressure coefficients according to NBR 6123 [4] presented more conservative results. In the

X-direction, however, the analyses considering the pressure coefficients according to the CFD simulation [5] yielded slightly higher values of displacements, with differences of about 10.7% in the average peak values. Since this direction has a very pronounced stiffness compared to the Z-direction, it is necessary to take into account that the displacements become very small, which makes it more difficult to obtain a good accuracy of the results, since unfavorable effects can have a significant impact on the results.

An example that must be taken into account is the unusual and asymmetrical geometry of the building, which leads to local pressure concentrations that can be detected in the CFD simulation [5] but are not considered in the recommendations of NBR 6123 [4]. Another relevant factor that needs to be considered is the fact that in the four analyses with different wind incidence [0°(+), 90°(+), 0°(-) and 90°(-)], the displacements are relatively close in the X-direction (as well as the accelerations), showing that the values in this direction may suffer from a significant influence of building torsional effects on the results.

7 Conclusions

In this study, the nondeterministic dynamic structural behaviour of a high-rise building when subjected to wind actions was investigated, taking into account the application of pressure coefficients along the facades of the building based on the use of CFD simulations [5] and the Brazilian standard NBR 6123 recommendations [4]. This way, the following conclusions can be drawn from the results presented in this investigation:

1. When considering the displacement results in the Z-direction (CFD: 0.102 m; NBR 6123: 0.135 m), it can be seen that they exceed the normative limit (0.082 m). Regarding the acceleration results in the Z-direction (CFD: 0.137 m/s²; NBR 6123: 0.155 m/s²), the normative limit is exceeded as well (0.1 m/s²). These results show the importance of considering the nondeterministic dynamic structural response in the design of high-rise buildings.
2. Regarding the differences between the results of the two analyses, the analysis considering the pressure coefficients according to NBR 6123 [4] in the Z-direction (flexible direction) led to greater results (therefore more conservative) them the analysis considering the pressure coefficients according to the CFD simulation [5].
3. In the X-direction (stiffer direction), the obtained results of displacements (CFD: 0.019 m; NBR 6123: 0.017 m) were far from the normative limit (0.082 m). The same occurred with the acceleration results (CFD: 0.029 m/s²; NBR 6123: 0.055 m/s²), where the normative limit is 0.1 m/s². Particularly in the acceleration results, it is worth noting that there was a fair difference when comparing the results of the two analyses (NBR 6123 is two times greater). Considering this difference, and taking into account the high stiffness in this direction, external interferences in the results should not be ruled out, such as the unusual and asymmetrical geometry of the building and the possible influence of torsional effects.

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