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Vibration Analysis of Tall Buildings: AnInvestigation into the Effects of Geometric Nonlinearity and Aerodynamic Damping

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ABSTRACT: *This study evaluates the dynamic structural behaviour and human comfort levels of tall buildings under wind loads, incorporating the effects of geometric nonlinearity and aerodynamic damping. A case study is conducted on a 48-storey steel-concrete composite building with a height of 172.8 m, subjected to nondeterministic wind-induced dynamic forces. The building's finite element model was developed using the Finite Element Method (FEM) via the Ansys software, taking into account soil-structure interaction to achieve a realistic representation of its dynamic behaviour. The structural response was assessed based on displacement and acceleration results, with wind velocities ranging from 5 m/s [18 km/h] to 45 m/s [162 km/h]. The conclusions of this investigation pointed out to the fact that geometric nonlinearity significantly impacts the building's dynamic response, with horizontal translational displacements differing by up to 27% and accelerations by up to 43%. On the other hand, when the aerodynamic damping was considered, the contribution was not significant to the structure dynamic response, with maximum differences up to 5% for the displacements and up to 10% for the accelerations. Finally, it must be emphasized that the building human comfort assessment indicated that excessive vibrations and human discomfort are expected for wind velocities from 90 km/h.*

Keywords: *dynamic structural behaviour, tall buildings, steel-concrete composite buildings, geometric nonlinearity, aerodynamic damping, human comfort assessment.*

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I. INTRODUCTION

Dynamic analysis of tall buildings has become increasingly significant in structural engineering due to the growing prevalence and height of modern urban constructions as seen in Figure 1, which shows the world's tallest buildings. As cities expand vertically, skyscrapers and towering structures face unique challenges related to dynamic forces, particularly those induced by wind. Wind-induced vibrations can have substantial impacts not only on structural integrity but also on occupant comfort and building durability. Therefore, understanding and mitigating these effects is crucial to ensuring the safety and functionality of tall buildings throughout their lifespan [1].

The recent projects focused on tall buildings have embraced straightforward structural systems to enhance construction velocity, reduce costs, and increase the versatility of built spaces [1]. However, this construction method has resulted in a reduction of the natural frequencies of these structures, rendering them more vulnerable to dynamic wind forces. As a result, human comfort often becomes the main consideration when evaluating serviceability limit states. For a trustworthy assessment of human comfort, it is essential to accurately describe the dynamic wind loads by comparing them with natural wind studies. Consequently, it has become vital to examine the interaction between wind and tall buildings to refine structural designs and prevent serviceability limit state issues. Accurately characterizing the structural model and wind loads in the project is of utmost importance [1-4].

The forces exerted by wind on tall buildings are particularly complex due to their interaction with the structure's geometry and height. Wind can induce a range of vibrations and oscillations that affect the stability and performance of the building. These vibrations can lead to resonance issues and amplify oscillations, potentially compromising safety and comfort. One of the key challenges in analysing wind effects is their nondeterministic nature. Unlike constant loads, wind forces are variable and can change unpredictably due to factors such as turbulence, gusts, and variations in wind velocity and direction [1]. Investigations [1,4-5] provide detailed analyses associated to the dynamic behaviour of tall buildings under such variable wind loads, offering valuable insights into how these unpredictable forces can be anticipated and managed effectively.

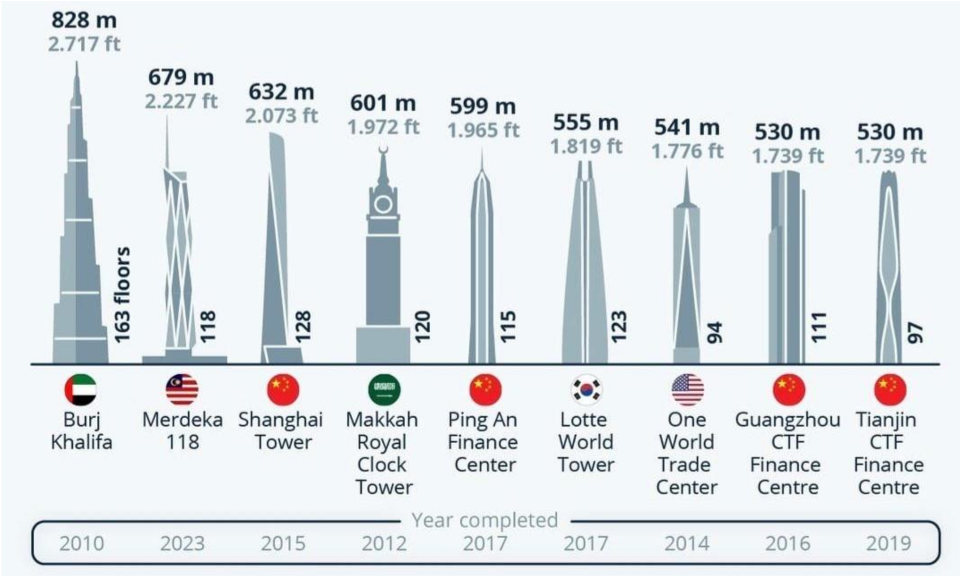


Figure 1: The tallest buildings worldwide in 2024

A critical aspect of dynamic analysis for tall buildings is the aerodynamic damping. This form of damping arises from the interaction between the airflow and the structure, helping to dissipate vibration energy and reduce oscillation amplitudes. In tall buildings, aerodynamic damping plays a vital role in maintaining structural stability and enhancing occupant comfort. Depending on the structure velocity, the dynamic response can be reduced due to the aerodynamic damping effect. In most scenarios, the structural velocity induced by wind excitation is relatively low, leading to negligible changes in dynamic pressure. However, in flexible structural systems, these velocities can become significant and may substantially influence the dynamic pressure values [6]. The research works [7-8] explore how aerodynamic damping can be incorporated into dynamic models, leading to more accurate predictions and control of vibrations in high-rise buildings.

In addition to the aerodynamic damping, geometric nonlinearity is another important factor in the dynamic analysis of tall buildings. Large deformations and dynamic forces can lead to nonlinear behaviours, complicating the analysis and requiring advanced methods to accurately predict the structure's response [9]. The effect of geometric nonlinearity in the design of tall buildings becomes important when the structure is subjected to both vertical and horizontal loads, such as wind forces. In such cases, the deformed structural system may experience higher internal forces than those predicted by a linear analysis [9]. While these effects are typically negligible in rigid structures, they become more pronounced in flexible structures, necessitating a detailed investigation [10-11]. The research work [12] discusses the necessity of considering geometric nonlinearity to ensure that dynamic models accurately represent the real response of structures under dynamic loads, particularly in tall buildings.

The interplay of all these factors (wind effects, including the nondeterministic nature, the aerodynamic damping, and the geometric nonlinearity) presents a significant challenge for structural engineers designing tall buildings. Effective integration of these elements into dynamic analyses is essential for ensuring that these structures meet safety requirements while also providing comfort and functionality. As vertical construction trends continue to grow, understanding and applying advanced dynamic analysis techniques will become increasingly critical for the success and safety of skyscrapers and other high-rise buildings [1].

The aim of this study is to evaluate the dynamic structural behaviour of a 48-storey steel-concrete composite building, with a height of 172.8 metres, when subjected to non-deterministic wind actions. The analysis includes the consideration of geometric nonlinearity and aerodynamic damping effects. Numerical modelling of the building will be conducted using the Finite Element Method (FEM), with both linear and nonlinear geometric analyses performed using the Ansys software [13].

Based on the mean maximum values of displacements and accelerations, determined on the steady-state response, this study have concluded that the effect of geometric nonlinearity led to relevant differences on the investigated building dynamic structural response, with maximum differences up to 27% to displacements and up to 43% to accelerations. Conversely, the contribution of aerodynamic damping was not significant to the building structural response, with maximum differences up to 5% for horizontal translational displacements and up to 10% for the accelerations.

II. PROPOSED METHODOLOGY TO THE DYNAMIC STRUCTURAL ANALYSIS

To assess the vibrations induced by the kinetic energy of wind gusts on structures (nondeterministic wind actions), a numerical procedure was applied for dynamic analysis, accounting for time-varying wind forces, consistent with previous research [1]. The procedures used in each of the analyses conducted in this research are represented in a simplified manner by the flowchart shown in Figure 2.

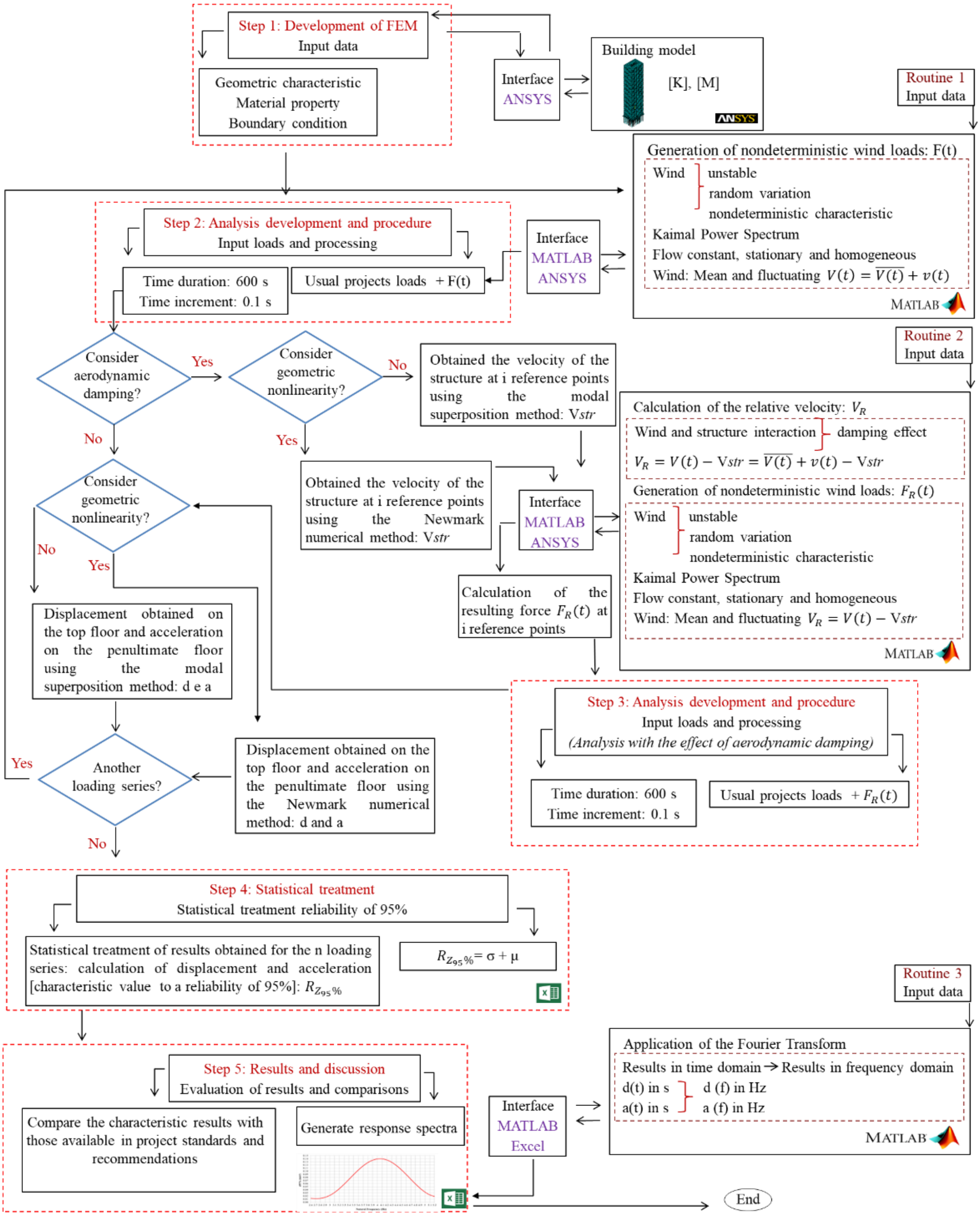


Figure 2: Proposed analysis methodology: transient dynamic analysis

The analysis incorporated standard structural damping for steel-concrete composite structures, with aerodynamic damping directly factored into the determination of dynamic wind pressures using the relative velocities between the structure and the wind. Additionally, geometric nonlinearity was evaluated to understand its impact on the structure's dynamic behaviour. The wind velocity was modelled as a time-dependent function comprising a mean component and a fluctuating component. The mean wind velocity was derived from isopleths specified in NBR 6123 [14], while the fluctuating velocity was determined using statistical parameters, including probability distribution and power spectrum. The proposed methodology accounts for the influence of aerodynamic damping caused by the relative motion between the structure and the wind, both acting in the same direction. However, phenomena such as vibrations induced by von Kármán vortices, galloping, hammering, or draping were excluded from consideration.

Considering the nondeterministic nature of wind loads, a nondeterministic approach to analysis is required. The wind load was determined using statistical methods, with velocity fluctuations characterised as a stationary and ergodic random process. Since the methodology relies on instantaneous velocity calculations, the analysis was conducted in the time domain, enabling the dynamic wind forces to be calculated incrementally over time [1].

In step 1, the finite element model is developed based on the geometric characteristics, material properties, and boundary conditions of the building model, composed of a composite steel and concrete structure. In step 2, the nondeterministic dynamic analysis is conducted, considering duration of 600 seconds and a time increment of 0.1 seconds. In addition to the usual design forces, the nondeterministic force, obtained through a routine developed in Matlab, is considered. Four scenarios may arise depending on the consideration of the effects of geometric nonlinearity and damping in the analysis, to obtain the displacements and accelerations on the top and penultimate floors of the building, respectively. In step 3, when considering the effect of aerodynamic damping, the relative velocity between the wind and the structure is calculated, as well as the new nondeterministic force, using a routine developed in Matlab [1].

The operation is performed for defined series of n loadings, obtaining the displacements and accelerations for each series. Subsequently, in step 4 a statistical treatment is applied to obtain the characteristic displacements and accelerations, considering a 95% confidence level. The results are compared with those obtained from standards and design recommendations. Finally, in step 5the dynamic response in the frequency domain is obtained using the Fourier series with a routine developed in Matlab [1].

The analysis methodology was applied to the structure of a steel-concrete composite building with 48 floors and 172.8 m height. The results of the dynamic structural response for the building were compared with the results obtained when the effects of geometric nonlinearity and aerodynamic damping are considered. For the development of the study, seven hundred and forty nondeterministic dynamic analyses were performed: two hundred related to linear analyses, one hundred and eighty associated to geometric nonlinear, one hundred and eighty corresponding to linear analyses with the effect of the aerodynamic damping, and one hundred and eighty related to nonlinear geometric including the effect of the aerodynamic damping. In addition, twenty modal analyses were carried out: two were associated to linear analyses and eighteen were considered nonlinear. The details of each procedure will be discussed in the next sections of the paper.

III. NONDETERMINISTIC WIND DYNAMIC LOADS

Wind is a naturally occurring phenomenon that exhibits inherent variability, making its properties nondeterministic. Unlike predictable and constant forces, such as gravitational force, wind is influenced by numerous dynamic factors, including, for example, the temperature and atmospheric pressure. These factors contribute to random fluctuations in wind velocity and direction, resulting in a complex, unpredictable behaviour that challenges traditional methods of analysis. To produce a nondeterministic dynamic wind series in this study, the wind flow was modelled as unidirectional, stationary, and homogeneous. This assumption implies that the main flow direction remains constant over time and space and that the wind's statistical properties do not vary during the simulation period [1].

To account for these random variations, wind is often modelled using stochastic processes, such as the use of power spectra or time series analysis. These models can capture the statistical properties of wind, including its frequency distribution and turbulence intensity, enabling a more realistic representation of its effects on structures. The Kaimal spectrum, for example, is frequently utilised to describe the turbulent components of wind in the context of dynamic structural analysis, considering how factors like building height influence wind response [1].

Equations (1) and (2) show the expressions to calculate the energy spectrum, where f represents the frequency in Hz, SV denotes the spectral density of the longitudinal turbulence component of the wind in m²/s, x is a dimensionless frequency.

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

$$x(f,z) = \frac{f\,z}{\bar{V}_z} \tag{2}$$

The mean wind velocity, $\overline{V}_z$, in m/s, relative to the height z, in m, is determined utilising Equation (3). The parameter $\overline{V}_{10}$ represents the project mean wind velocity at a height of 10 meters, calculated over 10 minutes using Equation (4). The parameter p denotes the exponent of the power law variation for S2. The basic wind velocity, V_0 (in m/s), is determined over a 3-second interval and adjusted using the factors, S_1, the topographic factor, and S_3, the statistical factor associated with the probability of structural failure, as specified in NBR 6123 [14]. The friction velocity u^* (in m/s) was calculated based on the use of Equation (5), with a Kármán k constant equal to 0.4 and z_0 corresponding to the roughness length in meters.

$$\overline{V}_z = \overline{V}_{10}\left(\frac{z}{10}\right)^p \quad (3)$$

$$\overline{V}_{10} = 0.69\, V_o S_1\, S_3 \quad (4)$$

$$u^* = \frac{k\overline{V}_Z}{\ln(^z/_{z_o})} \quad (5)$$

Equation (6) represents the turbulent component of the wind velocity, v(t), which is simulated as a random process derived from the summation of a finite number of harmonics. In this representation, N denotes the number of divisions in the power spectrum, f is the frequency in Hz, Δf is the frequency increment, θ is the random phase angle uniformly distributed in the range of [0-2π], and t represents time in seconds.

$$v(t) = \sum_{i=1}^{N} \sqrt{2S^v(f_i)\Delta f}\, \cos\,(2\pi f_i\ +\ \theta_i) \quad (6)$$

In this research work, the wind pressure acting on the building façades was assumed to be directly proportional to the wind velocity, following the classic Davenport model incorporated in the Brazilian design standard NBR 6123 [14]. Accordingly, the dynamic wind pressure, q(t) (in N/m²), can be calculated using Equation (7), where $\overline{V}$ is the mean part of wind velocity in m/s.

$$q(t) = 0.613\ [\overline{V}\ + v(t)]^2 \quad (7)$$

Subsequently, with the dynamic wind pressure acting on the structure, the dynamic wind load, F(t), in N, was calculated at each structural section of the building over time, using Equation (8). The parameter C_{ai} represents the drag coefficient in the "i" direction and is influenced by the relationships between the structural dimensions and can be determined according to NBR 6123 [14]. The influence area is represented by parameter A_i, in m².

$$F(t) = C_{ai} q(t) A_i \quad (8)$$

Consequently, Equation (8) can be rewritten based on the expansion of Equation (9), where C_D represents the drag coefficient corresponding to the angle of attack, V_0 is the wind basic velocity, and p is the exponent of the potential law of variation of the S_2 factor, as defined by NBR 6123 [14].

$$F(t) = 0.613\ C_D\ A_i \left[V_0\left(\frac{z}{z_0}\right)^p + \sum_{i=1}^{N} \sqrt{2S^v(f_i)\Delta f}\ \cos\,(2\pi f_i\ +\ \theta_i)\right]^2 \quad (9)$$

The aerodynamic damping mathematical formulation was directly considered in the wind pressure calculations, keeping in mind the relative velocity between the wind and the structure, both in the same direction. Therefore, the wind pressure and relative velocity can be calculated based on Equations (10) to (12).

$$q_{wind} = \frac{1}{2}\rho V_R^2 = 0.613 V_R^2 \quad (10)$$

$$V_R = [V(t)\text{-}V_{str}] \quad (11)$$

$$V(t) = \overline{V}(z) + v(t) \quad (12)$$

The parameter q_{wind} represents the wind dynamic pressure; ρ is the specific mass of the air under normal conditions of pressure; V_R is the relative velocity between the wind and the structure at the considered node; V_{str} is the structure's velocity in the direction of interest at the considered node; V(t) is the total wind velocity, where $\overline{V}$ denotes the mean wind velocity in m/s, and v(t) represents the turbulent component of the wind velocity.

Equation (10) presents the classical formulation for calculating the dynamic wind pressure, as outlined in NBR 6123 [14], with the modification of the adopted reference velocity. On the other hand, it must be emphasized that Equation (11) introduces the relative velocity between the wind [V(t)], and the structure [V_{str}], aiming to include the effect of the aerodynamic damping. In most cases, the velocity of the structure, induced by the wind, is either low or negligible, which does not significantly affect the dynamic pressure values. Nevertheless, in the case of flexible structures, substantial velocities can occur, potentially leading to a notable impact on dynamic pressure values [1].

Dynamic wind loads are calculated as the sum of two components: a turbulent component (nondeterministic dynamic loading) and a static component (mean wind) as observed in Equation (12). The new nondeterministic dynamic force that considers the effect of aerodynamic damping, Equation (13), can be calculated from the wind pressure expression, obtained through Equation (10), substituting it in Equation (8). Accordingly, Equation (13) can be written in the expansion of Equation (14).

$$F_R(t) = 0.613\ C_{ai} V_R^2 A_i \tag{13}$$

$$F_R(t) = 0.613\ C_D\ A_i \left[V_0 \left(\frac{z}{z_0}\right)^p + \sum_{i=1}^{N} \sqrt{2S^v(f_i)\Delta f}\ \cos\left(2\pi f_i + \theta_i\right) - V_{str} \right]^2 \tag{14}$$

IV. INVESTIGATED STEEL-CONCRETE COMPOSITE BUILDING

The analysed steel-concrete composite building consists of 48 floors, each with a floor height of 3.6 meters. The total height of the structural system is 172.8 meters. The building presents a floor plan measuring 45 meters in length and 32 meters in width, with the central core dimensions being 27 by 9 meters. The main beams are constructed from W460x106 steel profiles, while the secondary beams utilise W410x60 profiles [1].

The steel used is the standard ASTM A572 grade. The concrete slab has a thickness of 15 cm, and the steel columns are constructed from HD profiles (steel ASTM A913), with all geometric characteristics provided in Table 1 [1]. The properties of steel and concrete are shown in Table 2 and Figure 3 illustrates the floor plan of the structure.

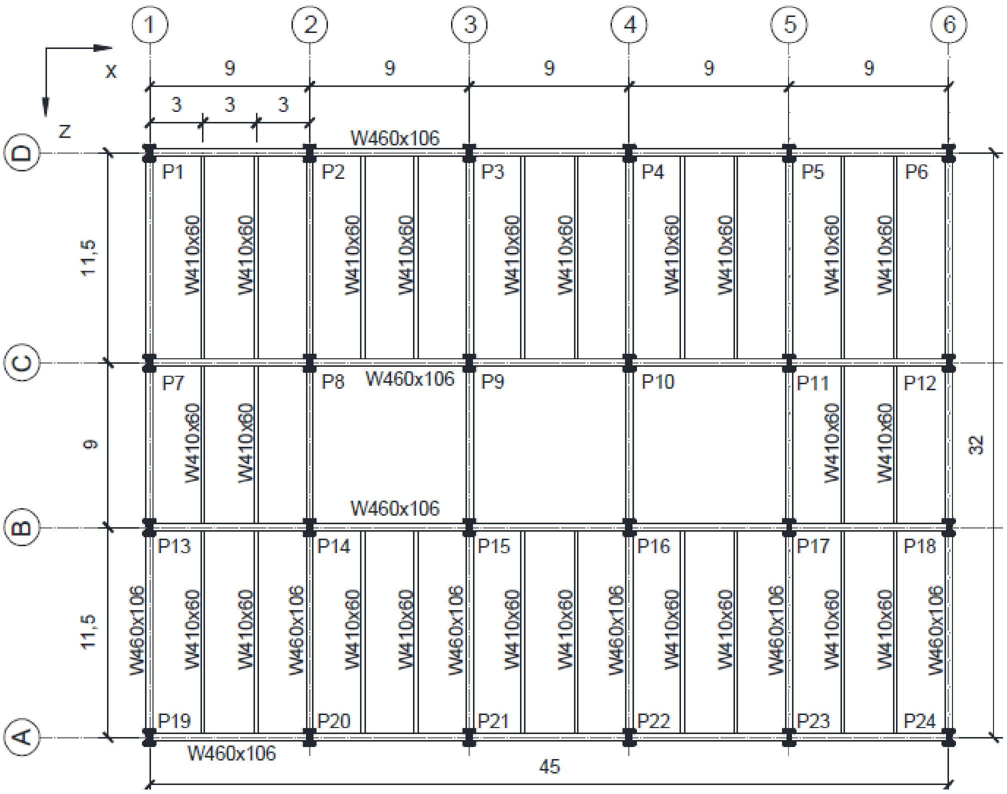


Figure 3: Structural design of the steel-concrete composite building.

Table 1: Steel profiles of the columns of the structural building.

Storey	Centre Core	Facade
1 to 10º	HD 400 x 990	HD 400 x 551
11 to 20º	HD 400 x 818	HD 400 x 382
21 to 30º	HD 400 x 667	HD 320 x 245
31 to 40º	HD 400 x 421	HD 260 x 172

Table 2: Material properties of the structural model.

Material properties	Steel	Concrete

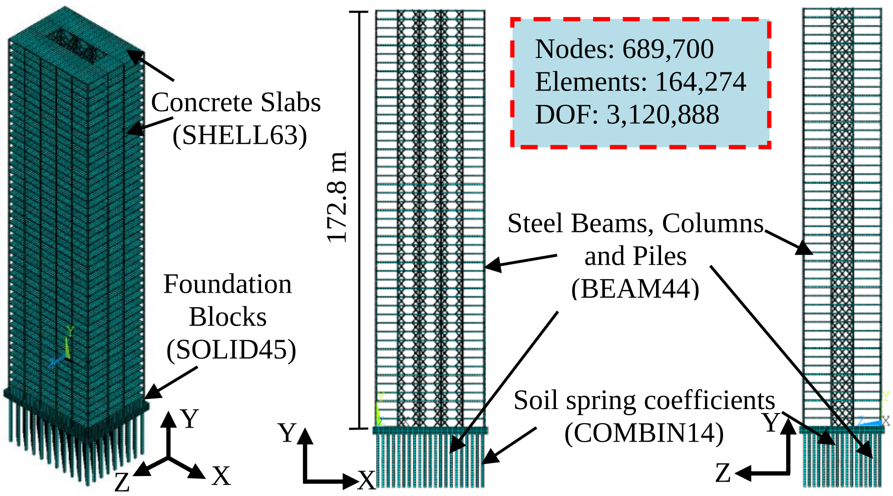
Characteristic strength [f_y and f_{ck}] (MPa)	345	30
Modulus of elasticity [E_{cs} and E_s] (GPa)	205	26
Poisson's ratio (ν)	0.3	0.2
Specific weight [γ_c and γ_s] (kN/m³)	78.5	25

V. FINITE ELEMENT MODELLING OF THE BUILDING

The steel-concrete composite building was analysed using the Ansys software [13], employing standard discretisation techniques associated with the Finite Element Method (FEM). The finite element model of the building satisfied the mesh convergence study previously conducted [1]. In the numerical modelling, the steel beams, columns, and piles were represented using the BEAM44 three-dimensional finite elements, which incorporated both bending and torsional effects. The concrete slabs of the building were simulated using SHELL63. The foundation block was discretised based on the use of the SOLID45 element. The soil spring coefficients were modelled using the COMINB14 element. Figure 4 shows that the foundation (piled raft) of the building was modelled to consider the effect of the soil-structure interaction.

The model utilised to represent the interaction between the soil and the structure was the Winkler model. This model simplifies the interaction by considering the soil as a series of independent springs, each with stiffness proportional to the soil's reaction modulus. In the present case, the foundation considered is a piled raft, with the piles subjected to lateral loads. In this approach, the soil is modelled by independent horizontal springs [1].

The full interaction between the concrete slabs and steel beams was taken into account in the study, ensuring that the nodes of the finite element model were coupled to prevent slip. Both steel and concrete were assumed to exhibit linear elastic behaviour, and all structural sections of the model remained planar in the deformed state. The final computational model adopted used 689,700 nodes and 164,274 elements, resulting in a numerical model with 3,120,888 degrees of freedom [1].



a) Three-dimensional view b) Front view c) Lateral view

Figure 4: Finite element model of the steel-concrete composite building

Geometric nonlinearity appears in the theory of elasticity both in the equilibrium equations, which are written using the deformed configurations, and in the deformation-displacement relations, which include nonlinear terms in the displacements and their derivatives. An incremental-iterative procedure is used to trace the equilibrium path of the structure over time. The principle of virtual displacements for deformable bodies is given by $\delta W_{int} = \delta W_{ext}$ [1].

Considering this condition, Equation (15) represents the equilibrium condition of the system, where $\tilde{T}_{ij}$ represents the Piola-Kirchhoff II stress tensor; ε_{ij} represents the Green–Lagrange strain tensor; ${}^{t+\Delta t}R$ refers to the virtual work of the external forces; the superscript t + Δt refers to the final configuration and the subscript t to the final configuration reference. This expression considers Green–Lagrange deformations and displacement increments expressed in terms of the reference configuration, ${}^{t+\Delta t}_{t}\varepsilon_{ij} = {}_{t}\varepsilon_{ij}$, decomposed into linear and nonlinear portions, ${}_{t}\varepsilon_{ij} = {}_{t}e_{ij} + {}_{t}\eta_{ij}$. The solution to the problem can be obtained with numerical integration methods.

$$\int_{V_t} {}^{\Delta t}_{t}\tilde{T}_{ij}\delta\, {}^{0}_{t}\varepsilon_{ij} dV_t + \int_{V_t} {}^{t}_{t}T_{ij}\delta\, {}_{t}e_{ij} dV_t + \int_{V_t} {}^{t}_{t}T_{ij}\delta\, {}_{t}\eta_{ij} dV_t = {}^{t+\Delta t}_{t}R \quad (15)$$

Equation (16), which corresponds to the governing equilibrium equation of structural dynamics, can be obtained by spatial discretization of the structure. [M]; [C]; [K]; $\{F^a\}$; $\{\ddot{u}\}$;$\{\dot{u}\}$; {u} represent the mass matrix; damping matrix; stiffness matrix; applied load vector; acceleration vector; velocity vector and displacement vector, respectively.

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F^a\} \quad (16)$$

The commercial finite element software Ansys (Ansys, 2022) utilises Newmark's time integration method to solve transient problems, although more complex in terms of calculation, this approach was deemed appropriate due to the effect of nonlinearity. For nonlinear dynamic solutions, the methodology combines the Newton-Raphson method with Newmark's method [1,9]. Equation (17) is used in the implicit method to obtain the solution. Geometric nonlinearity was incorporated using the total Lagrangian formulation, which considers large displacements and rotations [1,9].

$$\{u_{n+1}\} = [K]^{-1}\{F_{n+1}{}^{a}\} \quad (17)$$

VI. FREE VIBRATION ANALYSIS: NATURAL FREQUENCIES AND VIBRATION MODES

The analysed steel-concrete composite buildingThrough a free vibration analysis (modal analysis), it was possible to obtain the natural frequencies and vibration modes of the steel-concrete composite building model, based on the use of the Ansys program (Ansys, 2022). In this investigation, the linear modal analysis was performed, in which there is no load application on the structure. In addition, the nonlinear modal analysis was also performed, considering on the use of prestressing loads. It is noteworthy that for the nonlinear modal analysis (prestressed), which aims to evaluate the effects of geometric nonlinearity on the eigenvalues and eigenvectors, the structure is considered in its deformed position.

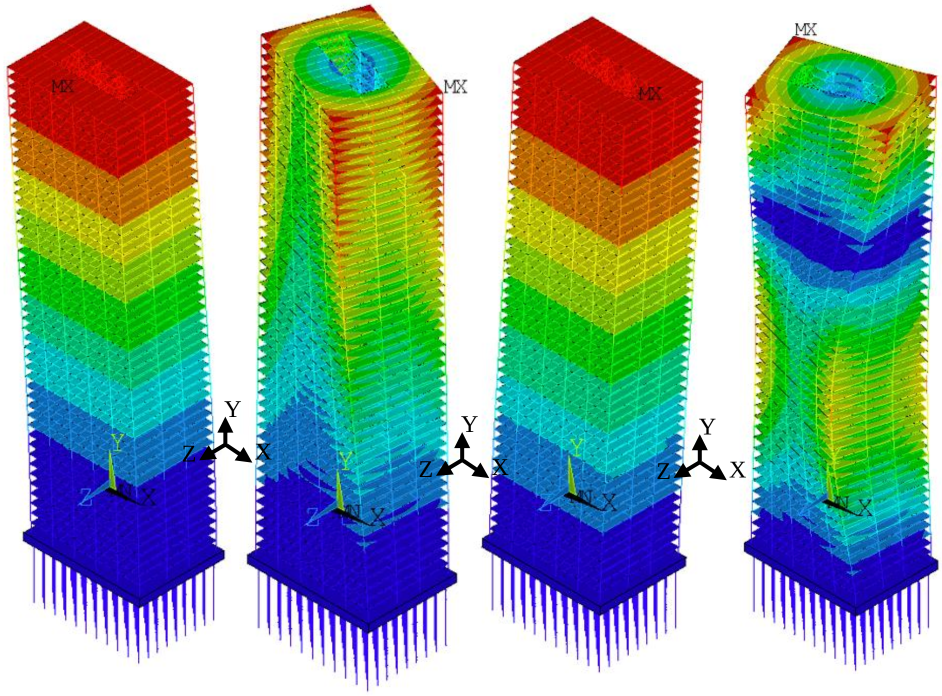
The loads utilised to provoke the deformed position of the building are associated to the usual design loads (vertical loads: self-weight, permanent loads, overloads; and horizontal loads: static wind loads). This way, for the calculation of static wind loads, intervals of 18 km/h were considered, starting at 18 km/h up to 162 km/h, covering most of the of basic wind velocities present in NBR 6123 [14].

Table 3 shows the first four natural frequencies of the building and Figure 5 represents the first four vibration modes. The mode shapes illustrate the vibration characteristics of the building; the red colour represents the maximum modal amplitude, while blue indicates the minimum. It is noteworthy that only the vibration modes of the linear modal analysis were presented, since despite the existing differences on the results of the natural frequencies of the system, the vibration modes remained unchanged (linear and nonlinear modal analysis).

Table 3: Natural frequencies of the linear and nonlinear model.

Frequency (Hz)	Linear Model	Geometric Nonlinear Model Velocity - V_0 (km/h)								
		18	36	54	72	90	108	126	144	162
f_{01}	0.161	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146
f_{02}	0.188	0.172	0.172	0.172	0.172	0.171	0.171	0.170	0.169	0.169
f_{03}	0.194	0.182	0.182	0.182	0.182	0.182	0.182	0.182	0.182	0.182
f_{04}	0.565	0.536	0.536	0.536	0.536	0.536	0.536	0.536	0.536	0.536

The fundamental frequency value of the investigated building in the soil-structure model was verified as 0.161 Hz (f_{01} = 0.161 Hz), 10% higher than the value calculated in the nonlinear modal analysis (f_{01} = 0.146 Hz). This is particularly significant because, in addition to the reduction in the natural frequencies of the structure due to the effects of geometric nonlinearity, as outlined in the Brazilian design standard NBR 6123 [14], buildings with natural frequency values lower than 1 Hz, especially those with low structural damping, may exhibit substantial floating dynamic along-wind response, indicative of excessive vibrations.



1º Vibration mode	2º Vibration mode	3º Vibration mode	4º Vibration mode
Bending around X	Torsion around Y	Bending around Z	Torsion around Y
f_{01} = 0.161 Hz	f_{02} = 0.188 Hz	f_{03} = 0.194 Hz	f_{04} = 0.565 Hz

Figure 5: Vibration modes of the analysed steel-concrete composite building

VII. RESULTS DISCUSSION: NONDETERMINISTIC DYNAMIC STRUCTURAL ANALYSIS

The nondeterministic dynamic analyses were developed considering the modelling expressed in Figure 1. The forces used in the dynamic analysis are the usual vertical design forces, in addition to the horizontal loads (nondeterministic dynamic wind actions) that were applied to the building facade, see Figure 4. The maximum horizontal displacements values were calculated at the building top (H = 172.8 m) and the maximum accelerations values were determined at last building floor storey (H = 169.2 m). In this work, four of analyses were developed: linear and geometric nonlinear with and without aerodynamic damping. In addition, twenty series of nondeterministic dynamic wind loading were generated, used for the statistical treatment of the response. Table 4 presents the parameters used to generate the wind series.

Table 4: Parameters used to generate the nondeterministic wind series

NBR 6123 [14] design parameters	Parameters
Basic Wind Velocity (V_0)	35 m/s [126 km/h]
Terrain Category	IV
Recurrence Time	10 years
Topographic Factor (S_1)	1
Parameters for Roughness Factor (S_2)	b = 0.84, p = 0.135 and Fr = 0.69
Probability Factor (S_3)	0.78
Time Duration and Time Increment	600 seconds and 0.1 second

Table 5 represents the dynamic structural response of the investigated building, related to the statistical analysis of the response (thirty nondeterministic wind series) and taking into account the numerical accuracy for the assessment of the nondeterministic steady state response. Is possible to conclude that significant variations are observed in the displacements and accelerations of the building when the effect of geometric nonlinearity is included in the dynamic analysis (forced vibration), with maximum differences up to 27% for horizontal translational displacements and 43% for the accelerations.

Table 5: Dynamic structural response of the building [V_0 = 18 to 162 km/h]

Wind Velocity(km/h)	Typeof Analysis	Velocity - V_0 (km/h)								
		18	36	54	72	90	108	126	144	162
Displacement (m)	Nonlinear	0.004	0.018	0.047	0.084	0.146	0.211	0.288	0.373	0.510
	Linear	0.003	0.015	0.038	0.080	0.122	0.182	0.262	0.347	0.408
	%	13%	27%	25%	5%	19%	16%	10%	7%	25%
Acceleration (m/s²)	Nonlinear	0.003	0.013	0.036	0.067	0.121	0.175	0.231	0.321	0.472
	Linear	0.002	0.010	0.028	0.053	0.093	0.132	0.199	0.253	0.330
	%	20%	34%	31%	26%	30%	32%	16%	27%	43%

The parametric study related to the wind basic velocities, considering the effect of geometric nonlinearity, indicated that for intervals of 5 to 20 m/s [18 to 72 km/h], the calculated mean maximum values of accelerations do not exceed the limit value for the studied building established by NBR 6123 [14] (alim = 0.10 m/s²), meeting human comfort criterion. However, for velocities of 25 to 45 m/s [90 to 162 km/h], the human comfort criterion is violated. Considering the mean maximum horizontal displacements, when comparing these values with the limit established in NBR 8800 [15] [H/400: 172.8/400 = 0.43 m], for velocities from 18 to 144 km/h, the displacement limit is attended. However, for a velocity of 162 km/h the recommended limit is violated.

Considering the human comfort criterion proposed by Hirsch and Bachmann [16], the analysed building would fall into the imperceptible category when the basic wind velocity is less than 15 m/s [54 km/h], perceptible for 20 and 25 m/s [72 and 90 km/h] and uncomfortable for 30 to 45 m/s [108 to 162 km/h] when considering peak and ten peaks mean values and the effect of geometric nonlinearity.

To evaluate the aerodynamic damping effect on the building's structural response, the basic wind velocity of V_0 = 35 m/s [126 km/h] NBR 6123 [14] was utilised to determine the displacements and accelerations considering the statistical treatment associated with the twenty wind load series. The building's dynamic response with comparisons between the responses associated with the linear and the geometric nonlinear models as shown in Table 6.

It was concluded, by evaluating Table 6 that significant quantitative changes occur to the mean maximum values of the building's displacements and accelerations, calculated in the steady state response, when the effects of geometric nonlinearity and aerodynamic damping are considered. Conversely, when the effect of aerodynamic damping is available, there is a reduction in the mean maximum displacements and accelerations. It is possible to verify the changes that occurred in the building's dynamic response when the effect of aerodynamic damping is considered, with maximum differences of up to 5% for horizontal translational displacements and up to 8% for the accelerations. Furthermore, although the inclusion of aerodynamic damping reduces the maximum values obtained, it does not have a significant impact on the behaviour of the structure under analysis.

Table 6: Displacements and accelerations: effect of aerodynamic damping [V_0 = 126 km/h]

Structural Response	Linear Model			Geometric Nonlinear Model		
	No aerodynamic damping	Aerodynamic damping	%	No aerodynamic damping	Aerodynamic damping	%
Displacement (m)	0.262	0.251	4	0.288	0.272	5
Acceleration (m/s²)	0.199	0.188	5	0.231	0.213	8

Based on the effect of the aerodynamic damping, the mean maximum values of accelerations calculated for a wind basic velocity of 35 m/s [126 km/h] exceed the limit value established by NBR 6123 [14] (a_{lim} = 0.10 m/s²), violating the human comfort criterion. The conclusion is the same for both the linear model and the nonlinear geometric model. Based on Hirsch and Bachmann's criterion [16], the building would fall in the 'uncomfortable' classification for the linear and nonlinear geometric models considering the peak and ten peaks mean values. On the other hand, when the mean maximum horizontal displacement values were investigated it was concluded that recommended limit is attended [NBR 8800 [15]: H/400 = 172.8/400 m = 0.43 m], as presented in Table 6.

Figures 6 and 7 show, respectively, the dynamic structural response in time domain to displacements of the building's top node and accelerations to the top floor of the building (see Figure 4), taking into account nondeterministic linear dynamic analysis in both directions considering the basic wind velocity of 35 m/s [126 km/h], for the series that better represents the dynamic analysis after the statistical analysis procedure. It is possible to observe the effects of geometric nonlinearity and aerodynamic damping in the dynamic structural analysis by varying the values of displacements and accelerations in different situations.

Figure 8 illustrates, in frequency domain, the linear and geometric nonlinear dynamic structural response of the building [V_0 = 35 m/s (126 km/h)], with and without the effects of aerodynamic damping, where the differences between the values of the natural frequencies of the building is verified. The results considered the wind load series that produced the values closest to the characteristic values of the system response.

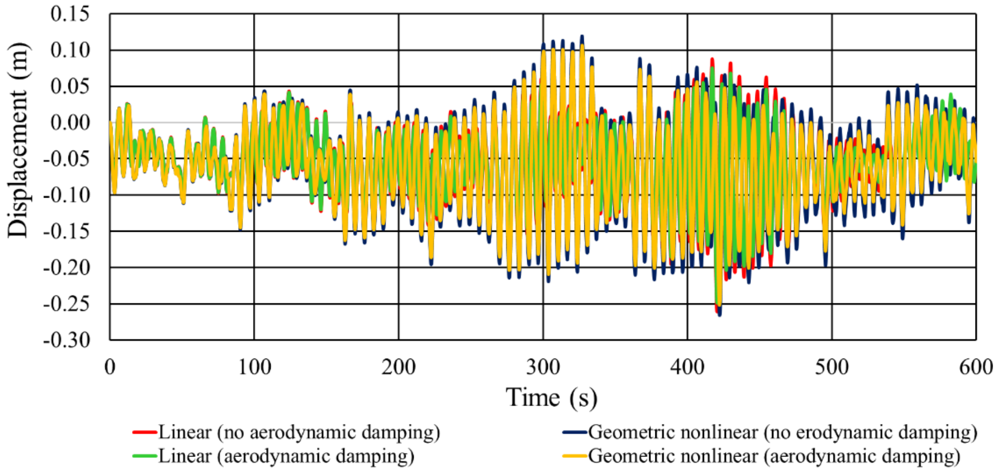


Figure 6: Geometric nonlinearity and aerodynamic damping effects (displacements) V_0 = 126km/h

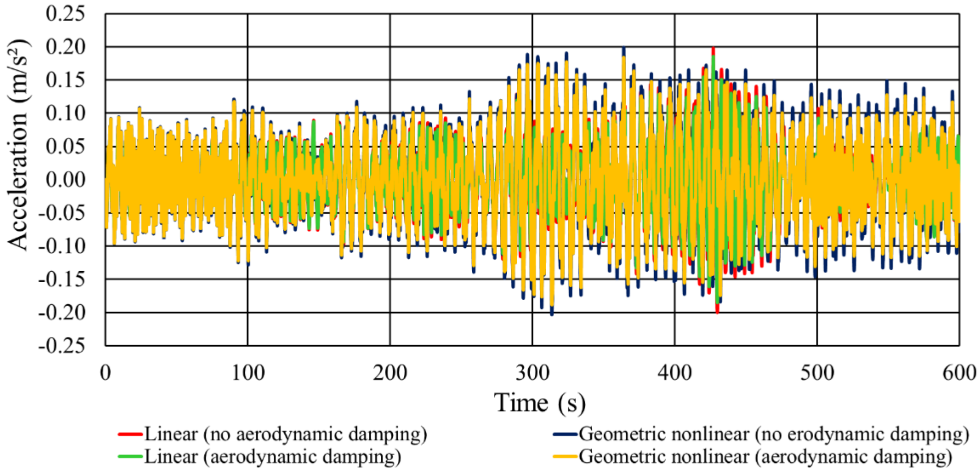


Figure 7: Geometric nonlinearity and aerodynamic damping effects (accelerations) V_0 = 126km/h

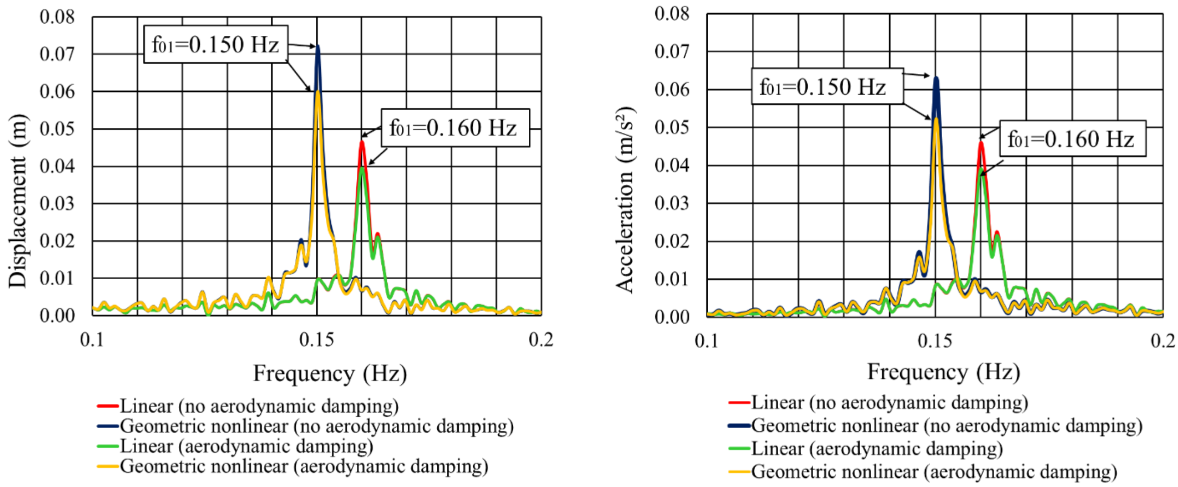


Figure 8: Dynamic response (frequency domain): displacements and accelerations V_0 = 126 km/h

VIII. CONCLUSIONS

The developed analysis methodology introduces an assessment of tall buildings human comfort considering the nondeterministic wind actions, based on the effects of geometric nonlinearity and aerodynamic damping. This approach allows for a more accurate and realistic analysis of the structural behaviour under variable and unpredictable wind conditions. The relevance of this work is related to the inclusion of characteristics that are often neglected in real-world design situations. This way, to ensure an even more faithful representation of reality, the soil-structure interaction was included in the analysis through detailed foundation modelling. From the results obtained regarding the dynamic response of the analysed steel-concrete composite building, the following conclusions can be drawn:

1. First, the dynamic structural response of investigated building was modified, when the effects of the geometric nonlinearity and the aerodynamic damping were considered in the analysis, with changes in the displacements and accelerations values.

2. The extensive parametric analysis related to the basic wind velocities indicated that from the range of 5 to 20 m/s [18 to 72 km/h], the mean maximum values of accelerations calculated through the dynamic analysis do not exceed the human comfort limit value recommended by Brazilian design standard [14] (a_{lim} = 0.10 m/s²). However, for wind velocities from the range of 25 to 45 m/s [90 to 162 km/h], the investigated building human comfort criterion was violated and excessive vibrations are expected.

3. Considering the parametric study related to the wind basic velocities [18 km/h to 162 km/h] and the statistical analysis of twenty nondeterministic wind series, it was concluded that the effects of geometric nonlinearity caused significant changes in the building's dynamic structural response, with maximum differences of up to 27% in displacements and up to 43% in accelerations.

4. On the other hand, considering the basic wind velocity of 126 km/h and the statistical analysis of twenty nondeterministic wind series, it was verified that the effects of aerodynamic damping resulted in changes to the building's dynamic response, with maximum differences up to 5% for displacements up to 8% for accelerations.

5. Finally, having in mind the investigated building dynamic structural response performed in the frequency domain, it must be emphasized that the geometric nonlinearity effect has produced significant modifications on the displacements and accelerations values, related to the structure response energy transfer levels when subjected to wind actions.

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