Assessment of Building Nondeterministic Dynamic Structural Behavior considering the Effect of Geometric Nonlinearity and Aerodynamic Damping

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Received: 14 August 2024 | Revised: 15 September 2024 | Accepted: 22 September 2024

 DOI: https://doi.org/10.48084/etasr.8743

ABSTRACT

The objective of this research is to evaluate the dynamic structural response of tall buildings subjected to wind loads, taking into account the influence of geometric nonlinearity and aerodynamic damping. The project focuses on a steel-concrete composite structure with 48 floors and a height of 172.8 m, examining its response to wind non-deterministic dynamic actions. The building finite element model was developed based on the Finite Element Method (FEM), using the ANSYS computational program, and considering the soil-structure interaction effect, with the objective of obtaining a realistic representation of the dynamic behavior. The building dynamic response was obtained based on the displacement and acceleration values, determined with the consideration of a wind velocity range between 5 m/s (18 km/h) and 45 m/s (162 km/h). The findings of this study indicate that when the effect of geometric nonlinearity was incorporated into the analysis, the dynamic response of the investigated building exhibited notable discrepancies. The maximum differences observed in the horizontal translational displacements and accelerations were 30% and 45%, respectively. In contrast, the inclusion of aerodynamic damping had a negligible impact on the structural dynamic response, with maximum differences of 5% for displacements and 10% for accelerations.

Keywords-tall buildings; steel-concrete composite buildings; geometric nonlinearity; aerodinamic damping

I. INTRODUCTION

The analysis of tall buildings has gained significant importance in structural engineering due to the increasing prevalence of and height reached by modern urban constructions. As urban areas continue to expand vertically, skyscrapers and other towering structures are confronted with distinctive challenges pertaining to dynamic forces, particularly those induced by wind. The impact of wind-induced vibrations on buildings is not limited to structural integrity; they can also affect occupant comfort and the durability of the building itself. It is therefore imperative to gain an understanding of these effects and to implement measures to minimize them in order to ensure the safety and functionality of tall buildings throughout their lifespan. The forces exerted by wind on tall buildings are particularly complex due to the interaction between the wind forces and the structure's geometry and height. Wind can induce a variety of vibrations and oscillations that impact the stability and performance of the building. Such vibrations have the potential to give rise to resonance issues and amplify oscillations, thereby compromising the safety and comfort of the occupants. One of the principal difficulties encountered in the analysis of wind effects is their inherently non-deterministic nature. In contrast to constant loads, wind forces are variable and can change unpredictably due to factors such as turbulence, gusts, and variations in wind velocity and direction. The studies conducted in [1-3] offer comprehensive insights into the dynamic behavior of tall buildings subjected to variable wind loads. These analyses provide valuable guidance on how to anticipate and effectively manage the impact of these unpredictable forces. A key element of dynamic analysis for tall buildings is the phenomenon of aerodynamic damping. This form of damping arises from the interaction between the airflow and the structure, facilitating the dissipation of vibration energy and the reduction of oscillation amplitudes. In tall buildings, the role of aerodynamic damping is of critical importance with regard to the maintenance of structural stability and the enhancement of occupant comfort. The dynamic response may be diminished, contingent upon the velocity of the structure, as a consequence of the aerodynamic damping effect. In the majority of instances, the velocity of the structure that is generated when it is excited by wind is relatively low, which has no impact on the dynamic pressure values. However, in the case of flexible structural systems, these velocities can be significant and may have a considerable impact on the dynamic pressure values [4]. Authors in [5, 6] investigated the potential for incorporating aerodynamic damping into dynamic models, with the objective of achieving more accurate predictions and control of vibrations in high-rise buildings. In addition to the aerodynamic damping, the geometric nonlinearity represents a significant factor in the dynamic analysis of tall buildings. The occurrence of significant deformations and the presence of dynamic forces can result in nonlinear behaviors, which can render the analysis more intricate and necessitate the usage of sophisticated methodologies to accurately anticipate the structure's response. In the design of tall buildings, the geometric nonlinearity effect becomes relevant when the structure is simultaneously subjected to vertical and horizontal actions, such as wind actions. This is due to the fact that the load applied to the deformed structural system can result in higher values of effort when compared to those calculated based on a linear analysis [7]. In rigid structures, these effects are typically insignificant and can be disregarded. However, in flexible structures, such effects become significant and necessitate analysis [8, 9]. Authors in [10] highlighted the importance of incorporating geometric nonlinearity into dynamic models to ensure accurate representation of the structural response to dynamic loads, particularly in tall buildings. The interplay of these factors (wind effects, including the non-deterministic nature, the aerodynamic damping, and the geometric nonlinearity) presents a significant challenge for structural engineers engaged in the design of tall buildings. It is imperative that these elements be effectively integrated into dynamic analyses to ensure that these structures meet safety requirements while also providing comfort and functionality. As the construction of vertical structures continues to expand, it is imperative to gain a comprehensive understanding of advanced dynamic analysis techniques to ensure the success and safety of skyscrapers and other high-rise buildings [1]. The objective of this research is to evaluate the dynamic structural behavior of a steel-concrete composite building, where the effects of geometric nonlinearity and aerodynamic damping are considered. The numerical modeling of the building is performed using the FEM, and linear and nonlinear geometric analyses are conducted based on the use of the ANSYS program [11]. The study's findings indicate that the effect of geometric nonlinearity resulted in notable discrepancies in the dynamic structural response of the investigated building, with maximum differences of up to 30% in displacements and up to 45% in accelerations. In contrast, the impact of aerodynamic damping was found to be relatively minor, with maximum discrepancies of up to 5% for horizontal translational displacements and up to 10% for accelerations.

II. ANALYSIS METHODOLOGY

In order to evaluate the vibration caused by the kinetic energy of wind gusts in structures (nondeterministic wind action), a numerical procedure was employed for dynamic analysis with variable wind forces over time [1]. The effects of normal structural damping on structures composed of steel and concrete were considered. Aerodynamic damping was incorporated directly into the calculation of dynamic wind pressures through the use of relative velocities between the structure and the wind. The impact of geometric nonlinearity on the dynamic behavior of the structure was also evaluated. The wind velocity can be expressed as a time function comprising a mean value and a floating component. In the proposed methodology for analysis, the mean value was obtained from isopleths derived from NBR 6123 [12], while the floating velocity was determined through the application of statistical parameters, including probability distribution and power spectrum. The methodology was applied to the structural analysis of a 48-story, 172.8-meter steel-concrete composite building. The results of the dynamic structural response were compared with the results obtained when the effects of geometric nonlinearity and aerodynamic damping were considered. The methodology is associated with the influence of aerodynamic damping due to the relative movement between the structure and the wind, both of which are acting in the same direction. The influence of von Kármán vortices, galloping, hammering, and draping on the vibrations is not considered in this analysis. The wind load was determined through the application of statistical methods, with the velocity fluctuations represented by a random, stationary, and ergodic process. Given that the procedure was based on instantaneous velocity calculations, it is necessary to perform the analysis in the time domain. This allows for the calculation of the dynamic forces of the wind at time increments [1]. The methodology employed in each of the analyses conducted in this research project is presented in the flowchart illustrated in Figure 1. In order to develop the study, seven hundred and forty non-deterministic dynamic analyses were conducted. Of these, two hundred were related to linear analyses, one hundred and eighty were associated with geometric nonlinear analyses, one hundred and eighty corresponded to linear analyses with the effect of the aerodynamic damping, and one hundred and eighty were related to nonlinear geometric analyses including the effect of the aerodynamic damping. Furthermore, twenty modal analyses were conducted, comprising two linear analyses and eighteen nonlinear ones. The present research was based on the findings of several studies, in order to assess the building dynamic structural response associated with both loading directions. These entail wind effects, including the non-deterministic nature, the aerodynamic damping, and the geometric nonlinearity. However, only the results pertaining to the most unfavorable loading direction with respect to the investigated building dynamic response are presented.

III. NONDETERMINISTIC DYNAMIC WIND FORCE

Due to the inherent randomness of wind properties, deterministic considerations may prove inadequate in accurately predicting their behavior. In order to generate a non-deterministic dynamic wind series, it was assumed that the wind flow was unidirectional, stationary, and homogeneous. This implies that the direction of the main flow remains constant over time and space, and that the wind statistical characteristics remain consistent when the simulation period is performed. This research project employs the Kaimal power spectrum, taking into account the impact of the building height on dynamic response.

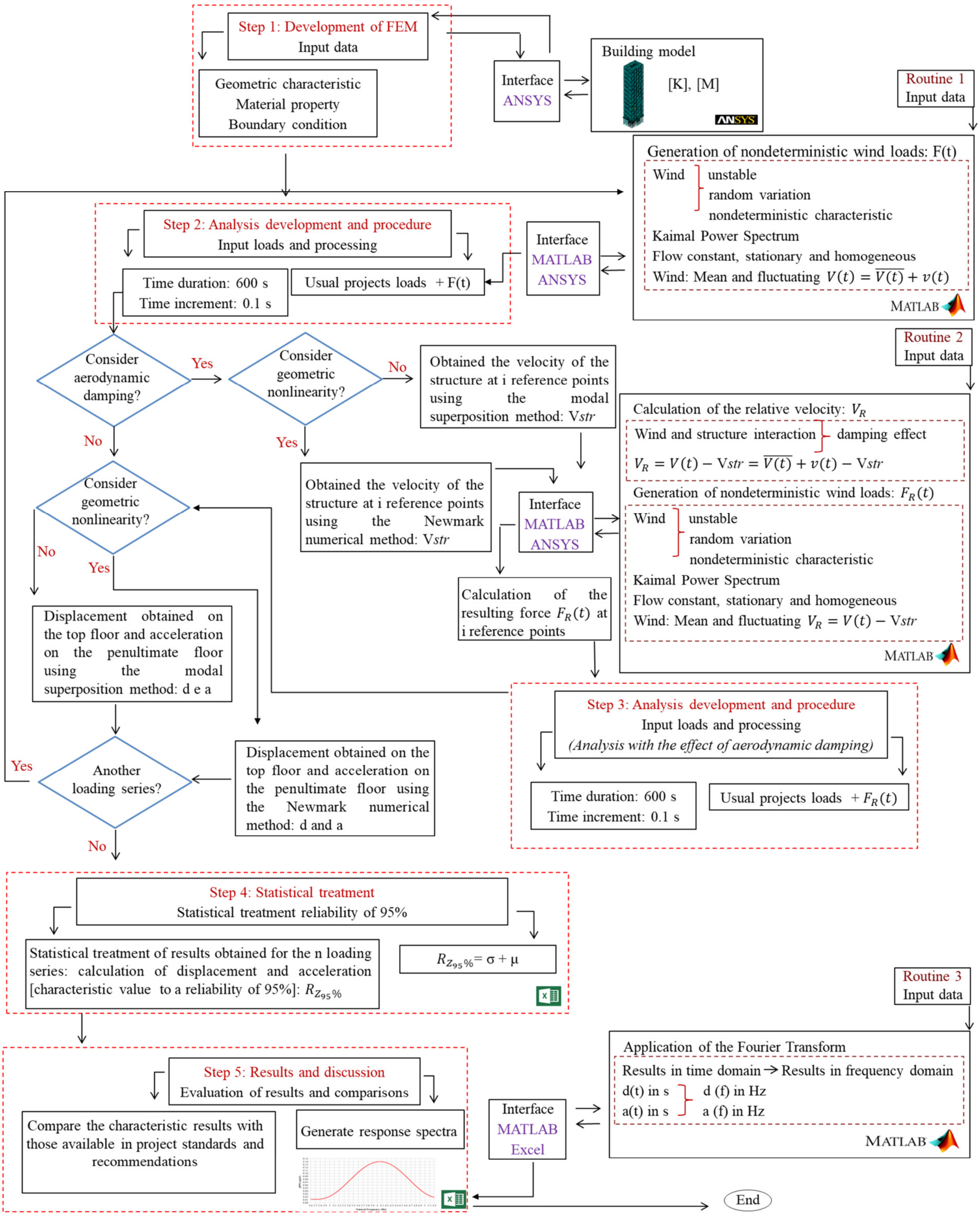

Fig. 1. Analysis methodology proposed to the dynamic structural analysis.

Equations (1) and (2) show the expressions that calculate the energy spectrum:

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

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

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, $\overline{V}_z$ represents the mean wind velocity relative to the height in m/s and z is the height in meters. The expressions to calculate the velocities are:

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

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

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

where $\overline{V}_{10}$ is the project average velocity at 10 meters from the ground, calculated in 10 minutes and p is the exponent of the potential law of variation of S_2, V_0 is the wind basic velocity, calculated in a 3-second interval, S_1 is the topographic factor, and S_3 is the statistical factor associated with the destruction probability, according to NBR 6123 [12]. The friction velocity u* is obtained in m/s, with a Kármán k constant equal to 0.4 and z_0 corresponding to the roughness length in meters. The turbulent part of wind velocity $v(t)$, simulated based on a random process obtained from the sum of a finite number of harmonics, is given by:

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

where N corresponds to the number of power spectrum divisions, f is the frequency in Hz, Δf is the frequency increment, θ represents the random phase angle uniformly distributed in the range of [0-2π], and t is the time in sec. In this study, it was assumed that the wind pressure acting on the building's facades was a direct function of the wind velocity, as in the Davenport classic model adopted in the Brazilian design standard NBR 6123 [12]. This means that the wind pressure can be calculated according to (7), where q(t) is the dynamic wind pressure in N/m² and $\overline{V}$ is the mean part of wind velocity in m/s:

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

After that, with the dynamic wind pressure acting on the structure, it was possible to calculate the dynamic wind load along the time F(t), in N, at each investigated building structural section, where C_{ai} is related to the drag coefficient in the "i" direction and A_i represents the influence area in m². The drag coefficient C_{ai} depends on the relationships between the dimensions of the investigated structure and can be determined through NBR 6123 [12]:

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

Consequently, (8) can be expanded:

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

where C_D is 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 according to NBR 6123. The aerodynamic damping mathematical formulation was directly considered in the wind pressure calculations, with due consideration of the relative velocity between the wind and the structure, both in the same direction. Therefore, the wind pressure and relative velocity can be calculated as:

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

$$V_R = [V(t)\text{-}V_{str}] \quad (2)$$

$$V(t) = \overline{V}(z) + v(t) \quad (3)$$

where q_{wind} is the wind dynamic pressure; ρ is the specific mass of the air under normal conditions of pressure (101320 Pa) and temperature (15°); V_R is the relative velocity between wind and structure, in the node considered; V_{str} is the structure velocity, in direction, in the considered node; $V(t)$ is the wind velocity, $\overline{V}$ is the mean part of the wind velocity in m/s, and $v(t)$ is the turbulent part of the wind velocity. Equation (10) presents the classical formulation for the dynamic wind pressure calculation, as outlined in NBR 6123 [12], with the modification of the adopted reference velocity. In the conventional formulation, wind velocity is adopted as the reference velocity; in contrast, this version employs the relative velocity between the wind and structure. The novel non-deterministic dynamic force that considers the impact of aerodynamic damping, is given by:

$$F(t) = 0.613\, C_D\, A_i \left[V_0\left(\frac{z}{z_0}\right)^p + \sum_{i=1}^{N}\sqrt{2S^v(f_i)\Delta f}\, \cos\,(2\pi f_i\, +\, \theta_i)\, -\, V_{str}\right]^2 \quad (13)$$

IV. STEEL-CONCRETE COMPOSITE BUILDING

The steel-concrete building has 48 floors, each 3.6 m high, and the structural system has a total height of 172.8 m. The building is 45 m long and 32 m wide (floor plan), and the central core is 27 m × 9 m. The main girders are made of W460x106 steel sections, and the secondary girders are made of W410x60 sections [1]. Figure 2 shows a floor plan of the building (dimensions in meters). The steel used is conventional ASTM A572. The concrete slab is 15 cm thick and the steel columns are made of HD profiles (steel ASTM A913), with all geometric characteristics being presented in Table I. The concrete used in the model has a compressive strength (f_{ck}) of 30 MPa, an elasticity modulus (E_{cs}) of 26 GPa, a Poisson's ratio (v) of 0.2 and a specific gravity (γ_c) of 25 kN/m³. The steel used has characteristic strength (f_y) of 345 MPa, Young's modulus (E_s) of 205 GPa, Poisson's ratio (v) of 0.3, and specific gravity (γ_s) of 78.5 kN/m³.

V. FINITE ELEMENT MODELING

The steel-concrete composite structure was analyzed using the ANSYS program, employing the conventional discretization techniques associated with the FEM. The finite element model of the building demonstrated satisfactory convergence with the previously performed mesh convergence study. In the numerical modeling, the steel beams, columns, and piles were represented using three-dimensional finite elements (BEAM44), which accounted for bending and torsional effects. The concrete slabs of the building were simulated using finite shell elements (SHELL63), while the foundation block was discretized with the SOLID45 element. The COMINB14 element was employed to model soil spring coefficients. As shown in Figure 3, the foundation (piled raft) of the building was modeled to account for the influence of soil-structure interaction.

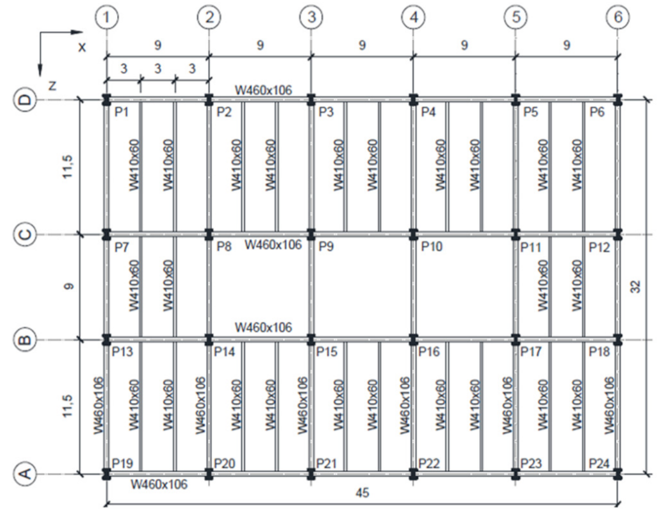

Fig. 2. Structural project of the steel-concrete composite multi-story building: H = 172.8 m.

TABLE I. STEEL PROFILES OF THE STRUCTURAL MODEL

Floor	Centre Core Columns	Facade Columns
1 to 10	HD400x990	HD400x551
11 to 20	HD400x818	HD400x382
21 to 30	HD400x667	HD320x245
31 to 40	HD400x421	HD260x172
41 to 48	HD400x187	HD260x114

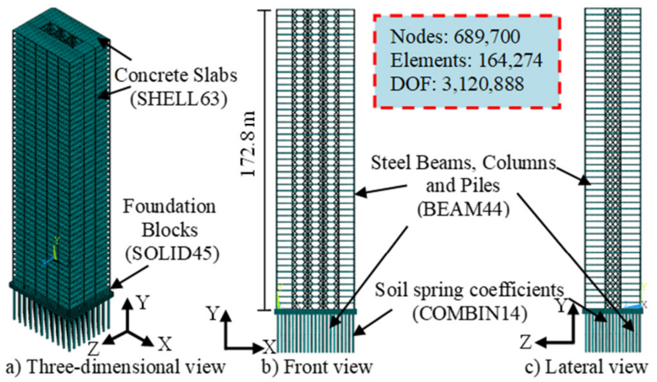

Fig. 3. Steel-concrete composite building finite element model: H = 172.8 m.

In this research project, the classical Winkler model was used to represent the interaction between the soil and the structure. This model simplifies the interaction by considering the soil as a series of independent springs, with each spring having stiffness proportional to the soil's reaction modulus. In the case study building, the foundation in question is a piled raft, with the piles subjected to lateral loads. In this numerical approach, the soil is modeled as a series of independent horizontal springs. The full interaction between the concrete slabs and the steel beams was considered in the study, and the nodes of the finite element model were coupled to prevent the occurrence of slips. It was assumed that steel and concrete exhibited elastic linear behavior, and that all structural sections of the model remained plane in the deformed state. The final computational model adopted used 689,700 nodes and 164,274 elements, resulting in a numeric model with 3,120,888 degrees of freedom. The theory of elasticity incorporates geometric nonlinearity in two key areas: the equilibrium equations, which are formulated using deformed configurations, and the deformation-displacement relations, which encompass nonlinear terms in displacements and their derivatives. An incremental-iterative procedure is employed to trace the equilibrium path of the structure over time. The principle of virtual displacements for deformable bodies is given by:

$$\delta W_{int} = \delta W_{ext}$$

The governing equilibrium equation of structural dynamics, can be obtained through the spatial discretization of the structure:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F^a\} \quad (14)$$

where $[M]$, $[C]$, $[K]$, $\{F^a\}$, $\{\ddot{u}\}$, $\{\dot{u}\}$, $\{u\}$ represent the mass matrix, damping matrix, stiffness matrix, applied load vector, acceleration vector, velocity vector, and displacement vector, respectively. The commercial finite element software ANSYS [11] employs the Newmark's time integration method to address transient problems. Despite the increased complexity of the calculations involved, this approach proved sufficient in light of the nonlinear effect. In the case of nonlinear dynamic solutions, the methodology in question combines the Newton-Raphson method with Newmark's method, as outlined in [1, 7] The total Lagrangian formulation was employed to incorporate the effects of geometric nonlinearity, allowing for the consideration of significant displacements and rotations:

$$\{u_{n+1}\} = [K]^{-1}\{F_{n+1}{}^{a}\} \quad (15)$$

VI. MODAL ANALYSIS: EIGENVALUES AND EIGENVECTORS

The natural frequencies (eigenvalues) and vibration modes (eigenvectors) of the building were calculated using numerical extraction methods (modal analysis) through a free vibration analysis, deploying the ANSYS program [11]. In this investigation, a linear modal analysis was conducted, wherein no load was applied to the structure. Furthermore, a nonlinear modal analysis was carried out with the application of prestressing loads. It is important to note 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 employed to induce the deformed configuration of the building are analogous to the conventional design loads (vertical loads: self-weight, permanent loads, and overloads, and horizontal loads: static wind loads). In order to calculate the static wind loads, intervals of 18 km/h were considered, starting at 18 km/h and extending up to 162 km/h. This approach encompasses the majority of the basic wind velocities outlined in NBR 6123 [12]. The initial four natural frequencies of the edifice are delineated in Table II, and the initial four vibration modes are exhibited in Figure 4. The mode shapes indicate the tendency of the building's vibration. The color red represents the maximum modal amplitude, while blue denotes the minimum. It is noteworthy that only the vibration modes of the linear modal analysis were presented, as the existing differences in the values of the natural frequencies of the system did not affect the vibration modes (linear and nonlinear modal analysis).

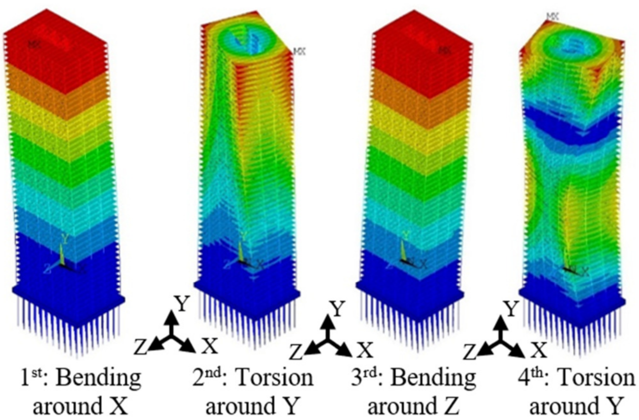

Fig. 4. Vibration modes of the investigated steel-concrete composite building: soil-structure interaction model.

TABLE II. NATURAL FREQUENCIES OF THE BUILDING

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 analyzed building in the soil-structure model was validated as 0.161 Hz (f_{01} = 0.161 Hz), exhibiting a 10% increase relative to the value estimated in the nonlinear modal analysis (f_{01} = 0.146 Hz). This is of particular significance given that, in addition to the reduction in the value of the natural frequencies of the structure due to the effects of geometric nonlinearity in accordance with the Brazilian design standard NBR 6123 [12], buildings exhibiting natural frequency values below 1 Hz, particularly those with low structural damping, may demonstrate a notable floating dynamic along-wind response, indicative of excessive vibrations.

VII. NONDETERMINISTIC DYNAMIC ANALYSIS

In developing the analysis methodology for the building nonlinear dynamic structural response, in addition to the customary vertical design loads, the non-deterministic dynamic wind actions were applied to the building facade, as presented in Figure 2. The maximum horizontal displacement values were calculated at the top of the building (height: 172.8 m) and the maximum acceleration values were determined at the last floor of the building (height: 169.2 m). In this study, four distinct analyses were developed: a linear analysis and three geometric nonlinear analyses, with and without aerodynamic damping. Furthermore, twenty series of nondeterministic dynamic wind loading were generated for the purpose of statistical analysis of the response. The parameters used to ascertain the wind series are wind basic velocity (V_0) ranging from 18 to 162 km/h, terrain category IV, recurrence time of 10 years, topographic factor (S_1): 1, probability factor (S_3): 0.78, roughness factor (S_2): b = 0.84, p = 0.135, and F_r = 0.69. In light of the findings presented in Table III, which pertain to the statistical analysis of the response (twenty non-deterministic wind series), and considering the requisite numerical precision for evaluating the non-deterministic steady-state response, notable alterations emerge in the values of the displacements. The placements and accelerations of the studied building when the effect of geometric nonlinearity is considered in the dynamic analysis (forced vibration) exhibit significant differences, with maximum discrepancies of up to 27% for horizontal translational displacements and 15% to 43% for the accelerations.

TABLE III. DYNAMIC STRUCTURAL RESPONSE OF THE BUILDING

Wind Velocity (km/h)	Type of 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 of basic wind velocities, which included an examination of the impact of geometric nonlinearity on peak values, revealed that for intervals between 5 and 20 m/s (18 and 72 km/h), the maximum mean values of accelerations derived from dynamic analysis do not exceed the threshold value specified by NBR 6123 (a_{lim} = 0.10 m/s²), and thus satisfy the criterion of human comfort. Nevertheless, for velocities between 25 and 45 m/s (90 and 162 km/h), the criterion for human comfort is not met. In terms of mean maximum horizontal displacements, a comparison of the peak values with the limit established in NBR 8800 [13] (H/400: 172.8/400 = 0.43 m) reveals that, for velocities from 18 to 144 km/h, the displacement limit is satisfied. Nevertheless, at a velocity of 162 km/h, the limit is exceeded. In order to examine the impact of aerodynamic damping on the building's structural response, a wind velocity of V_0 = 35 m/s (126 km/h) [12] was employed to ascertain the displacements and accelerations, with due consideration of the statistical treatment associated with the twenty wind load series. Table IV portrays the building's dynamic response, with a comparison between the responses associated with the linear and the geometric nonlinear models. There are notable quantitative alterations in 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 taken into account. Conversely, the incorporation of aerodynamic damping results in a reduction in the mean maximum displacements and accelerations. The impact of aerodynamic damping on the building's dynamic response can be verified by examining the changes that occur when this effect is taken into account. The maximum differences observed in the horizontal translational displacements and accelerations were 5% and 8%, respectively. While the inclusion of aerodynamic damping does result in a reduction in the maximum values obtained, this is not a significant factor in the overall behavior of the structure under analysis.

TABLE IV. 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

In comparing peak values, it is evident that the maximum mean values of accelerations obtained by dynamic analysis for a velocity of 35 m/s (126 km/h) exceed the limit value established by NBR 6123 (alim = 0.10 m/s²), thereby violating the human comfort criterion. This is due to the effect of aerodynamic damping. The same conclusion is reached for both the linear model and the nonlinear geometric model. Figure 5 shows the linear and geometric nonlinear dynamic structural response of the examined steel-concrete composite building (V0 = 35 m/s, or 126 km/h) in the frequency domain, with and without the effects of aerodynamic damping. The figure presents the clear discrepancy between the natural frequencies of the building with and without aerodynamic damping. The results were based on the wind load series, which yielded values that were most closely aligned with the characteristic values of the system response.

VIII. CONCLUSIONS

The proposed methodology for analyzing tall buildings introduces a general approach for assessing their dynamic structural behavior when subjected to non-deterministic wind actions. This methodology considers the effects of geometric nonlinearity and aerodynamic damping. In order to ensure an even more accurate representation, the effect of soil-structure interaction was also included in the dynamic analysis, based on a detailed numerical modeling of the building foundation. In light of the aforementioned findings, the following conclusions can be drawn with regard to the steel-concrete composite building under investigation (H=172.8 m, total mass: 4.56×10^7 kg, stiffness: 1176 kN/m):

- It can be concluded that the inclusion of the effects of geometric nonlinearity and aerodynamic damping in the analysis resulted in a modification of the building dynamic response, with alterations in the observed displacements and accelerations.
- A parametric study was conducted to investigate the impact of wind velocities (18 km/h to 162 km/h) on the statistical treatment of twenty non-deterministic wind series. The findings revealed that the geometric nonlinearity effects have resulted in notable alterations in the building dynamic response, with maximum discrepancies of up to 27% for displacements and up to 43% for accelerations.
- With regard to the fundamental wind velocity of 126 km/h and the statistical analysis of twenty non-deterministic wind series, it was demonstrated that the aerodynamic damping effects have resulted in alterations to the building's dynamic response, with maximum discrepancies of up to 5% for displacements and up to 8% for accelerations.

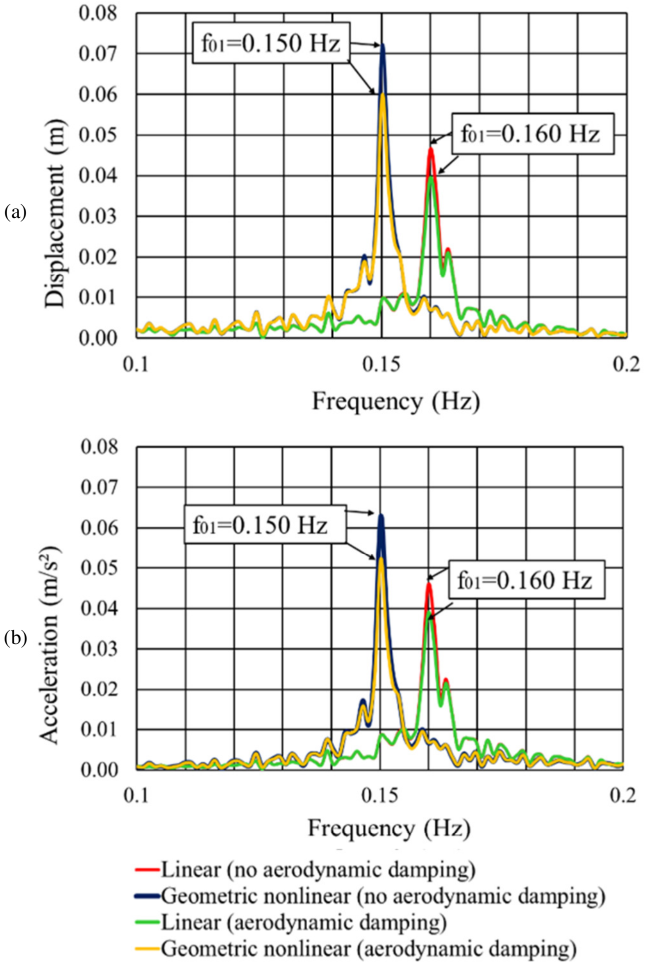

Fig. 5. Dynamic response (frequency domain): (a) displacements and (b) accelerations [V_0 = 126 km/h].

- In the context of the evaluated building dynamic response in the frequency domain, it is crucial to underscore that the effect of geometric nonlinearity has resulted in alterations to the displacement and acceleration values associated with the structure's response energy transfer levels when subjected to wind actions.
- It is crucial to highlight that this methodology enables a more precise and realistic examination of the structural dynamics of tall buildings subjected to random wind actions. The significance of this research lies in its incorporation of attributes related to the developed analysis methodology that are frequently overlooked in actual

design scenarios. By emphasizing these factors, the study aims to prompt structural designers to consider the potential implications for structural project sizing, which could result in excessive vibrations. The proposed analysis methodology not only enhances the level of accuracy of the numerical analyses, but also contributes to the assessment of the serviceability limit states of tall buildings.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support for this investigation provided by Brazilian Science Foundation's CAPES, CNPq and FAPERJ.

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