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Dynamic analysis of the action of the wind acting in a standardized tall building

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Abstract. Buildings are increasingly tall and slender, which requires greater attention to ensure comfort and safety for users. From a structural point of view, special attention should be paid to the dynamic effects caused by the wind. Considering such effects in the design of a building, today, is facilitated by computational tools that provide values of basic parameters such as amplitude and frequency. In this work, dynamic analysis was performed through numerical simulation using the SAP2000 v.15 program for modeling the CAARC Standard Tall Building. Different scenarios were considered, where the drag force calculated according to ABNT NBR 6123:1988 was applied. Such efforts were calculated for the 0^o and 90^o directions in relation to the building axes, each being applied in two ways: on the building axis and with the eccentricity determined by rule to consider the torsion effects on the building. The results regarding the top displacement, frequency and period were analyzed. It was noted that the 90^o efforts applied off-axis resulted in the greatest displacements and frequency. From this analysis it is demonstrated the importance of analyzing the dynamic effects in the considerations of eccentric performance of the wind because, this can represent the most critical situation and, therefore, necessary for the structural dimensioning of the building.

Keywords: CAARC Standard Tall Building, Eccentricity, Twist

1 Introduction

Taller and more slender buildings have become a common standard among new constructions, both to obtain greater use of the soil, but also to show grandeur and power in the world economic scenario as defended by Antony Wood [1]. With the increase in the height of buildings, there is a greater complexity of structural calculations, among all the efforts to be considered. Studies such as Blessmann and Riera [2], reported the strong interference of the effects from the moment of torsion that should not be neglected in the construction. With the proof that the wind actions must be considered in the design, the challenge is to represent the most reliable real situations.

The present work is a continuation of previous works in which the influence of static efforts from the action of the wind was verified. Viera et al [3] highlighted the importance of wind analysis in the survey of interfering efforts in a building, in addition to showing the need for more advanced studies in this sector, as there may be cases that are not well represented only by the limits and indications proposed by the Brazilian standard [4]. Following this same line of reasoning [5] , compared the calculation procedure between the Brazilian standard [4] and the New Zealand standard [6], showing that the foreign standard can serve as an improvement objective for the national standard, establishing guidelines more faithful to reality.

Therefore, the main objective is to explain how to take into account the dynamic efforts in structural calculations. To accomplish this feat, a dynamic analysis of a standardized building is carried out, already tested in a wind tunnel by Vieira [7], subject to actions indicated by the Brazilian norm [4] and analyzing results of displacement, frequency and period to obtain the most critical situation, which must be included in the efforts applied to the building to be analyzed. All the factors and coefficients adopted in this work aim to represent the greatest similarity with the possible reality, that is why we sought to analyze the most critical directions indicated by norm, in addition to situations in which the presence of neighborhood is considered in the torsion calculation, because as confirmed by Vieira et al [7] with this consideration, efforts can be maximized up to 60 times in relation to the values obtained for the construction reference considered in isolation.

2 Methods and results

In order to obtain a coherent analysis of the dynamic effects, the modeling of a standardized building already tested in a wind tunnel was carried out by Viera [7], being a model reduced in order to have a more consistent structural analysis, so that could get closer to what is real in a building. The reduced model of the studied building is shown in Figure 1 below.

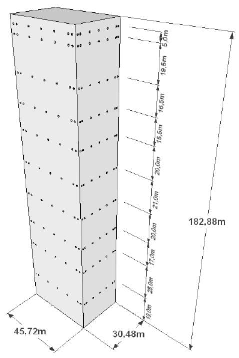


Figure 1. Small model under study

The entire process consists of two stages, the first of which is a follow-up of the instructions provided for in the standard for obtaining the efforts considered, the next step was modeling and obtaining parameters such as displacement, period and frequency in the SAP2000 software.

2.1 Effort calculation procedure

The forces to which the analyzed building was subjected in the computational analysis were defined from the calculation procedure indicated by the standard. ABNT NBR6123: 1988 [4] prescribes that the building must be analyzed with efforts in two directions, 0 ° and 90 °. In addition, the surrounding situation can generate high significance in the results, so the possibility of a neighborhood to the building in question was also analyzed, so that this characteristic can be considered in calculations, the standard indicates the use of an eccentricity for the application of efforts in relation to the axis of the structures.

For the calculation of forces at 0 ° and 90 °, different coefficients are taken into account that express the building's usage and topography characteristics. All of these parameters will be explained below, which are necessary to obtain the drag force from the use of eq. 1:

$$F_a = C_a q A_e \tag{1}$$

Where:

- Drag force (F_a): Component of the global wind force that will be applied to the modeled building, being calculated for the two main directions, 0 ° and 90 °;
- Drag coefficient (C_a): Coefficient determined by Figure 4 present in the Brazilian standard [4], which takes into account the relationships between the dimensions of the building. This coefficient is also determined for the two directions of application of the efforts;
- Area of influence (A_e): Orthogonal projection area of the building, structure or structural element on a plane perpendicular to the wind direction. Through the 4 stipulated height ranges, the area of influence of the points of application of the efforts was obtained;

- Dynamic pressure (q): The dynamic pressure exerted on the analyzed building area is determined by eq. 2:

$$q = 0.613{V_k}^2 \tag{2}$$

Where:
- Characteristic speed (V_k): The characteristic speed determined by eq. 3, will be the parameter that will represent all the details of the analyzed situation, containing each of the coefficients that represent topography, use and region.

$$V_k = V_0 S_1 S_2 S_3 \tag{3}$$

Where:
- Basic speed (V_0): Speed of a burst of 3s, exceeded on average once in 50 years, 10m above the ground, in an open, flat field. It is determined by study of each of the regions of the country, being presented by the standard [4] through isopletas, the location of the study in question gives us a speed of 30m/s;
- Topographic factor (S_1): Coefficient that takes into account the terrain relief, in this case because it is a flat terrain we have $S_1 = 1$;
- Terrain roughness, building dimensions and height over the terrain (S_2): Coefficient that considers the combined effect of the terrain roughness, building dimensions and speed variation with the height above the terrain. The determination of this coefficient was performed according to the calculation of Table 1 of the [4] standard, obtaining the data presented in Table 1:

Table 1. Factor S_2

$z(m)$	S_2
45.72	0.98
91.44	1.08
137.16	1.14
182.88	1.18

- Statistical factor (S_3): Coefficient that considers the level of security required according to the use of the building, as it is a residential building, we have $S_3 = 1.00$.

With all the necessary parameters and characteristics determined through eq. 1, we obtained the forces shown in Table 2:

Table 2. Drag forces

$z(m)$	$F_0(kN)$	$F_{90}(kN)$
45.72	1439.11	2407.74
91.44	1156.86	1935.51
137.16	1290.70	2159.44
182.88	697.47	1166.93

With the forces defined, the last parameter to be determined are the eccentricities so that the effect of a neighborhood can be considered. In order to make this consideration, according to the Brazilian standard [4], the calculation is defined by eq. 4 and 5:

$$e_a = 0.075a \tag{4}$$

$$e_b = 0.075b \tag{5}$$

The eccentricities e_a and e_b correspond to the major and minor sides, respectively. Such directions are in relation to the consideration of the wind incidence at 0 ° and 90 °. Thus, the two situations to be studied are represented as in Figures 2 and 3, both were adapted from Vieira [7]:

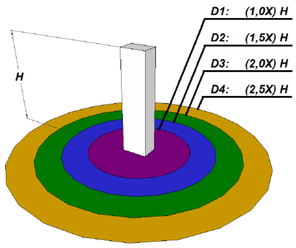


Figure 2. Isolated building situation

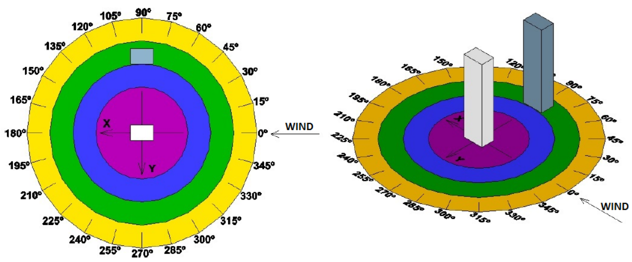


Figure 3. Building situation with a neighborhood

2.2 Modeling

In this work, the linear dynamic analysis was performed by means of numerical simulation using the SAP2000 v.15 program for modeling the CAARC High Standard Building. SAP2000 consists of finite element software with a 3D interface so that the modeling, analysis and dimensioning of various situations in structural engineering can be carried out in an integrated manner. In this work, the program was used to more easily obtain parameters necessary for the dynamic analysis of a building.

According to Wilson et al. [8], the program uses methods in which the behavior of the system is given by the following equation 6:

$$M\ddot{u} + C\dot{u} + Ku = R \tag{6}$$

Where M, C and K are the mass, damping and stiffness matrices, respectively. $\ddot{u}$, $\dot{u}$, u and R are the nodal displacements, velocities, accelerations and vector of external forces, respectively.

In the software, it used a solid three-dimensional element composed of eight nodes and six degrees of freedom per node. The following degrees of freedom are at the nodal level: translational displacements in the x, y and z directions, and rotations θ_x, θ_y, θ_z. All materials were considered homogeneous, isotropic and with linear mechanical behavior.

According to Wilson et al. [8], in the calculation of modes and frequencies, the program stores the mass and stiffness matrices. The mass matrix is diagonal with partially null diagonal elements. Dynamic analysis initially requires solving the generalized eigenvalue problem given by the equation 7:

$$K\emptyset = \omega^2 M\emptyset \tag{7}$$

Where ω and $\emptyset$ are the frequencies of free vibration and the modes, respectively.

The program assumes only the smallest eigenvalues and corresponding automobiles. Thus, the previous equation 7 can be rewritten as equation 8:

$$K\emptyset = M\emptyset\Omega^2 \tag{8}$$

Where $\Omega^2 = diag(\omega^2)$ is the diagonal of the matrix with the smallest eigenvalues and $\emptyset$ stores the corresponding M-orthomalized eigenvectors ($\emptyset_1$, $\emptyset_2$..).

Two different procedures are used in the program to solve the system of equations: the first is a determinant research technique performed when the stiffness matrix can be contained in high-speed storage in a block; the second procedure is a subspace iteration solution used for systems of large order or frequency range. In both techniques the direct solution of the eigenvalue problem is obtained without a transformation to the standard form [8] .

The building was modeled as solid, as shown in Figure 4, being divided into 4 bands in the direction of height and with the forces applied on the axis and with the eccentricities, these forces shown in Table 2.

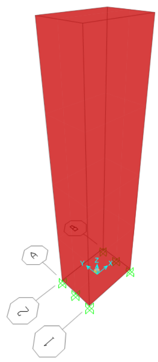


Figure 4. Modeled building

The same building was analyzed in four different situations, in Table 3 there is a description of the number of nodes and elements present in each model.

Table 3. Modeling discretization

Situation	Number of nodes	Number of elements
Effort at 0 °	30	8
Effort at 90°	30	8
Effort at 0 ° with eccentricity	210	8
Effort at 90 ° with eccentricity	210	8

2.3 Results

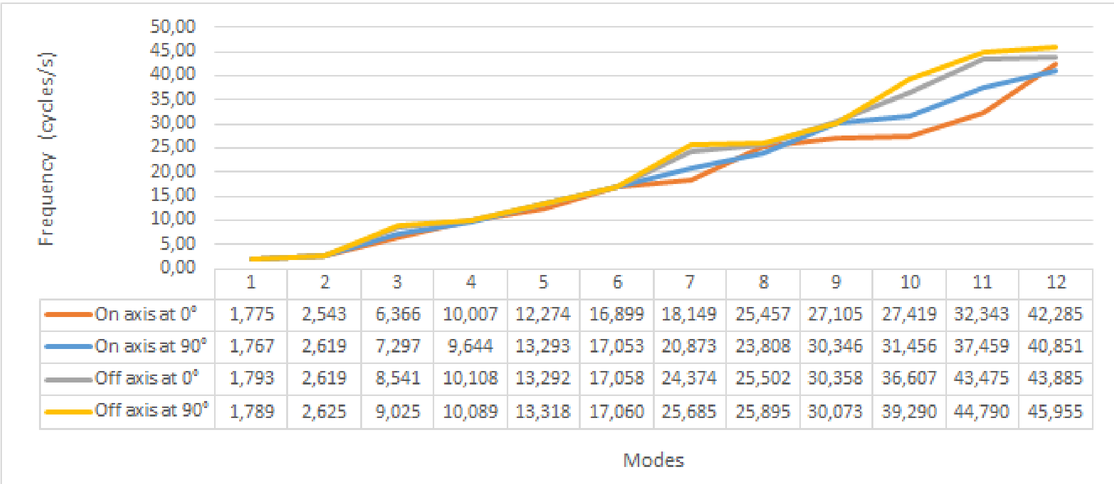
The modeling process mentioned above was made for 4 situations, namely: 0 ° and 90 ° efforts on the vertical axis of the building and 0 ° and 90 ° efforts with eccentricity. From the SAP2000, top displacement results, frequency and period were obtained for each situation analyzed, which will be presented below.

The first analysis to be made will be on the frequency and period of each of the situations. The frequency corresponds, in a building subject to vibration, to the number of cycles completed in a unit of time, the period being the time necessary for one of these cycles to be completed.

As shown in Figures 5 and 6, performing data analysis as indicated by the norm, buildings with periods longer than 1s show important fluctuating responses, in these cases only the use of the S_2 factor does not it is sufficient to represent the efforts in a reliable way. In the cases presented, we had only periods shorter than 1s, therefore, only with the appropriate choice of the factor S_2 we have the total dynamic response, the sum of the average and the floating portion, consistent with the indications by rule. Anyway, it is worth noting that among the period responses found, the situations on the axis presented more critical values than when compared to the values using eccentricity.

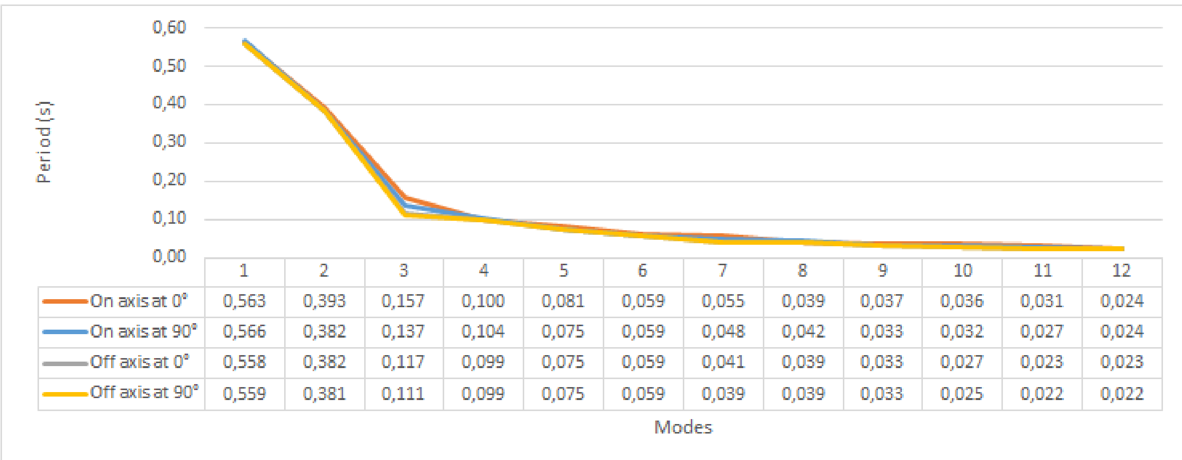
The next data to be analyzed is the displacements, to enable a direct comparison between all the situations depicted here, we chose to perform the displacement analysis at the point of application of the effort at the top of the building and also the analysis of the module of these displacements. , this way the comparison of the intensity of the displacements obtained can be made. From these considerations, as shown in Figure 7, it is possible to notice that the modeling with efforts applied at 90 ° and with the use of eccentricity presents higher displacement values, being the most critical situation in this parameter.

The displacement from the dynamic response in all points of the building should not be disregarded before an analysis and obtaining its magnitude, as it must be guaranteed that the structure and supports of the building in question will be sufficient to absorb this movement without causing greater damage.



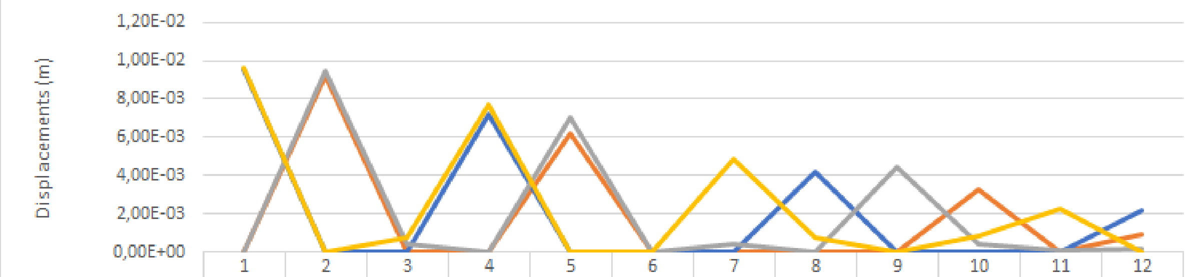
	1	2	3	4	5	6	7	8	9	10	11	12
On axis at 0°	1,775	2,543	6,366	10,007	12,274	16,899	18,149	25,457	27,105	27,419	32,343	42,285
On axis at 90°	1,767	2,619	7,297	9,644	13,293	17,053	20,873	23,808	30,346	31,456	37,459	40,851
Off axis at 0°	1,793	2,619	8,541	10,108	13,292	17,058	24,374	25,502	30,358	36,607	43,475	43,885
Off axis at 90°	1,789	2,625	9,025	10,089	13,318	17,060	25,685	25,895	30,073	39,290	44,790	45,955

Figure 5. Frequencies obtained from SAP2000



	1	2	3	4	5	6	7	8	9	10	11	12
On axis at 0°	0,563	0,393	0,157	0,100	0,081	0,059	0,055	0,039	0,037	0,036	0,031	0,024
On axis at 90°	0,566	0,382	0,137	0,104	0,075	0,059	0,048	0,042	0,033	0,032	0,027	0,024
Off axis at 0°	0,558	0,382	0,117	0,099	0,075	0,059	0,041	0,039	0,033	0,027	0,023	0,023
Off axis at 90°	0,559	0,381	0,111	0,099	0,075	0,059	0,039	0,039	0,033	0,025	0,022	0,022

Figure 6. Cycles obtained from SAP2000



	1	2	3	4	5	6	7	8	9	10	11	12
On axis at 0°	4,48E-12	9,25E-03	2,96E-11	6,03E-11	6,16E-03	2,90E-05	9,69E-10	1,11E-08	4,03E-09	3,27E-03	3,62E-09	9,20E-04
On axis at 90°	9,54E-03	1,31E-14	1,44E-11	7,21E-03	5,60E-10	2,00E-05	4,63E-10	4,21E-03	7,06E-09	8,16E-10	9,06E-09	2,17E-03
Off axis at 0°	1,63E-07	9,48E-03	4,46E-04	5,33E-06	7,06E-03	3,30E-05	4,34E-04	3,50E-05	4,48E-03	4,00E-04	7,30E-05	2,08E-04
Off axis at 90°	9,62E-03	9,88E-08	7,30E-04	7,68E-03	2,50E-06	2,10E-05	4,89E-03	7,73E-04	1,40E-05	8,75E-04	2,30E-03	7,52E-06

Figure 7. Top offsets obtained from SAP2000

3 Conclusion

At the end of this work, it is possible to highlight the need for a dynamic analysis of the building to be designed, so that if it is necessary to consider the floating portion in the efforts, the procedures and indications in the Brazilian standard can be used [4], so it will have guaranteeing a safe and comfortable building for its users, in addition to contributing to the explanation of how the building's analysis should be done, with description of the entire procedure by standard and the use of software. It is worth remembering that other parameters can be of great value in this process, one can extend the calculations to the maximum acceleration which, according to the standard, directly influences comfort when the building is intended for human occupation.

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Authorship statement. The authors confirm that they are solely responsible for the authorship of this work, and that all material that has been included here as part of this article is owned (and authored) by the authors or has the permission of the owners to be included on here.

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