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Experimental study in wind tunnel of interference effects on the reduced model of the CAARC building

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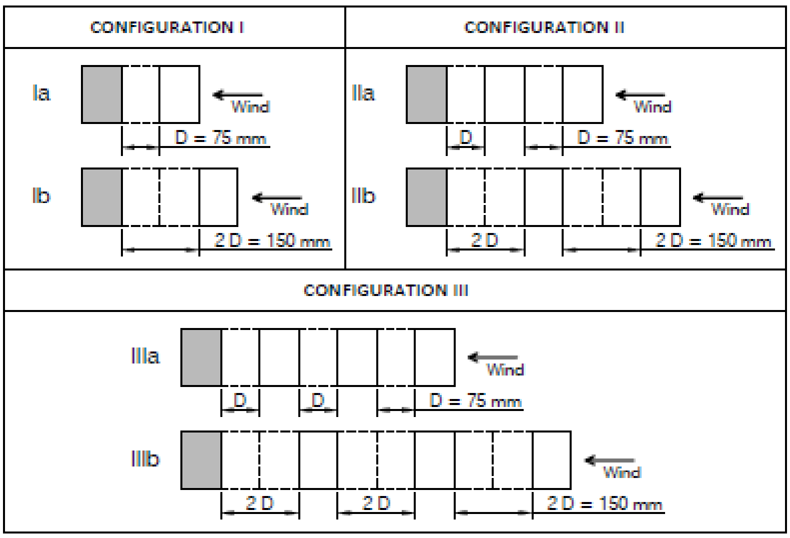
Abstract

The increasing verticalization of urban environments led to the consideration of loads influenced by horizontal forces arising from the action of the wind. Different neighborhood densities alter the flow behavior and reflect on interference effects. An extensive study developed in the wind tunnel through aerodynamic characterization in the reduced model of the CAARC building, simulated with the insertion of distinct windward neighborhood densities in three configurations, I (one interfering model), II (two models) and III (three models), with different relative positions between the models, D and 2D, where D is the smallest dimension of the model, aiming to understand the interaction relationship between such parameters. Based on the results, both the insertion and number of interfering buildings, and the variation in spacing, influence on the determination of the coefficients. The results indicated that the FV values are mainly given as a function of the proximity and size of buildings directly in the surroundings, most forces on the x-axis have been increased (96.2%), on y-axis, most actions have been reduced (65.4%).

Keywords

Wind action; structures; tall buildings; neighborhood effects; vicinity factor; aerodynamics.

Graphical abstract



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1 INTRODUCTION

With the increasing verticalization of urban areas, with the growing demand for tall buildings, combined with market demands for more rational works, full of comfort and safety, and added to the economy of materials, lead to the use of new constructive techniques in the development of buildings taller, slender and flexible, more resistant materials and the consideration of loads with influence of horizontal forces, resulting from the action of the wind on buildings. A reflection on population growth and as a result of urbanization demonstrates the significant transformations in urban agglomerations in large cities, through the verticalization of buildings and densification of these built-up areas, requiring new concepts and a review of structural calculation methodologies.

Among these requests acting in the various buildings, there is the importance of the action of the wind as a horizontal load. Wind is considered a meteorological phenomenon formed by the movement of air in the atmosphere, generated through the influence of various factors and natural phenomena. Wind flow on the earth's surface is directly affected by friction caused by the interaction of air movement with the natural and artificial surface roughness, which as well as convection processes caused by thermal variations in the atmosphere, cause turbulence, a mechanical agitation in the wind runoff (Blessmann, 1995).

Great events arising from the action of wind, aroused the growing interest in this direct request in buildings and several related studies have been developed over the years. Determining these requests is a fundamental step in the correct dimensioning of structures and has aroused the interest of many researchers, given the increased demand for bolder and slender buildings, with static and dynamic effects, not adequately provided for in normative recommendations and codes.

The “NBR6123:1988 – Forças devidas ao vento em edificações” (ABNT, 1988), is the brazilian standard that sets the conditions required in the consideration of forces due to static and dynamic action of the wind in various structures, aiming at the various possible effects for the calculation of buildings, bringing a series of definitions and procedures for the consideration and analysis of wind performance in some forms of structures, given certain situations and incidences oh the flow. The standard does not apply properly to buildings with unusual shapes, dimensions or locations, in these cases, special studies must be carried out using experimental tests in wind tunnels.

In the analysis of wind action considering the presence of buildings in the neighborhood, with buildings grouped in close proximity, each component present in this space can affect the aerodynamic field of the others, influencing the loads due to the wind. Such changes in wind action, caused by the presence of neighboring buildings, can both protect the building as generate an unfavorable action, due to the large number of variables involved in the process, such as size, position and shape of the buildings, incidence directions of the wind and topographic factors (Khanduri et al., 1998).

Several studies were carried out in other countries, considering the changes in wind load through interference effects, caused by the presence of neighboring buildings, however, due to the fact that there are thousands of totally different neighborhood situations, new studies and guidelines are still needed, that cover a greater number of situations. These needs are explained by reasons such as the complex nature of these problems, even for a single interfering building, by the scarcity of experimental data suitable for different situations, and also by the widely accepted notion that wind loads in a building should generally be less severe if surrounded by other structures than when isolated, although very adverse effects were observed (Cho et al., 2004).

Due to the importance of these interference effects caused by neighboring buildings, the NBR6123:1988 contains the “Anexo G – Efeitos de vizinhança”, which deals specifically with these interactions, through the calculation of the vicinity factor (FV), which is a fundamental parameter for definition, via normative procedures, of the force that the wind will exert on a building, considering such obstacles that the wind must overcome until reaching the studied structure. The vicinity factor indicated by the standard is the result of an extensive and systematic study of the interaction between one or two prismatic buildings in different relative distance positions, however, different studies indicate a change in these factors, when the insertion of other interfering buildings is performed. In this sense, there is the relevance of an analysis of the relationship between different neighborhood densities and spacing between buildings, influencing the neighborhood interference effects and in the determination of vicinity factors.

2 METHODOLOGY

The determination of aerodynamic forces in tall buildings, considering all parameters and variables that influence this loading, can be complex to solve through normative methods, especially for unconventional buildings, therefore, experimental methods must be adopted, via tests in wind tunnels. The importance of studying the action of wind through experimental methods was established with the observation of the effects, sometimes disastrous, of the action of wind on tall buildings. These studies, initially were conducted in aeronautical wind tunnels, where it was found that the simulations led to differing results from reality (Blessmann, 2011). Thus, with the advancement of aerodynamics and the contribution of several researchers, tunnels and techniques were developed that simulated the atmospheric boundary layer, making the models results reduced, adequate and in agreement with real buildings.

The extensive study developed in this work consisted in performing an aerodynamic characterization in the reduced model of the building CAARC Standard Tall Building, through the insertion of different neighborhood densities to windward of this aerodynamic model, with different relative positions between the models, to understand the relationship between such parameters in the characterization of neighborhood interference effects. The research tools used are the Wind Tunnel Prof. Joaquim Blessmann, the application of the recommendations of NBR6123:1988 and studies by other investigators. Through tests in wind tunnels, it is possible to analyze in a more adequate way, the interferences that occur in the interactions between wind and structure.

The CAARC Standard Tall Building, is a tall building conceived in 1969 by the Commonwealth Advisory Aeronautical Research Council (CAARC), designed as a simple building model, used as a standard for comparison between techniques and experimental tests in boundary layer wind tunnels, calibration of these equipments, and still, resulting in greater reliability in the data obtained through these tests, being requested for dynamic tests and pressure measurements on the facades. The CAARC is a prismatic building with a rectangular cross section, with measurements at full scale 30.48m x 45.72m x 182.88m, and its reduced aerodynamic model with dimensions of 75.00mm x 112.50mm x 450.00mm.

For the aerodynamic characterization, tests were carried out, considering the model in an isolated situation and with different neighborhood densities, inserted to the windward side, differentiated by the addition of interfering models and different relative positions, through increasing the spacing between the adopted models, according to each neighborhood configuration. Were used three (3) different configurations, with 2 (two) relative spacing positions between the models for each neighborhood configuration, totaling 6 (six) settings assay. The dumb models follow the same prismatic configuration of the rectangular cross section of the CAARC aerodynamic model. The relative positions between the models were called with the parameter D, which is the dimension of the shortest side of the cross section of the model, so D = 75.00 mm. The dumb models are positioned aligned to windward in the direction of incidence of the Wind at 90°. Thus, neighborhood configurations used in this study, are:

- Configuration I: 2 (two) buildings, 1 (one) instrumented model and 1 (one) dumb model (Figure 1), with D and 2D spacing;
- Configuration II: 3 (three) buildings, 1 (one) instrumented model and 2 (two) dumb models (Figure 2), with D and 2D spacing;
- Configuration III: 4 (four) buildings, 1 (one) instrumented model and 3 (three) dumb models (Figure 3), with D and 2D spacing.

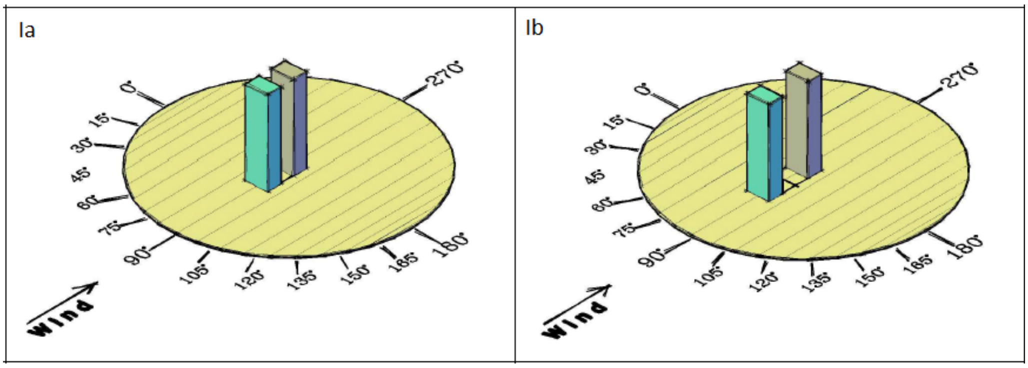

Figure 1 Perspectives of tests and wind incidence angles in Configuration I

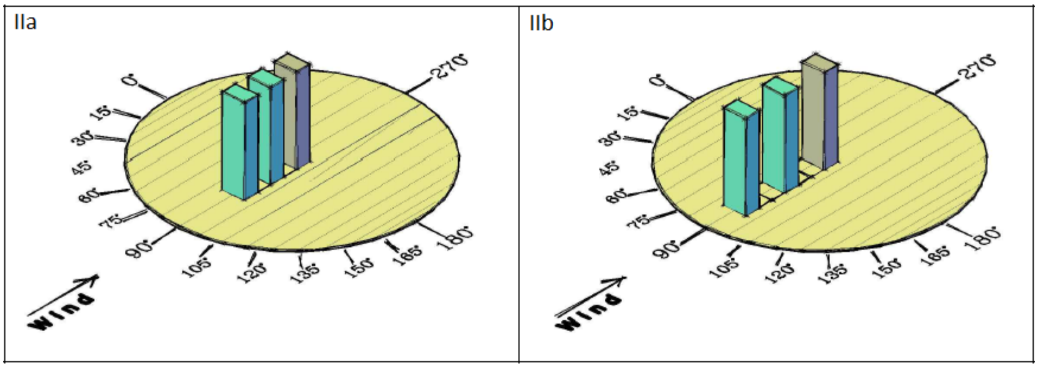

Figure 2 Perspectives of tests and wind incidence angles in Configuration II

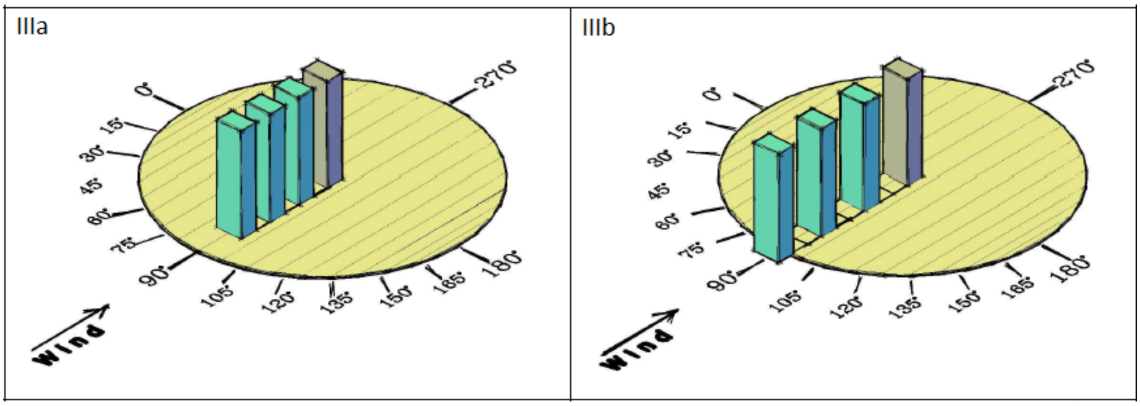

Figure 3 Perspectives of tests and wind incidence angles in Configuration III

The aerodynamics coefficients on the surface of the structures, are obtained through pressure time series by means of measurements in the tests, which are used electrical pressure transducers connected to conveniently tubes arranged on the surface of the model, that record hundreds of readings for each pressure tap with a predetermined acquisition time interval, sending to a computer, this time series of pressure measured in mmH_2O (Blessmann, 1982; Loredo-Souza et al., 2012).

From the integration of these time series records of pressures due to wind, can find the average pressure coefficient ($\bar{c}_p$), the rms pressure coefficient ($\tilde{c}_p$), the maximum pressure coefficient ($\hat{c}_p$) and the coefficient of pressure minimum ($\check{c}_p$). Thus the $\bar{c}_p$ is given by the following equation (Carpeggiani, 2004; Loredo-Souza et al., 2006):

$$\bar{c}_p = \frac{\frac{1}{T}\int_0^T p(t)\, dt}{q} \tag{1}$$

where:
$\bar{c}_p$ – mean pressure coefficient (adm);
T – sampling time interval (s);
$p(t)$ – instantaneous pressure, on the surface of the building, measured in relation to the reference static pressure (N/m^2) ;
t – time (s);
q – dynamic pressure of reference: $q = \frac{1}{2}\rho\bar{V}^2$ (N/m^2);
ρ – specific mass of the air (kg/m^3);
$\bar{V}$ – average speed of reference (m/s).

Considering that the peak pressures measured in the tests do not act simultaneously on the entire structure of the model, the mean pressures can be integrated to provide mean values of shear forces and bending moments acting on the building. The force coefficients in the direction of the x and y axes are given by the ratio between the vector sum of the forces acting in the area of influence of each pressure tap and the product of the dynamic pressure by the total area of incidence of the wind, in relation to the x and y axes (Loredo-Souza et al., 2006; Vieira et al., 2018):

$$C_x = \frac{F_x}{q\, B_y\, H} \text{ and } C_y = \frac{F_y}{q\, B_x\, H} \tag{2}$$

where:
C_x and C_y – global force coefficients in the x and y directions (adm);
F_x and F_y – total forces, at the base of the building , due to the incidence of the wind in the x and y (N) direction;
q – dynamic pressure of reference at the top of the building (N/m^2);
B_x and B_y – nominal dimensions of the cross-section of the building (m) ;
H – reference height (m).

3 EXPERIMENTAL PROGRAM

The tests in wind tunnel for the acquisition of experimental data in this work followed a standard experimental procedure, performed in the analyzes carried out at the Laboratório de Aerodinâmica das Construções (LAC) of the Universidade Federal do Rio Grande do Sul (UFRGS). The experimental program adopted, described in the following topics, presents the main characteristics of the Wind Tunnel Prof. Joaquim Blessmann and general descriptions of the essays.

3.1 Wind Tunnel Prof. Joaquim Blessmann

The use of tunnels as an option for wind action simulation, is an alternative, given the large number of parameters that influence the interference effects on wind loads, hindering the possibility of standardization of these factors and analytical calculation. In the cases of projects that are subject to this type of interference, the literature is searched for case studies with the same characteristics, however, there are situations where the load levels are high, the building has high height or not geometry conventional, and so it is necessary to conduct the test are in a wind tunnel, simulating the actual conditions of the building, targeting projects with a higher level of safety (Khanduri et al., 1998).

In the area of tests and analysis of wind performance in structures, Brazil has a renowned laboratory specializing in simulations through reduced-scale building models, located in the city of Porto Alegre/RS, specifically at UFRGS, where tests are carried out in the Wind Tunnel Prof. Joaquim Blessmann, located in LAC. From simple buildings to large skyscrapers, there are several structures that are directly in contact with the action of the wind and were tested in this laboratory, such as bridges, viaducts, industrial silos, football stadiums, among others. Evidencing the benefits of the tunnel as a project tool, enabling the construction of tall buildings, slender and with bold architectural projects.

The Wind Tunnel Prof. Joaquim Blessmann, Figure 4, is pioneer in Latin America, being in operation since 1977, specifically designed for static and dynamic tests of civil construction models, allowing the simulation of the main characteristics of the natural wind, being a closed return wind tunnel reference. Such tunnels have the advantage of lower energy consumption, a working area close to atmospheric pressure and the retention of erosion particles and other signals.

Figure 4 Wind Tunnel Prof. Joaquim Blessmann (Araújo et al., 2012)

3.2 Description of tests

For the correct analysis of structures in wind tunnel, which involves a strong interaction between the model and the flow, in order to obtain consistency between the results and reality, in addition to the reprodution of the natural wind and its characteristics, a scaled-down model that is as close as possible to reality must be carried out, especially in the primordial points for analysis. Attention should be paid to the limitations imposed by the tunnel, such as dimensions of the test chamber and speed range, so that the geometric scale used in the reduced model can be determined. A correct modeling implies that the dimensionless parameters of similarity are exactly the same in the real structure and in the model used (Núñez et al., 2012).

For the study, the reduced aerodynamic model of the CAARC (Figure 5) was used, and the rigid model was adopted due to its characteristics and the type of data acquisition required, made of acrylic and instrumented with pressure taps that perform instantaneous measurements of pressures due to the action of the wind, properly distributed over the external faces of the model. The dumb model, non-instrumented, are made of plywood sheets, serving only as an interference barrier to the flow, according to each neighborhood.

Figure 5 Reduced model of CAARC inside the Wind Tunnel Prof. Joaquim Blessmann

The tests in the wind tunnel were carried out with the aerodynamic model of CAARC, first in an isolated situation, then with the neighborhood configurations, according to the relative positions adopted between the models, as indicated in the flowchart (Figure 6), providing data that were transformed into pressure coefficients without interference from topography, terrain roughness and neighboring buildings, and data that registered the influence of neighboring buildings on wind flow. For this study, aiming to obtain data only with the interference of buildings located to the windward side, the model under study was inserted in a region of smooth topography, in order to minimize the influence of relief on the acquisition of coefficients.

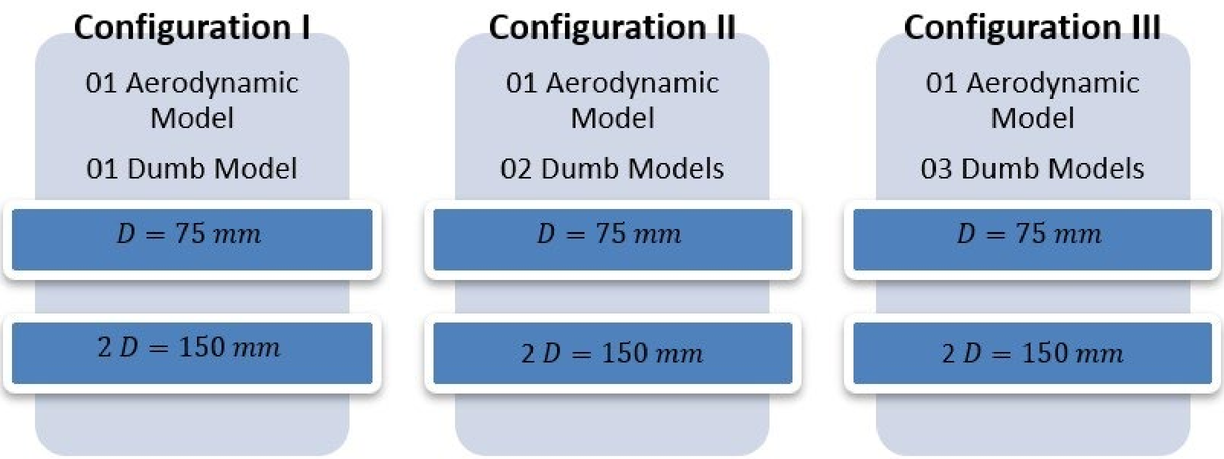

Figure 6 Test flowchart

The distribution of pressure taps in the aerodynamic model, allows the determination of the pressures in the model, and these instantaneous pressures, measures in each one of neighborhood configurations, Ia, Ib, IIa, IIb, IIIa and IIIb, in 19 wind incidence angles, rotating the test table from 0 to 270°, with measurements every 15° of incidence. For this, there is the use of a turntable with the model under analysis positioned in its center, with the dumb models, representatives of the neighborhood densities, positioned to the windward side of this model, in the direction of wind incidence at 90°. In Figure 7 we have the representation of Configuration IIIb, with the reduced models of the buildings located inside the wind tunnel.

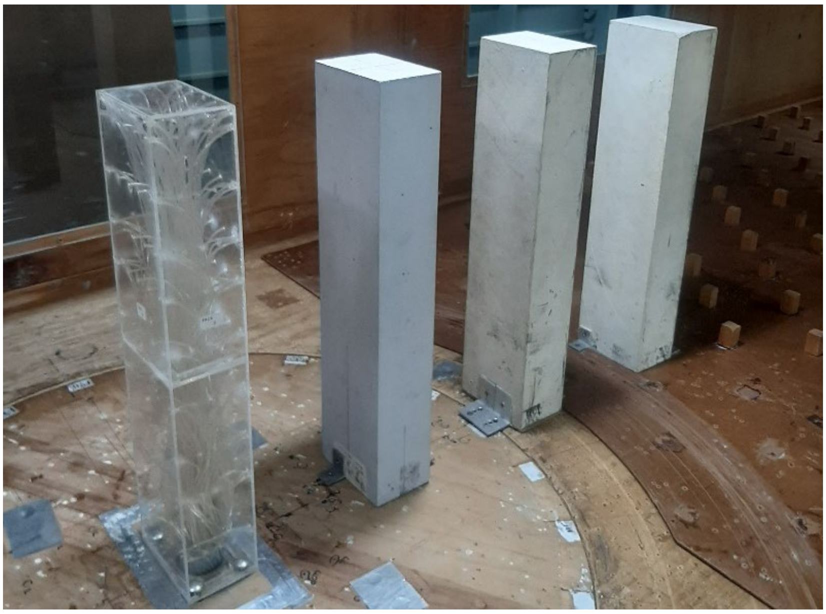

Figure 7 Representation of a test configuration inserted in the wind tunnel

For the correct simulation of wind flow and data acquisition, it is necessary in addition to the preparation of instrumentation, such as the elaboration of the reduced models and the turntable for the layout of the models, the preparation of tools for the measurement of speeds and reproduction of the characteristics of this flow inside the tunnel. The tests were carried out on the M-II table of the Wind Tunnel Prof. Joaquim Blessmann, along with the implementation of simulation techniques for natural wind characteristics, through the use of passive methods, known generically as roughness method, barrier and mixing device, according to the devices shown in Figure 8.

Figure 8 Devices inside the tunnel to simulate the profile with exponent p = 0.23

4 RESULTS AND DISCUSSIONS

The results of this study correspond to an analysis of the influence of different neighborhood densities in the characterization of interference effects in an aerodynamic model, differentiated by the addition and increase of the spacing between the interfering models. To this end, the mean pressure coefficients ($\bar{c}_p$) were calculated by integrating the time series records of pressures for each configuration tested in the tunnel. Then the shear forces on the base of building were found for each configuration, determined by the sum of the forces in x and y of each installed pressure taps on the surface of the model, considering the sines and cosines directors of the pressure taps. Finally, for each angle of incidence, the force coefficients were calculated, in terms of the mean transverse and longitudinal responses, according to the test configurations performed, isolated ($C_{x,iso}$and $C_{y,iso}$) and with neighborhood ($C_{x,cv}$ and $C_{y,cv}$).

Enabling the analysis of the interference effects of the buildings inserted in the surroundings, caused by these different neighborhood densities, through the test configurations with pressure measurements at the 19 angles of wind incidence, rotating the test table from 0 to 270°, with measurements every 15°. Allowing the determination of vicinity factors (FV), for each of the configurations, obtained by dividing the force coefficients of the configurations with neighborhood by the isolated configuration.

In Figure 9 we have the results obtained for the isolated configuration, showing the variation of the force coefficients (C_x and C_y) as a function of the angle of incidence of the wind, with the measurement of pressures from 0 to 345°, used throughout of the study, enabling the analysis of the influence of the neighborhood in the aerodynamic model.

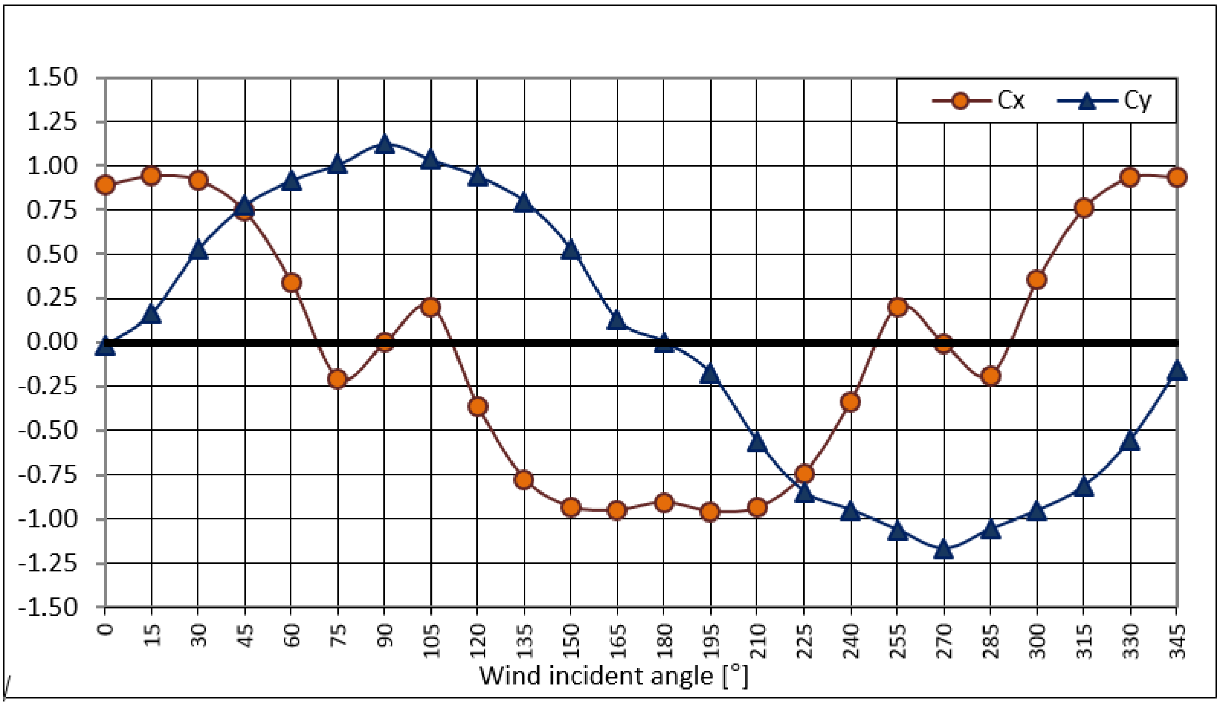

Figure 9 Force coefficients (Cx and Cy) in the Isolated Configuration

In the analysis of the results, a procedure was adopted for all the proposed configurations, Ia, Ib, IIa, IIb, IIIa and IIIb, comparing the variation of the force coefficients in x and y, in the isolated configuration and with the presence of the neighborhood, $C_{x,iso}$ and $C_{x,cv}$, $C_{y,iso}$ and $C_{y,cv}$, as a function of the angle of incidence of 0 to 270°. Thus, the results for the force coefficients, Figure 10 and Figure 11, showing the overlapping of graphs of force coefficients in the x and y axes, respectively, considering all ess the tested configurations in tunnel wind.

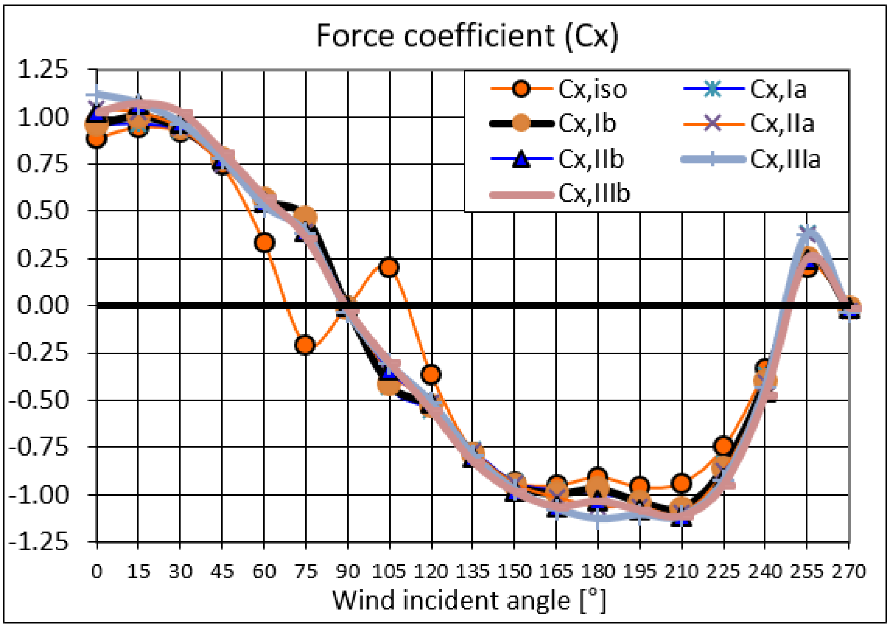

Figure 10 Force Coefficient (Cx) in all configurations

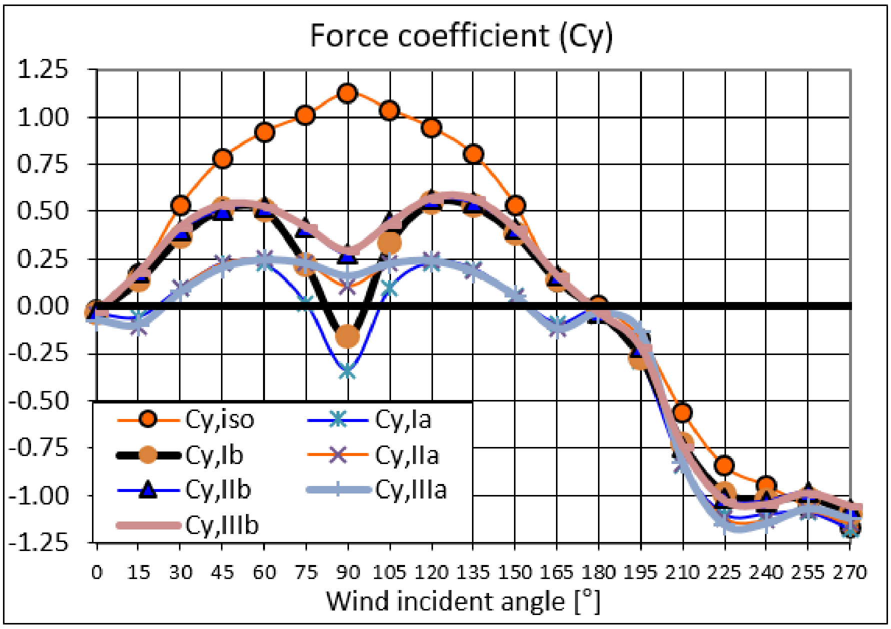

Figure 11 Force Coefficient (Cy) in all configurations

The force coefficients on the x-axis are partially similar in all settings with neighborhood, and in all wind angles of incidence, with minor variations in the coefficients around the angles 165° to 195°, differing from the isolated setting mainly at angles of 75° and 105°, with an inversion in the values. In these angles, the isolated configuration, there is indicative of the occurrence of a phenomenon widespread in Den Hartog's criterion, when a structure damped not undergoes one sinusoidal harmonic excitation (Den Hartog, 1947; Pacheco Huacho, 2014). However, the presence of the neighborhood in the surrounding, acted positively, mitigating the occurrence of this effect, in all configurations.

In contrast to the force coefficients on the x-axis, which did not suffer major interference with the increase and distance of the buildings in the surroundings, the force coefficients on the y-axis showed considerable differences, according to the insertion and variation in the quantity and spacing of the buildings. A marked reduction in the coefficients in all configurations, between the angles of 15° to 165°, were observed, highlighting the accentuated reductions in the actions of the wind at the angle of 90°, characterizing an intense protective effect. Thus, proving that the action of the wind in a building varies a lot, depending directly on the number and specific location of buildings present in the surroundings in the neighborhood.

It is noteworthy that the highest values of the force coefficients in the x and y axes were observed for incidence angles when the interfering models were on the lee side of the aerodynamic model, in the configurations with greater proximity between the models, probably caused by the mat formed by the model itself, giving rise to more significant effects. In the isolated configuration, the highest coefficients were -0.96 on the x-axis, at the angle of incidence at 195°, and -1.17 on the y-axis, at 270°. In configurations with neighborhood, the higher coefficient on the x-axis was observed in Configuration IIIa, -1.13, on the angle of incidence to 180°, on the y-axis, the highest value was noted in Configuration Ia, -1.18, on the angle of wind incidence at 270°.

The study of vicinity factors, in this work, in terms of angles wind incidence in relation to the x and y axes, followed the recommendations relating to the increase and reduction of wind actions in the study model, values above 1 represent increased wind loads, on the other hand, values below 1 indicate a reduction in the actions of the wind on the building. During the analysis of the results, the most influential configurations and wind incidences in the structural design were highlighted, presenting cases of both increase and reduction in loads. The Figure 12 presents the relationship between increase and decrease in the x and y axes, respectively, comparing the change in these factors as each neighborhood configuration adopted in this study.

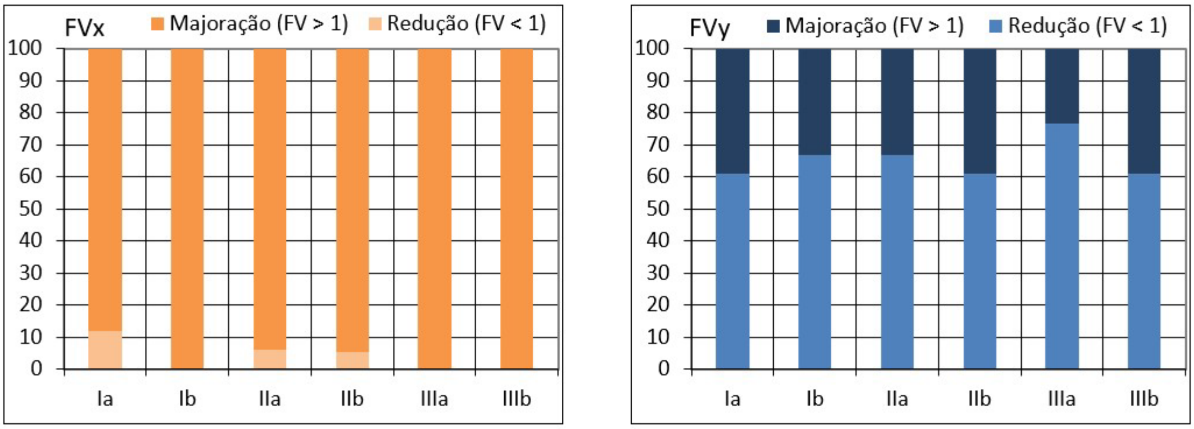

Figure 12 Results (FVx and FVy) in percentage according to the settings

For the FVx, it is observed the absolute predominance of wind increase actions in all tested configurations. The Configuration Ia, with only one building and smaller distance, presented a higher percentage of reduction actions, although significantly small, followed by the reduction of this action, according to the addition of new interfering models and greater distances. In other words, on the x-axis, the presence of the neighborhood tends to increase the wind loads, following the increase in the density of the neighborhood. On the other hand, for the FVy, there is a greater balance in the actions of the wind, with a greater predominance of reduction actions. With the addition of new interfering models and greater distances, highlights the increase in actions of reduce wind loads.

The Table 1 presents the overall results obtained in this study wind tunnel, through the percentage of occurrence, for vicinity factors calculated for both axes, FVx and FVy, adding up the results of all tested configurations. It is noteworthy that the discarded results are related to very small values of the force coefficients for the numerator and denominator, as a consequence, resulting in vicinity factors very high. In general, the vast majority of forces on the x-axis were increased, corresponding to 96.2% of the actions, against 3.8% of the reduced actions. On the other hand, on the y-axis, most shares were reduced, corresponding to 65.4%, against 34.6% of the increased shares, showing greater balance between shares.

Table 1 Total results (FVx and FVy) in percentage

FV	Results			Reduction (FV < 1)		Increase (FV > 1)	
	Totals	Valid	Discarded				
FVx	114	106	8	4	3.8%	102	96.2%
FVy		107	7	70	65.4%	37	34.6%

Following with the analyzes of the vicinity factors (*FV*), calculated through the horizontal force coefficients for each angle of incidence and each configuration, it is possible to carry out a comparative analysis between the values found with the recommendations of NBR6123:1988, which indicate *FV* values ranging from 1.0 to 1.3 in their Annex G. The results in Figure 13, showing the change in these factors as each neighborhood configuration, divided between those that are below the lower limit of 1.0 of the brazilian standard, those that comply with the limits between 1.0 and 1.3, and those that exceed the upper limit of 1.3.

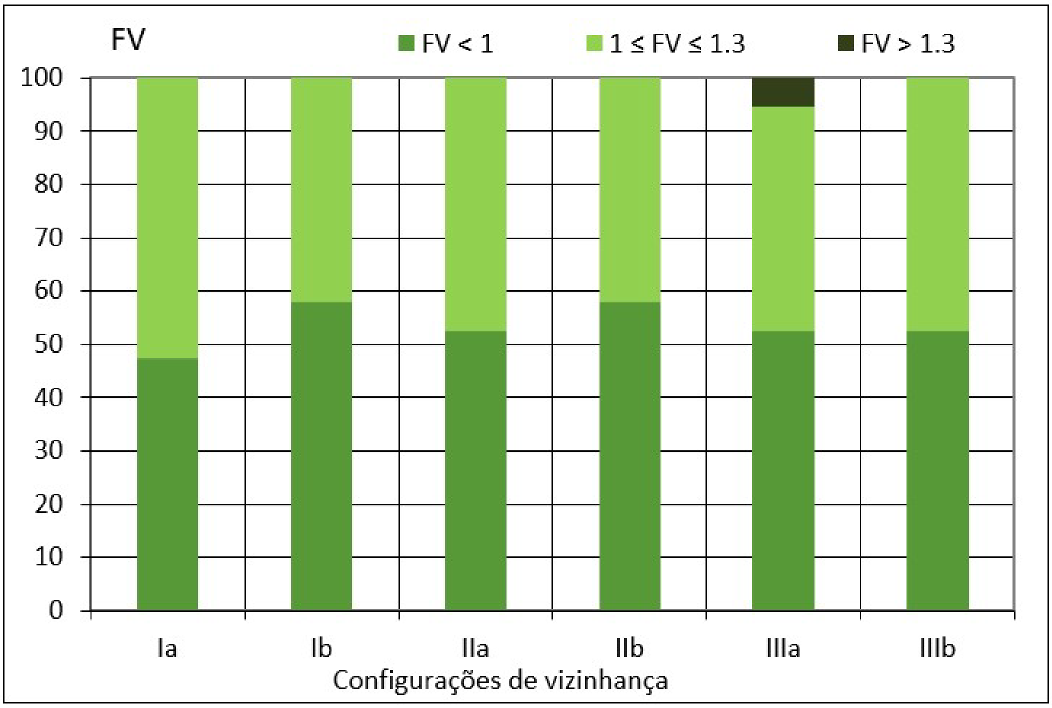

Figure 13 Results (FV) in percentage according to the settings

The Table 2 presents the total results, through the percentage of occurrence for the vicinity factors (FV), adding up the results of all tested configurations. As noted above, most factors are below the lower limit, corresponding to 53.5% of the values, the results between the limits recommended by the standard are 45.6%, with only 0.9% representing a single value exceeding the upper limit.

Table 2 Total results (FV) in percentage

FV	Valid Results	FV < 1		1 ≤ FV ≤ 1,3		FV > 1,3	
	114	61	53.5%	52	45.6%	1	0.9%

Analyzing the results of vicinity factors (FV), through percentage of occurrence, as the adopted settings, has been that most of the factors are below the lower limit, indicating a protective effect on actions related to the amount and proximity of the interfering buildings. It is observed that the neighborhood configurations with smaller distances between the models, resulted in a larger vicinity factors, cases of configurations Ia, IIa and IIIa. Most of these results are within the limits of the standard, with only one configuration being observed, IIIa, with a single factor exceeding the upper limit of 1.3 of NBR6123:1988, however, considerably within the limits, given its value of 1.31.

5 CONCLUSION

In general, the results presented in this study demonstrate the importance of carrying out tests in wind tunnels in specialized laboratories, according to the study of unconventional buildings, the complexity of the surrounding neighborhood and/or impossibility of applying the recommendations of available standards and codes, stressing the importance of considering the effects of wind action, especially taking into account the phenomena of interference of the neighborhood caused by buildings in the surroundings.

Considering the studies that resulted in the parameters adopted in the brazilian standard, composed of one or two interfering buildings, the addition of other models in the surroundings of the model under study with different spacings, influence the results of the vicinity factors, however, do not significantly change such values, being in accordance with the recommendations of Annex G of NBR6123:1988. Showing that the FV values are mainly given as a function of the proximity and size of the buildings directly in the surroundings. These studies are indicate the clear need for further work in the area, aiming to adapt the recommendations of the brazilian standard regarding the use of this parameter.

Therefore, this study included the analysis of the influence of these parameters, through coefficients determined in a wind tunnel and analytical calculation of the vicinity factors, on the effects of interference of the neighborhood. Promoting the proposal of new studies for “Anexo G – Efeitos de vizinhança” of NBR6123:1988 and the contribution to the research developed in this area of study, adding to the extensive database of the Laboratório de Aerodinâmica das Construções (LAC) of the Universidade Federal do Rio Grande do Sul (UFRGS).

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