Original Article

Latin American Journal of Solids and Structures
www.lajss.org

Experimental study of the neighborhood effects on the mean wind loading over two equivalent high-rise buildings

Abstract
This paper presents a series of results with respect to the mean values of shear, base moment and torsion acting in a building obtained through an experimental wind tunnel study using the standard building proposed by the Commonwealth Advisory Aeronautical Research Council (CAARC) as building reference. In the loading determination, the interference of a neighboring building with similar geometric characteristics to the CAARC was simulated, considering variations of positioning and spacing in relation to the reference building. It was concluded that the presence of the neighboring building increased the mean loads in the reference building for a significant number of directions considered. In the case of the considered deviations and the proposed provisions by this study, it was concluded that the vicinity factor that would contemplate the majority of the results obtained in the tests should increase the wind loads by at least 60% in relation to the values obtained for the building reference considered in isolation.

Keywords
vicinity effect; wind action; building aerodynamics.

Gregorio Sandro Vieira [a]*
José Luis Vital de Brito [b]
Acir Mércio Loredo-Souza [c]

[a] Universidade Federal de Uberlândia, Faculdade de Engenharia Civil, Uberlândia, MG, Brasil. E-mail: gregorio.vieira@ufu.br

[b] Universidade de Brasília, Programa de Pós-Graduação em Estruturas e Construção Civil, Brasília, DF, Brasil. E-mail: jlbrito@unb.br

[c] Universidade Federal do Rio Grande do Sul, Laboratório de Aerodinâmica das Construções, Porto Alegre, RS, Brasil. E-mail: acir@ufrgs.br

*Corresponding author

http://dx.doi.org/10.1590/1679-78253560

Received: November 28, 2016
In Revised Form: September 11, 2017
Accepted: October 16, 2017
Available online: February 02, 2018

1 INTRODUCTION

The construction of tall buildings is very common in large urban areas. Among the reasons for this practice, the greater use of urban area is certainly one of the determining factors.

In the search for less valuable land, many enterprises are built farther away from the densely built metropolitan areas. In many cases, such buildings are unique in their regions, but with the consequent local development, more buildings of similar size begin to be erected. The result of this is a change the wind flow in the region and the change from an isolated building situation to a set of buildings.

The interference of high-rise buildings interaction effects has been a subject of several researchers' studies for decades. It can be said that these studies began with the evaluation of the effects at the Empire State Building in New York due to the construction of two nearby buildings by Harris (1934). From this study, many researches on the interference of neighboring constructions have been made (Melbourne and Sharp, 1977; Blessmann, 1985, 1992, Thepmongkorn et al., 2002, Tang and Kwok, 2004, Lam et al., 2008 and 2011, Kim et al., 2015a, b). In addition to experimental and measurement studies in real buildings, many researchers have developed numerical simulations of these effects (Tutar and Oguz, 2002, Blocken et al., 2007, Jana et al., 2015). Kim et al (2015b) point out that establishing a guideline to evaluate interfering wind loads, whether global or local, is an extremely complex problem because of the large number of variables involved. Thus, one of the great challenges of these researchers is to work the effects of these interferences in a computational way and try to adequately represent the real situation.

Searching to meet the structural and normative conceptions, most studies seek to establish guidelines in order to determine the effects of interference of neighboring buildings on the wind loadings and the responses produced in the buildings to determine the structural parameters to be considered. In general, the parameters used in codes and standards determine limiting conditions such as the direction of wind incidence and height of neighboring buildings. As an example, the Eurocode 1: 2010 - Part 1-4: General Actions, Wind Actions, of Instituto Português da Qualidade (2010), which recommends considering the influence of neighboring constructions in the determination of the average wind in order to verify the effect of the turbulence increase in the wake of these buildings. In its Annex A.4, this code presents a conservative procedure to determine the wind speed based on the height of the neighboring building, analyzing parameters such as the height of the building under study and its smaller cross-sectional dimension.

In order to increase knowledge regarding the interference of neighboring buildings in the action of the wind on another building, the present study investigated the effects of the interference of a neighboring building, with identical geometric characteristics to the building under study, on the resulting mean forces in the directions of the X and Y axes, base moment around the X and Y axes and torsion around the axis of the building under study. For the data collection, the variation of the wind incidence was performed from 0º-345º, with increments of 15º. In addition to the wind direction, the distance from the neighboring building was varied considering four contours of distances and three alignments between edification in study and neighboring building. The discussion of the results is presented through graphics that represent the aerodynamic coefficients for each one of the studied loading mechanisms comparing the results of the building considered in isolation with the building subject to the interference of a neighbor. For a possible comparison with results of other researchers, the geometry of the buildings followed the same proposal standardized by the Commonwealth Advisory Aeronautical Research Council (CAARC).

2 EXPERIMENTAL PROGRAM

2.1 Simulation of the natural wind

The experimental program was developed at the Laboratório de Aerodinâmica das Construções (Building Aerodynamics Laboratory) of the Universidade Federal do Rio Grande do Sul (Federal University of Rio Grande do Sul), herein identified by LAC-UFRGS, located in the city of Porto Alegre, Brazil. The tests were performed at Prof. Joaquim Blessmann boundary layer wind tunnel. This tunnel has two test sections with dimensions 1.30m x 0.90m x 9.32m and 2.50m x 2.10m x 12.00m, being suitable for the correct simulation of the atmospheric layer where the buildings are tested (Blessmann, 1990). A 1:406 scale model was built and a boundary layer wind flow was simulated with the characteristics indicated in Figure 1.

2.2 Details of model and instrumentation

Two buildings were considered. The instrumented model was named the main building and the other neighboring building was named the mute model, both with identical transversal section and height in scale to the model proposed by CAARC. Considering the scale factor, the reduced models used in the test had a cross section with 75mm x 112mm and a height of 450mm. The main building had a total of 280 pressure taps spread over ten vertical levels. At each level seven pressure taps were arranged per face of the building, as can be observed in Figure 2. Figure 3 shows the different positions of the mute model, as well as the deviations considered in this study. Three alignments have been determined, with alignment V1 coinciding with the Y direction of the main building, alignment V2 is parallel to the diagonal of the main building but displaced so that its projection in this direction does not overlap the main building. Finally, the alignment V3 has the same direction as the diagonal of the main building and it is aligned to it. In addition to these alignments spacings were established directly related to the height of the main building. Each spacing corresponded to the distance between the center of the study building and the boundary of the outline of a circle whose diameter was calculated by reference to the height H of the main building. In total, four contours with diameters of 1.0H, 1.5H, 2.0H and 2.5H, denominated by D1, D2, D3 and D4 respectively. The neighboring building was positioned, for each alignment, in a location immediately outside each contour, totaling twelve distinct vicinities, three for each contour. For each vicinity, twenty-four wind incidences were considered, starting with the 0º direction and varying 15º from there until completing a turn at 345º, resulting in a total of 288 case studies.

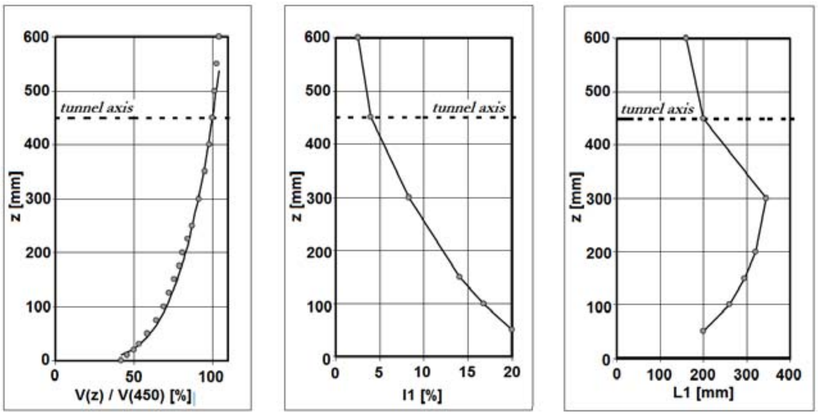

Figure 1: Characteristics of the simulated boundary layer wind, with velocity profile power law exponent p = 0.23

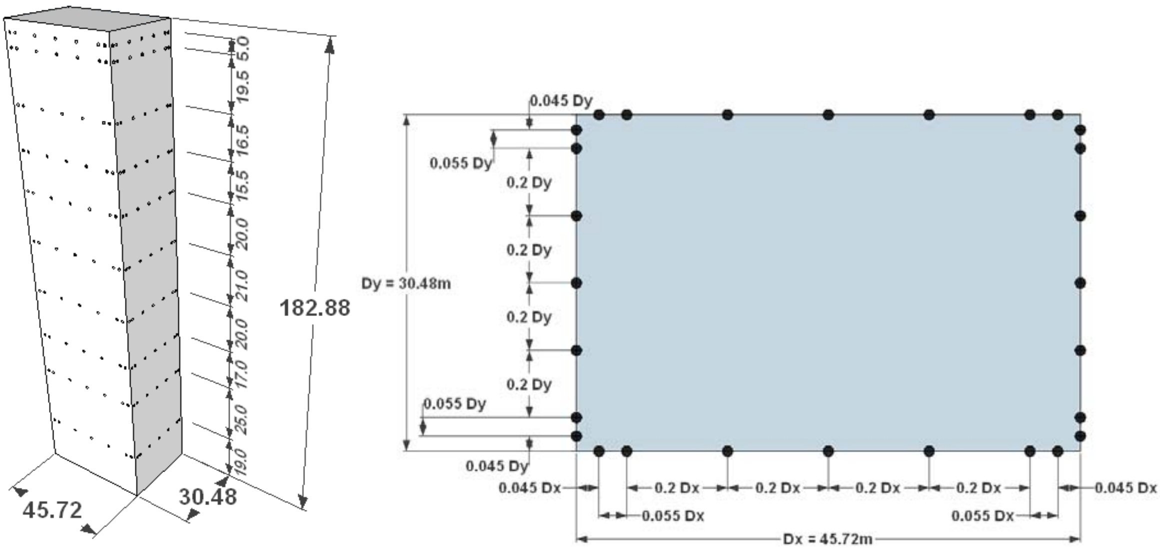

Figure 2: Equivalent full-scale distribution of the pressure taps in the CAARC building (unit: m)

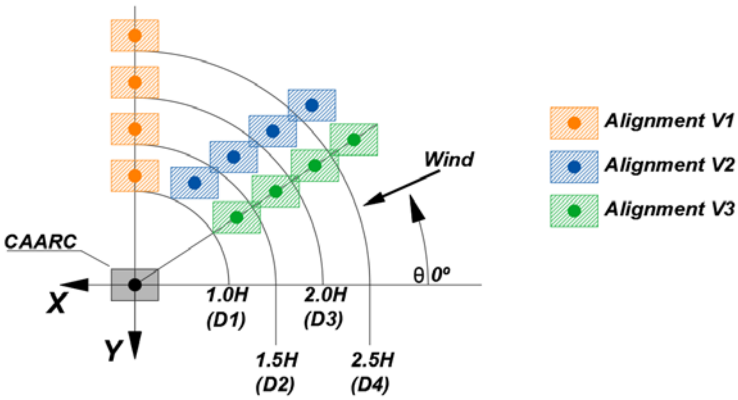

Figure 3: Indication of the positioning of the neighboring building in the coordinate system of the experiment

2.3 Definition of the Force, Base Moments and Torsion Coefficients

A MANOAIR 500 Schiltknecht electronic manometer, with resolution of 0.1 Pa and accuracy of 0.2 Pa was used to measure temperature and pressure inside the test chamber at the time of the experiment. In order to obtain the instantaneous pressures a Scanivalve Type ZOC33-Dantec simultaneous type floating acquisition equipment at an acquisition rate of 20 kHz and imprecision of 0.12% was adopted. For each wind direction and for each tap over the surface of the model, 8192 pressure readings, in mmH2O, were performed in a range of 16s. Some pictures of the equipment are shown in Figure 4. From these pressure time series, only the mean values are presented in this work. The average values were divided by the average dynamic pressure in the period of the readings, thus obtaining the dimensionless pressure coefficients.

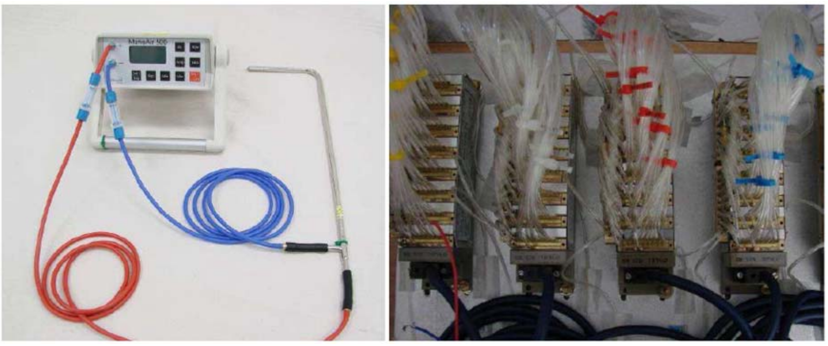

Figure 4: *Data reading equipment: (a) Manoair and hoses connecting to the feetometric rings ; (b) Scanivalve with 64 channels of pressure measurement per module.*

The resulting force coefficients in the direction of the main axes was calculated according to forces acting on the area of influence of each pressure take, by the product of the dynamic pressure by the total area of the wind face, According to expressions 1 and 2:

$$C_{F_x} = \frac{F_x}{qB_yH} \tag{1}$$

$$C_{F_y} = \frac{F_y}{qB_xH} \tag{2}$$

At where:
• F_x, F_y: global force in the direction of the X and Y axes;
• C_{Fx}, C_{Fy}: coefficient of force in the direction of the X and Y axes;
• q: dynamic wind pressure;
• B_x, B_y: nominal dimensions of the transversal section of the building;
• H: height of the building.

The bending moment coefficients around the X and Y axes were determined according expressions 3 and 4:

$$C_{M_x} = \frac{M_x}{qB_xB_yH} \tag{3}$$

$$C_{M_y} = \frac{M_y}{qB_xB_yH} \tag{4}$$

At where:
• M_x, M_y: Moment of flexion around the main axes X and Y;
• C_{Mx}, C_{My}: Coefficient of flexion around the principal axes X and Y;

Torsion of the coefficient around vertical main building axis is indicated in expression 5:

$$C_T = \frac{M_T}{qB_xB_yH} \tag{5}$$

At where:
• M_T: Torque moment around the torsion axis;
• C_T: Coefficient of torsion;

2.4 Vicinity Factor

A way to quantify the interference of a building on its neighbor was through the Vicinity Factor (FV). With the values of the pressure coefficients calculated according to the expressions of the previous item, the FV is calculated as the ratio between the coefficient found considering the presence of the neighboring building and the coefficient considering the isolated building, as shown in expression 6:

$$FV = \frac{C_{with\ neighborhood}}{C_{isolated}} \tag{6}$$

At where:
• C: Aerodynamic coefficient under study;
• FV: Vicinity Factor

3 RESULTS AND DISCUSSIONS

In order to have a parameter to compare with the results obtained in this research, the limits established by the Brazilian Code NBR 6123:1988, of Associação Brasileira de Normas Técnicas (1988), were adopted - since this establishes a criterion to consider the effects of neighboring buildings. In Annex G of the code, NB-6123 establishes that indicate as presented by expression 7 must be applied. It is worth noting that, due to the complexity of determining wind effects in oblique directions to the building axes, the code predicts wind incidence only in directions at 0º and 90º.

$$\begin{aligned} &\frac{s}{d^*} \leq 1.0 \ldots\ldots\ldots\ldots\ldots\ldots FV = 1.3 \\ &\frac{s}{d^*} \geq 3.0 \ldots\ldots\ldots\ldots\ldots\ldots FV = 1.0 \end{aligned} \tag{7}$$

Where:
• s: Distance between the confronting faces of neighboring buildings;
• d*: The smaller side dimension of the building under study, or half the diagonal of the building under study. Whichever is smaller.

Figures 5, 6 and 7 present the values loads of the load coefficients for all the studied confirmations. It is observed that in all situations the neighboring building interferes in all due to the action of the wind in the main building, sometimes increasing them and at other times exerting a protective effect reducing them.

From figure 5 we can see that the protective effects are more significant when the neighboring building is closer and positioned frontally to the study building as it can be seen in the direction of wind incident of 90º, figure 5 (b) and (c). However, it can be observed that when the neighbor with the same distance is positioned to the leeward, in the wake of the main building the tendency of protection is inverted and there is a significant increase of the previously reduced efforts. Even at the windward it is possible to observe that the neighbor has the effect of elevating the forces as can be observed in the incidences of 60º and 120º, figure 5 (b) and (c) for the neighbor positioned in the limit of the contour D3 and D4. In the case of torsion, it was found that, the proximity between the neighbors promoted the increase of this twist as can be observed in figure 5 (e) for the 75º, 105º and 120º directions.

For the V2 alignment situation, it is observed that, as for the alignment V1, the neighboring building promotes situations of protective effect that is more efficient when it is to the windward, in a frontal direction and with smaller deviations as can be seen in the figure 6 (a) and (d) for the directions in the range of 30° to 60°. It is observed that, except for the mentioned directions, a great part of the results, with the neighbor positioned to the windward, or to the leeward, the results are presented larger than the values considering the isolated main building demonstrating the influence of the neighboring building on the main loading.

For V3 alignment the protection effect is observed at larger intervals as shown in Figure 7 (b) and (c) between the 15° and 75° directions. It is also observed that for directions immediately afterwards there is a significant increase of the loads modally dual the Venturi effect caused by the two buildings raising the wind velocity and generating the increase of the pressures in the main building. In the case of torsion there is a reversal of direction in relation to what occurs with the building considered separately, focusing on the range of directions between 30° and 75°.

Tables 1, 2 and 3 present an analysis of the results collected in the tests for the determination of the force coefficients for the X and Y directions. The amount of data collected is provided for each effort, the number of results discarded, the number of results that were within the limits of Vicinity Factor established by the Brazilian wind code, the number of results that were above these limits, and the intensity of vicinity factors that were above the code limits. These same criteria were used in the elaboration of tables 4 to 6 for the moments in the base around the axes X and Y, and for the tables 7 to 9 for the calculation of the torsion. The discarded results are results of values of Vicinity Factors that were very high values in some specific directions, however, without in fact making a great effort in such directions. Because it is a ratio between two values, what happened in these situations was a division by a number very close to zero, which could lead to a misleading analysis of the other results.

Tables 1 to 5 show that most of the results considered valid are above the limits established in the code, reaching 84.7%, 82.4% and 78.3% for alignments V1, V2 and V3 respectively. Also a large distribution can be seen from these results along the four-lane intensities proposed for all studied spacings.

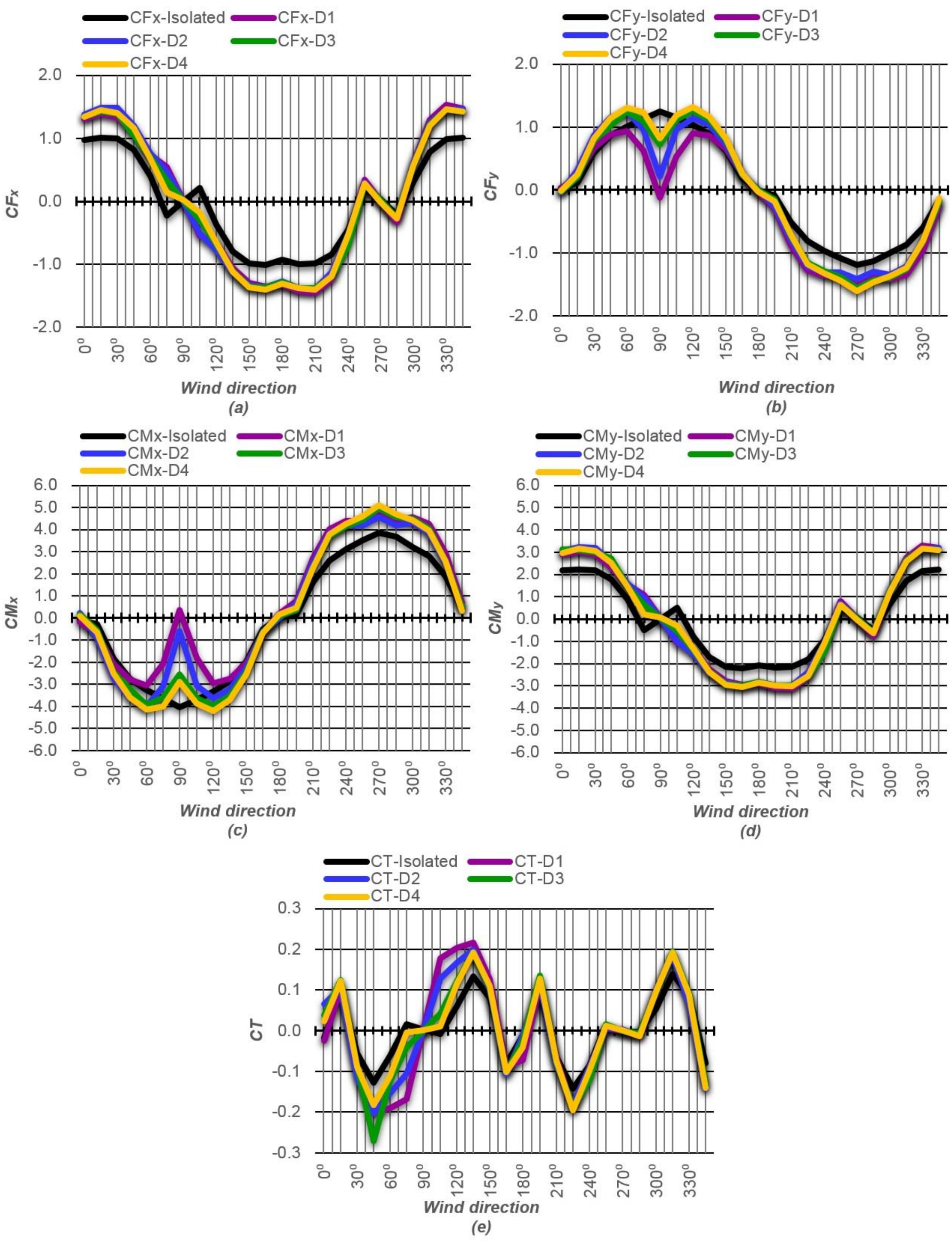

Figure 5: *Load coefficients for the alignment V1: (a) Resultant force in the direction of the X axis; (B) Resultant force in the direction of the Y axis; (C) Base moment around axis X; (D) Moment at the base about the Y axis; (E) Around the CAARC vertical central axis.*

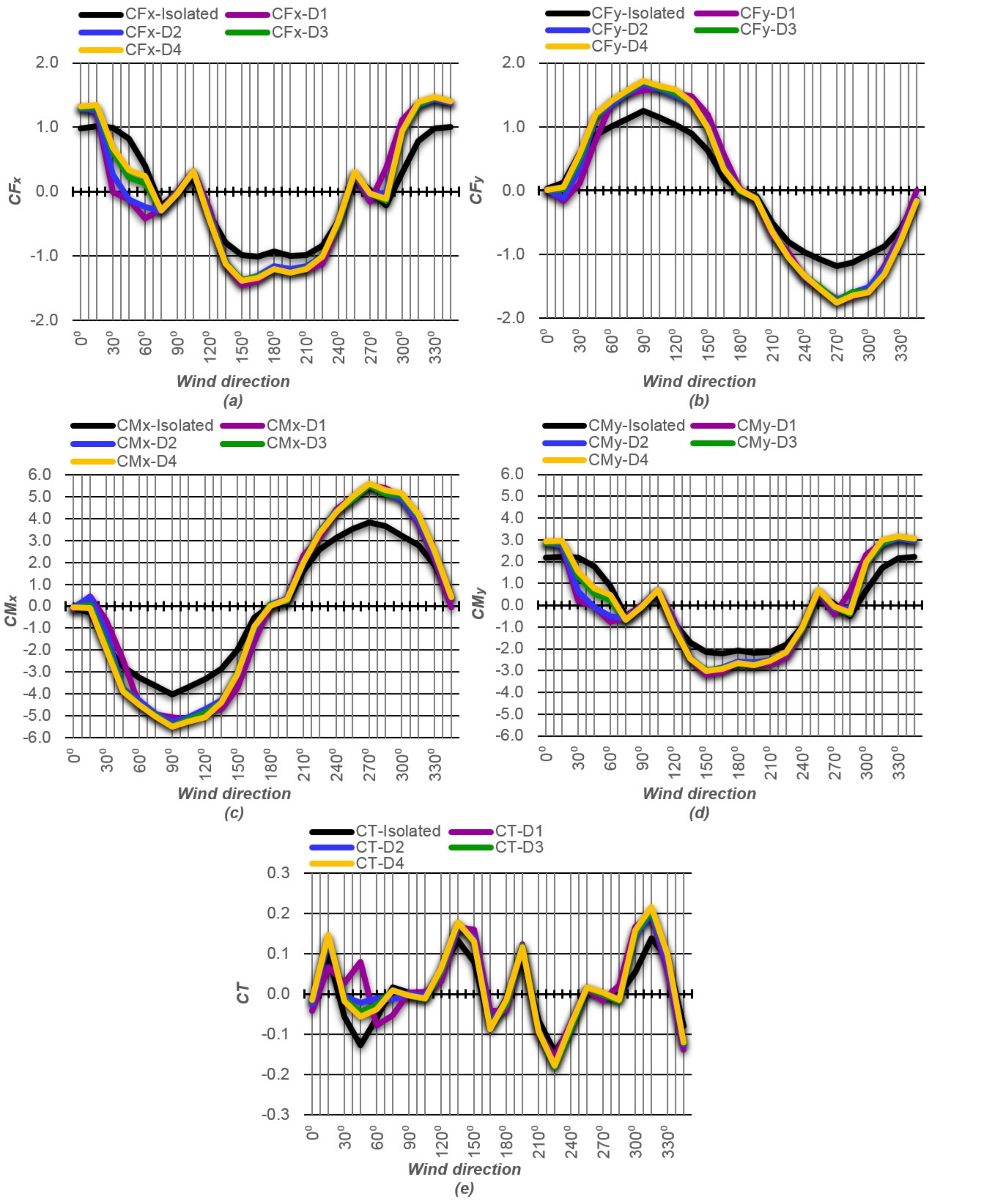

Figure 6: *Load coefficients for the alignment V2: (a) Resultant force in the direction of the X axis; (B) Resultant force in the direction of the Y axis; (C) Base moment around axis X; (D) Moment at the base about the Y axis; (E) Around the CAARC vertical central axis.*

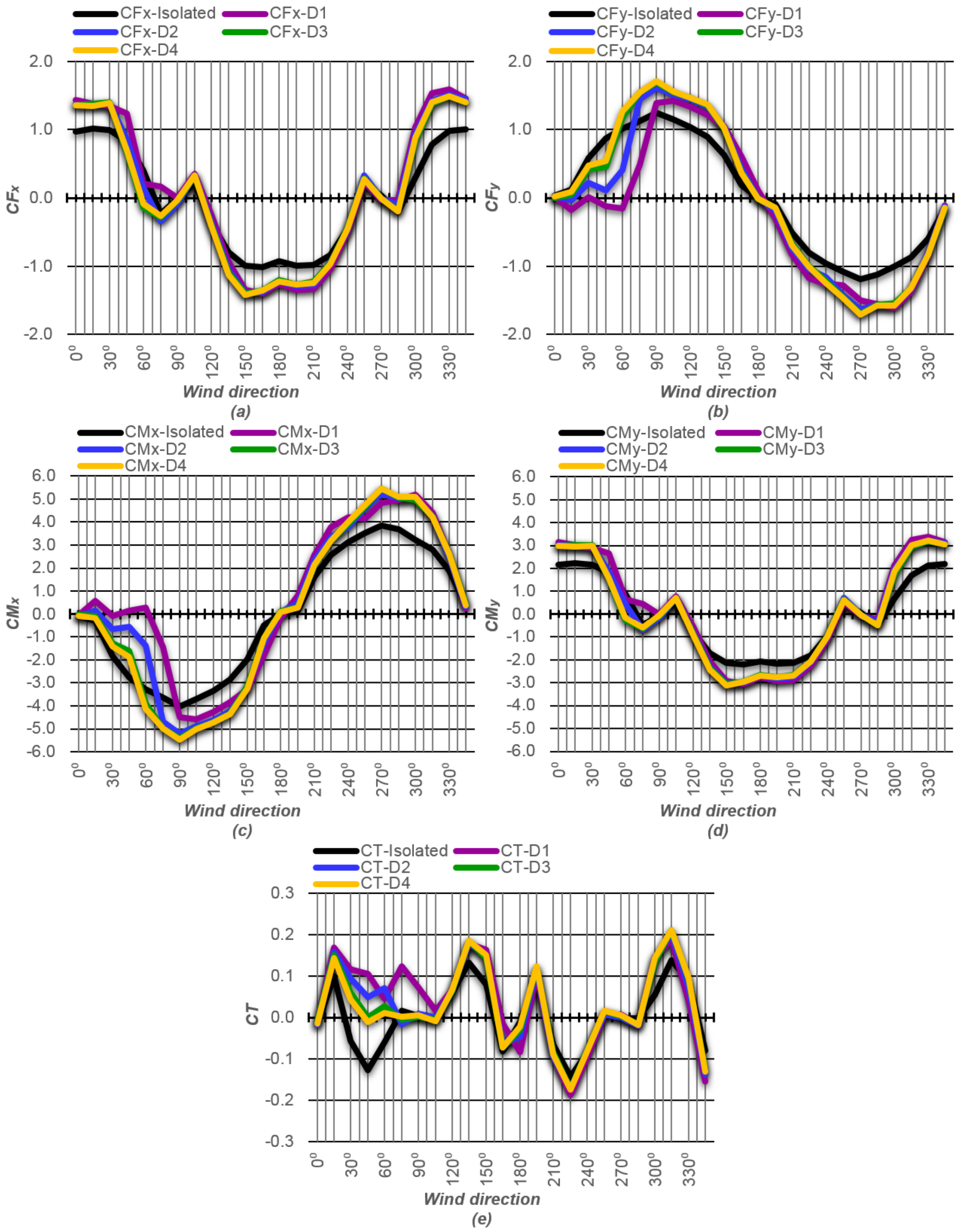

Figure 7: *Load coefficients for the alignment V3: (a) Resultant force in the direction of the X axis; (B) Resultant force in the direction of the Y axis; (C) Base moment around axis X; (D) Moment at the base about the Y axis; (E) Around the CAARC vertical central axis.*

Table 1: *Results of vicinity factors for the resulting force in the X and Y directions for the alignment V1*

Vicinity	Results	Discarded results	FV within the limits of the code	FV above the code limits	FV intensity above code limits			
					FV ≤ 1.2	1.2 <FV≤ 1.4	1.4 <FV≤ 1.6	FV > 1.6
FV-FX-V1D1	24	1	1	22	0	8	7	7
FV-FY-V1D1		1	9	14	1	4	5	4
FV-FX-V1D2		1	1	22	1	6	10	5
FV-FY-V1D2		3	3	18	5	9	3	1
FV-FX-V1D3		1	1	22	0	10	8	4
FV-FY-V1D3		1	4	19	0	13	3	3
FV-FX-V1D4		1	3	20	0	6	11	3
FV-FY-V1D4		2	3	19	2	14	2	1

Table 2: *Results of vicinity factors for the resulting force in the X and Y directions for the alignment V2*

Vicinity	Results	Discarded results	FV within the limits of the code	FV above the code limits	FV intensity above code limits			
					FV ≤ 1.2	1.2 <FV≤ 1.4	1.4 <FV≤ 1.6	FV > 1.6
FV-FX-V2D1	24	1	5	18	2	9	4	3
FV-FY-V2D1		1	4	19	2	7	7	3
FV-FX-V2D2		1	5	18	3	9	4	2
FV-FY-V2D2		1	4	19	0	8	9	2
FV-FX-V2D3		1	4	19	3	10	4	2
FV-FY-V2D3		1	3	20	1	10	8	1
FV-FX-V2D4		1	5	18	1	11	4	2
FV-FY-V2D4		2	3	19	1	7	9	2

Table 3: *Results of vicinity factors for the resulting force in the X and Y directions for the alignment V3*

Vicinity	Results	Discarded results	FV within the limits of the code	FV above the code limits	FV intensity above code limits			
					FV ≤ 1.2	1.2 <FV≤ 1.4	1.4 <FV≤ 1.6	FV > 1.6
FV-FX-V3D1	24	0	5	19	4	8	3	4
FV-FY-V3D1		1	6	17	2	6	4	5
FV-FX-V3D2		1	4	19	3	7	6	3
FV-FY-V3D2		1	6	17	0	10	4	3
FV-FX-V3D3		1	5	18	2	9	5	2
FV-FY-V3D3		1	4	19	2	9	5	3
FV-FX-V3D4		1	4	19	4	9	4	2
FV-FY-V3D4		1	5	18	0	9	6	3

Tables 4 to 6 present the results in relation to the moments around the axes of the base. Also for this effort it is clear that the great majority of the results collected are above the limits proposed by the Brazilian code. In this case, 88.1%, 84.5% and 80.4% of the results found for alignments V1, V2 and V3 respectively were above these limits. Even with the variation of distance between the main building and the neighboring building, the results found in this alignment, which exceeded the codeative limit, also present themselves in a well distributed way among the intensity ranges proposed in this study.

Table 4: *Results of vicinity factors for momentum in the base around the X and Y directions for the alignment V1*

Vicinity	Results	Discarded results	FV within the limits of the code	FV above the code limits	FV intensity above code limits			
					FV ≤ 1.2	1.2 <FV≤ 1.4	1.4 <FV≤ 1.6	FV > 1.6
FV-MX-V1D1	24	2	8	14	1	4	5	4
FV-MY-V1D1		1	1	22	0	9	6	7
FV-MX-V1D2		2	4	18	7	7	3	1
FV-MY-V1D2		1	1	22	1	7	9	5
FV-MX-V1D3		2	3	19	3	11	3	2
FV-MY-V1D3		1	1	22	1	12	6	3
FV-MX-V1D4		1	3	20	2	14	3	1
FV-MY-V1D4		1	3	20	0	8	9	3

Table 5: *Results of vicinity factors for momentum in the base around the X and Y directions for the alignment V2*

Vicinity	Results	Discarded results	FV within the limits of the code	FV above the code limits	FV intensity above code limits			
					FV ≤ 1.2	1.2 <FV≤ 1.4	1.4 <FV≤ 1.6	FV > 1.6
FV-MX-V2D1	24	1	3	20	2	6	8	4
FV-MY-V2D1		2	5	17	1	11	3	2
FV-MX-V2D2		2	2	20	0	8	9	3
FV-MY-V2D2		2	4	18	3	10	3	2
FV-MX-V2D3		1	3	20	1	10	8	1
FV-MY-V2D3		1	4	19	2	12	3	2
FV-MX-V2D4		1	2	21	2	7	9	3
FV-MY-V2D4		1	5	18	2	10	4	2

Table 6: *Results of vicinity factors for momentum in the base around the X and Y directions for the alignment V3*

Vicinity	Results	Discarded results	FV within the limits of the code	FV above the code limits	FV intensity above code limits			
					FV ≤ 1.2	1.2 <FV≤ 1.4	1.4 <FV≤ 1.6	FV > 1.6
FV-MX-V3D1	24	1	6	17	2	7	2	6
FV-MY-V3D1		0	5	19	3	9	5	2
FV-MX-V3D2		2	5	17	0	10	4	3
FV-MY-V3D2		1	3	20	4	9	5	2
FV-MX-V3D3		1	4	19	2	9	6	2
FV-MY-V3D3		1	5	18	2	11	3	2
FV-MX-V3D4		1	5	18	0	10	5	3
FV-MY-V3D4		1	3	20	5	10	3	2

Tables 7 to 9 present the results found for the torsional moment around the axis of the main building. It can be observed that the amount of discarded results is significantly higher than in the case of other efforts. This is due to the behavior of the building in relation to this effort in which there are many inversions of the torsion direction with the variation of the direction of wind incidence, as can be observed in Figures 5 (e), 6 (e) and 7 (e). Also for this effort, most of the results were above the code ative limits, reaching 63.0%, 47.8% and 54.7% for alignments V1, V2 and V3 respectively. In the case of torsion, a greater distribution of results with a Vicinity Factor intensity is observed above 1.6, especially when the neighbor is positioned frontally to the main building.

***Table 7:** Results of torsion around the CAARC for V1 alignment*

Vicinity	Results	Dis-carded results	FV within the limits of the code	FV above the code lim-its	FV intensity above code limits			
					FV ≤ 1.2	1.2 <FV≤ 1.4	1.4 <FV≤ 1.6	FV > 1.6
FV-CT-V1D1	24	6	7	11	0	4	3	4
FV-CT-V1D2		5	3	16	3	6	2	5
FV-CT-V1D3		2	2	20	3	5	4	8
FV-CT-V1D4		2	3	19	3	8	4	4

***Table 8:** Results of the torsion around the CAARC for the alignment V2*

Vicinity	Results	Dis-carded results	FV within the limits of the code	FV above the code lim-its	FV intensity above code limits			
					FV ≤ 1.2	1.2 <FV≤ 1.4	1.4 <FV≤ 1.6	FV > 1.6
FV-CT-V2D1	24	7	9	8	2	4	2	0
FV-CT-V2D2		7	10	7	1	5	1	0
FV-CT-V2D3		6	8	10	5	3	2	0
FV-CT-V2D4		4	7	13	4	6	3	0

***Table 9:** Results of torsion around CAARC for V3 alignment*

Vicinity	Results	Dis-carded results	FV within the limits of the code	FV above the code lim-its	FV intensity above code limits			
					FV ≤ 1.2	1.2 <FV≤ 1.4	1.4 <FV≤ 1.6	FV > 1.6
FV-CT-V3D1	24	8	9	7	2	3	0	2
FV-CT-V3D2		10	7	7	2	3	2	0
FV-CT-V3D3		5	7	12	4	5	3	0
FV-CT-V3D4		4	7	13	4	5	4	0

Tables 10 to 13 present the data of the efforts for vicinity proposals V1, V2 and V3 positioned at the boundary of the contours of D1 to D4 respectively. Sums of all results obtained in all assays are given. The limits of NBR-6123 have been taken as reference, where contours with spacings between 0.17H and 1.0H are considered, where H represents the height of the building. The number of results that were within the limits proposed by the code were highlighted, as well as the values that exceeded these limits, including indicating the percentage of these in relation to the results considered valid. As in the tables presented above, the results of VF that exceeded the code limits are divided into four intervals where, in addition to the amount of results in each interval, the respective percentage of these results is presented in relation to the total of readings out of code, besides the accumulated percentage of results compared with the total of readings considered, in order to verify from which index the results would be contemplated by the confidence interval (CI).

Many researchers performed work within this range proposed by code. More than half of the vicinity positions proposed by Thepmongkorn et al (2002) were in this range. For a single wind direction, similar to the 90º direction of this study, they found interference indexes of up to 2.6 for the moment around the X axis, index of 3.4 for the moment around the Y axis and index of 1.9 for torsion. Tang and Kwok (2004) used settings very similar to those of Thepmongkorn and in their evaluations for a wind direction equivalent to 90º, verified that the presence of a neighboring building produced displacements with interference index of up to 1.6 in the same wind direction, 1.8 in the case of transverse displacements, and in determining the torsion angle they found the index of 1.9. Oliveira (2009) worked with spacings between 0.25H to 0.6H. Studying the dynamic effects of the wind acting frontally to the building, equivalent to the direction 90º of the present study, where it found indices of increment of the transversal, longitudinal and torsion in the building superior to 2.0, and in some cases this index reached much higher levels. Fontoura (2014) worked with spacings of 0.25H and 0.63H, including the presence of other buildings with different heights and different positions. The efforts studied by it reached elevation rates of 1.6 for the resulting force, 2.0 for base flexion and 2.2 for the torsion moment.

As in the work of these researchers, it can be verified for all situations with the neighboring buildings positioned at the border of the D1 contour, both in situations where they were to the windward, and in the situations in which they were positioned to the leeward, that a great part of the results exceeded the limits proposed by the Brazilian codes in relation to all the efforts analyzed. On the studied efforts, the least that contain results outside the code limits is the torsion with 51.0% is shown in table 10. All other efforts had at least 72.0% of the results above the limits indicated by the code. Using a confidence interval in which at least 95% of the population of the results should be contemplated, in the case of neighbors with boundary distance D1, all efforts would require a VF with an index above 1.6, as observed in previous mentioned researchers' studies.

Studies with neighboring buildings positioned at distances above 1.0H are more unusual. Thepmongkorn et al (2002) in their study, also considered the presence of neighboring buildings for spacings between 1.0H and 1.5H. In these cases, they found vicinity interference indexes of up to 1.7 for the moment around the X axis, from 2.3 for momentum around the Y axis and 1.5 for torsion, values lower than the situations with the nearest vicinity, but still above the limits proposed by the Brazilian Code. Tang and Kwok (2004) reached indexes of the order of 1.7 for the displacement towards the wind, 1.4 for transverse displacements and 1.8 for the torsion angle of their study, values close to those found for nearest positioned neighbors.

In situations where the neighbors were positioned at the boundary of the D2 contour, the twisting was also the effort that least presented results outside the code limits with 45.2% of the valid values, as presented in table 11. For the other efforts calculated for this contour an even more critical situation is observed where at least 78.0% of the results were above the code limits. Using the same confidence interval principle for this case, torsion would be the only effort met with the use of a VF with an index of 1.6. This index is very close to the indexes found by Thepmongkorn et al (2002) and Tang and Kwok (2004) in their researches.

Thepmongkorn et al (2002) proposed few situations where the neighbor was in the range between 1.5H to 2.0H of displacement. In these cases, they found vicinity interference rates of up to 1.4 for the moment around the X axis, 1.5 for momentum around the Y axis and 1.3 for torsion. For this region, Tang and Kwok (2004) found interference indexes of the order of 1.4 for displacements in the wind direction, 1.5 in the transverse direction and 1.6 in the torsion angle. It is observed a proximity between the interference rates in both researches.

For the situation in which the neighbors were positioned at the boundary of the D3 contour, the torsion continues being the effort, among those studies, one of that presents less results outside the code limits. Even so, a significant increase in the amount of results above these limits could be observed for all efforts where the torsion presented 71.2% of the above results and the other efforts were all above 84.0% according to the data presented in Table 12. Also in this case, the VF, to meet the confidence interval, should be greater than 1.6.

Finally, the vicinity proposals positioned at the boundary of the D4 contour, even though they were further apart, presented a large amount of results outside the code limits where the torsion had more than 72.6% of the results above these limits and the other efforts above 82.0%, as can be observed in table 13. As in the other contours, in this case, the VF would also need to be greater than 1.6.

Table 10: ***Result for contour D1***

Loads	Results	Discarded results	FV within the limits of code	FV above the code limits		Intensity of FV out of code										
						FV ≤ 1.2			1.2 <FV≤ 1.4			1.4 <FV≤ 1.6			FV > 1.6	
				Results	(%)	Results	(%)	Acumulated results (%)	Results	(%)	Acumulated results (%)	Results	(%)	Acumulated results (%)	Results	(%)
FX-D1	72	2	11	59	84.3	6	10.2	24.3	25	42.4	60.0	14	23.7	80.0	14	23.7
FY-D1		3	19	50	72.5	5	10.0	34.8	17	34.0	59.4	16	32.0	82.6	12	24.0
T-D1		21	25	26	51.0	4	15.4	56.9	11	42.3	78.4	5	19.2	88.2	6	23.1
MX-D1		4	17	51	75.0	5	9.8	32.4	17	33.3	57.4	15	29.4	79.4	14	27.5
MY-D1		3	11	58	84.1	4	6.9	21.7	29	50.0	63.8	14	24.1	84.1	11	19.0

Table 11: Result for contour D2

Loads	Results	Discarded results	FV within the limits of code	FV above the code limits		Intensity of FV out of code										
						FV ≤ 1.2			1.2 <FV≤ 1.4			1.4 <FV≤ 1.6			FV > 1.6	
				Results	(%)	Results	(%)	Acumulated results (%)	Results	(%)	Acumulated results (%)	Results	(%)	Acumulated results (%)	Results	(%)
FX-D2		2	9	37	80.4	6	16.2	32.6	16	43.2	67.4	10	27.0	89.1	5	13.5
FY-D2		2	10	36	78.3	0	0.0	21.7	18	50.0	60.9	13	36.1	89.1	5	13.9
T-D2	72	17	17	14	45.2	3	21.4	64.5	8	57.1	90.3	3	21.4	100.0	0	0.0
MX-D2		4	7	37	84.1	0	0.0	15.9	18	48.6	56.8	13	35.1	86.4	6	16.2
MY-D2		3	7	38	84.4	7	18.4	31.1	19	50.0	73.3	8	21.1	91.1	4	10.5

Table 12: Result for contour D3

Loads	Results	Discarded results	FV within the limits of code	FV above the code limits		Intensity of FV out of code										
						FV ≤ 1.2			1.2 <FV≤ 1.4			1.4 <FV≤ 1.6			FV > 1.6	
				Results	(%)	Results	(%)	Acumulated results (%)	Results	(%)	Acumulated results (%)	Results	(%)	Acumulated results (%)	Results	(%)
FX-D3		3	10	59	85.5	5	8.5	21.7	29	49.2	63.8	17	28.8	88.4	8	13.6
FY-D3		3	11	58	84.1	3	5.2	20.3	32	55.2	66.7	16	27.6	89.9	7	12.1
T-D3	72	13	17	42	71.2	12	28.6	49.2	13	31.0	71.2	9	21.4	86.4	8	19.0
MX-D3		4	10	58	85.3	6	10.3	23.5	30	51.7	67.6	17	29.3	92.6	5	8.6
MY-D3		3	10	59	85.5	5	8.5	21.7	35	59.3	72.5	12	20.3	89.9	7	11.9

Table 13: Result for contour D4

Loads	Results	Discarded results	FV within the limits of code	FV above the code limits		Intensity of FV out of code										
						FV ≤ 1.2			1.2 <FV≤ 1.4			1.4 <FV≤ 1.6			FV > 1.6	
				Results	(%)	Results	(%)	Acumulated results (%)	Results	(%)	Acumulated results (%)	Results	(%)	Acumulated results (%)	Results	(%)
FX-D4		3	12	57	82.6	5	8.8	24.6	26	45.6	62.3	19	33.3	89.9	7	12.3
FY-D4		5	11	56	83.6	3	5.4	20.9	30	53.6	65.7	17	30.4	91.0	6	10.7
T-D4	72	10	17	45	72.6	11	24.4	45.2	19	42.2	75.8	11	24.4	93.5	4	8.9
MX-D4		3	10	59	85.5	4	6.8	20.3	31	52.5	65.2	17	28.8	89.9	7	11.9
MY-D4		3	11	58	84.1	7	12.1	26.1	28	48.3	66.7	16	27.6	89.9	7	12.1

4 CONCLUSIONS

The purpose of the vicinity factor is to take in account the wind effects caused in a certain building due the presence of other buildings in the proximity of this one. In general, the criterion for predicting the use of this factor is the distance between buildings.

The final considerations made from the analysis of the results presented previously considered the position of the neighboring building as well as its distance to the instrumented building.

In all the situations analyzed in this study it was demonstrated that the presence of a building alters the wind loads in a building next to this one. It is evident that the changes of major interest for the structural analyzes are those that promote the increase of the load values to be considered. For this it is of great importance to know if such increase occur, what would be the situations in which they occur and what the intensity of the increases.

With the results found, it could be concluded that if the neighbor is positioned in the windward or leeward of the building, this will generally promote an increase in the loads which will be determined by the wind direction.

Even considering four different boundary limits in this study, for the determination of the Vicinity Factor, only in some cases the statistical criterion of confidence interval, in which at least 95% of the results are to be considered, was met.

Another point that could be observed is that the intensity of effort required to contemplate the elevations of efforts occurred in the situations proposed in this study would be at least 60% of the values of efforts found for a building considered as acting alone, situation adopted by NBR 6123.

Finally, it is clear the need to further research in order to clarify the protection effects promoted by the presence of a vicinity building and, mainly, the question of the necessity of the majoring efforts. Considering the presence of more than one building as well as the effects of soil-structure and fluid-structure interactions are parameters that can contribute significantly in this field of research.

5 ACKNOWLEDGMENTS

The authors are grateful for the financial support of CNPq (Brazil), which made this research possible. Also thanked is the staff of the Laboratório de Aerodinâmica das Construções of the Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, for the availability and dedication in carrying out the tests of this work.

References

Associação Brasileira de Normas Técnicas. (1988) NBR 6123: Forças devidas ao vento em edificações. Rio de Janeiro, Brasil.

Blessmann, J. (1990). Aerodinâmica das Construções. Sagra. Porto Alegre, Brasil.

Blessmann, J. (1985). Buffeting effects on neighbouring tall buildings. Journal of Wind Engineering and Industrial Aerodynamics, Amsterdam, v. 18: 105-110.

Blessmann, J. (1992). Neighbouring wind effects on two tall buildings. Journal of Wind Engineering and Industrial Aerodynamics, Amsterdam, v. 41-44: 1041-1052.

Blocken, B., Carmeliet, J. and Stathopoulos, T. (2007). CFD evaluation of wind speed conditions in passages between parallel buildings – effect of wall-function roughness modifications for the atmospheric boundary layer flow. Journal of Wind Engineering and Industrial Aerodynamics, Amsterdam, 95 ed.: 941-962.

Fontoura, P. C. C. N. O. (2014). Estudo experimental em túnel de vento dos efeitos de vizinhança em edifícios altos. Tese de doutorado. Programa de Pós-Graduação em Estruturas e Construção Civil da UnB, Brasília, Brasil: 318.

Harris, C. L. (1934). Influence of neighboring structures on the wind pressures on tall buildings. Bureau of Standards Journal of Research: 103-118.

Instituto Português da Qualidade. (2010). EUROCÓDIGO. Eurocódigo 1 - Acções em estruturas. Parte 1-4: Ações gerais - Ações do vento. Caparica, Portugal.

Jana, D., Bhaduri, T. and Dalui, S. K. (2015). Numerical study of optimization of interference effect on pentagonal plan shaped tall building. Asian Journal of Civil Engineering, 8 ed.: 1123-1153.

Kim, W., Yoshida, A. and Tamura, Y. (2015a). Variability of Local Wind Forces on Tall Buildings due to Neighboring Tall Building. 14th International Conference on Wind Engineering. Porto Alegre, Brazil: 12.

Kim, W., Tamura, Y. and Yoshida, A. (2015b). Interference effects on aerodynamic wind forces between two buildings. Journal of Wind Engineering and Industrial Aerodynamics, Amsterdam, 147 ed.: 186-201.

Lam, K. M., Zhao, J. G. and Leung, M. Y. H. (2008). Interference effects on wind loading of a row of closely spaced tall buildings. Journal of Wind Engineering and Industrial Aerodynamics, Amsterdam, 96 ed.: 562-583.

Lam, K. M., Zhao, J. G. and Leung, M. Y. H. (2011). Wind-induced loading and dynamic response of a row of tall buildings under strong interference. Journal of Wind Engineering and Industrial Aerodynamics, Amsterdam: 573-583.

Melbourne, W. H.; Sharp, D. B. (1977). Cross-wind response of structures to wind action. In: FOURTH INTERNATIONAL CONFERENCE ON WIND EFFECTS ON BUILDINGS AND STRUCTURES, 1975, Heathrow/UK. Proceedings. Cambridge: 343-358.

Oliveira, M. G. K. (2009). Desenvolvimento de uma Balança Dinâmica de Três Graus de Liberdade para Estudos dos Efeitos de Flexo-Torção em Edifícios Altos Submetidos à Ação do Vento. Tese de doutorado. Programa de Pós-Graduação em Engenharia Civil da UFRGS, Porto Alegre, Brasil: 207.

Tang, U. F., and Kwok, K. C. S. (2004). Interference excitation mechanisms on a 3DOF aeroelastic CAARC building model. Journal of Wind Engineering and Industrial Aerodynamics, Amsterdam: 1299-1314.

Thepmongkorn, S., Wood, G. S. and Kwok, K. C. S. (2002). Interference effects on wind-induced coupled motion of a tall building. Journal of Wind Engineering and Industrial Aerodynamics, Amsterdam: 1807-1815.

Tutar, M., and Oguz, G. (2002). Large eddy simulation of wind flow around parallel buildings with varying configurations. Fluid Dynamics Research, 31 ed.: 289-315.