Interference Effects on the Wind Load Evaluation of a High Building Group by Wind Tunnel Tests

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ABSTRACT: The Argentine wind code CIRSOC 102 specifies wind load factor values for structures of regular shapes. When the structure has unusual shapes or significant neighborhood effects, the regulation suggests studies in wind tunnels. This paper presents the results of studies realized in the UNNE Wind Tunnel to assess wind loads on three tower projected in Mar del Plata City, Argentina. Tests were conducted with natural wind simulation according to the local terrain roughness. Incident wind changes caused by neighboring buildings were evaluated from measurements of mean and fluctuating velocities. Local pressure, global force and moment coefficients on each tower model were measured for twelve wind directions. Changes caused by the interference of the model itself on the incident wind characteristics were determined. To analyze the effects of interference due to the proximity between the three towers, the results obtained were compared with values measured considering the highest tower isolated. The analysis of the results shows the importance to simulate the incident wind characteristics and the neighborhood influence and complementary evaluations of instantaneous pressures and pedestrian comfort are suggested.

KEY WORDS: Wind Load Coefficients; Incident Wind; Building Configuration.

1 INTRODUCTION

Wind load factor values for structures of regular shapes and small sizes are specified in Argentine wind action on building Code CIRSOC 102 [1], but when the structure has unusual shapes or significant neighborhood effects, the regulation suggests studies in wind tunnels. Wind loads from wind tunnel tests incorporate the influence of the neighboring environment. Blessmann & Riera [2] mention a wind tunnel study realized by Harris in 1934, where the construction of two new towers next to the Empire State Building is analyzed. The obtained results indicated a 200 % increasing of the torque in the principal building. They also investigated the interaction between two square prisms [3]. The results shown torque values larger than three times with respect to measurements obtained in the isolated model. Tests carried out by Whitbread [4] indicated that static loads measured in the Quantas Center Towers, Sydney, are increased up to 20% when the interaction of the wind with two towers is considered. Similar behavior was obtained by Ruschewey [5] when the vibration response was analyzed by a dynamic model adding a leeward model. Sakamoto & Haniu [6] analyzed the influence of the obstacle location considering the main model and the obstacle of equal size. The influence on drag and lift forces is perceptible up to distances of sixteen times (longitudinal direction) and four times (transverse direction) the structure width. All results emphasized the importance of reproducing interference effects caused by obstacles of similar size to the main building. However, all analyzed cases are related to models of regular geometric shape, a specific type of incident wind where the mean stream flow direction is perpendicular to the face of the main model.

In this work, a different situation is analyzed. Wind loads on a group of three buildings are investigated by wind tunnel tests realized in the Laboratorio de Aerodinámica of the Universidad Nacional del Nordeste (UNNE). The towers of the architectural complex have irregular geometric shape, the incident wind characteristics are different according to the considered wind direction and there is a near surrounding with obstacles of similar height to the building group. The three towers have different height, but the highest is 71 m.

2 EXPERIMENTAL ARRANGEMENTS

Tests were realized using a static model according to the Argentine Wind Code CIRSOC 102. Neighboring environment and incident wind characteristics at real situation were considered in the model tests. Three rigid models were built in 1:200 scale, reproducing the relevant aerodynamics details.

External mean pressures on the tower models were measured at mean wind velocity of 25 m/s. Twelve incident wind directions, from 0º to 360º were tested. Local pressure, global force and moment coefficients on each tower were determined.

Changes caused by the interference of the model itself on the incident wind characteristics were determined. Mean and fluctuating velocities were measured with the hot wire anemometer and the experimental values obtained were compared with measured values on the undisturbed boundary layer flows.

2.1 The UNNE Wind Tunnel

The "Jacek Gorecki" wind tunnel of the Universidad Nacional del Nordeste, UNNE, Resistencia, Argentina, is a low velocity atmospheric boundary-layer wind tunnel [7]. It is a 39,56 m long channel with a contraction and a 22,8 m long rectangular test section (2,40 m width, 1,80 m height). Two rotating tables are located in the test section to place structural or aerodynamic models. Boundary layers with zero pressure gradient can be achieved by vertical movement of the roof. The test section is connected to the velocity regulator and to the 2,25 m diameter blower. It is operated by a 92 kW electric motor at 720 rpm.

2.2 Atmospheric boundary layer simulation

The simulation of natural wind on the atmospheric boundary layer was performed by means of the Standen method [8]. Roughness surface and two Irwin truncated spires [9] were used and the length of roughness surface on wind tunnel floor was changed according the test. The scale factor obtained by the Cook method [10] was 1: 200 (Figure 1).

The velocity profile can be described by the power law or the logarithmic law. The CIRSOC 102 code adopted the power law exponent n to characterize different types of terrain. Two boundary layer winds are used in these tests. The main characteristics (mean velocity and turbulence intensity profiles) are indicated in Figure 5. The BL1 and BL2 boundary layers are closed to open sea ($n = 0{,}09$) and terrain suburban ($n = 0{,}14$) respectively [11].

2.3 Model description and instrumentation

The rigid models of the three towers model were built in 1:200 scale, reproducing the relevant aerodynamics details (Figure 2). External pressures taps were placed on three models and local pressures were measured for twelve incident wind directions, from 0º to 360º. Local pressure, global force and moment coefficients on each tower were determined by surface integration. Pitot-Prandtl tubes and hot wire anemometers were used to evaluate the mean flow and turbulence characteristics. Local pressures were measured by a multi-manometer, a scanivalve system and electronic pressure transducers. In each tower model 78 pressure taps were distributed. The evaluation process requires obtaining the centre of gravity. It was determined in simplified form by structural data. The location of gravity center, the reference axis system and the incident wind direction are indicated in Figure 3.

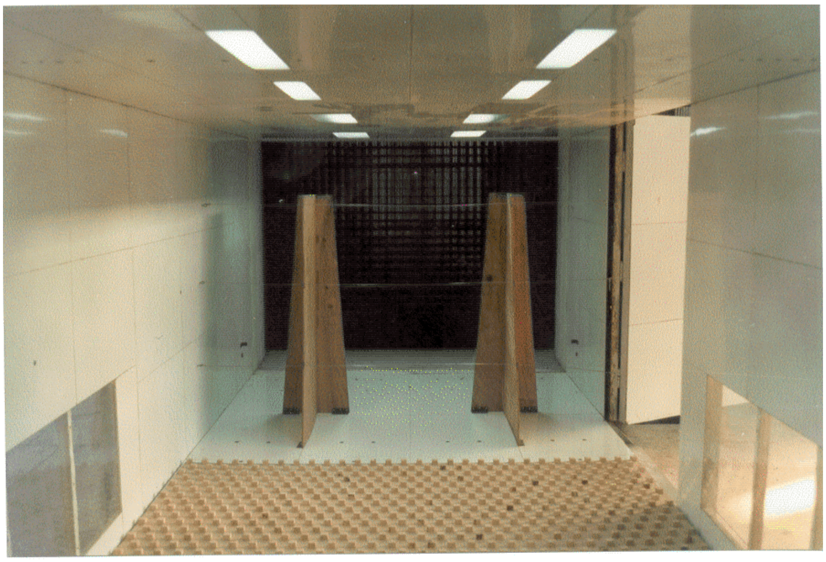

Figure 1. Wind tunnel simulation of the atmospheric boundary layer.

3 WIND LOAD COEFFICIENTS

3.1 Local pressure coefficients

Average pressure local coefficients are defined as:

$$c_e = \frac{\Delta pe}{q_z} \tag{1}$$

where Δpe is the difference between the surface model pressure and the reference pressure and q_z is the dynamic pressure measured at reference height (highest model h_{ref} = 0,355 m).

Figure 2. Building complex scale model (1:200).

3.2 Force and moment coefficients

The force coefficient is defined, as:

$$C_{F\,i} = \frac{\sum_{j=1}^{n} c_{p\,j}\; S_j\; sen\beta_j}{A_M} \tag{2}$$

where S_j is the tributary area, β_j angle determined by the normal to surface and the Y axes, and A_M is the reference area. The bending momentum coefficient is defined, as:

$$C_{M\,i} = \frac{\sum_{j=1}^{n} c_{p\,j}\; S_j\; \cos\beta_j\; h_j}{A_M\; H_{T_i}} \tag{3}$$

where n is the pressure tap number and H_T is tower total height.

The height H_R and the direction θ of the resultant force (relative to the Y axis) were determined using bending and resultant force components. The torsion coefficient was calculated by the force components and the gravity center. This coefficient is defined for i (x, y) as:

$$C_{M\,z_i} = \frac{\sum_{j=1}^{n} c_{p\,j}\; S_j\; \cos\beta_j\; e_{x\,j}}{A_M\; L_R} \tag{4}$$

where L_R is the characteristic length of the reference area.

The total torsion coefficient is:

$$C_{MT} = C_{M\,z_x} + C_{M\,z_y} \tag{5}$$

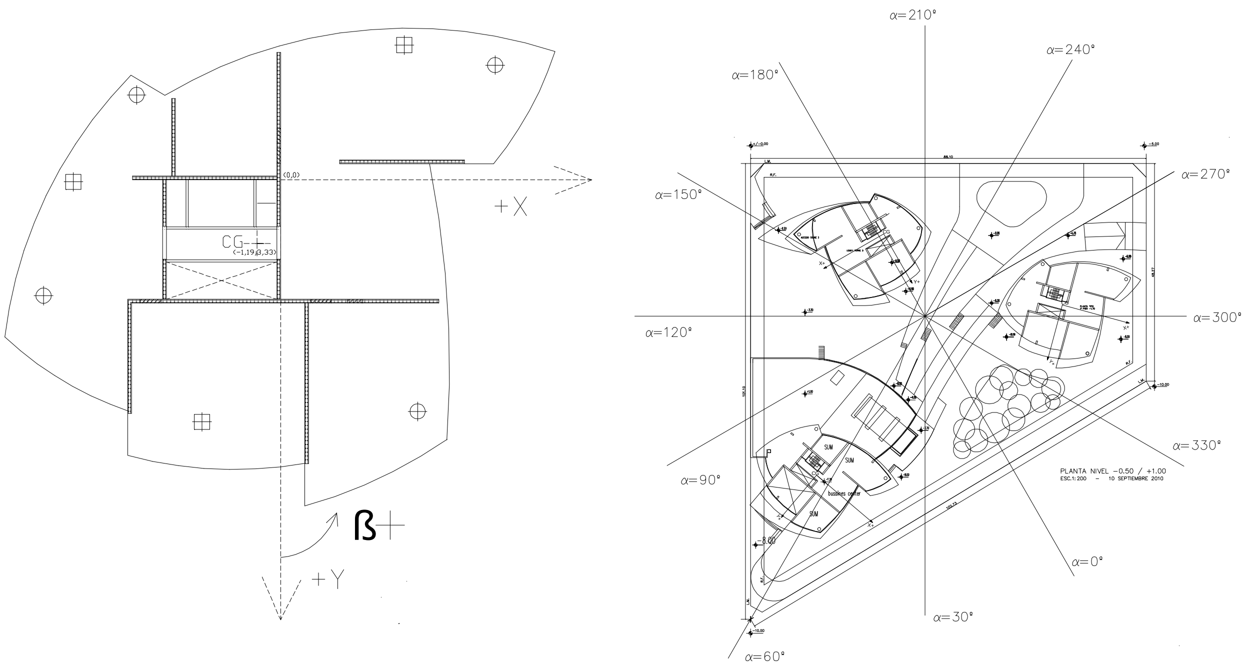

Figure 3. Location of gravity center and reference axis - Incident wind directions and tower locations.

4 ANALYSIS OF LOAD COEFICIENTS

Coefficients of force (C_{FX}, C_{FY}), bending moment (C_{MVY}, C_{MVX}) and torsion (C_{MT}) are shown in Tables 1, 2 and 3, for each wind direction considered. The height H_R and the direction θ are indicated too. The maximum force coefficient is obtained (C_{FX} = -1,29) when the Tower II is placed in windward position, completely exposed to open sea wind (wind incident direction of 0º). Torre III shows high values (C_{FY} = 1,16 and 1,12) for incident wind direction of 180º and 210º corresponding to flow simulation of suburban terrain. The expected highest values of force coefficient for Tower I at 0º incident wind were not obtained due to the protection effects of the environment surrounding.

Incident wind directions of 30º and 330º caused the maximum values of torsion coefficient (C_{MT} = -0,004) for Tower III. The tower is located to leeward of the other two towers, but the frontal face is exposed to the wake and the wind is accelerated product of the relative location of the windward towers.

To analyze the interference of the tower group, the isolated Tower I was tested. In table 4 shows coefficient ratio for Tower 1 (isolated/surrounding environment). Isolated tower coefficients are larger than architectural complex coefficients. The higher difference happened for wind direction from 150° to 300° when Towers II and III are placed to windward of Tower I. Wind direction of 210° is the most relevant situation. Force and bending coefficients change significantly. The wind acts directly on the Tower III, causing a wake on the position of Tower I.

5 EVALUATION OF INTERFERENCE EFFECTS AND INCIDENT WIND MODIFICATIONS

In addition to the two types of boundary layer flows considered (open sea and suburban terrain), it is important to analyze wind modifications in the tower neighborhood. These modifications will depend of the incident wind direction. For this purpose, measurements of the wind velocity were realized on the windward position of the model (approximately 0,30 m from the tower location). Wind directions corresponding to 0º and 180º were analyzed. The location between towers I and III, in the vicinity of the tower II was also analyzed for the wind direction of 130º (Figure 4). Hot wire anemometer was used for these measurements.

Flow modifications are shown in the Figure 5 by a comparison between the experimental values obtained for BL1 (wind direction 0º), BL2 (wind direction 180º), BL1 mod., BL2 mod. and BL2 edif. Experimental values for BL1 and BL2 fit to n=0,09 and n=0,14, respectively. Profiles modified by the model were obtained on the wind ward location (BL1 and BL2 mod.)

and on a location between towers I and III (BL2 edif. in the vicinity of tower II). In general, a reduction of mean velocity and an increase of turbulence intensity are observed especially at lower positions.

Table 1: Force, bending and torsion coefficients for Tower I

Wind Direction	Tower I						
	C_{FX}	C_{FY}	C_{MVY}	C_{MVX}	C_{MT}	H_R [m]	θ (y)
0	-1,02	-0,29	-0,50	-0,09	0,002	0,186	-105,9
30	-0,90	-0,67	-0,44	-0,31	0,002	0,187	-126,7
60	-0,47	-0,76	-0,20	-0,40	0,001	0,194	-148,6
90	0,09	-0,49	0,08	-0,28	0,0002	0,230	169,3
120	0,45	-0,32	0,23	-0,18	0,00001	0,207	125,5
150	0,62	-0,08	0,31	-0,03	0,001	0,192	97,5
180	0,51	0,14	0,22	0,10	-0,001	0,177	74,9
210	0,03	0,26	0,04	0,22	-0,0003	0,326	7,3
240	-0,09	0,81	-0,03	0,41	-0,002	0,195	-6,4
270	-0,11	0,91	-0,06	0,45	-0,003	0,194	6,7
300	-0,32	0,15	-0,18	0,10	0,0004	0,231	-64,8
330	-0,96	-0,05	-0,47	-0,01	0,003	0,199	-93,3

Table 2: Force, bending and torsion coefficients for Tower II

Wind Direction	Tower II						
	C_{FX}	C_{FY}	C_{MVY}	C_{MVX}	C_{MT}	H_R [m]	θ (y)
0	-1,29	-0,62	-0,63	-0,31	-0,002	0,171	-115,9
30	-0,44	-0,94	-0,19	-0,46	0,001	0,165	-154,8
60	0,04	-0,85	0,04	-0,42	0,001	0,171	177,1
90	0,11	-0,19	0,06	-0,10	-0,0001	0,173	148,8
120	0,01	-0,30	0,02	-0,13	0,0001	0,157	177,3
150	-0,03	0,17	-0,01	0,08	0,0002	0,157	-8,7
180	0,42	0,85	0,19	0,42	0,0003	0,169	26,1
210	0,29	0,64	0,12	0,30	-0,0004	0,162	24,2
240	0,02	0,99	0,02	0,53	-0,003	0,186	1,2
270	-0,04	0,78	-0,06	0,40	-0,003	0,177	-3,2
300	-0,13	0,04	-0,10	0,02	0,0002	0,270	-73,0
330	-1,10	-0,33	-0,55	-0,14	0,002	0,172	-106,8

Table 3: Force, bending and torsion coefficients for Tower III

Wind Direction	Tower III						
	C_{FX}	C_{FY}	C_{MVY}	C_{MVX}	C_{MT}	H_R [m]	θ (y)
0	-0,04	-0,65	-0,02	-0,33	-0,003	0,165	-176,3
30	-0,09	-0,47	-0,05	-0,23	-0,004	0,155	-168,6
60	0,58	-0,24	0,32	-0,13	0,0003	0,176	112,0
90	0,66	-0,28	0,36	-0,16	0,001	0,176	112,8
120	0,46	0,31	0,27	0,14	-0,0001	0,177	56,5
150	0,24	0,88	0,14	0,44	-0,002	0,159	15,4
180	0,01	1,16	0,00	0,60	-0,003	0,166	0,3
210	-0,19	1,12	-0,11	0,59	-0,0001	0,167	-9,7
240	-0,46	0,55	-0,25	0,30	0,0001	0,172	-39,8
270	-0,58	0,06	-0,30	0,04	-0,002	0,166	-84,0
300	-0,19	-0,05	-0,12	-0,02	-0,002	0,194	-104,5
330	0,04	-0,67	0,03	-0,35	-0,004	0,166	176,3

Table 4: Ratio coefficients (force, bending and torsion), height and direction for Tower I.

Wind Direction	Ratio of coefficients (isolated/Environment)						
	C_{FX}	C_{FY}	C_{MVY}	C_{MVX}	C_{MT}	H_R [m]	θ (y)
0	1,04	0,76	1,08	0,89	1,00	1,05	0,96
30	1,08	0,69	1,09	0,81	0,20	1,07	0,91
60	0,64	1,17	0,80	1,13	1,00	1,02	1,08
90	2,00	1,47	1,13	1,21	-1,00	0,82	0,98
120	1,04	1,53	1,04	1,33	4,00	0,94	1,09
150	1,02	0,75	1,00	0,33	1,00	1,00	1,00
180	1,12	1,79	1,23	1,40	-1,00	1,08	0,88
210	11,67	3,12	4,25	1,86	3,33	0,60	3,18
240	-1,67	1,20	-2,67	1,20	1,50	1,01	-1,38
270	-1,00	1,00	-1,00	1,00	1,00	1,00	1,00
300	1,91	2,53	1,72	2,00	2,50	0,87	0,89
330	0,93	4,00	0,96	6,00	1,00	0,98	1,10

Velocity values are indicated in dimensionless form (U/U_{ref}). This fact does not allow appreciating the velocity increase for BL2 edif. measurements. The rise mean velocity is about 45%. The turbulence intensity increase at lower positions is also important. This fact could cause greater pressure fluctuations in that region.

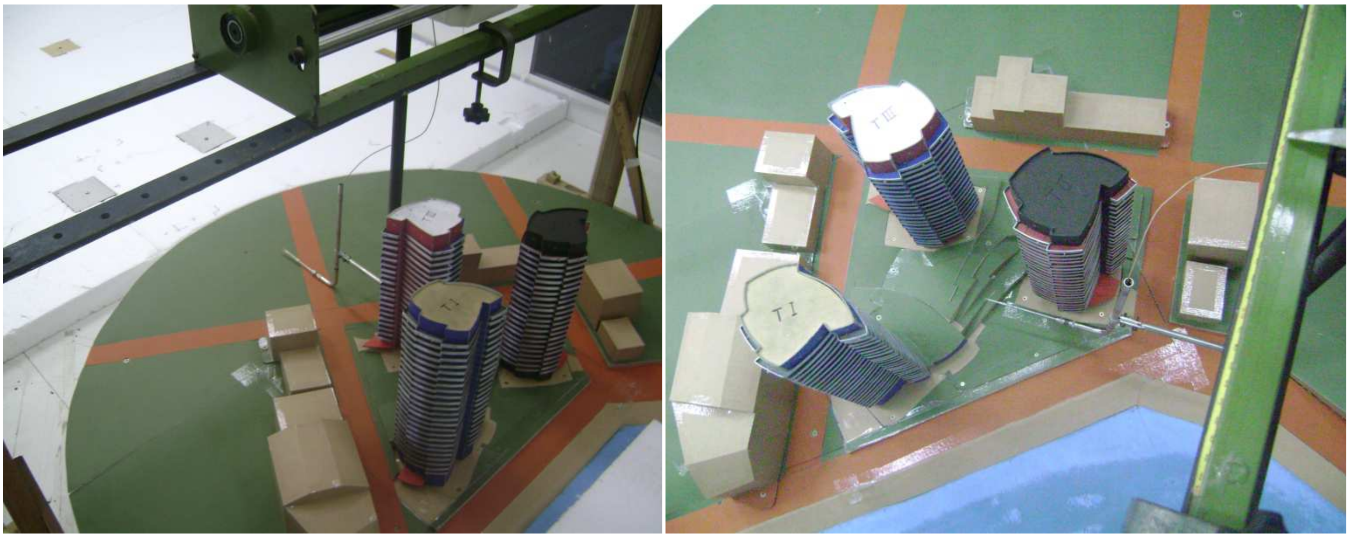

Figure 4. Hot-wire measurements at the proximity of the model.

Spectra of the longitudinal turbulence component for the three situations (BL1 mod, BL2 mod. and BL2 edif.) obtained at 0.25 m height are shown in Figure 6. Values obtained for BL1 mod. and BL2 mod. are very similar. In both cases, the inertial zone is noticeable between 50 and 1000 Hz. Some alterations appear in the spectrum measured between the towers I and III (BL2 edif.). Greater energy contents are observed and the inertial region is not so clearly defined.

Finally, dimensionless spectra are also shown in Figure 6. The von Kármán spectrum is added to compare experimental model values and atmospheric data. This comparison allows verifying the good agreement of BL1 mod. and BL2 mod. with the von Kármán spectrum. With respect to BL2 edif. spectrum, it is possible to estimate the displacement of the vortex generation zone. This fact is product of the windward building interference.

Based on the result analysis, it can be noted:

a) Mean velocity values decrease at the windward area of buildings.

b) The turbulence intensity increases at lower part of buildings (region closer to the surface). In terms of velocity fluctuations, this increase only occurs for CL2 edif. (between towers) where there is an increase of mean velocity too.

c) The spectral analysis complements the evaluation of velocity fluctuations. Turbulent energy distribution corresponds to a developed boundary layer for BL1 and BL2 mod. measurements whereas a spectral distortion appears in the BL2 edif. case. A turbulent component of mechanical origin alters the energy distribution with respect to the distribution of the von Kármán spectrum. It is important to observe that the quasi-static approach for wind load analysis considers that pressure fluctuations are caused by the velocity fluctuations of the incident wind. In this sense, results obtained for BL2 edif. suggest instantaneous pressure measurements to evaluate wind loads. That is, the use of peak or RMS pressure values would be recommendable.

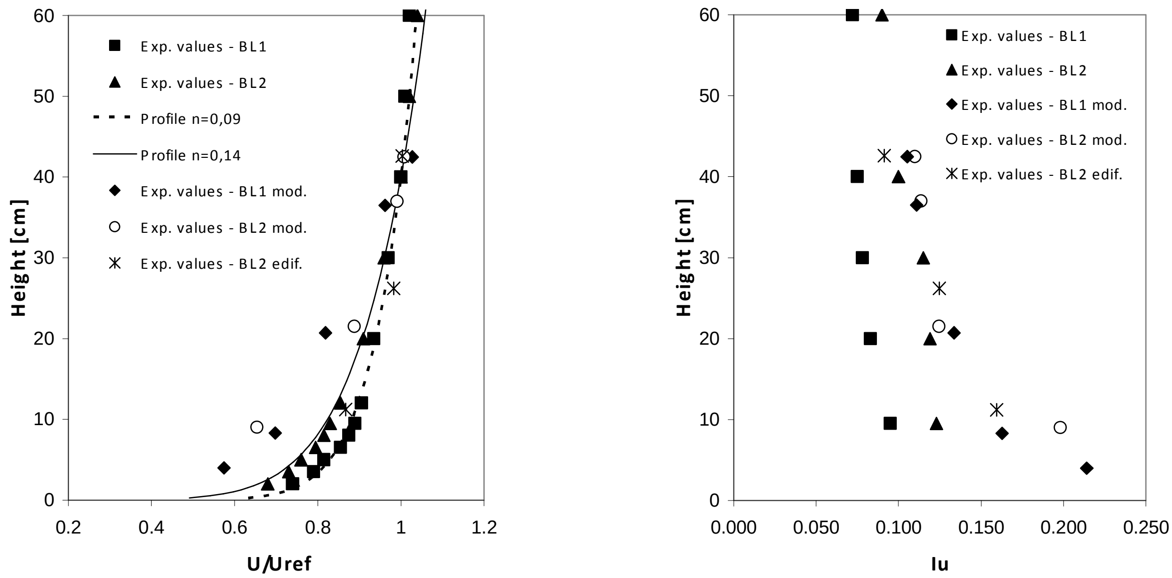

Figure 5. Mean velocity and turbulence intensity profiles.

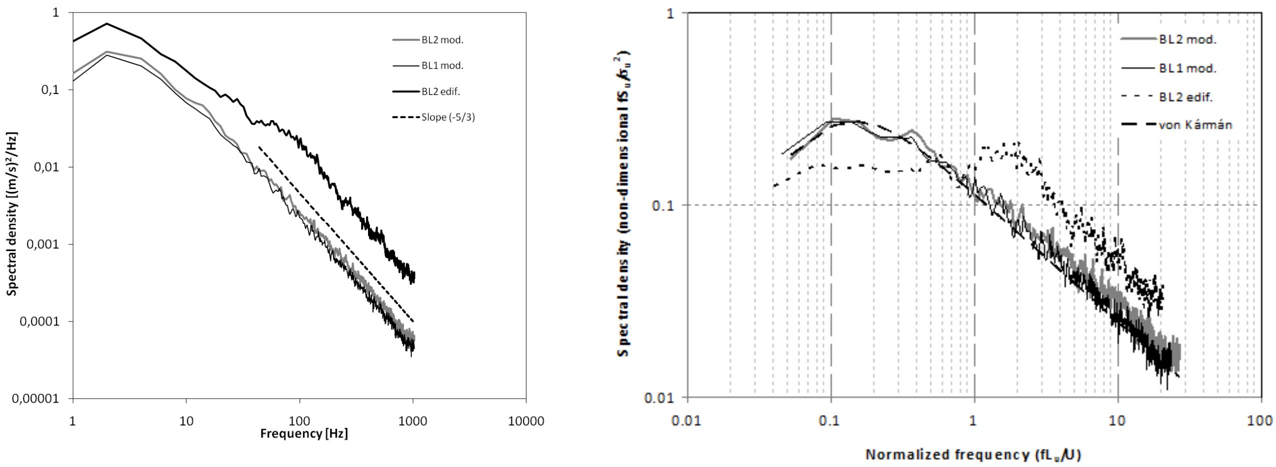

Figure 6. Turbulence and dimensionless spectra of modified incident wind.

6 CONCLUSIONS

The work presents the wind load evaluation procedure for a three tower complex by means of wind tunnel tests where interference effects caused by towers, topography and immediate environment were considered. Incident wind simulation and interference effects are very significant in the case of two different types of incident wind characteristics. A comparison of the results on the building complex and on the isolated tower was realized to verify this behavior. Modifications of mean velocity, turbulence intensity and energy fluctuation spectra suggest that fluctuation pressure analysis should be implemented to improve the local effect evaluation, as well as the study of pedestrian comfort should be realized in areas close to the surface.

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