EXPERIMENTAL STUDY OF THE AERODYNAMIC EFFECTS ON A MONUMENT

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Abstract - This paper presents an experimental study performed in a wind tunnel of a monumental reinforced concrete cross of 162 m height and a period of vibration close to 4s. Its flexibility and the geometrical shape of its elements (foot, cusp and crossbar) makes it highly susceptible to wind effects. Both the atmospheric boundary layer simulation and the cross model are described. For various angles of wind incidence, the bending and torsional moment coefficients measured at the base with a high-frequency balance device are presented; these coefficients could be useful in the revision of the structural design.

I. INTRODUCTION

The taller a structure is, generally, the more sensitive to wind effects. The interaction of wind flow and a structure is a somewhat complex phenomenon, in which the structure responds in various ways. In addition to longitudinal dynamic loads (in the direction of the wind), there may be transverse and torsional loads caused by an asymmetric distribution of wind pressures and vortex shedding. At an early stage, the design must consider these and other factors for the safety and stability of a structure. Knowing the values of the aerodynamic coefficients, distribution of pressures and critical speeds (through experimental simulations in wind tunnels or numerical simulations), allow adjusting the design of the structure: reinforcing, lightening its components or making changes in its geometric shape. On the other hand, one of the most and socially significant types of building structures are architectural monuments and sculptures. Generally, each of these works is unique as they have a complex geometry that requires greater attention when determining their design loads.The Cross Memorial (CM) is an initiative promoted by the people of the city of Monterrey and is an integral part of a community project that seeks the development of the inhabitants of a specific suburban neighborhood. The monument will have a height of 169 m, approximately, and will be built in the upper part of an extended long hill. For the objectives of this study, the topography of the hill is not considered but an urban terrain exposure type. With respect to the expected structural behavior of the CM, it can be said that it is a slender structure (period of vibrating close to 4s), so it is highly susceptible to wind effects due to its flexibility and geometric shape of its elements (foot, cusp and crossbar). Wind-produced instability phenomena generally include bending and twisting modes of vibrating which may cause vibration phenomena such as vortex sheddingat low wind speeds ([1]-[2]-[3]).Therefore, the purpose of this study is to determine experimentally, by means of the balance force method in a wind tunnel, the dimensionless coefficients of bending and torsion moments at the base of the CM under different angles of wind incidence. These global coefficients of forces are useful in the revision of structural design, especially in the evaluation of torsion, since in the current design codes the magnitude of the torsion to be considered for this type of special structure is not considered or is unknown. Finally, a discussion is made of the behavior of the structure under wind loads.

II. DESCRIPTION OF THE STRUCTURE

The CM is a structure with rectangular sections of reinforced concrete, both at the footing, as well as the top and crossbar. The foothas a height of 129m and the cusp of 40m for a total height of the post of 169m. The cross section of the stick is hollow and has variable section with height, where the base is 12m x 12m and is reduced to a section of 7m x 7m at the maximum height, see Fig. 1. Also, the cross sections of the arms are rectangular and hollow, reducing towards the free ends from a section of 8m x 8.4m to a section of 7m x 7.3m. Fig. 2 shows in elevation the overall dimensions of the CM. At the base of the CM there is a basement/footing of approximately 9m in height, with a pyramidal trunk geometry of 60m x 40m at the base and 24m x 24m at the top.

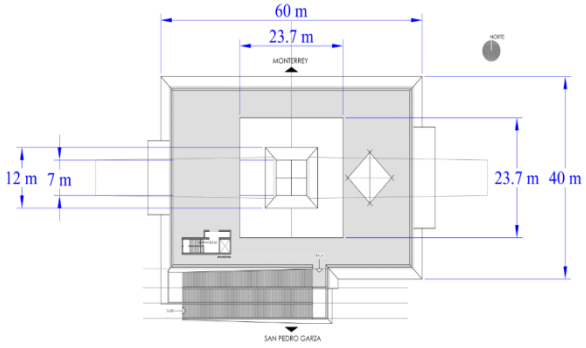


Fig. 1 General dimensions of the CM, plan view.

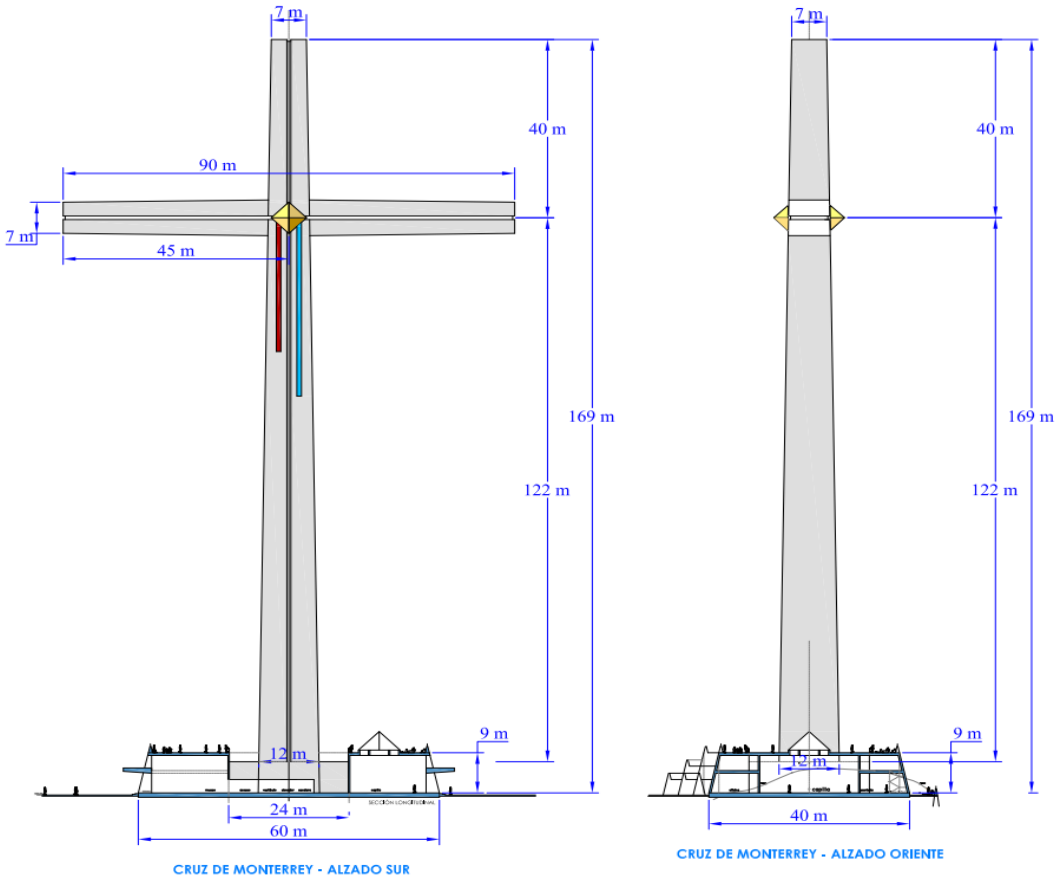


Fig. 2 General dimensions of the CM, elevation view

III. ON-SITE WIND CHARACTERIZATION

An important aspect in the studies of structures under wind effects, is the determination of the conditions or wind climate at the site of interest. For this purpose, records were collected from three weather stations near the site, and whose locations are shown in Fig. 3, being the "Monterrey N. L" station the nearest to the CM site.

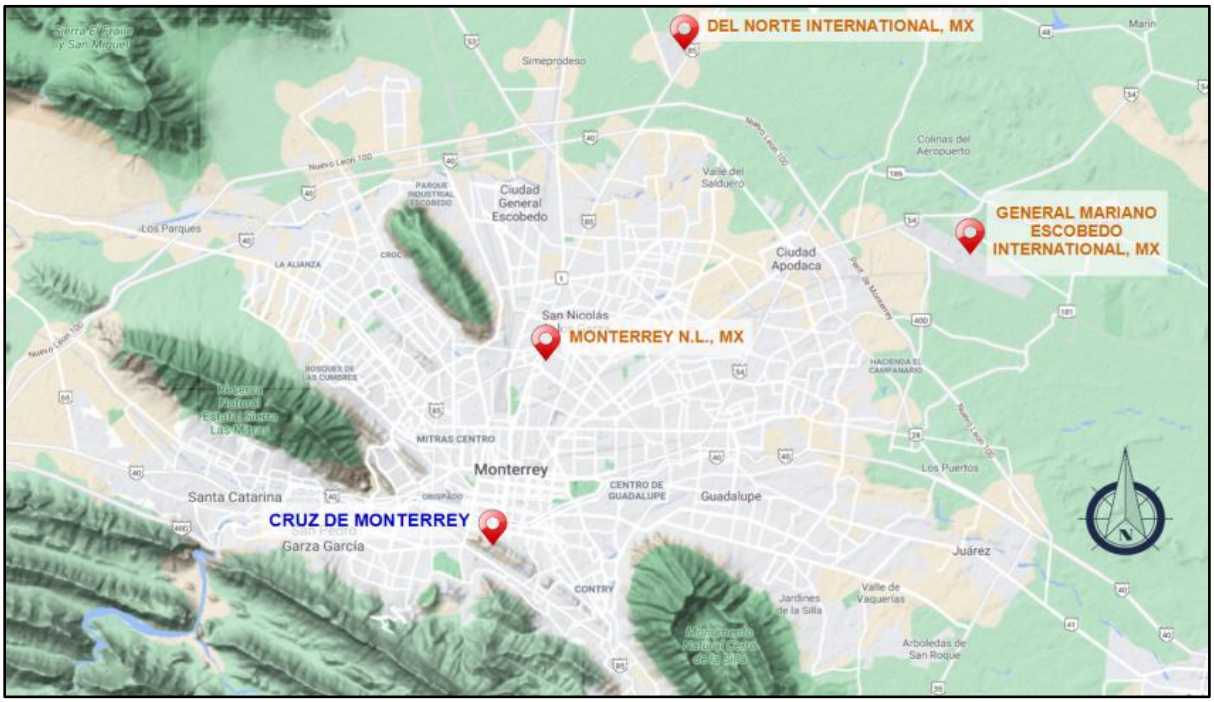


Fig. 3 Location of weather stations

In order to compare with the provisions of the Wind Manual for Design of Civil Works[4], data of each meteorological station were processed in accordance with the recommendations of the World Meteorological Organization [5], such that records were consistent with the topography of a open terrain, at a height of 10 m above ground level and with an averaging time of 3s. Once the information was corrected for each station, an analysis of extreme values was elaborated based on the statistical analysis of annual maximum values, and with the adjustment to a Gumbel probability density distribution it was possible to calculate the regional velocities for return periods of 10, 50 and 200 years. Figs.4 to 6 show the maximum annual wind speed values for each season analyzed, and Table 1 presents a summary of the estimated wind speeds for the return periods of 10, 50 and 200 years.It is observed in Table 1 that wind speeds obtained with the statistical model are comparable with those of [5]. Therefore, and in accordance with the importance of the structure, it is proposed to use a value close to 170 km/h (47m/s), as wind design speed that corresponds to a return period of 200 years and an averaging time of 3s. Thus, for a rough terrain (site terrain) and an averaging time of 1 hour, the proposed speed is 105 km/h (29 m/s) at a height of 10 m above the ground level.

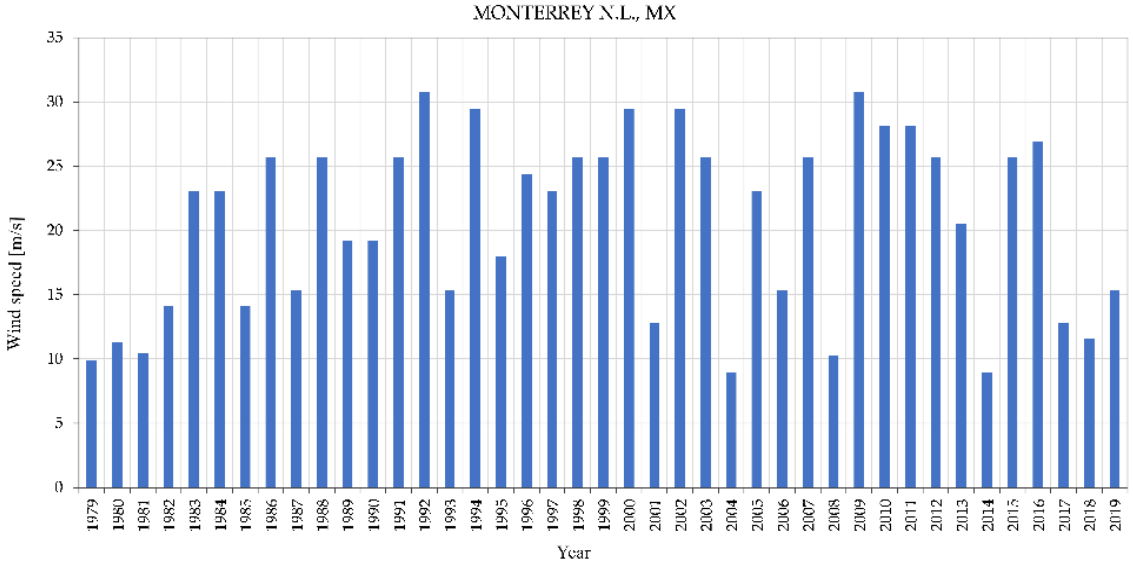


Fig. 4 Maximum annual wind speeds, Monterrey N.L. station

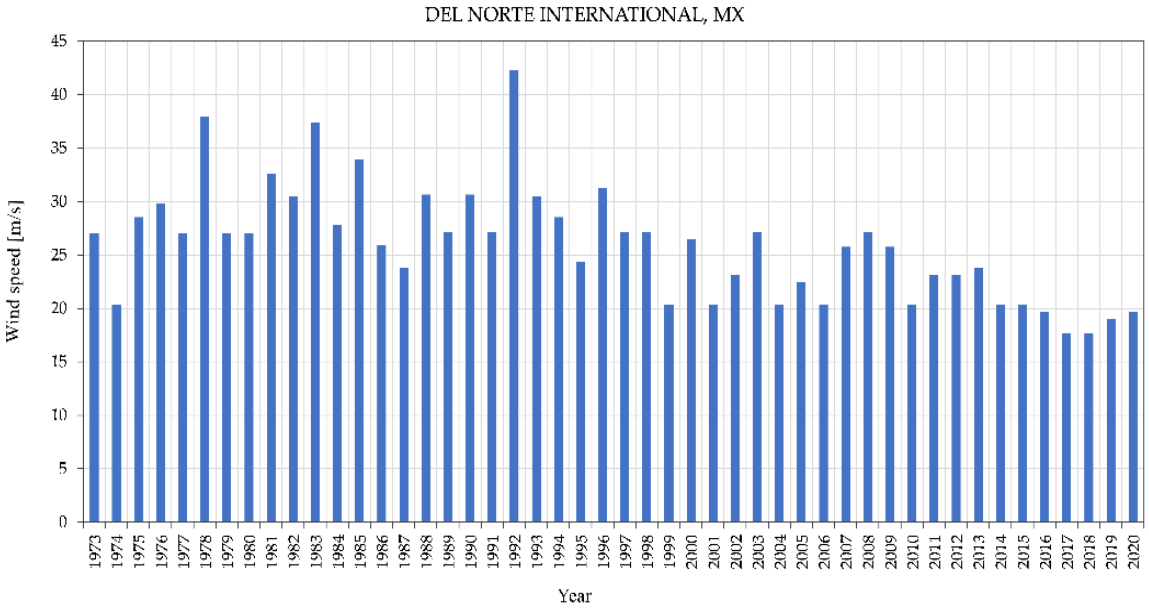


Fig. 5 Annual maximum wind speeds, Del Norte Int.

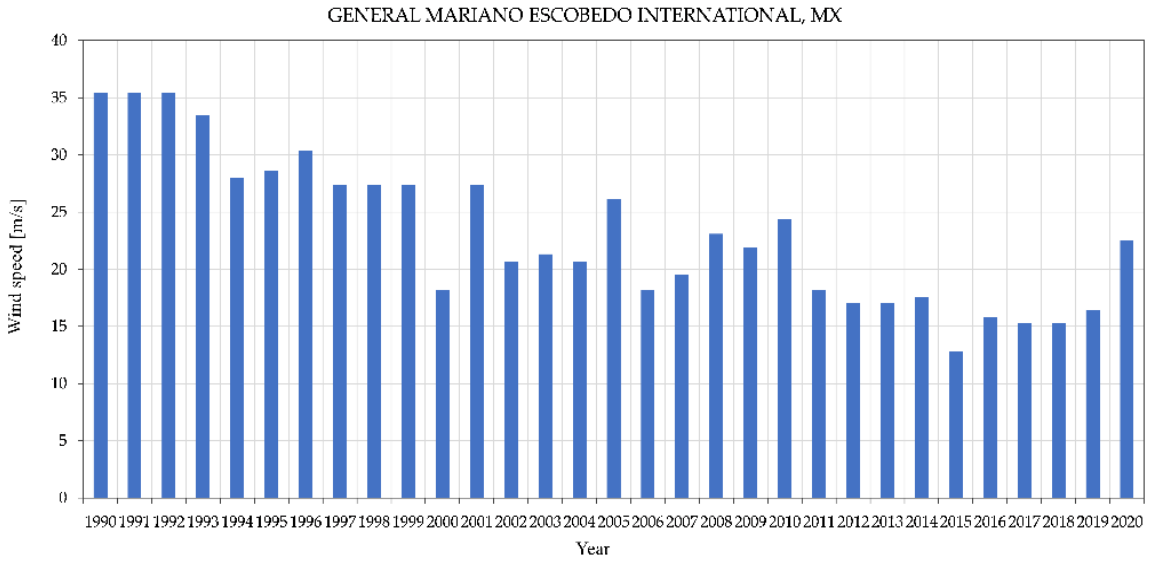


Fig. 6 Maximum annual wind speeds, station Gral. Mariano Escobedo Int.

Return period (years)	Monterrey N.L. (km/h)	Del Norte International (km/h)	Gral. Mariano Escobedo Int. (km/h)	MOC-CFE (2019) (km/h)
10	107	114	110	123
50	139	144	144	143
200	167	170	173	160

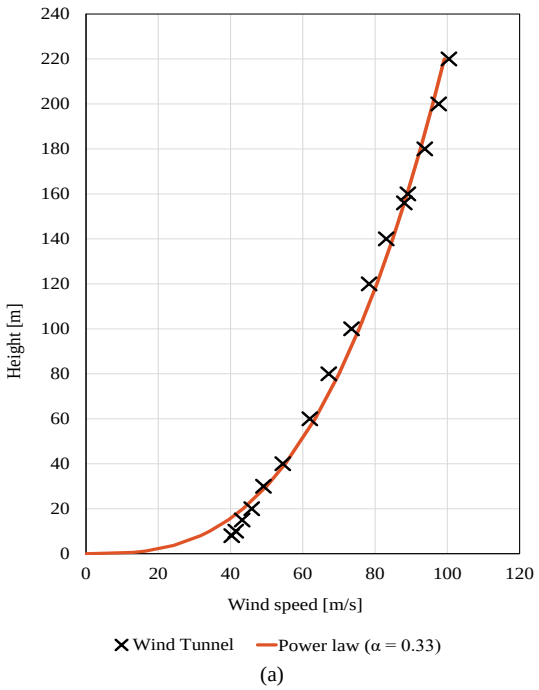
Table 1 Estimated wind speeds for each station with the statistical model of extremes and the MOC-CFE (terrain open and averaged of 3s).

IV. WIND TUNNEL STUDY

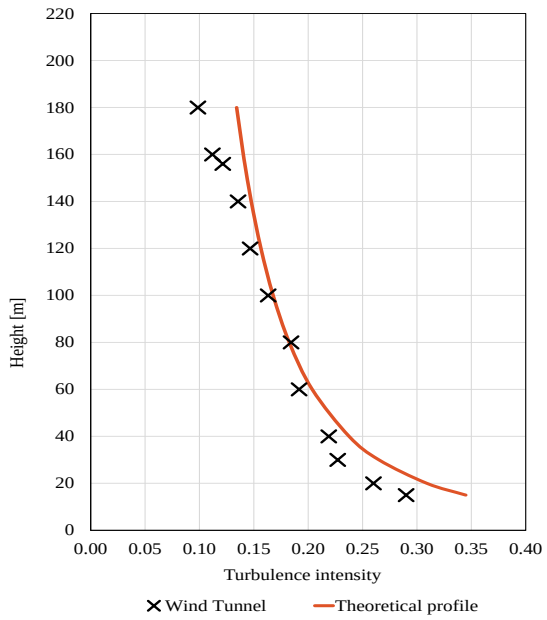
For the simulation in the wind tunnel, a geometric scale of 1:200 and a wind speed scale of 1:14.14 (Froude scale) were used; passive devices were used as well. This technique consists of the placement of roughness on the tunnel floor along with turbulence generators that can be bars or vertical elements (for example, triangular or elliptical wedges), or barriers on the floor that can be of constant height or toothed. Since the late 60s, several authors (for example,[6]-[7]-[8]-[9]-[10]-[11]- [12]-[13]; and others) have used various passive simulator devices in order to create more realistic medium wind and turbulence profiles. [7] and [13], using roughness, barrier and mixing devices, developed simulation techniques particularly suited to reproduce a neutrally stable boundary layer.In this study, passive devices were used in the wind tunnel to generate an atmospheric boundary layer corresponding to a type of urban terrain, that is, with an α parameter of 0.33 according to the power law, which describes the variation of the average wind with the height as

$$\bar{\mathbf{u}}(\mathbf{z}) = \mathbf{u}_{\mathbf{ref}} \left(\frac{\mathbf{z}}{\mathbf{z}_{\mathbf{ref}}}\right)^{\boldsymbol{\alpha}} \qquad (1)$$

where u_ref is a reference velocity at a given height z_ref and α is a shape parameter that depends on the type of terrain. Fig. 7 shows the simulated mean wind speed and turbulence intensity profiles in the wind tunnel (on a natural scale). Fig. 8 shows the CM model and the passive simulators in the wind tunnel test section.



(a)



(b)

Fig. 7 Simulated wind profiles in wind tunnel: (a) Meanspeed and (b) Turbulence intensity

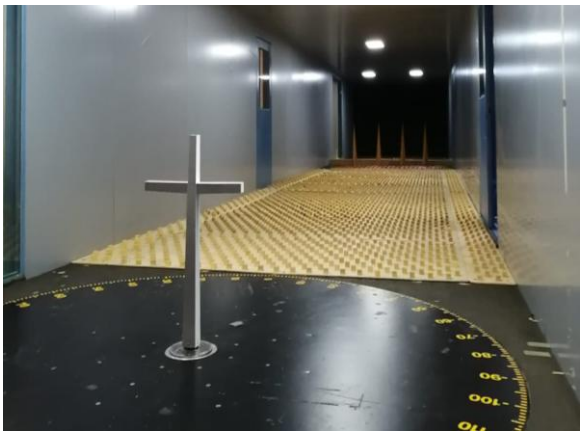


Fig. 8 View of the CM model and passive generators in the wind tunnel test area

V. HIGH FREQUENCY FORCE BALANCE (HFFB) METHOD

To predict wind loads and the response of buildings in a wind tunnel, it is generally considered appropriate to use a rigid model with the geometric shape of the actual structure. The two main measurement methods, which use rigid models, are high-frequency pressure integration (HFPI) and high-frequency force balance (HFFB) ([3]-[14]-[15]).The latter uses a high-frequency balance of force to measure wind-induced global forces at the base of a rigid model. These forces are related to pressure distributions along the height of the structure. The model must be light and rigid so that the measurements reflect only the fluctuations of the applied wind load and not the vibrations of the model itself. The HFFB method allows to build and test a simple model (unlike an aeroelastic model) to analyze various sets of dynamic properties (for example, mass, stiffness and damping) without having to modify the model and repeat the tests in the wind tunnel. For this reason, the HFFB method has proven to be a cost-effective wind tunnel tool. For a building with a linear modal shape, it is possible to use the moments at the base directly to represent the generalized forces induced by the wind, and which are related to the distribution of pressure along the height of the building. For the general case of nonlinear modal forms, several refinements are possible, both in the assembly of the physical test and in the analysis. For the study of the CM, the HFFB method was used to determine the shear forces and the torsional and flexural moments at the base of a model simulating different angles of wind incidence (in a range of 0° to 180°). Global forces are presented in the form of average dimensionless coefficients, given by:

$$\mathbf{CM_y} = \frac{\mathbf{M_y}}{\mathbf{0.5\rho U_H^2 H^2 B}} \quad (2)$$

$$\mathbf{CM_x} = \frac{\mathbf{M_x}}{\mathbf{0.5\rho U_H^2 H^2 B}} \quad (3)$$

$$\mathbf{CM_z} = \frac{\mathbf{M_z}}{\mathbf{0.5\rho U_H^2 H^2 B}} \quad (4)$$

where M_y, M_x and M_z are the bending and torsional moments, respectively, ρ is the air density ~0.92kg/m3, U_H is the reference velocity (measured at cross height H ~81cm) and B is the width of the cross base ~6cm. Fig. 9 shows the 1:200 scale CM model mounted on the high-frequency force sensor or transducer [16]. The model was manufactured with 3mm extruded PVC plates in order to make it light and rigid. Figs. 10 and 11 present the reference system of the forces and the wind directions, respectively.





Fig. 9cm rigid Model Mounted on the Transducer or High Frequency Balance

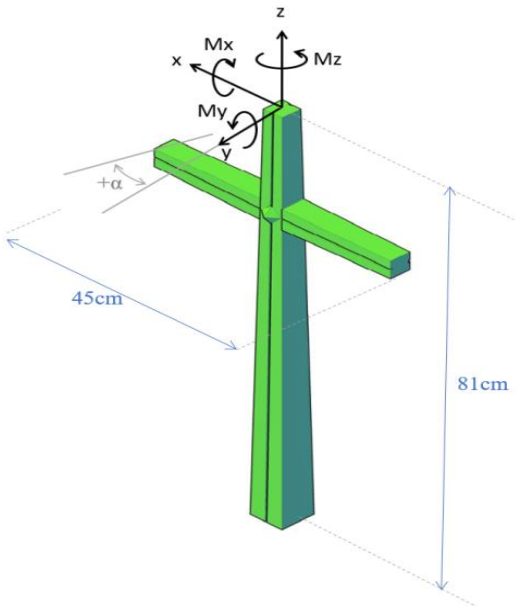


Fig. 10 CM Model: Dimensions and coordinate system

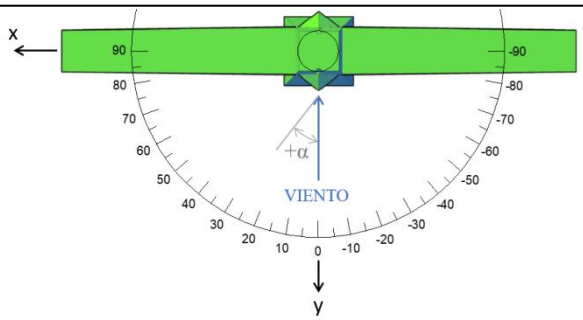


Fig. 11 CM Model: wind incidence direction

VI. WIND TUNNEL TEST RESULTS

Fig. 12 shows the bending moment coefficient in the X direction for each angle of incidence. It can be observed that the flexion is maximum for 0° and 180°, as expected, since in these directions we have the largest area exposed to the wind and the axes of the structure are aligned to the direction of the flow. A symmetry can also be observed in the results with respect to the angle of 90° due to the symmetry of the structure. Fig. 13 shows the bending moment coefficient in the Y direction, also for each angle of incidence.

As expected, a maximum is observed at the angle of 90° because the axis of the structure is aligned with the airflow. Like the previous figure, a symmetry with respect to the angle of 90° can be observed because the structure is symmetrical. Fig. 14 shows the torque moment coefficient for each angle of incidence. It is observed that the maximum torque occurs when the wind is incident at angles of 25° to 30°, approximately.

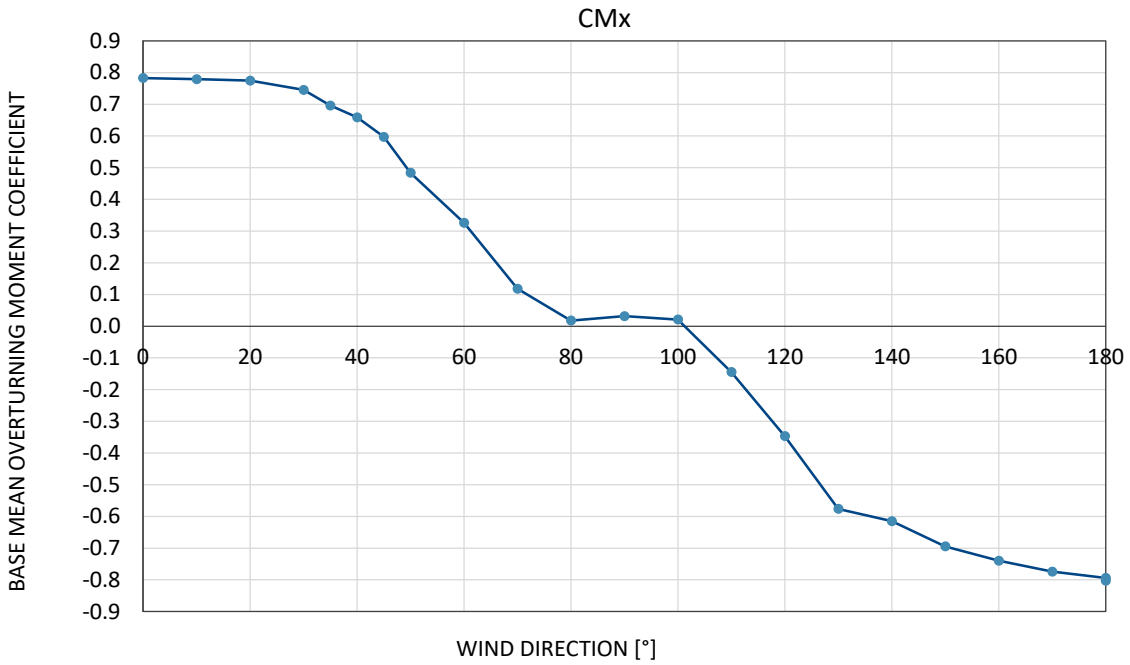


Fig. 12 Mean over turning moment coefficients in direction X, for each angle of wind incidence

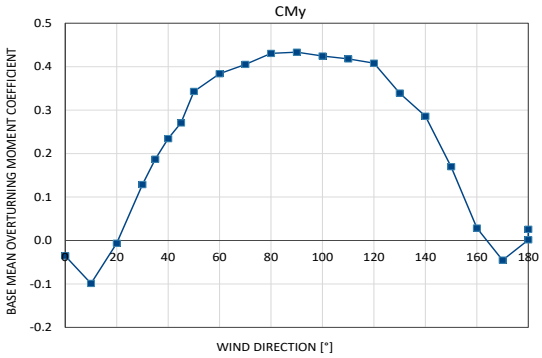


Fig. 13 Mean overturning moment coefficients in the Y direction, for each angle of wind incidence

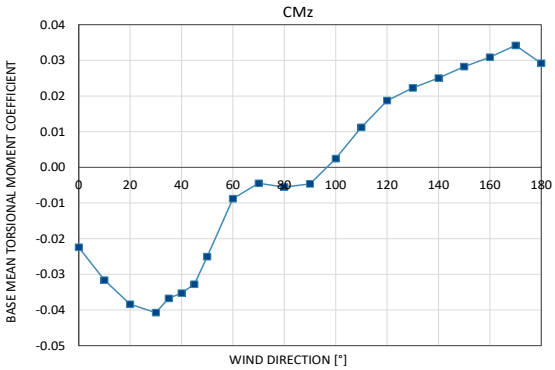


Fig. 14 Mean torsional coefficients in the Z direction, for each angle of wind incidence

VII. CONCLUSION

To ensure the safety and stability of a structure sensitive to wind effects, it is necessary to know at an early design stage the longitudinal, transverse and torsional loads caused by an asymmetric distribution of turbulent wind pressures, particularly if it is a special structure such as an architectural monument or sculpture due to its complex geometry that requires more careful attention in determining its design loads. This paper is focused on estimating the aerodynamic wind loads on a cross-shaped monument based on wind tunnel tests using the HFFB method. For this purpose, the characteristics of an atmospheric boundary layer of an urban terrain type were simulated in the wind tunnel. The moment coefficients of bending and torsion at the base of the structure were determined under different incidences of turbulent wind. These coefficients are useful in the revision of the structural system resistant to wind loads, especially for the revision of the torsional response. This paper shows that the HFFB method has the advantage that the total load on complex geometries can be estimated using a rigid and simple model.

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