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WIND INDUCED DYNAMICS OF A PRISMATIC SLENDER BUILDING WITH 1:3 RECTANGULAR SECTION

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1 INTRODUCTION

Developments in structural materials and design technology in civil engineering have led to designs that satisfy strength requirements but are often very flexible. These flexibilities lead to unfavorable dynamic responses that may affect on the structural serviceability and occupants comfort when the structure is subjected to dynamic loads like strong winds and earth-quakes. Traditionally, responses of these structures can be evaluated analytically using some codes and formulas (for example [5]). However, these standards provide little guidance for the critical across-wind and torsional responses. Wind tunnel measurements and finite element modeling (FEM) of the structures are an effective alternative for determining these responses.

This paper presents a detailed study to investigate the aerodynamics and aeroelastic behavior of a slender tall building with $B/D = 2.56$ rectangular section (B: chord length, D: thickness). The building represents a rectangular prism which is a common shape of buildings, bridge decks and bridge towers. Both 2D sectional and 3D rigid models are used for wind loads determination. The 2D model was used to further the understanding of the aeroelastic behavior of the prism. In this study, it has been shown that the effect of turbulence and the wind attack angle is a key point that affects very much on both displacement and acceleration responses of the tower. The main objective of the present study is to further the understanding of wind effects on tall buildings and the behavior of high-rise structures under wind conditions by means of wind tunnel tests in order to apply such knowledge to design.

2 AERODYNAMICS OF THE RECTANGULAR PRISM

In the year 1934, Tiejens and Prandtl provided the definition of a “bluff-body” [1]. The statement provided that if a bluff-body has sharp edges, for which the separation point is defined at the leading edge, there are no Reynolds number effects on the aerodynamics of the body.

Given Tiejens and Prandtl assumption, the impossibility of doing tests at Reynolds numbers equal to full-size, tests at low Reynolds can reduce the cost of wind tunnel operation. Reynolds

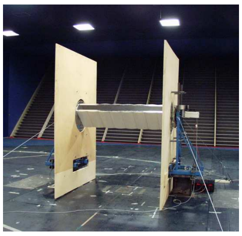

Figure 1: The sectional model on the dynamometric balance.

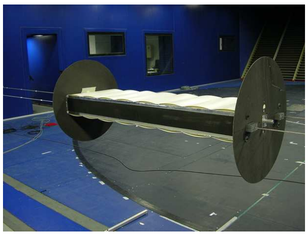

Figure 2: The sectional model elastically suspended.

Figure 3: The $3D$ model in smooth-flow.

number similitude was many times "relaxed" in the past for doing investigations on civil structures at low Reynolds ($Re \cong 10^3 - 10^4$). However, recent studies have disputed the assumption made by Tiejens and Prandtl. Simiu and Scanlan [2] collected data from different sources regarding the drag coefficient, C_D, versus the elongation ratio B/D of rectangular prisms with sharp edges. They showed that if the prism has a $4 < B/D < 1$ the values of C_D are unique. On the other hand, there is a grey zone for the elongation ratios $2 < B/D < 4$ where the C_D shows some dispersions which gives an indication Reynolds number sensitivity.

The behavior of prisms in this B/D range must be considered in the design stage as their aerodynamics is strongly affected by flow conditions [3]. Among all the parameters, the lift coefficient, C_L, is the most sensitive parameter to the angle of attack and the level of turbulence in the incoming flow.

3 WIND TUNNEL TESTS

The experiment was carried out in the Boundary Layer Test Section of the Wind Tunnel at Politecnico di Milano, that is $4m$ high, $14m$ wide and $36m$ length. The tower considered in this study represents a common high-rise building with geometry very similar to a regular rectangular prism. The outer dimensions of the full-scale building are $217m$ height, $57.6m$ width, and $24m$ depth.

A 2D sectional and 3D rigid models were used for wind tunnel tests. The sectional model was used to evaluate both the static and the aeroelastic behavior under two dimensional flow. For the first analysis it was hanged by a multicomponent load cell at each side; the cells were mounted on a mechanism driven by a motor allowing $360deg$ rotation of the entire model as shown on Fig. 1. In this manner it was possible to change the angle of attack and to measure for every configuration the drag, lift, and moment force components. Aeroelastic behavior was studied by elastically supporting the 2D model to the walls of the test section, as indicated in Fig. 2. In order to obtain surface pressure measurements, that is necessary for predicting wind loads for the FEM model, a rigid 3D model of the tower was used. The 3D model is indicated in Fig. 3.

4 EXPERIMENTAL RESULTS

The first results was obtained using the rigidly supported sectional model tested in low-turbulence flow with an angle of attack $\alpha = \pm 90deg$ (Fig. 1).

Figure 5 gives the trend of the lift coefficient, C_L, versus the wind attack angle, α. It is shown on the figure that there is a sharp change in the C_L values from positive to negative over a small variations in the wind attack angle ($-4 < \alpha < 4$). Such sharp sudden changes may cause galloping dynamic instability which should be considered for the design of such structures [4]). However, at higher turbulence intensities, this phenomenon tends to disappear (detailed study

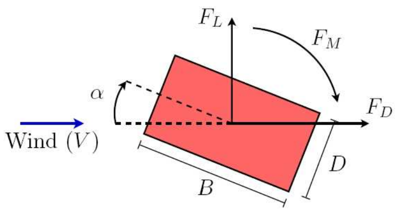

Figure 4: The symbols used for showing the results.

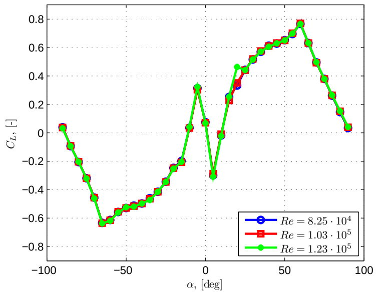

Figure 5: Lift coefficient, C_L versus α for 2D model.

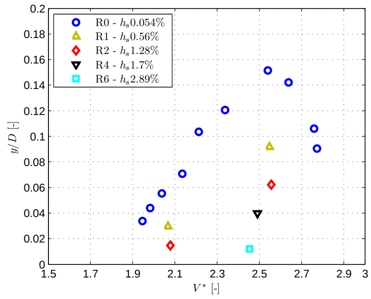

Figure 6: Steady-state across-wind response y/D, $\alpha = 0deg$.

about this behavior is present in [6]).

In the second stage, the 2D sectional model was elastically suspended in order to evaluate the energy introduced by the wind in the two regions with C_L negative slope and the structural damping, h_s, necessary to control this potential instability. The test underline the angle of attack $\alpha = 0deg$ as the most critical for the galloping instability of the section, in a range of reduced velocity $2 < V^* < 2.8$ ($V^* = V/(f_s \cdot B)$. Figure 6 shows the displacements y/D at $\alpha = 0deg$ in this range of velocity (y: across-wind displacements). This response tends to increase with the increase of V^*, again it decreases with the increase of the wind speed. It is evident that this phenomenon is due to the effect of vortex shedding. In order to control this instability, the damping was increased until the value $h_s = 2.7\%$. This amount of damping could be used (by Scruton Number similitude) as an indicator for the minimum required structural damping to avoid such instability produced by vortex shedding under these wind conditions.

5 WIND RESPONSE OF THE FULL SCALE TOWER

Displacement and acceleration responses of the tower can be evaluated numerically for occupants comfort reasons. FEM of the full-scale building tower with the first six modes is shown on Fig. 7. Equations of motion governing the behavior of the structure under wind loads are:

$$\mathbf{M\ddot{X}} + \mathbf{C\dot{X}} + \mathbf{KX} = \mathbf{F(t)} \tag{1}$$

where $\mathbf{X} = [\ \mathbf{x} \quad \mathbf{y} \quad \mathbf{z}\ ]^{\mathbf{T}}$ is a $(3n \times 1)$ vector and n is the number of nodes while $\mathbf{x}$, $\mathbf{y}$, and $\mathbf{z}$ are vectors of nodal displacements in x, y, and z directions respectively. $\mathbf{F(t)} = [\mathbf{F_x(t)}\ \mathbf{F_y(t)}\ \mathbf{F_z(t)}]$, in which $\mathbf{F_x(t)}$, $\mathbf{F_y(t)}$, and $\mathbf{F_z(t)}$ are $(n \times 1)$ vectors of nodal external forces acting in x, y, and z directions respectively. Time history of the pressure forces acting at each external surface node is obtained by integrating wind pressure over the corresponding effective surface area to give the three components of the force. However, forces acting on the internal nodes are obviously equal to zero. Using the first six modes given from the FEM, with the next transformation

$$\mathbf{X} = \mathbf{\Phi q} \tag{2}$$

where $\mathbf{\Phi}$ is $(3n \times 6)$ matrix of eigenvectors and $\mathbf{q}$ is (6×1) vector of generalized displacements. Substituting by into and premultiplying by $\mathbf{\Phi^T}$, one obtain

$$\mathbf{\Phi^T M \Phi \ddot{q}} + \mathbf{\Phi^T C \Phi \dot{q}} + \mathbf{\Phi^T K \Phi q} = \mathbf{\Phi^T F(t)} \tag{3}$$

By assuming the damping matrix, $\mathbf{C}$, to be a proportional damping, the above equations results into six uncoupled equations. Simulink is used for the numerical solution of these equations.

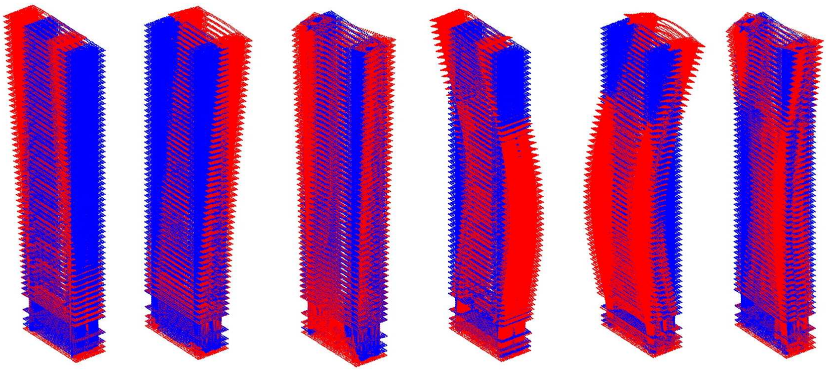

Figure 7: FEM (2644 nodes), the first six natural frequencies are: 0.145, 0.153, 0.255, 0.451, 0.627, and 0.881 Hz respectively.

6 CONCLUSIONS

2D sectional model both rigidly and elastically supported was used to further the under standing of the wind flow around a tall building with the outer shape that is close to a rectangular prism. The 2D rigid sectional model indicated sensitivity to galloping instability at low turbulence. The 2D aeroelastic model is used to predict the minimum structural damping that should be used to avoid such instabilities. Aerodynamic loads acting on 3D rigid model of the prism based on an experimental approach using the Boundary Layer wind tunnel test section are utilized with a FEM of the building to predict its dynamic responses under wind loads. This approach has the advantage of combining along-wind, across-wind and torsional responses altogether. The technique used allows for considering higher modes of vibration. The effect of the wind incident angle is very important as the highest values of the displacement and acceleration responses may occur at angles rather than $0deg$ or $90deg$ (at which it is difficult to calculate such responses using traditional codes). However, the procedure developed permits the displacement and acceleration levels of tall buildings to be estimated at the preliminary design stages.

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