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Wind loads and vortex shedding analysis on the effects of the porosity on a high slender tower

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ABSTRACT

This paper presents a detailed experimental study finalized to evaluate the effect of the porosity on the dynamic behavior of a civil structure. The structure considered is an original architectonic complement erected on top of a new tall building. Its cladding, made of perforated steel plates, forms an intricate three-dimensional spiral characterized by five different diameters which decrease along the height of the structure.

The main objective of the tests is to evaluate the effect of the porosity of the external perforated panels, comparing the dynamic response obtained from the in-service configuration (permeable panels) and the results obtained with non-porous panels. This comparison showed that the porosity of the panels is of great importance and can completely change the dynamic behavior of the whole spire. This study has a realistic relevance as the structure could be subjected to atmospheric icing which could block up the panels and change their porosity.

Wind tunnel tests were performed on 1:50 scaled rigid and aeroelastic models in smooth and turbulent flow conditions. The effect of the porosity was estimated comparing wind actions in terms of global wind loads at the base of the spire, local wind load on a panel and the structure's proneness to vortex induced vibrations. The analysis carried out highlights on the great influence of porosity in the dynamic response of the structure, mainly in relation to vortex shedding induced vibrations, which were almost absent with porous panels, but very strong in the case of non-porous panels.

1. Introduction

The tower, or spire, investigated in this study is included in one of the largest projects underway in Milan for the redevelopment of an area of abandoned railyards adjacent to the Garibaldi train station. The spire, which is erected on top of a 139 m tall building, consists of a supporting lattice framework structure 80.44 m high, clad with perforated steel and glass plates, Fig. 1. Considering the height of the building, the spire's maximum elevation from the ground is 220 m. The external cladding is not regular, but forms an intricate three-dimensional spiral characterized by five different diameters which decrease along the height of the structure. Only a small area of the panels is made of glass (a portion at the bottom of the spire), while most of them are perforated steel plates.

The structural response of the tower is governed by the internal lattice framework. A review of the literature indicates that much research has been conducted into the aerodynamic behavior of lattice tower structures, showing that their dynamic response is highly three dimensional and not easy to predict (Zou et al., 2008). In particular oscillation amplitudes of displacements and accelerations in the cross-wind direction could be as great as or even larger than those in the along-wind direction (Glanville and Kwok, 1995; Ballio et al., 1992). In addition, the tower considered in this research has a three dimensional cladding which, even if not regular and porous, could lead to wind induced vibrations and fatigue damage (Repetto and Solari, 2010; Irwin et al., 2008).

The present study is focused on the influence of porosity. In fact the flow through the panels modifies the pressure distribution and, as a result, the wind loads and the dynamic response of the whole structure. The realistic relevance of this analysis is that, owing to its position, the spire can be subjected to atmospheric icing which could make parts of the external panels non-porous (Fikke et al., 2006), causing possible severe damage to the structure (Sundin and Makkonen, 1998; Mulherin, 1996).

Not many experimental data are available on wind interaction with permeable civil structures. Most of them regard wind loads on structures such as greenhouses, panels or roofs (Briassoulis et al., 2010; Robertson et al., 2002; Letchford, 2001; Letchford et al., 2000; Richards and Robinson, 1999; Cheung and Melbourne, 1988); these results show that the wind loads on perforated structures are generally lower than those on the same non-porous surfaces. More

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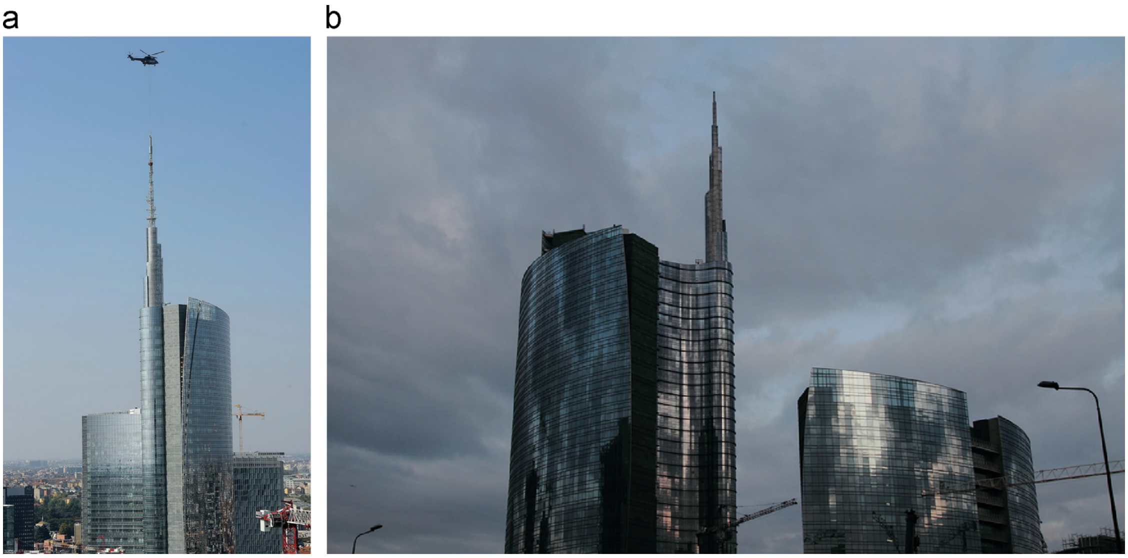

Fig. 1. The 139 m tall spire object of this study. (a) The bold final stage of its erection. (b) The final structure.

systematic studies regard flow around porous cylinders (Fransson et al., 2004; Mathelin et al., 2001): in particular they show how vortex shedding can be reduced or suppressed by manipulating the flow around the cylinder through the application of suction or blowing.

The aim of the tests was to evaluate the effects of the porosity of the panels of this very particular spiral-shape slender structure on the dynamic response. The analysis was carried out comparing wind actions in terms of global wind loads at the base of the spire, local wind load on a panel and the structure's proneness to vortex induced vibrations.

2. Wind tunnel tests

Wind tunnel tests were performed at the 1.5 MW closed-circuit wind tunnel of the Politecnico di Milano, Italy. The large dimensions of the boundary layer test section (4 m high, 14 m wide and 36 m long) permitted a very large geometric scale $\lambda_L = 1/50$ ($\lambda = model/real$), while maintaining lower blockage effects. Large scale testing is advantageous in the general context of wind engineering tools for the following reasons: adverse scaling effects (such as those due to violation of Reynolds number similitude) can be reduced, and some building' external geometric details are too small to be reproduced in small-scale tests. This means that as far as concerns vortex shedding the hypothesis is that the wind tunnel tests performed in the subcritical region are more conservative than the real full scale structure condition. On the other hand, the full scale structure will be in the post-critical region.

In order to consider possible effects due to the singular position of the spire, the model was placed at a height of 0.7 m from the floor level, over a base simulating the upper part of the building. The first natural frequencies of the building (0.238 Hz 0.254 Hz and 0.321 Hz, respectively the first two flexural and the first torsional modes) are low compared to the lower frequencies of the spire so that the modes between the building and the spire are uncoupled. For this reason the building was not dynamically considered in the present study and only its external shape was reproduced, Fig. 2(a).

To verify the sensitivity to the Reynolds number, some tests were repeated changing the wind speed. The analysis was carried out comparing the overall wind load at the base of the spire in terms of drag and lift coefficients and on a pressure tap in terms of pressure coefficient. These coefficients were stable in the range of wind speeds tested.

2.1. Flow configuration

Wind tunnel tests were performed in smooth and turbulent flow, respectively called SF and TF below. In the first condition (SF) the wind speed is constant along the height of the test section and the turbulence is lower than 2%, while in turbulent flow the vertical velocity and turbulence profile were simulated by means of spire and roughness elements positioned at the entrance of the test section. The turbulent flow profiles are similar to those typical of an area covered with buildings, but they do not follow a precise target since the main goal of the work was the comparison between the two conditions of porosity on dynamic behavior, in the same flow conditions. Fig. 3 shows the characteristic of the flow in the test section in terms of mean wind speed (Fig. 3(a)) and turbulence intensity profile (Fig. 3(b)). Pressure measurements were carried out in turbulent flow, while smooth flow is the worst condition considering vortex shedding excitation and the best way to test in order to discover possible aerodynamic instability.

2.2. Rigid model

The rigid model of the spire, Fig. 2(a), allowed the measurement of the global wind loads, in terms of forces and moments at its base, and the pressure on some external panels. To ensure high quality measurements the model was made as stiff as possible, to ensure high structural frequencies and a quasi-static behavior under wind loads. It is a static model which reproduces the geometry of the full-scale structure in terms of aerodynamic surfaces and details. For this reason great care was taken in scaling the external surface geometry and porosity, while the internal lattice framework was not reproduced as it was the real structure.

2.3. Aeroelastic model

The vortex shedding investigation was carried out using the aeroelastic model, Fig. 2(b). The design and making of the aeroelastic model were on the basis of the modal parameters obtained from a finite element model of the real structure. Froude similitude criteria were adopted for scale reduction, leading to a factor $\lambda_F = 7$ for frequency scaling ($\lambda = model/real$) and to a factor