Engineering Structures 68 (2014) 24–32

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Wind loads on a high slender tower: Numerical and experimental comparison

M. Belloli, L. Rosa *, A. Zasso

Politecnico di Milano, Department of Mechanical Engineering, via G.La Masa 1, 20156 Milan, Italy

ARTICLE INFO

Article history:
Received 9 August 2013
Revised 18 February 2014
Accepted 26 February 2014
Available online 25 March 2014

Keywords:
Wind tunnel tests
Wind loads
Aeroelastic model
Rigid model
High slender tower
Structural dynamics
Codes
Porous surface

ABSTRACT

This paper compares the wind loads measured experimentally in wind tunnel tests and those predicted by Eurocode on a high slender tower with a porous external surface forming an intricate three-dimensional spiral. In the experimental tests a rigid and an aeroelastic model of the tower were tested in low and high turbulent flow conditions. The aim of the wind tunnel tests was to evaluate the wind actions at the base of the structure and, comparing the results from the two models, to verify the presence of possible aerodynamic effects, such as force fields due to fluid–structure interaction. The along wind dynamic response of the tower calculated experimentally was then compared with the results obtained numerically using Eurocode, under the hypothesis of negligible aeroelastic effects. It was found that Eurocode may underestimate the effect of certain exposures. Aerodynamic damping was also evaluated.

1. Introduction

Wind turbulence causes a fluctuating load on a structure which, most probably will start to vibrate. If these vibrations are expected to be significant, the dynamic response must be considered in the design stage. This response can be calculated using two different approaches: numerically, using the codes, or experimentally with wind tunnel tests on an aeroelastic model of the structure.

This paper deals with a very particular and slender tower, or spire, part of one of the largest projects underway in Milan to redevelop an area of abandoned railway yards near the Garibaldi station.

The spire is built on the top of a 139 m tall building and consists of a supporting lattice framework structure 80.44 m high, covered 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 covering is not regular. It forms an intricate three-dimensional spiral with five different diameters decreasing along the height of the structure.

Only one small area of the spire is made by glass (a portion at the bottom of the structure), while most of the panels are perforated steel plates. The structural response of the tower is governed by the lattice framework. A review of the literature shows that extensive research have been carried out into the responses of lattice tower structures, and it shows that their behavior is highly three-dimensional and not easy to predict, Zou et al. [22]. In addition, the circular external shape of the spire, though if not regular, could lead to wind induced vibrations and fatigue damages, Argentini et al. [2]; Repetto and Solari [15]; Irwin et al. [12].

The aim of the wind tunnel tests was to evaluate the wind actions in terms of wind loads at the base of the spire and its the maximum accelerations. Low and high turbulent flow conditions were tested on rigid and aeroelastic models of the spire. The results collected from these two different models formed the reference database for the main purpose of this paper: to highlight the analogies and differences among the base forces, measured on the two models used, also taking into account inertial effects. In other words, the main goal is to verify the presence of possible aerodynamic effects, such as force fields due to fluid–structure interaction. If no feedback is observed in the aerodynamic loads on the structural motion, the foundation loads, including the inertial forces, will be a function not of the spire's motion but only of the incoming wind characteristics. In this case no aeroelastic model should be necessary, but the response of the structure could be calculated numerically e.g. [17].

This assumption has been also analyzed comparing the structural dynamic response obtained from the wind tunnel tests with the wind actions calculated numerically. A number of international

* Corresponding author. Tel.: +39 223998076.
E-mail address: lorenzo.rosa@polimi.it (L. Rosa).

http://dx.doi.org/10.1016/j.engstruct.2014.02.030
0141-0296/

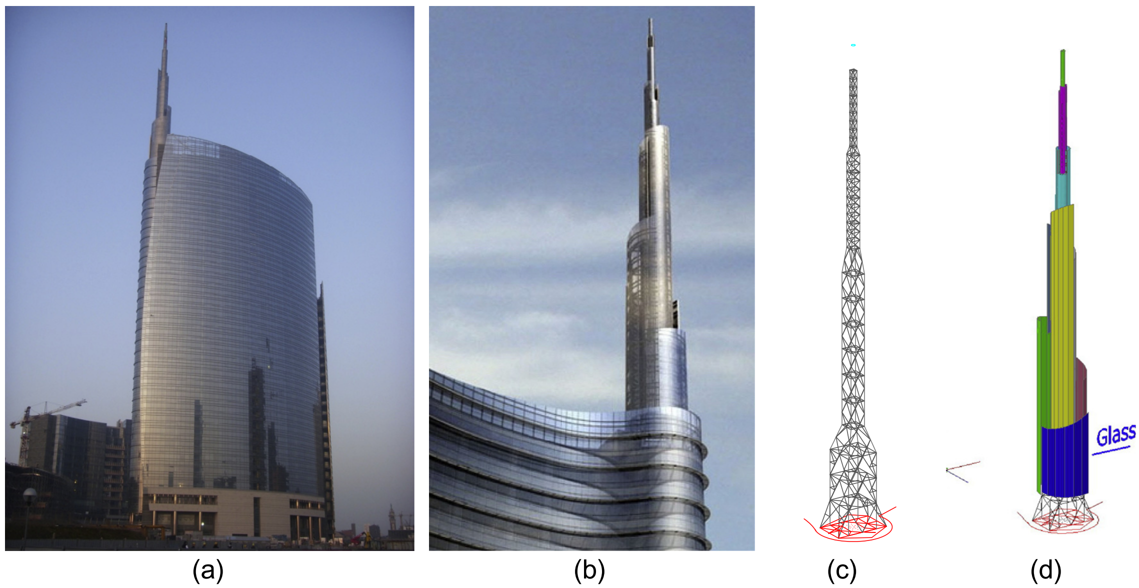

Fig. 1. (a) The building with the spire on its top. (b) Close up of the spire. (c) The supporting lattice framework of the spire. (d) The three-dimensional steel plates which cover the lattice structure. The blue part is made by glass, the others parts are made by perforated steel plates.

codes and standards provide guidelines and procedures for assessing the along-wind effects on tall structures and inconsistencies exist among the wind effects predicted by the various codes and standards under similar flow conditions Zhou et al. [21]. In this work the procedure given by Eurocode Eurocode Hansen and Dyrbye [11], Eurocode1 [7], and Ruscheweyh [18] has been used. The comparison was carried out in terms of peak, gust and structural factors related to the along-wind response of the tower.

This structure has also been studied by the authors in another work in which the main topic of the research was the porosity of its cladding [4,3]. In particular the dynamic response obtained from the in-service configuration (permeable panels) and the results obtained with the structure with non-porous panels were compared. This comparison showed that the porosity of the panels is of great importance and can completely change the dynamic behavior of the whole spire.

2. Wind tunnel tests

Wind tunnel tests were performed at the Boundary Layer Wind Tunnel of the Politecnico di Milano (http://www.windtunnel.polimi.it). The large dimensions of the test section (4 m high, 14 m wide and 36 m long) permitted to choose a geometric scale $\lambda_L = 1/50$, that made possible models with very accurate external geometry and the attaining of a Reynolds Number that would give the best information on full-scale conditions. As far as vortex shedding is concerned the hypothesis is that wind tunnel tests performed in the subcritical region are more conservative than real full-scale structure condition. The full-scale structure would find itself in the post-critical region.

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, over a base simulating the upper part of the building. No other tall buildings are present in the area, so this part of the building was enough to simulate to boundary conditions for the wind tunnel test on the spire. Furthermore 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 mode) are lower than first natural frequency 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 study and only its external shape was reproduced, Fig. 2(a).

2.1. Rigid model

The rigid model of the spire permitted measurement of the global wind loads in terms of forces and moments at its base. To ensure accurate measurements, great attention was cared to make the model as rigid as possible, so as to obtain high structural frequencies and a quasi-static behavior under wind loads. In particular, the dynamometric balance acts as a spring at the base of the model and the first natural frequency along the weak axis of the system model and balance was 12.5 Hz. This value is greater than the frequency content introduced by the turbulent wind and than the first natural frequency of the aeroelastic model (see Fig. 9), so the measurements on the rigid model were filtered with a low pass filter $f_{cutt} = 10$ Hz. Only the exact geometry of the external covering surface was reproduced in the model. The internal lattice framework was not reproduced since it does not give any contribution to the aerodynamic behavior of the structure, which is governed by the external surface. Fig. 2(a) shows the rigid model in the test section. The perforated panels were not geometrically scaled, but the same loss coefficient k was maintained Letchford et al. [13] to guarantee the same flow conditions on the rigid model and the prototype.

2.2. Aeroelastic model

The aeroelastic model (see Fig. 2(b)) was designed and constructed on the basis of the modal parameters obtained from a finite element model of the real structure. Froude similitude criteria was adopted for scale reduction, leading to a factor $\lambda_F = 7$ for frequencies scaling ($\lambda = model/real$) and a factor $\lambda_V = 1/7$ for velocity scaling. Froude similitude criteria, which considers the influence of gravitational forces in aeroelastic phenomena and are usually used for testing long span bridges, were chosen for these tests so as to achieve an optimal compromise between the geometric scale adopted, the range of wind speeds available (the maximum velocity in the test section is 14 m/s) and advantages in the construction and tuning of the aeroelastic model