Journal of Wind Engineering & Industrial Aerodynamics 174 (2018) 391–403

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

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

Wind tunnel study of wind effects on a high-rise building at a scale of 1:300

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ARTICLE INFO

Keywords:
Atmospheric boundary layer
Wind load
High-rise building
Turbulence

ABSTRACT

The objective of the present paper is to investigate the unsteady characteristics of the global and local wind loads and their relationships with the oncoming atmospheric boundary layer through wind-tunnel tests on a high-rise building with a well-defined atmospheric boundary layer at a 1:300 scale. Complete information on wind (mean velocity profile, turbulence intensity, power spectrum of the fluctuation, etc.) and global and local wind loads is analyzed. The results of the present study show that, depending on the location, wall-pressure forces on the tower are under the influence of the upstream flow or the shear layers that form at the upstream corners of the building or both of them. Good agreement between the literature and the present study is found regarding the Strouhal number characteristics of the most energetic frequency in the wall-pressure spectra. Based on the analysis of the spectral coherence between wall-pressure signal at different pressure tap locations, the loss of the strong spectral signature for the global wind force in the longitudinal direction is attributed to the loss of phase coherence between pressure signals on these sides.

1. Introduction

With ever higher buildings being built or planned to be built throughout the world, prediction of local and global wind loads are critical key factors for structural design. Given the increasing number of extreme meteorological events, understanding, modeling and predicting building response to these unsteady loads are of the utmost importance (Irwin, 2009). For more than fifty years, these challenges have been addressed through the use of small-scale modeling performed in wind tunnels based on unsteady global force and local pressure measurements with various terrain and building configurations (see for instance the work of Davenport, 1961; Lin et al., 2005; Kareem, 1997; Surry and Djakovich, 1995; Tanaka et al., 2012). In particular, attention has been directed to the accurate estimation of pressure fluctuations, which is critical when dealing with structural vibrations and resulting fatigue. From that point of view, not only the mean and standard deviation levels of wall-pressure are important, but also its spatio-temporal correlation structure (Surry and Djakovich, 1995; Kareem, 1997; Bartoli and Ricciardelli, 2010; Huang and Chen, 2007). Lateral force on high-rise buildings generally exhibits well-marked periodicity (Huang and Chen, 2007), which is a direct consequence of anti-phase pressure fluctuations acting on opposite lateral faces (Surry and Djakovich, 1995; Kareem, 1997; Daniels et al., 2013). Spectral content of pressure fluctuations on the windward face of tall buildings has been shown to be directly related to that of the oncoming flow (Davenport, 1967; Bartoli and Ricciardelli, 2010). In that case, the ratio between the crosswind dimension of the building and the integral length scale of the longitudinal velocity component plays a key role (Bartoli and Ricciardelli, 2010). This points out the important role that the nature of the upstream flow, and therefore its turbulence characteristics, plays on the mean (Ganapathi et al., 2017; Mara et al., 2014) and instantaneous wind loads (Kareem, 1992; Fritz et al., 2008).

Parallel to the extensive experimental research conducted on wind loads, numerical methods to simulate turbulent flows developing over and around obstacles have also been the subject of sustained research effort and have now matured enough to become applicable to wind engineering problems (Dagnew and Bitsuamlak, 2014; Daniels et al., 2013; Tamura, 2008; Tamura et al., 2008). Among the various computational methods ranging from Reynolds-averaged Navier-Stokes method (RANS) to Direct Numerical Simulation (DNS), Large-Eddy-Simulation (LES) is one of the most promising as it enables the access to the unsteady flow dynamics (contrary to RANS) at an affordable computational cost (as opposed to DNS). Apart from the need of extensive computational resources and precise numerical scheme and turbulence models, one of the greatest challenge to conduct accurate LES simulation of the flow around buildings immersed within an atmospheric boundary layer is to impose

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https://doi.org/10.1016/j.jweia.2018.01.017
Received 22 September 2017; Received in revised form 11 January 2018; Accepted 12 January 2018

realistic instantaneous inflow conditions, that match accurately the characteristics of the upcoming flow for the targeted building and terrain configurations (Druault et al., 2004; Xie and Castro, 2008; Tabor and Baba-Ahmadi, 2010; Aboshosha et al., 2015). Therefore, as pointed out by Dagnew and Bitsuamlak (2014), wind tunnel experimental data are indispensable for correct boundary prescription and validation of LES.

As can be seen from the above, accurate modeling of global and local wind loads on buildings relies on the proper modeling of the oncoming flow, both from an experimental or a numerical point of view. Thus, based on wind tunnel tests performed on a square-plan tall building model, the objective of the present paper is to investigate the unsteady wind effects on the global and local loads (via high frequency balance and multi-point unsteady pressure measurements) but also on the wake-flow in the building near-field (via Particle Image Velocimetry, PIV). Special attention is also devoted to the proper characterization of the oncoming boundary layer, in terms of one- and two-point statistics. The intention here is, via detailed wind tunnel measurements of the mean velocity profile, spectra of the fluctuations of the three velocity components and the associated turbulence integral length scales, to provide the necessary information needed to prescribe the correct inlet condition to LES computations as well as information on both local and global wind loads and on the wake flow for proper validation and characterization of numerical simulations.

The description of both the experimental set-up and the characteristics of the upstream flow are provided in the next section. In the third section the characteristics of the global wind loads are investigated and compared with those of the local wind loads. Observed phenomena are described using the spectral coherence between different pressure taps. PIV measurements performed to analyze the wake flow around the building are then presented. The last section is devoted to the general conclusion of the study.

2. Experimental details

In this section, a description of the experimental apparatus and procedures and a presentation of the characteristics of the generated boundary layer are provided. In the following, x, y and z denote the streamwise (i.e x points downstream when the wind incidence is zero), lateral and vertical directions, respectively. This coordinate system is relative to the tower, in which the wind incidence is referred to as θ. Using the Reynolds decomposition, each instantaneous velocity component can be decomposed into its mean value U, V or W and its fluctuating part u, v, or w, along the streamwise, lateral and vertical directions, respectively. The standard deviation $\sqrt{\overline{u^2}}$ of any quantity u is denoted as σ_u, where the overbar $^-$ is the time average operator.

2.1. Experimental set-up

2.1.1. Wind tunnel

All the wind tunnel tests were performed in the NSA wind tunnel at CSTB (Nantes, France), which is a close-loop wind-tunnel with a 20 m long, 2 m high and 4 m wide test-section. This wind tunnel is particularly dedicated to the simulation of wind over large structures (stadiums, bridges, museums, etc.) and towers (or high-rise buildings). Its large dimensions can allow for the reproduction of natural wind at scales ranging between 1:100 and 1:400 for the usual local and global measurements, and up to 1:1000 for studies on topographic models. The long test section makes it possible to place, upstream of the target model, different sets of roughnesses and turbulence generators in order to reproduce a wind profile conforming to that perceived by the building on the site. The velocity of the flow in the wind tunnel is adjustable from 0 to 30 m/s. The floor of the wind tunnel is equipped with a turntable to position models from 0 to $360^\circ \pm 1^\circ$. A heat exchanger permits a temperature regulation of $\pm 0.5^\circ$C in the range of $+5$ to $+45^\circ$C.

2.1.2. Scaling and model

The tower was modeled with a wall-mounted prism of square cross-section with dimensions of 10 cm$\times$10 cm$\times$49 cm ($H = 49$ cm is the height of the tower model and $D = 10$ cm the tower model width) which corresponds to a tower of height 147 m represented at the scale of $1 : 300$. The reference height H_{ref} was chosen at $2/3$ of the height of the tower ($H_{ref} = 33.3$ cm for the model, about 100 m in full-scale). The wind velocity in the wind tunnel at the reference height, $U_{ref} = 10$ m/s, is equivalent to 24 m/s in full-scale. This corresponds to a wind speed of 16 m/s measured at a height of 10 m, which is in the range of reference speeds for most areas in France, region 2 in the Eurocode (2005). Thus, considering the length scale $L^* = 1/300$, and the speed scale $U^* = 10/24 = 0.42$, the time scale is estimated as $T^* = L^*/U^* = 8 \times 10^{-3}$. It implies that 2 min of acquisition represent 4 h in full-scale, and an acquisition frequency of 400 Hz is equivalent to a full-scale frequency of 3.20 Hz.

To perform the different measurements, two tower models were built. The first model is made of Plexiglas which allows for optical access for the PIV measurements. The second model equipped with 265 pressure taps was used to measure the unsteady pressure distribution on the model walls as shown in Fig. 1. The pressure taps closest to the corners of model are located at $D/20$ (1.5 m in full-scale). More taps are positionned around the corners because the most complex zones are expected there,

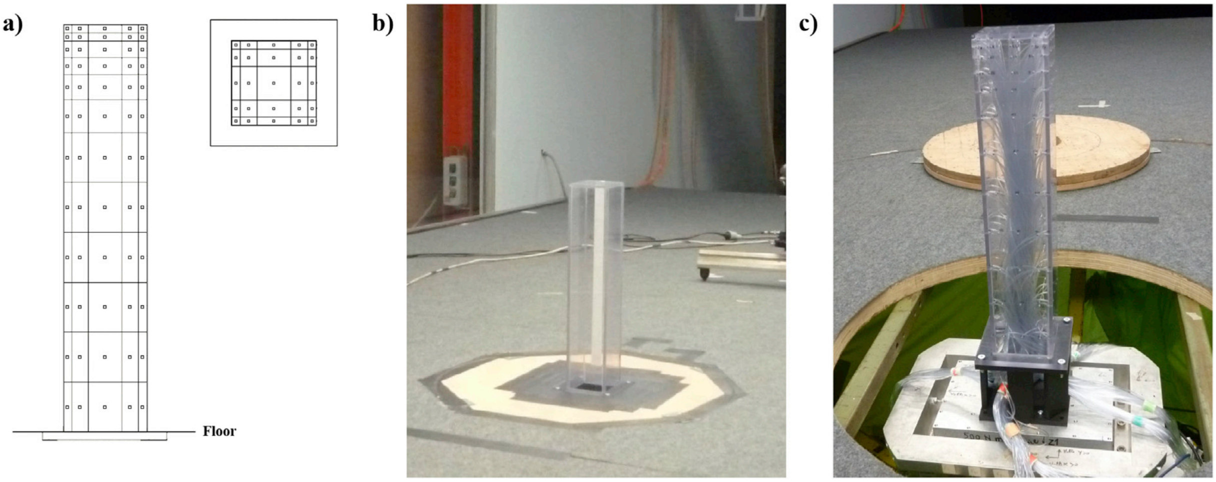

Fig. 1. a) Distribution of pressure taps on each side and on the roof of the tower model, b) Tower model for PIV measurements, c) Tower model with pressure taps for pressure distribution measurements on the model walls and force balance access under the floor. Note that the floor opening was closed during all tests.