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Wind loads and structural response: Benchmarking LES on a low-rise building

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ABSTRACT

The correct and safe design of structures subjected to the wind actions requires a realistic estimate of the wind effects on their resisting systems. In this context, the present paper proposes a complete numerical study that, starting from Large Eddy Simulation of the turbulent flow around a low-rise building, arrives to the assessment of the wind loading effects, that is the evaluation of design forces in all structural elements. Since it is well known that a realistic representation of the turbulent features found in the lower part of the atmospheric boundary layer is required in order to obtain accurate predictions of the structural response, firstly, the incoming flow turbulence is synthetically generated by means of the Modified Discretizing and Synthesizing Random Flow Generator technique. Then, the obtained synthetic fluctuation field is used as inflow condition for the subsequent Large Eddy Simulations taking into consideration different angles of attack. Results in terms of pressure distributions statistics are analyzed and systematically compared to experimental data. Finally, starting from both simulated and experimental pressure fields, dynamic structural analyses are performed and results directly compared in terms of design forces in the structural elements.

1. Introduction

The evaluation of wind effects often represents a delicate point in the design of light and slender structures relevant for Civil Engineering applications. Currently, standard design practice often involves the use of wind tunnel tests aimed at characterizing the wind action taking into consideration the aerodynamic behavior of the building itself and the expected site conditions in terms of terrain roughness and surrounding obstacles.

More recently, Computational Wind Engineering is receiving increasing attention and, in the next future, it can be foreseen that numerical simulations based on Computational Fluid Dynamics (CFD) will gradually complement and/or substitute the well established experimental practice in a number of wind engineering applications [1–5]. In fact, numerical approaches could potentially lead to remarkable savings in terms of time needed to set up the analyses and provide a flexible and powerful tool able to investigate phenomena which might be difficult to be represented when scaled models are adopted. Nevertheless, it should be noticed that, when bluff bodies are analyzed, CFD results often appear to be inaccurate even when simple geometries are considered [6–11]. This is often due to the fact that the local stability criteria of shear layers, usually detached in correspondence of sharp edges, can strongly affect the overall flow arrangement rendering the global flow organization extremely sensitive to local behaviours. Unfortunately, such local effects are well known to be deeply influenced by the incoming flow characteristics, such as turbulence intensity and turbulence length scales [12] but, when computational models are considered, also by the adopted discretization schemes, the mesh sizing and the adopted turbulence model. The relative role of such aspects is nowadays not fully assessed and only a few studies tried to investigate the issue on a statistical base in order to validate CFD as a methodology rather than concentrating on a specific test case solved by adopting a particular setup [11].

In addition to the previously presented difficulties, exactly as in wind tunnel tests, another crucial aspect is represented by the generation of appropriate inflow conditions. In fact, an accurate evaluation of wind loads can not leave aside a realistic representation of the turbulent structures found in the lower part of the atmospheric boundary layer (ABL). In wind tunnel practice, the need for an artificial reproduction of the ABL led engineers to design boundary-layer wind tunnels with long working sections. In particular, Tieleman et al. [13] investigated the distributions of mean, standard deviation and peak pressures on the roof of a low-rise building immersed in a turbulent boundary layer

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considering different roughness configurations. He concluded that much attention should be paid to the correct representation of the horizontal incoming turbulence intensity, in particular at the roof height. A review of available experimental techniques which might prove useful also in numerical simulations, together with new considerations useful to improve the quality of wind tunnel tests, have been proposed by Tieleman [14].

Regarding the wind flow around low-rise buildings, a large number of studies have been proposed in the literature aiming at comparing numerical results to wind tunnel and full scale measurements [15]. In particular, Richards et al. [16,17] focused on the Silsoe Structures Building and compared wind tunnel measurements to numerical and full scale measurements, showing that a satisfactory agreement between the different data is obtained in terms of mean pressure coefficient, while differences increase when the fluctuating pressure coefficient and turbulent kinetic energy fields are analyzed. More recently, Ozmen et al. [18] investigated the wind flow around low-rise buildings with gabled roofs having different pitch angles, showing that in the recirculation regions and mixing layer results obtained by means of numerical simulations deviate with respect to experimental measurements, in particular in terms of turbulent kinetic energy.

From all previous considerations it is clear that, aiming at assessing the reliability of numerical simulations as a design tool, a careful validation of the accuracy of the results obtained by means of numerical models is mandatory before extensive application in practical cases. Such validation, should take into consideration all the aforementioned aspects and investigate their relative importance with respect to the evaluation of design values which are, indeed, the main quantity of interest. On such regard, it is observed that the most common validation approaches in the wind engineering field are based on systematic comparisons between numerical and experimental data in terms of pressure statistics usually up to the second order [19–21]. It should be noted that, although such way of proceeding surely represents the first step of the aforementioned validation process, it can not be considered sufficient in order to fully assess numerical simulations as a design tool with respect to the dimensioning of structural systems. In fact, the characteristics of the pressure field, which contribute to the definition of the design loads, inevitably include also the pressure field spatial coherence, its spectral content and its higher order moments distributions. Although systematic comparison of all such quantities would be theoretically possible, the resulting picture would probably not be of straightforward interpretation.

In the present paper, in order to overcome such difficulties, a synthetic approach is adopted. In particular, a low-rise building, for which wind tunnel tests results are publicly available, is considered. Firstly, Large Eddy Simulations (LES) are performed leading to the numerical evaluation of unsteady pressure distributions for all the building surfaces exposed to the wind action. The inflow conditions for such simulations are synthetically generated by means of the Modified Discretizing and Synthesizing Random Flow Generator technique (MDSRFG) which allows to obtain a solenoidal fluctuating velocity field allowing to control its temporal and spatial correlations. According to standard practice, results are firstly analyzed in terms of integral forces and pressure statistics distributions on the building. Then, starting from both experimental and numerical results, dynamic structural analysis are performed for each considered attack angle leading to the definition of design envelopes which contains peak values of the design forces for each considered structural element. The comparison between such design envelopes, obtained by considering experimental and simulated pressure fields, allows to obtain direct indications regarding the accuracy of numerical models in terms of design forces. By adopting such a way of proceeding, all elements contributing to the definition of the structural response are naturally taken into account, so providing a synthetic comparison of the predictions of the adopted numerical model with respect to experimental evidences.

The paper is organized as follows. Section 2 describes the setup used to obtain experimental data while Section 3 describes the computational model adopted for the proposed simulations and discusses the obtained numerical results in terms of pressure statistics distributions by comparing them with available experimental data. Then, Section 4 analyses wind loads effects on the structure directly in terms of internal forces. Finally, in Section 5 some conclusions are drawn.

2. Wind tunnel setup

In this section, the experimental setup adopted to obtain pressure data used in the following for comparison with numerical results is described. Experiments were carried out at the Boundary Layer Wind tunnel of the Tokyo Polytechnic University (TPU) and are publicly available for download [22]. The database of the Tokyo Polytechnic University provides pressure measurements for a wide range of low-rise and high-rise buildings at different angles of attack and for different terrain roughness conditions. In the present work the attention is focused on a low-rise building with gabled roof without eaves. The considered geometry is characterized by a height (H_0) to breadth (B) ratio equal to $2:4$, a depth (D) to breadth (B) ratio equal to $3:2$ and a roof pith angle (β) equal to 9.4° (see Fig. 2(a)). In experiments the length scale was set at $1/100$, leading to a model with $B = 160$ mm, $D = 240$ mm and $H_0 = 80$ mm. The wind tunnel section was 2.2 m wide and 1.8 m high, leading to a blockage ratio lower than 1%. The wind field profile reproduced in the wind tunnel corresponded to that of terrain category III according to the Architectural Institute of Japan (AIJ) standards [23]:

$$U(z) = 1.7\left(\frac{z}{Z_G}\right)^{\alpha} U_{ref}, \quad Z_b < z \leqslant Z_G, \tag{1}$$

$$U(z) = 1.7\left(\frac{Z_b}{Z_G}\right)^{\alpha} U_{ref}, \quad z \leqslant Z_b, \tag{2}$$

where the exponent α is equal to 0.2, Z_G is a reference height of the ABL equal to 450 m, Z_b represents the characteristic dimension of the surface roughness element and it is equal to 10 m while U_{ref} is the reference wind velocity measured at a height of 10 m (previously introduced quantities should be intended to be in full scale). In the wind tunnel tests here adopted for reference U_{ref} is equal to 7.4 m/s and it is measured at a height equal to z_{ref} = 0.1 m from the wind tunnel floor.

In wind tunnel tests, also the turbulence intensity profile as prescribed by AIJ, has been reproduced. This profile is reported in Eqs. (3) and (4) for the terrain category III:

$$I(z) = 0.1\left(\frac{z}{Z_G}\right)^{-\alpha-0.05}, \quad Z_b < z \leqslant Z_G, \tag{3}$$

$$I(z) = 0.1\left(\frac{Z_b}{Z_G}\right)^{-\alpha-0.05}, \quad z \leqslant Z_b. \tag{4}$$

As in standard wind tunnel practice, the correct wind velocity profiles have been obtained by means of turbulence-generating spires and square blocks as roughness elements placed upstream the model.

It is noticed that, according to the experimental setup, the blocks distribution adopted in the preliminary simulation is uniform over the bottom of the wind tunnel, so an empirical