Engineering Structures 35 (2012) 18–28

Contents lists available at SciVerse ScienceDirect

Engineering Structures

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

Characteristics of surface wind pressures on low-rise building located among large group of surrounding buildings

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ARTICLE INFO

Article history:
Received 1 February 2011
Revised 19 October 2011
Accepted 20 October 2011
Available online 7 January 2012

Keywords:
Low-rise building
Wind pressure coefficient
Urban street canyon
Amplification effect
Local wind speed profile

ABSTRACT

Systematic wind pressure measurements were conducted in order to investigate the effect of a large group of surrounding buildings on wind pressures on a typical low-rise building. The primary purpose of this work was to understand and quantify the effects of nearby structures for engineers/designers, especially with regard to maximum and minimum values. Various ranges of area densities and measurement points were considered under a turbulent boundary layer representing a suburban area. Results show that although the mean pressure coefficient decreases as the area density increases and when the measurement points are located at the downstream side, the fluctuating component increases significantly, giving larger maximum and minimum coefficients than those for an isolated building.

1. Introduction

Isolated low-rise buildings have received much attention and there is a well established understanding of the mechanism of mean and fluctuating forces on them. However, one of the problems associated with prediction of wind forces on low-rise buildings is a lack of information available to engineers when they are located among a large group of surrounding buildings. Low-rise buildings are normally built in large groups, thus forming urban street canyons. When a low-rise building is exposed to an atmospheric turbulent boundary layer, it can be regarded as one of the roughness elements because its height is approximately the same as those of surrounding buildings, and the wind pressures are significantly influenced by neighboring structures.

From both structural and environmental viewpoints, it is very important to understand how flows are modified and hence how wind pressures are influenced. Flow patterns around buildings determine wind force characteristics, pressure distributions and scalar dispersion around them. Depending on distances to nearby buildings, building heights, arrangement patterns, building shapes and characteristics of incident flow, these flow patterns are altered by overlapping and interacting, governing the wind force/pressure characteristics as well as the nature of ventilation and dispersion of pollutants in urban street canyons. Aerodynamic and environmental characteristics are related to the re-developed flow over or within the urban street canyon, and the re-developed flow is said to be classified by three regimes: isolated roughness flow, wake interference flow and quasi smooth or skimming flow. This regime classification, first suggested by Morris [1], had previously only been identified in connection with 2-dimensional roughness elements, and it was later confirmed that the existence of three types of flow regime was applicable to 3-dimensional roughness elements (Lee and Soliman [2]; Hussain and Lee [3]). These flow regimes are shown to depend on roughness geometry, area density and arrangement pattern as well as the characteristics of the incident flow.

Many previous studies have examined the wind load characteristics of low-rise buildings with neighboring structures as a form of urban street canyon and reported that the wind loads on such buildings are different from those on an isolated low-rise building. Due to the complex nature of the problem and the lack of reliable data or analytical procedures for predicting the wind load effects, very limited data are available to engineers/designers. The current standards and codes of practice, such as AIJ-RLB (2004) [4], give little guide to engineers/designers in assessing wind loads in a situation where unusual wind effects are expected due to the proximity of surrounding buildings, implying the need for wind tunnel tests. A detailed and comprehensive study on interference effects of grouped low-rise buildings was carried out by Holmes and Best [5]. Their results, with those of Hussain and Lee [3], are reflected in the AS/NZS code in terms of a shielding multiplier (between

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doi:10.1016/j.engstruct.2011.10.024

0.7 and 1.0), depending upon separation distance, dimensions and the number of upstream buildings [6]. Stathopoulos [7] reported some general understandings of the effect of nearby buildings and the difficulties for the codification due to complexity of the problems. Khanduri et al. [8] discussed enormous possible interference effects for low-rise as well as tall buildings. Ahmad and Kumar [9] investigated the interference effects of wind loads on low-rise hip roof buildings. Two other cases included one similar building and three similar buildings placed on the upstream side at 15 different locations. The amplification and shielding effects were observed in both cases, however, the effects were more significant for the case with one similar building and for the case with three similar buildings, only the shielding effect was observed at most locations. A large number of wind tunnel tests and full-scale measurements for the investigation of upstream buildings were conducted by Stathopoulos's group (Wang and Stathopoulos [10,11], and Zisis and Stathopoulos [12]). Wang and Stathopoulos [10,11] evaluated the effect of upstream exposure on wind loading. They pointed out that peak wind loads are basically affected by short distance roughness characteristics rather than further terrain properties, and these loads can be determined by considering a fetch of 300–400 m. Zisis and Stathopoulos [12] investigated the pressures and uplift forces on a full-scale testing facility, asserting the impact and importance of varying upstream terrain properties to resulting wind-induced loads. Chang and Meroney [13] investigated the effect of surrounding buildings arranged in various symmetric configurations with different separation distances, and concluded that shielding effects are significant especially when the street canyon is narrow, and the effects are greater in urban cases than in open country cases. Sun et al. [6] investigated peak pressure coefficients through a huge number of wind tunnel tests, and reported that although the shielding effects were significant in most of cases, the peak pressure coefficients can be increased by 100% in some cases. Zhang and Sarkar [14] investigated the influence of surrounding buildings on flow around a two-story gable-roof building using PIV under an atmospheric boundary layer and tornado-like wind. They pointed out that various vortices were formed around the test building with varying layout of surrounding buildings, and a more complicated vortex system was induced by tornado-like wind than by the atmospheric boundary layer. Lien et al. [15] and Zhang et al. [16] simulated the flow patterns for different building arrangements to validate the numerical modeling and to investigate the effect of surrounding buildings, pointing out that upstream buildings significantly affect wind loads and flow patterns on the target building.

Most of these previous studies considered small groups of surrounding buildings, e.g. the surrounding buildings are arranged within limited small ranges such as within a turntable ([5,6,9,14–16]), highlighting the fact that shielding effects increase with number of nearby structures, hence reducing wind loads on a building. In the present work, in order to investigate and quantify the effect of surrounding buildings on wind pressures applied to a low-rise building, systematic wind pressure measurements were conducted. The parameters considered include area density C_A (i.e. separation distances between nearby structures) and upstream distance L_{fetch} (i.e. number of upstream buildings). To identify the effect of arrangement on wind pressure, pressure measurements were conducted for a staggered arrangement (STG in Fig. 1(b)) as well as a standard arrangement (STD in Fig. 1(b)) for an area density of 25%. Moreover, to identify the effects of incident flow, pressure measurement for a smooth surface (SS) without spires and upstream roughness blocks together with a rough surface (RS) with spires and upstream roughness blocks was made for an area density of 44%. Based on these results, more comprehensive understandings and guidelines can be provided to practitioners.

2. Outline of wind tunnel test

Wind tunnel tests were performed at the Tokyo Polytechnic University in Japan. Its working section was 2.2 m wide, 1.8 m high and 19 m long, and the wind speed could be controlled from 0 to 15 m/s with a turbulence intensity of less than 1%.

A 0.1 m cubic model was used for the target low-rise building, and dummy models with the same size were used for nearby buildings. The target model was moved to the downstream side at specified intervals determined by area density (C_A). The area density, C_A, was defined as the ratio of the area covered by the building to the building lot area, and was varied as 6.25% (6%), 11.1% (11%), 16%, 25%, and 44%. The area density of 6% and 25% share the measurement points, and 11% and 44% share the measurement points. The difference between each pair was the number of dummy models between measurement points; when the area density was 6% (block distance: 3B) and 11% (block distance: 2B), there was one dummy model, while when area the density was 25% (block distance: 1B) and 44% (block distance: 0.5B), there was one more dummy model, meaning three dummy models between measurement points. This method was adopted to minimize the number of measurement points. A schematic of the wind tunnel tests is shown in Fig. 1.

Twenty-five pressure taps were installed in each surface including the roof, giving 125 pressure taps in total. They were equally spaced horizontally and vertically at $B/10$, $D/10$, and $H/10$ from the edge. At each pressure tap, a vinyl tube 800 mm long with an inner diameter of 1.4 mm was connected for pressure measurement. Tubing system effects on the measured pressures were removed by application of the transfer function and phase delays. All pressure taps were measured simultaneously with a sampling frequency of 781 Hz and low-pass filtered with a cut-off frequency of 300 Hz cascaded in each data acquisition channel to eliminate aliasing effects. The measuring time was adjusted such that 30 samples were obtained, making a total of over 327,680 data. A length scale of 1/150 and a time scale of 1/50 were assumed. Together with the pressure measurements, local wind speeds were measured from 0.1 to 0.4 m at each measurement point under all area densities. The local wind speed, U_H, at model height was used to obtain the velocity pressure, q_H, and the velocity pressure was used to obtain the pressure coefficients. After deriving the coefficients, moving averages corresponding to 0.05 s in full time scale were applied to obtain the sample statistics, i.e. mean, fluctuating, maximum and minimum coefficients for 12 s which is equivalent to 10 min in full time scale.

Using these sample maxima and minima, the maximum and minimum coefficients were calculated by the Cook–Mayne method, where the distribution was assumed as Fisher–Tippet Type 1. In the calculation, the probability level obtained corresponds to a non-exceedance probability of 78%. The mode and dispersion of Fisher–Tippet Type 1 were calculated using the modified Jensen and Frank method [17]. Based on the TVL method, a moving average time of 0.05 s was appropriate to a cladding/curtain wall element of 1 m in full length scale. The experimental wind direction was fixed at 0°, which is normal to the model surface.

The vertical distributions of mean wind speeds and turbulence intensities of the incident flows are shown in Fig. 2. A typical turbulent boundary layer (solid circle) representing a suburban flow with a power-law exponent of 0.2 with turbulence intensity at model height of about 23% was simulated for all area densities (referred as RS in Section 3.5). The wind speed, U_H, at model height was 7.2 m/s measured using a hot wire anemometer with an I-shaped probe. Circles in the same figure show the incident flow condition for a smooth surface only for an area density of 44% (referred as SS at Section 3.5). The mean wind speed and the turbu-