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Wind pressures on tapered and set-back tall buildings

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ABSTRACT

Recent tall buildings tend to have irregular and unconventional shapes as a prevailing but unavoidable trend, which is very effective for suppressing across-wind responses. Suppression of across-wind responses is a major factor in safety and habitability design of tall buildings, and the so-called aerodynamic modification method is comprehensively used. While the effectiveness of aerodynamic modification in reducing wind loads has been widely reported, there have been few detailed investigations of pressure fluctuations. The purpose of the present work is to investigate the spatio-temporal characteristics of pressure fluctuations applied to height-modified tall buildings comprehensively, including differences of vortex formation and shedding mechanism based on the previously reported mechanism of a conventional square tall building. The results show that taper and set-back affect on the bandwidth of power spectra and position of peak frequencies. And through taper and set-back, the height at which the vortex begins to form moves up, and due to the small building dimension, the vortex component formed at that height sheds from the building more frequently before an inverted conical vortex is formed over the whole height.

1. Introduction

The current tallest building in the world is the 828 m-high Burj Khalifa, which is over 300 m higher than Taipei 101, and the tallest buildings in the next decade will be Kingdom Tower (over 1000 m), which will be completed in 2018, making Burj Khalifa the third tallest building (http://www.skyscrapercenter.com/List/future-tallest-100-buildings, 2012). Current trend of tall building construction, i.e., manhattanization with various building shapes, requires attention. Their free-wheeling building shapes are expressed by taper, set-back, helical, openings, or combinations of these, reflecting architects' and engineers' challenging spirits for new forms. These irregular and unconventional building shapes are a resurrection of an old characteristic, motivated by new trends in architecture, but they have the advantage of mitigating across-wind responses, which is a major factor in safety and habitability of tall buildings.

The effectiveness of aerodynamic modifications in reducing wind loads has been widely examined, and they can be tentatively classified as corner modification and height modification (Kim and Kanda, 2010a). Corner modification includes corner cut, recess, chamfer and addition of fins (Kawai, 1998; Kwok et al., 1988), and height modification includes taper, set-back, opening, helical (twisting) and inclined (tilted) shape, and so on (Dutton and Isyumov, 1990; Kim and Kanda, 2010a, 2010b; Kim et al., 2011; Tanaka et al., 2012). In particular, Tanaka et al. (2012) conducted a series of wind tunnel tests to investigate aerodynamic characteristics and to evaluate the most effective building shape in wind-resistant design for 31 tall buildings with various aerodynamic modifications. Unlike structural modification, which controls mass, spring and damping directly in a governing equation of motion, aerodynamic modification controls forces applied to tall buildings by altering the separated shear layer or disturbing the alignment of the vortex over the whole height.

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However, most previous researches have focused on the results of mitigation effect in terms of wind forces (or local wind forces) and responses. And although many studies have been conducted to investigate the characteristics of pressure fluctuations, only the conventional building shapes with square/rectangular or circular cross-sections have been focused on the existing studies (Hui et al., 2013; Iungo et al., 2012; Kareem and Cermak, 1984; Lin et al., 2005; Okuda and Taniike, 1993). There have been few detailed investigations of pressure fluctuations, especially for the height-modified tall buildings. In the present work, the comprehensive spatio-temporal characteristics of pressure fluctuations on height-modified tall buildings including peak pressures, cross-correlations, power spectra and coherence were investigated through the synchronous multi-pressure sensing system techniques. The differences of vortex formations and shedding mechanisms were also investigated based on the previously reported vortex formation and shedding mechanism of a conventional square tall building. And, the effect of different flow conditions is examined from the variation of mean pressure coefficients and power spectral peaks.

2. Wind tunnel test

Wind tunnel tests were conducted in an Eiffel-type wind tunnel (1.8 m $\times$ 1.8 m $\times$ 12.5 m) at the University of Tokyo. Four tall building models were used: a prototype square prism (SQ), a building model with set-back at mid-height (SB), and two tapered building models with tapering ratios of 10% (TP1) and 5% (TP2). The bottom dimensions (B_B and D_B) were 40 m and the top dimensions (B_T and D_T) ranged from 24 m to 40 m depending on building shape, and the height (H) was 160 m in full scale. For all models, the side ratio was unity and the aspect ratio (H/B_B) was four (Fig. 1).

The models had 55 pressure taps on each surface connected to vinyl tubes 1.4 mm in inner diameter and 800 mm in length. The pressure taps were equally spaced horizontally at $D_h/5$ or $B_h/5$, and $D_h/10$ or $B_h/10$ from the edge of each surface, and vertically at $H/10$ and $H/20$ from the bottom and top. Here, H means total height of the models and h means any height of the models. Wind pressures were measured using a synchronous multi-pressure sensing system. The natural frequency of the piezoelectric transducer was about 1.7 kHz, and a low-pass filter of 500 Hz cutoff frequency was installed in each data acquisition channel to eliminate aliasing effects. In a run time, the reference differential pressure transducer was connected to a pitot-tube installed in the test section. The tubing effects were numerically compensated using the gain and phase shift characteristics of the pressure measurement system (Fig. 2).

Fig. 3 shows the definition of wind directions and location of pressure taps used in the present study. Pressure measurements were conducted in two ways: pressure measurement on one surface (Fig. 3(a)) and pressure measurement on opposite surfaces for the taps located at odd and even levels separately as shown in Fig. 3(b) and (c). Pressure measurement on one surface was conducted for wind directions from 0° to 180° at 15° intervals and pressure measurement on opposite surfaces was conducted for wind directions 0° and 90°. A sampling frequency was set to 1000 Hz, and the measuring time was adjusted such that over 40 samples were obtained. A length scale of 1/400 and a velocity scale of 1/70 were assumed, considering the design wind speed at 160 m in Tokyo, Japan. The reference wind speed U_H measured at the top of the models was used to calculate dynamic pressure, q_H, which was used to determine the wind pressure coefficients. The time series of pressure coefficients were filtered again by means of moving averages corresponding to

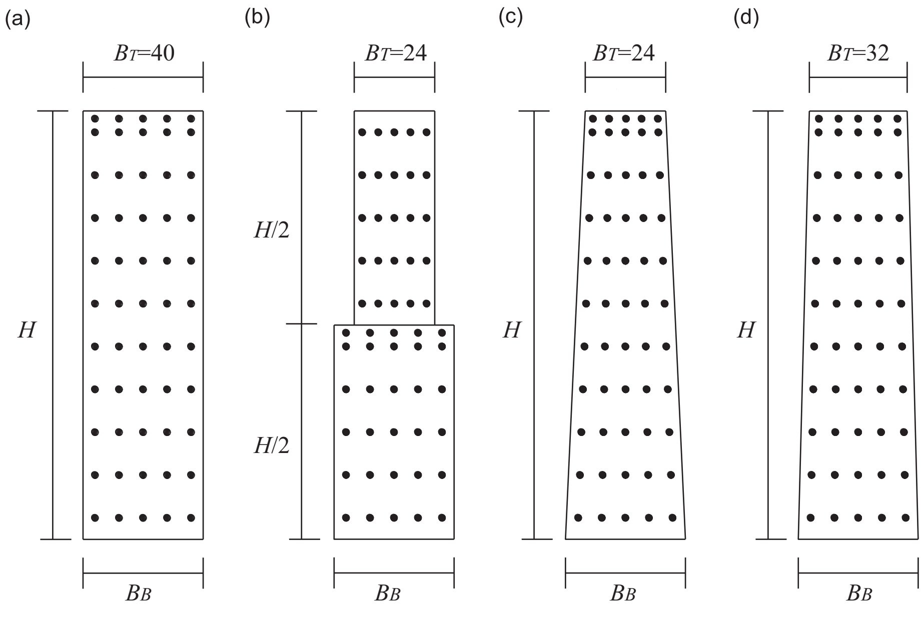

Fig. 1. Building shapes for wind tunnel test (B_B=40, H=160, unit: m). (a) SQ, (b) SB, (c) TP1 and (d) TP2.