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WIND-INDUCED RESPONSE REDUCTION OF A TALL BUILDING WITH AN INNOVATIVE FAÇADE SYSTEM

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ABSTRACT

The effects of a double-skin porous façade system on the wind-induced response of the Commonwealth Advisory Aeronautical Research Council (CAARC) Standard Tall Building were investigated via a program of wind tunnel model study conducted at the China Light and Power (CLP) Power Wind/Wave Tunnel Facility at the Hong Kong University of Science and Technology. For reduced wind velocities ranging from about 4 to 14, the dynamic alongwind, crosswind and torsional responses of the building were reduced significantly when vertical openings were introduced to the outer skin of the double-skin façade. The reduction in crosswind response at around the critical reduced velocity associated with vortex shedding when the incident wind was normal to the windward face of the building is particularly striking. These response reductions are attributable to the disruption to the vortex shedding process caused by channelling air flow created by vertical opening(s) and the double-skin façade system. Innovative façade systems such as these can be adopted in tall building design to utilise their wind-induced response reducing aerodynamic characteristics.

KEYWORDS

Double-skin façade, porous façade, tall buildings, wind-induced response, vortex shedding.

INTRODUCTION

To date the engineering community has seen structural façade systems as non-structural elements with high aesthetic value and a barrier between the outdoor and indoor environments. The role of facades in energy use in a building has been recognized and the industry is witnessing the emergence of many energy efficient façade systems. It has also been recognized that façade systems add some stiffness and damping to the overall building despite the new and modern systems, e.g., curtain walls, which add a relatively small amount of stiffness and damping to the overall building.

Despite these advancements, the façade has been rarely considered or designed as a potential wind-induced vibration controller for tall buildings, especially for vortex induced crosswind response of tall buildings as well as the reduction of alongwind response. This paper aims to change this and explores the reduction of wind-induced tall building motions through an innovative aerodynamic solution. This is made possible by the advent of multi-skin façade systems with cavity gaps as high as 1.6 meters to about 200 mm. Multi-skin façade systems are becoming more popular due to their energy efficiency, offering some degree of blast resistance, and the opportunity to use the cavity gap to install some of the essential services such as blinds with minimum cleaning maintenance requirements and other advantages.

Previous works by the authors (e.g. Samali et al., 2014) in building facade include the potential of utilising a moveable exterior façade in a double-skin façade system. The investigations have shown that with optimal choices of materials for enhancing the stiffness and damping of the brackets connecting the two skins, a substantial portion of wind-induced vibration energy can be dissipated, which leads to avoiding expensive lateral stiffening systems and/or space-consuming damper systems such as massive tuned mass or liquid dampers. Azad et al. (2013) have demonstrated that up to 50% of accelerations and displacements caused by winds can be reduced by a smart and efficient façade design, including purely passive systems with constant stiffness and damping or better, by a smart system possessing variable stiffness for different phases of façade movement. In addition, the same concept has also been adopted by Abtahi et al. (2013) to dissipate a large proportion of seismic energy when dealing with earthquake loads. A proper choice of similar and optimal stiffness and damping of brackets connecting the two skins can lead to an energy dissipating façade system and hence reducing the reliance on large ductility of the main structural framing system to dissipate seismic energy. This will lead to smaller ductility demand and hence a more efficient, easier and faster to build and a more economical structural system. Finally, some significant work has been undertaken by Zobec (2013) to study the response of façade systems to blast loads with the view to refine the current design practices, leading to safer and yet more economical designs.

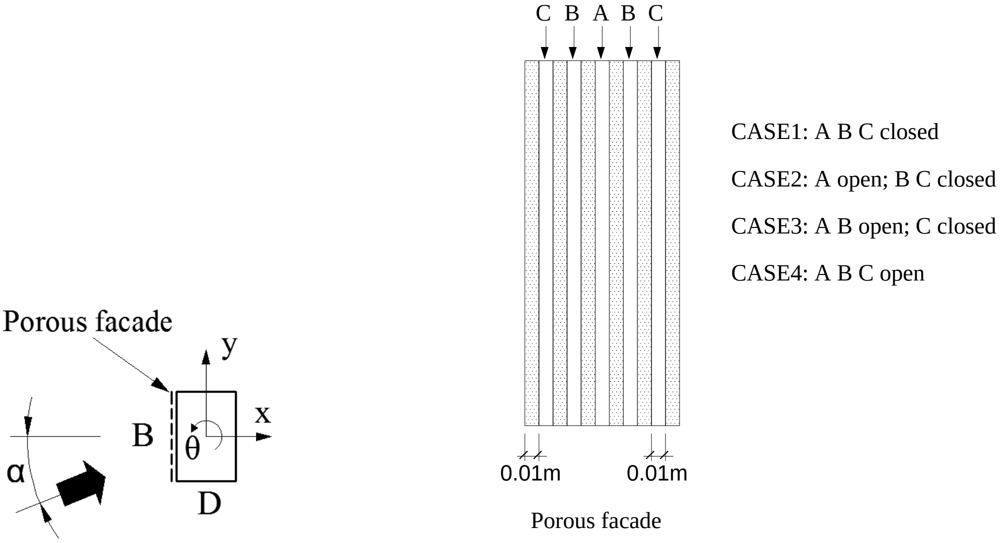
Aerodynamic shaping, such as tapering, corner shaping and modification, sculpturing and through building openings, has increasingly been adopted in the design of tall buildings due to aesthetic appeals and the ability to reduce wind loads and wind-induced dynamic responses (e.g. Tanaka et al., 2012, Kwok 2013). While the building facade plays a critical role in shaping a building and the building shape in turn affects the wind pressure acting on the facade, the facade system rarely plays a major role in the design process to reduce the building's wind loads and wind-induced dynamic responses. In this paper, the potential of creating intentional and optimal porosity in the external skin of a double-skin façade system, created by vertically aligned openings, is investigated. The results clearly demonstrate that such openings can significantly reduce the wind-induced responses of tall buildings, in particular vortex-induced crosswind response. This will potentially eliminate the need for installing large and space-consuming mechanical damper systems and therefore increase the prime leasable space available to the building owner with significant economic benefits.

WIND TUNNEL MODEL TESTS

Test Building

A 1:400 linear scale model of the CAARC Standard Tall Building (prototype: Height (H) 180 m, Breadth (B) 45 m, Depth (D) 30 m; model: H 450 mm, B 112.5 mm, D 75 mm) was tested. The test building was mounted on a 3 degree-of-freedom aeroelastic "stick model" test rig that modelled a linear mode shape in alongwind (x) and crosswind (y) pivoted at the base of the building, and a constant deflection mode shape for torsion (θ). The test building has a structural density of approximately 160 kg/m^3. Building model stiffness was provided by sets of linear springs that produced natural frequencies of 11.8, 11.5 and 17.7 Hz, and structural damping values of the building model were 1.01%, 0.95% and 1.33% of critical damping in alongwind (x), crosswind (y) and torsion (θ) axes, respectively.

A double-skin façade was mounted on the windward face of the plain building model with a gap of 5 mm between the outer and inner skin, as shown in Figure 1(a). The outer skin contains vertical openings that were kept open or closed, as shown in Figure 1(b), to create different porosity, allowing channelling airflow through the opening(s) and the double-skin facade.



(a) Double-skin façade on windward face (b) Double-skin facade with vertical openings
Figure 1. Test building model fitted with a porous double-skin facade

Wind Tunnel Test Setup

The model building was tested in the high-speed test section of the boundary layer wind tunnel at CLP Power Wind/Wave Tunnel Facility (WWTF) at the Hong Kong University of Science and Technology (HKUST), as shown in Figure 2. The tests were conducted in an open terrain wind model (i.e. AS1170.2:2002 open terrain category 2) with a longitudinal mean velocity profile power exponent of 0.15 and a longitudinal turbulence intensity of 0.10 at the top of the model building. The power spectral density function of the longitudinal turbulence was found to be consistent with a length scale of approximately 1:400.

Figure 2. Test building model with a double-skin facade in HKUST's boundary layer wind tunnel

Wind Tunnel Test Program

A program of benchmarking tests was conducted with the plain CAARC building model prior to the tests of the building model with a double-skin facade with different vertical opening configurations.

The results of benchmarking tests were compared and found to be consistent with published wind tunnel test results (Melbourne, 1975; Tang and Kwok 2004).

The following program of wind tunnel tests was conducted on the building model with a double-skin facade:

Angle of wind incidence α: 0°, 5°, 10°, 20°, 45°, as shown in Figure 1(a)
Vertical opening configuration: Cases 1, 2, 3 and 4, as shown in Figure 1(b)
Reduced wind velocity RV: 4, 6, 8, 9, 10, 11, 12, 14

The reduced wind velocity is defined as:

$$RV = \frac{U}{f_y B} \tag{1}$$

where U is the mean wind speed at the top of the building, f_y is the building natural frequency in the crosswind (y) direction, and B is the breadth of the building.

For each test, the mean and standard deviation responses in alongwind, crosswind and torsion (twist angle) were measured from the respective strain gauge bridges using a digital data acquisition system for a period equivalent to approximately 1 hour in prototype scale.

RESULTS AND DISCUSSIONS

The normalised mean alongwind, standard deviation alongwind, standard deviation crosswind and twist angle responses of the test building model with a double-skin facade are presented in Figure 3 for different vertical opening configurations, at angle of wind incidence $\alpha = 0°$, and for reduced wind velocities ranging from 4 to 14.

For incident wind normal to the test building model ($\alpha = 0°$), with the outer skin intact and with no opening (Case 1), the most noticeable and largest response is the dynamic crosswind response σ_y/B that peaks at around a reduced wind velocity of 10, which is the critical reduced wind velocity associated with vortex shedding. Evidently the vortex shedding process also generated significant torsional load and twist angle response θ. A noticeable peak in the dynamic alongwind response σ_x/B centred around the critical reduced wind velocity of 10 is also observed. This is attributable to energy transfer between the x and y axes due to the closeness of the two natural frequencies and also the strength of the vortex shedding process.

The introduction of vertical openings to the outer skin (Cases 2, 3 and 4) resulted in a significant reduction in mean alongwind, dynamic alongwind, dynamic crosswind and twist angle responses. The dynamic crosswind response exhibits the most dramatic reduction at around the critical reduced wind velocity of 10. Evidently channelling airflow through the openings and between the double-skin facade facilitated momentum injection into the separated shear layers at the building’s windward corners, and hence severely disrupted and weakened the vortex shedding process.

It is noteworthy that the different vertical opening configurations associated with Cases 2, 3 and 4 resulted in response reductions of similar magnitude. This suggests that the centre vertical opening (Case 2) is the most dominant, while the progressively larger vertical openings afforded by Cases 3 and 4 offer only marginally better response reductions.

While excitation associated with vortex shedding remains the dominant mechanism for angles of wind incidence up to about 10°, the introduction of vertical openings to the outer skin (Cases 2, 3 and 4) continues to offer a significant reduction in mean alongwind, dynamic alongwind, dynamic crosswind and twist angle responses, as shown in Figure 4 for a reduced wind velocity of 10. Interestingly, at an angle of wind incidence of 10°, there is a noticeable peak in the dynamics responses for both the crosswind and torsion directions. This is likely to be associated with the flow regime created by the vertical openings on the outer skin and the double-skin facade, although the exact cause is not known. This complex flow regime and the resultant effects on the separated shear layers and the vortex shedding process are worthy of further investigation experimentally and/or numerically.

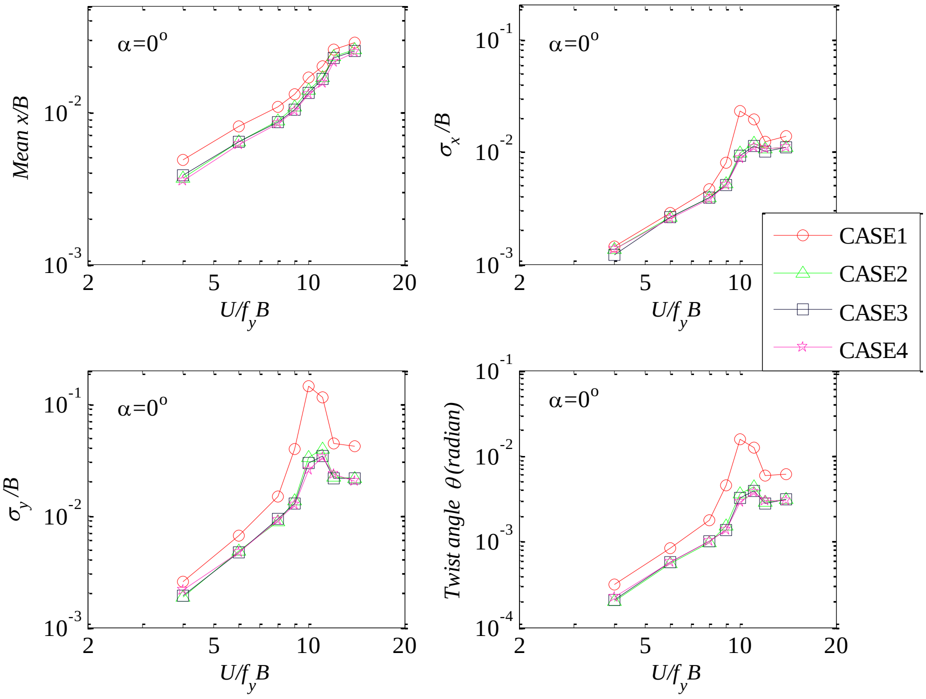


Figure 3. Wind-induced responses of test building model with a double-skin facade with different vertical opening configurations at α = 0 °

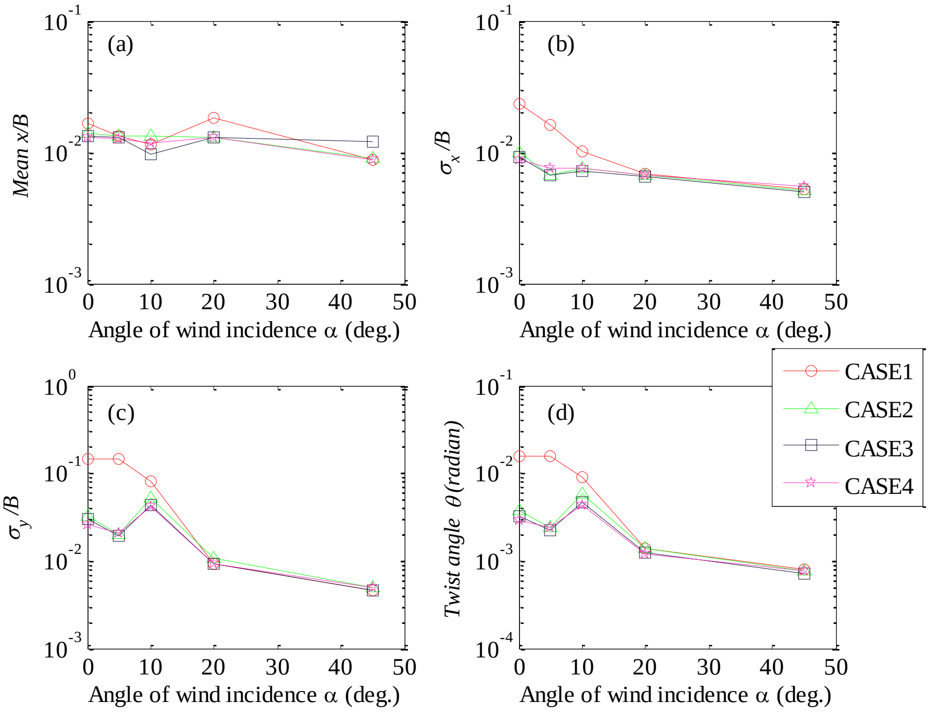


Figure 4. Wind-induced responses of test building model with a double-skin facade with different vertical opening configurations at reduced wind velocity of about 10

CONCLUSIONS

Wind tunnel model tests conducted on the CAARC Standard Tall Building showed that vertical openings introduced to the outer skin of a double-skin façade significantly reduced the dynamic alongwind, crosswind and torsional responses of the building for reduced wind velocities ranging from about 4 to 14. When the incident wind was normal to the windward face of the building, the reduction in crosswind response at around the critical reduced velocity of 10, which is associated with vortex shedding, is particularly striking. These response reductions are attributable to the disruption to the vortex shedding process caused by channelling air flow created by vertical opening(s) and the double-skin façade system. Innovative façade systems such as these can be adopted in tall building design to utilise their wind-induced response reducing aerodynamic characteristics.

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