Influence of Surrounding Buildings on Tornado-Induced Wind Loads of A Low-Rise Building

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ABSTRACT

Low-rise buildings located in the urban areas are generally surrounded by buildings of similar size. The interference of surrounding buildings has been found to be significant on wind loads in straight-line winds. In this study, systematic experiments of tornado-induced wind loads and flow patterns around a typical low-rise gable-roof building with different layouts of surrounding buildings were carried out in a laboratory. Effects of spacing, height ratios of the surrounding buildings to the test building and specific building orientations were considered. The results indicate that the reduction of the horizontal load is caused by sheltering effect from the surrounding buildings. The uplift load, however, could increase or decrease dependent on building orientation, layout and the type of the surrounding buildings. The complicated flow patterns around the test building are discussed and correlated to the wind loads. This study would improve the understanding of tornado-induced loads on a low-rise gable-roof building.

INTRODUCTION

Low-rise buildings are seldom isolated. They are usually surrounded by similar buildings which could influence their design wind loads as specified in building codes for an isolated building. There exist only a limited number of studies on interference effects of surrounding or adjacent buildings on a low-rise building in a straight-line wind (Khanduri et al. 1997; Sun et al. 2008, etc.). Some of these studies involve measurements of load or surface pressure. For example, Ahmad and Kumar (2001) examined interference effects of one and three similar buildings placed at upstream side of a hip roof building at fifteen locations in an atmospheric boundary layer wind tunnel. Remarkable effects on the surface pressure distribution were observed at critical roof positions of the test building (Ahmad and Kumar 2001). Other studies focus on simulating flow in different building arrangement or blocks by means of computational fluid dynamics (CFD) (He et al. 1997; Lien et al. 2004; Zhang et al. 2005), with the purpose of validating the numerical modeling and understanding the interference effects of surrounding groups of buildings. These studies indicate that the upstream buildings play a significant role on wind loads and flow structures of the test building in straight-line winds. To the authors’ best knowledge, there is no such study carried out regarding tornado-induced wind loads and flow patterns.

To quantify the interference effect on tornado-induced wind loads, systematic experiments were carried out in the Iowa State University (ISU) Tornado Simulator with typical configurations of a group of low-rise buildings. Wind loads on a low-rise gable-roof building model were first measured by varying the layout of surrounding buildings and compared with those of the isolated single building. Next, the flow structures in typical cases were visualized by Particle Image Velocimetry (PIV) technique. The purpose of flow study was to correlate the flow distribution around the test building model and in the street canyon surrounding the model with the resulting wind loads, and to better understand the mechanism of the interference effects.
FACILITY AND EXPERIMENT METHODS

ISU TORNADO SIMULATOR

To obtain accurate information of wind velocity field of a tornado and assess the wind loads on civil structures induced by tornados, a tornado simulator based on the mechanism of rear flank downdraft (RFD) has been built and operational at Iowa State University since 2005. The tornado simulator can generate a wide range of maximum tangential velocities ($V_{\theta\text{max}}$ from 6.9 m/s to 14.5 m/s) and vortex structures from a single-celled vortex to dual-celled vortices. A single-celled tornado vortex with $V_{\theta\text{max}}= 6.9$ m/s at the vortex core radius ($r_c$) of 0.23 m with a Swirl ratio (S) of 0.08 was produced (Haan, et al., 2008) and used in this study. Details of development, design and testing of this ISU tornado simulator can be found in Sarkar et al. (2005) and Haan et al. (2008).

BUILDING MODELS AND LOAD MEASUREMENT

One-story ($H_t=44.1$ mm) and two-story ($H_t=75.2$ mm) low-rise building models (test models) with a geometric scale of 1:100, a square plan (B or W=91.4 mm) and a gable roof (angle 15º) were constructed by rapid prototyping technique for load measurement. An aluminum rod was fixed to the center of the test model to connect it to a six-component load cell (30E12A-I40, JR3 Inc.) mounted underneath the ground plane of the tornado simulator. The surrounding building models were made out of styrofoam with the same dimensions as the test model. The test building model was positioned along the path of the vortex center. The building orientation, defined as the angle between the translation direction of the tornado and the roof ridge of the buildings, was set at 0º, 45º and 90º (see Figures 1 and 2). The layout of surrounding buildings in 1- row, 3-row and 5-row configurations was defined with spacings between buildings along the direction of the roof ridge (S1) and the normal direction to the roof ridge (S2) of the test model in terms of $H_t$. The tornado translation speed ($V_t$) was 0.30 m/s. Load data on the test model were continuously recorded at 500 Hz for 24 seconds to cover the full length of the tornado path. Data of ten identical runs were obtained for each case.

As tornado moves over a single building model, the tornado-induced wind loads follow a periodic pattern, as demonstrated by Sengupta, et al. (2008). Herein, the average peak force coefficients calculated for the ten runs for each case with surrounding buildings were compared with that of the isolated building case. The peak horizontal forces ($F_x$ and $F_y$) and peak uplift force ($F_z$) were normalized with the maximum tangential velocity $V_{\theta\text{max}}$ and the corresponding projected area ($A_x$, $A_y$ or $A_z$) of the test building model, defined as follows:

\[ CF_{x,y} = F_{x,y}/(0.5 \rho V_{\theta\text{max}}^2 A_{x,y}) \]  
\[ CF_y = \sqrt{CF_x^2 + CF_y^2} \]  
\[ CF_z = F_z/(0.5 \rho V_{\theta\text{max}}^2 A_z) \]  

Further, both the horizontal (CF$_{xy}$) and uplift force (CF$_z$) peak coefficients were normalized by the corresponding values for the isolated building case, and presented as interference factor (IF).

PIV MEASUREMENT

Flow around the test building model (made of 3.2 mm thick transparent acrylic material) and in the street canyon between adjacent buildings was assessed using PIV method. Smoke generated
from water-based solvent with a mean particle size of 1-3 μm was introduced for seeding the flow. The laser beam from a dual-head Nd:Yag laser with a pulse energy of 120 mJ was made into a thin light-sheet by optics to illuminate tracer particles. A CCD camera (Flowmaster 3) was mounted to capture 300 pairs of particle images at a frame rate of 8 Hz. The particle images were evaluated using an iterative multi-grid method with second-order accuracy and a final interrogation window of 32 x 32 pixels (Davis 6.2.2, LaVision). The mean velocity field was obtained by ensemble-averaging 300 instantaneous velocity fields for each case.

The building model was tested for an orientation angle (OA) of 0º and 90º. Figure 2 demonstrates the corresponding camera view that is always parallel to the ridge of the test building. As a result, the flow field was obtained in the central vertical plane of the test building. Due to the limited frequency of the current PIV system, the measurements were done with a stationary tornado (V_tr=0) at a quasi-steady state. The 2-story gable-roof building was used as the test building for these experiments.

![Figure 1: Layout of groups of buildings tested in the ISU Tornado simulator: (a) 5-row configuration for load measurements; (b) 3-row configuration for PIV measurements](image)

![Figure 2: Schematic diagram of building model orientation with respect to the tornado-like vortex translation (V_tr), (a) OA= 0º and (b) OA= 90º, and corresponding camera views for a stationary case (V_tr=0). The solid arrows show the directions of rotation and translation.](image)
RESULTS AND DISCUSSION

INTERFERENCE FACTORS OF LOAD COEFFICIENTS

Figure 3 shows the Interference Factor (or IF) of peak horizontal loads on the 2-story gable-roof test building surrounded by 2-story and 1-story buildings. The results for the 1-story gable-roof test building are not presented here for conciseness. The notations i x j mean i rows and j columns of buildings. The horizontal force coefficient ($C_{F_{xy}}$) decreases for the cases of the test building with surrounding 2-story buildings compared to that of an isolated building (Figure 3a), hence their IF values are lower than 1.0. The relative change in $C_{F_{xy}}$ of the test building for different building layouts with that of the isolated building case is compared in the following discussion. $C_{F_{xy}}$ decreases for the 1-row layouts ($S1=Ht$ and 0.5 $Ht$); a more remarkable change is observed at OA=0° and 90° than that at OA=45°. $C_{F_{xy}}$ decreases further for the 3-row layout ($S1=0.5Ht$, $S2=2Ht$) compared to the 1-row layouts. The relative decrease with respect to the isolated building case is around 20% for all three building orientations. For this layout, a decrease in $S2$ from 2$Ht$ to $Ht$ decreases the $C_{F_{xy}}$ by 27%, 28% and 39% at the three OAs, respectively, which is more than the 20% reduction. For the case of 5-row configuration with $S2$ as $Ht$, $C_{F_{xy}}$ of the test building is decreased by 30%, 33% and 44% at the three respective building orientations, which is not much different from the case of 3-row configuration with the same spacing. As the test building is surrounded by 1-story buildings, $C_{F_{xy}}$ generally decreases but the maximum reduction of $C_{F_{xy}}$ is about 16%, less than that of the corresponding case of 2-story surrounding buildings.

The decrement of the horizontal load occurs due to the sheltering effect from adjacent buildings. It is noted that the buildings in both directions (parallel and normal to the ridge of the test building) play important roles on tornado-induced wind loads, while only the upstream buildings have a more significant effect on wind loads in a straight-line wind.

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(a) Surrounded by 2-story buildings  
(b) Surrounded by 1-story buildings

Figure 3: IF of horizontal force coefficients ($C_{F_{xy}}$) of the test building in tornado
The IF values of uplift force coefficients ($CF_z$) for the surrounding building cases, however, are higher or lower than 1.0 depending on the building orientation as shown in Figure 4. While the surrounding 2-story buildings reduce the uplift load by 2%-34% of the test building at OA=90°, they increase the uplift load up to 33% at OA=0°. It is interesting to note that 1-row layouts cause the uplift load to decrease at OA=45°, but 3-row and 5-row configurations cause the uplift load to increase at the same OA. Similar trend for the cases of surrounding 1-story buildings can be seen in Figure 4b.

The uplift load results from the suction on building roof, which is closely related with the flow acceleration and roof vortex formed by flow separation. These flow features will be investigated in the following section.

**FLOW PATTERN AROUND THE TEST BUILDING**

**Flow around the test building surrounded by 2-story buildings**

The mean flow around the 2-story gable-roof building at OA=0° with 2-story surrounding buildings in different layouts is compared based on the streamline patterns as plotted in Figure 5. Flow around the single 2-story gable-roof building is regarded as the reference case. A small horse-shoe vortex occurs at the upstream side of the building due to the adverse pressure gradient of the stagnating flow. This flow characteristic is similar to what happens to a building embedded in a straight-line wind (Sousa, 2002). It is noticeable that no separation occurs at the roof edge, thus no roof vortex (separation bubble) is formed, which is usually observed in straight-line winds. In addition, a wake vortex appears adjacent to the leeward wall of the building. It is reasonable to see that the flow pattern around the single 2-story gable-roof building in a simulated tornado is different from that in a straight-line wind, considering that the tornado flow is a strong swirling three-dimensional flow.

In the 1-row configuration ($S_1=H_t$, in Figure 5b), flow in the upstream of the test building is not affected, that is, the horse-shoe vortex is still visible at the upstream side of the building. However, the wake vortex moves up and another large wake vortex appears further downstream of the test building, which is different from the single building case. Decrease in the spacing $S_1$ from $H_t$ to $0.5H_t$ (Figure 5c) leads to the formation of a large vortex close to the leeward wall, instead of two wake vortices in Figure 5b.
In the 3-row layout, flow at both the windward and leeward sides of the test building changes significantly. For the case of S1=0.5Ht and S2=2Ht (Figure 5d), a large-scale vortex forms on the windward side and the horse-shoe vortex disappears. On the leeward side, two wake vortices appear. As the spacing S2 deceases to Ht, two wake vortices appear in the canyon upstream of the test building, and a single large wake vortex forms near the leeward wall (Figure 5e).

The vortices in the canyon upstream of the test building do not show remarkable difference as the surrounding buildings increase from 3 to 5 rows (S1=0.5Ht, S2=Ht in Figure 5f), while the wake vortex in the leeward side is modified somewhat. The general impression is that wake region of the test building is more vulnerable to change under the effects of surrounding buildings at OA=0°.

Figure 6 depicts mean flow around the 2-story gable-roof building with adjacent 2-story buildings at OA=90°. For the case of the 2-story gable-roof single building, flow at OA=90° is quite different from that at OA=0° due to the fact that the incoming flow in the measured plane are mainly the radial velocity (Vr) and the vertical velocity (Vz) of the tornado winds. In this case, neither the horse-shoe vortex nor the wake vortex (usually observed in the straight-line winds) is seen. The most salient flow feature is that a separation vortex is formed above the rear half of the roof, which could be closely related with the higher uplift force acting on the test building at OA=90° than that at OA=0°. No wake vortex is visible, however, the streamline distribution shows seemingly diverging bifurcation line according to the critical point theory (Perry and Chong 1991). The diverging bifurcation line is often related with three-dimensional separation.

In the 1-row layout (Figure 6b and Figure 6c), the radial velocity above the roof is enhanced so much that the separation vortex does not form at both S1=Ht and 0.5 Ht. Flow in the leeward side does not change as compared to the case of the single building. In addition, the small horse-shoe vortex at the corner upstream of the test building can be seen for both cases.

The flow of 3-row layout (S1=0.5Ht and S2=2Ht in Figure 6d) is very similar to that of 1-row layout (S1=0.5Ht, in Figure 6c). Reducing the spacing S2 from 2Ht to Ht causes the reversed flow upstream of the test building. Also, the flow downstream of the test building is modified so that the bifurcation lines are not shown. Further increasing the surrounding buildings from 3-row to 5-row configuration does not cause any visible flow pattern modification.

**Flow around the test building surrounded by 1-story buildings at OA=0°**

Comparison of the flow pattern around the 2-story gable-roof building surrounded by 1-story buildings (in Figure 7) with the cases of the same building surrounded by 2-story buildings (in Figure 5) at OA=0° helped in the understanding of the effect of height ratio (H/Ht). It is observed that the vortices formed on the windward side of the building decrease in the quantity and intensity as the building is surrounded by 1-story buildings, especially in the cases shown in Figure 7 (d), (e) and (f). On the leeward side, the effects of reducing the spacing S2 and increasing the rows of surrounding buildings seem not evident.
Figure 5: Mean streamlines around the test building with surrounding 2-story buildings at OA=0°
Figure 6: Mean streamlines around the test building with surrounding 2-story buildings at OA=90°
CONCLUSIONS

Systematic experiments were carried out to study the interference effect of the surrounding buildings on the tornado-induced wind loads on a low-rise gable-roof building. The reduction of the peak horizontal load is caused by sheltering effect from the surrounded buildings. The peak uplift load, however, could increase or decrease dependent on building orientation and layout of the surrounding buildings.

Flow patterns around the test building vary according to the configuration of the spacing and height ratios. The results indicate that the surrounding buildings in both directions considerably affect the flow structure, resulting in variations of tornado-induced wind loads on the test building. At the building orientation angle (OA) of 0°, complicated vortex system form
and the wake region of the test building is more vulnerable to change under effects of surrounding buildings. At OA=90°, no distinctive vortex system is observed in the measured plane. However, bifurcation lines may be the clues of three-dimensional separation and vortex structures detectable in the orthogonal plane. For both building orientations, increment of adjacent buildings from 3-row to 5-row configuration plays minor effects on the flow patterns and the tornado-induced wind loads.

Further study on turbulence characteristics of the flow around the test building, in particular kinetic energy transfer between the mean flow and the fluctuations, will be performed to address the correlation of the flow patterns and tornado-induced wind loads.

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REFERENCES


