NUMERICAL EVALUATION OF WIND LOADS ON A TALL BUILDING LOCATED IN A CITY CENTRE

Ahmed Elshaer  
WindEEE Research Institute, Western University, Canada

Haitham Aboshosha  
Boundary Layer Wind Tunnel Laboratory, University of Western Ontario, Canada

Girma Bitsuamlak  
WindEEE Research Institute, Western University, Canada

Ashraf El Damatty  
WindEEE Research Institute, Western University, Canada

ABSTRACT

Estimation of wind-induced loads and responses is an essential step in tall building design process. Wind load for super tall buildings is commonly evaluated using boundary layer wind tunnel (BLWT) tests. However, the recent development in computational power and techniques is encouraging designers to explore numerical wind load evaluations using a Computational Fluid Dynamics (CFD) approaches. CFD can provide a faster estimation for building loads and responses with lower cost and satisfactory accuracy for preliminary design stages. The current study investigates the accuracy of evaluating wind pressure and building responses of a typical tall building (CAARC building). Two configurations are investigated, which are (1) standalone building and (2) located in a city center. Large Eddy Simulation (LES) numerical model is utilized adopting a newly developed synthesizing turbulence generator named Consistent Discrete Random Flow Generator (CDRFG). The adopted inflow technique is believed to provide good representation of wind statistics (i.e. velocity and turbulence profiles, spectra and coherency). Pressure distributions and building responses from the current study match with those obtained from boundary layer wind tunnel tests. The average difference between the pressure values between the current model and the BLWT is 4%. While the difference in building responses resulted from the LES model to those from BLWT is 6%. It was found that utilizing CDRFG in LES models provides an accurate estimation for building aerodynamic performance in an efficient computational time owing to its capability of supporting parallel processing.

Keywords: Wind load; CFD; Tall Building; Wind Response; Large Eddy Simulation (LES); Complex surrounding

1. INTRODUCTION

Tall buildings are considered one of the most sensitive structures to wind loads, which made wind load evaluation an essential aspect in the design of any tall buildings. Evaluation of wind loads and responses was extensively studied through numerous experimental researches using wind tunnel testing (e.g., Coyle 1931, Melbourne 1980 and Davenport 1975). In the last three decades, there have been significant improvements in computer technology, which encouraged the use of Computational Fluid Dynamics (CFD) in many wind engineering applications. Large Eddy Simulation (LES) models are one of the most efficient techniques in turbulence modeling, which were utilized in wind simulations around buildings in many previous studies, such as Nozawa and Tamura 2002, Braun and Awruch 2009, Dagnew and Bitsuamlak 2014 and Aboshosha et al. 2015. The majority of those studies primarily focused on standalone buildings without considering the effect of the adjacent structures. There are few studies that investigated the influence of single adjacent building such as Dagnew and Bitsuamlak 2013, while others studied a building located in a complex surrounding, for instance Dragoiescu et al. 2006.
Obtaining a precise wind-induced loads and responses requires careful selection of the upcoming wind properties (Huang and Li 2010). The authors developed an efficient technique for inflow generation, which called the Consistent Discrete Random Flow Generator (CDRFG) (Aboshosha et al. 2015). This technique provides a discrete flow field time series, which satisfy the target velocity and turbulence profiles in addition to continuity and coherency function. Those inflow properties are essential to get highly accurate simulation of the wind behavior (Davenport 1993 and Kijewski and Kareem 1998).

In the current study, the CDRFG technique is utilized to evaluate the wind pressure distributions and the building responses for a typical tall building in both standalone and surrounded configurations. This typical tall building is called the Commonwealth Advisory Aeronautical Research Council (CAARC) building, which has been extensively adopted in a number of experimental and numerical studies (Melbourne 1980, Dragoiescu et al. 2006, and Elshaer et al. 2016). The accuracy of the CDRFG technique is assessed by comparing the results obtained from the current work with previous numerical and experimental studies from the literature. Also, the effect of considering the surrounding structures is presented by comparing the building responses resulted from both the standalone and the surrounded configurations.

2. LARGE EDDY SIMULATION MODELS

The current numerical study is conducted to be similar to the wind tunnel test by Dragoiescu et al. 2006, which was conducted at Rowan Williams Davies and Irwin (RWDI) Inc.’s wind tunnel laboratory. The building is tested for two configurations: standalone and surrounded configurations. The length and time scales used are 1:400 and 1:100, respectively. The building is tested for open terrain exposure with mean wind velocity of 10 m/s at the building height and inflow profiles as shown in Figure 1. The latter profiles are utilized to generate the turbulent inflow using CDRFG technique. Computational domain dimensions are selected to satisfy the recommendations of COST 2007 Frank 2006. Symmetry plane boundary condition is assigned for the computational domain sides and top, while no-slip boundary condition is assigned for the bottom of the computational domain and all the buildings’ faces. Figure 2 shows the computational domain dimensions and boundary conditions adopted in the LES models. (STAR-CCM+ v.9.04) commercial CFD package is utilized to conduct the numerical simulations. For this purpose, a dynamic sub-grid scale model of Smagornisky 1963 and Germano et al. 1991. The time step for the transient simulation is 0.0005 sec to ensure the convergence and the accuracy of the analysis by maintaining the Courant Friedrichs-Lewy (CFL) number lower than 1.0. The analyses are conducted for 14,000 time steps, which represents 11.5 minutes in full-scale. The high performance computing facility at the University of Western (Shared Hierarchical Academic Research Computing Network, SharcNet) is utilized to perform the computations for the models (lasted for 11 hours using 128 cores).

Figure 1: Profiles measured from the wind tunnel and the fitted profiles for CFD
The computational domain is discretized using polyhedral control volumes. Properties of the grids are summarized in Table 1. As illustrated in Figure 2, grid sizes are divided into three zones. Zone 1 is located away from the building of interest where the grid size is maximized. Zone 3 is located close to the building of interest and its surroundings. Grid size in this zone is decreased to capture important details of flow structures in the wake zone and the front zone between the inflow and the building. Fifteen parallel meshes parallel to the building surfaces with a stretching factor of 1.05 is utilized in zone 3 to satisfy the recommendations by Murakami 1998, COST 2007 and Tominaga et al. 2008. Zone 2 is chosen in between zones 1 and 3 and has an intermediate grid size.

Figure 3: Grid discretization adopted in the standalone and surrounded configurations
Table 1: Properties of the grids

<table>
<thead>
<tr>
<th>Grid size</th>
<th>Standalone</th>
<th>Surrounded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>H / 10</td>
<td>H / 10</td>
</tr>
<tr>
<td>Zone 2</td>
<td>H / 30</td>
<td>H / 20</td>
</tr>
<tr>
<td>Zone 3</td>
<td>H / 70</td>
<td>H / 50</td>
</tr>
<tr>
<td>Total number of cells</td>
<td>1,510,000</td>
<td>1,920,000</td>
</tr>
</tbody>
</table>

3. WIND FLOW FIELD

Figure 4 shows the instantaneous velocity contour plot for standalone and surrounded configurations. As demonstrated by the figure, the approaching velocity field in the surrounded case varies from the standalone case due to the presence of other structures in front of the study building. The complex flow field demonstrates that the neighboring structures change the characteristics of the upcoming wind as it approaches the study building. The presence of the surrounding structures results in complex flow interference such as channeling and wake effects on the study building.

4. PRESSURE COEFFICIENT DISTRIBUTIONS

Figure 5 shows the mean pressure coefficients ($C_p$) distribution across a horizontal section at 2/3 of the building height compared with the experimental results obtained from the BLWT testing (Dragoiescu et al. 2006) and similar simulations from the literature (Huang et al. 2007; Dagnew and Bitsuamlak 2014). For the LES, the reference pressure is taken at a point on the inlet boundary at the building height. While in the experimental testing, the reference pressure is taken at the building height measured by the pitot-tube installed at the building height upwind of the turntable. As indicated in this figure, there is a very good agreement between the mean $C_p$ distributions resulted from the present LES and literature with those from the BLWT on both windward and leeward faces (i.e. ~2% on average). For the side faces, where the separation occurs, the current study provides also close pressure results to the BLWT measurements (i.e. ~3% on average). It is noticed that the maximum difference in mean $C_p$
between the LES and the experimental results located in the side faces, where the difference reached 12%. By comparing the mean pressures resulting from the current study and other numerical simulations, it appears that the LES model employed in the current study leads to a better matching results with the BLWT for the leeward and side faces. Figure 6 shows the distribution of the root-mean-square (rms) $C_p$ at the horizontal section at 2/3 of the building height resulted from the numerical and experimental results. The rms $C_p$ distribution resulted from the current LES model has a better agreement with the BLWT measurements than other the numerical simulations from the literature (i.e. ~ 4% on average).

![Figure 5: mean $C_p$ distribution over horizontal section of the building](image)

Figure 5: mean $C_p$ distribution over horizontal section of the building

![Figure 6: rms $C_p$ distribution over horizontal section of the building](image)

Figure 6: rms $C_p$ distribution over horizontal section of the building

Figure 7 indicates the mean $C_p$ distribution on the building faces for the standalone and the surrounded building configurations. By comparing the mean $C_p$ for the standalone and the surrounded building configurations, it is noticed that the neighboring structures significantly changed the pressure distribution on the building. The surrounded building experiences a sheltering effect as it is located in the urban canopy developed from the interference between wakes of the surrounding upstream buildings. This leads to unsymmetrical distribution of the mean $C_p$ for the surrounded building configuration compared to the symmetric distribution for the standalone case. Moreover, the absolute mean pressure values for the surrounded configuration is found to be lower than the values of the standalone configuration (i.e. 50% or more), which agrees with the findings of Kim et al. 2012. Figure 8 shows the distribution of the rms $C_p$ for the two configurations. For the surrounded building configuration, the rms pressure values are higher than those in standalone configuration (i.e. 40% on average). This reflects the higher turbulence in the surrounded case resulted from the presence of other surrounding structures. Those surrounding structures act as an additional roughness affecting the upcoming wind.
5. BUILDING RESPONSES

In order to calculate the building responses and wind-induced base moment spectra, the building base moment time histories are extracted from the LES. Figure 9 plots the obtained time histories of the base moments, where base moments around x, y and z-axis are in the along-wind, across-wind, and torsional directions. It is noted that lower along-wind moments are developed in the surrounded configuration compared to the standalone configurations. This decrease in the longitudinal moments for the surrounded configuration results from the shedding of surrounding structures located in the upstream of the study building. Concerning across-wind moments, higher values are developed in the surrounded configuration compared to the standalone ones. The rise in across-wind moments, for the surrounded configuration, is caused by the increase in wind turbulence component resulted from the surroundings.
Figure 9: Base moments around the x-axis (along-wind), y-axis (across-wind) and z-axis (torsional)

Figure 10 shows the smoothed Power Spectral Density (PSD) plot, which illustrates the energy distribution with the corresponding frequencies. The PSD plots are evaluated for the standalone and the surrounded configurations using the time history base moments acquired from the LES and the BLWT tests. As shown in this figure, the PSD obtained from the LES matches reasonably well with the experimental measurements in the along, across, and torsional wind directions with an average regression coefficient of 0.91. The agreement with the experimental results is found to be affected for the high frequency range. Although this does not seem to affect the overall base results, it can be further enhanced by using finer grid resolution (i.e. improving the LES cut-off frequency).

Using the spectra of the evaluated base moments, the dynamic responses of the CAARC building are evaluated using the method described by Zhou et al. (2003) and Chen and Kareem (2005). The natural frequencies of the building are assumed to be 0.15, 0.15 and 0.3 in the along-wind, across-wind and torsional direction. The damping ratio of the structure is assumed to be 1% while the density of the structure is 192 kg/m³. It is assumed that there is no coupling between the responses modes. The center of mass of the study building is assumed to coincide with its center of rigidity. All building responses are reported at the center of mass of each floor. The peak displacement, acceleration, and base moment are plotted in Figures 11, 12 and 13, respectively. The responses of the CAARC building obtained from the LES models are in agreement with those from the BLWT. Average difference between LES and wind tunnel responses is found to be 6% for both the standalone and surrounded building configurations. This indicates the accuracy of evaluating wind loads and responses using LES while employing the CDRFG technique in providing inflow field. Figures 11-13 also show that surrounded configuration has lower along-wind and torsional response (i.e. top deflection, acceleration and base moments) values than the values of the standalone configuration (i.e. 30% lower). While the across-wind responses of the surrounded configuration are higher than those of the standalone configuration (i.e. 15% higher). This results from the shedding effect introduced by the upstream and side surrounding buildings.
Figure 11: Peak top floor displacements

Figure 12: Peak top floor accelerations

Figure 13: Peak base moments
6. CONCLUSIONS

This study evaluated the aerodynamic response of tall buildings using LES. The method of Consistent Discrete Random Flow Generator (CDRFG) developed previously by the authors is used to generate the inflow boundary condition that satisfies the proper turbulence spectra and coherency. The CAARC building is modeled considering both standalone and surrounded configurations. This is to assess the accuracy of LES employing the CDRFG technique in evaluating tall building responses for both configurations. Results obtained from the LES model are compared with the results obtained from a previous boundary layer wind tunnel (BLWT) test and previous numerical simulations. The following conclusions can be drawn:

- The employed LES model using the CDRFG technique to simulate the inflow field leads to more accurate estimation for the wind pressure distributions on a tall building and its responses. Since, this model supports parallel computation, it allows for a time-efficient evaluation of the building aerodynamic behavior (i.e. in the order of 12 hrs.).
- Pressures obtained from the current LES model for the standalone building configuration are in in a very good agreement with the pressures measured in the BLWT. Mean pressure values obtained from the current LES model have a better agreement with the BLWT results compared to previous numerical models (i.e. ~ 3% on average). Also, rms pressure values obtained from the current LES model agree with the BLWT results compared to previous numerical models at the windward and leeward building faces. (i.e. ~ 4 % on average).
- Base moment spectra and building responses obtained from the current LES model well agree with the spectra and responses obtained from BLWT. Average difference between LES and BLWT responses is found to be less than 6% for both configurations.
- As expected, significant differences are noticed in terms of pressures and dynamic responses of the standalone and the surrounded configurations. In general, surrounded configuration has a lower mean pressure values (i.e. 50 % or more) and higher rms values (i.e. 40 % on average) than those of the standalone configurations. The along-wind and torsional responses of the surrounded configuration are found to be lower than the responses of the standalone configuration (i.e. 30 % lower). However, the across-wind responses of the surrounded configuration are found to be higher than the responses of the standalone configuration (i.e. 15 % higher). This indicates the importance of including the surrounding effects while evaluating the pressure distributions of a tall building and responses.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support from the National Research Council of Canada (NSERC) and Canada Research Chair (for the third author). The authors are grateful for the ShareNet for providing access to their high performance computation facility and excellent support from their technical staff. Last but not least, RWDI Inc. is greatly acknowledged for providing us with the wind tunnel data used for assessment. Findings and opinions expressed in this paper are those of the authors alone, and do not necessarily reflect the views of the sponsoring agency.

REFERENCES


COST. 2007. Best practice guideline for the CFD simulation of flows in the urban environment COST; Action 732.


SHARCNET is a consortium of colleges, universities and research institutes operating a network of high-performance computer clusters across south western, central and northern Ontario,” 2015; [Online]. Available: www.sharcnet.ca.

