Building Tomorrow's Society
Bâtir la Société de Demain

Fredericton, Canada
June 13 – June 16, 2018/ *Juin 13 – Juin 16, 2018*

PROGRESSIVE COLLAPSE OF LOW-RISE BUILDINGS UNDER WIND LOADS

Elshaer, Ahmed [1,4], Bitsuamlak, Girma[2] and Abdallah, Hadil [3]
[1] Department of Civil & Environmental Engineering, Western University, ON, Canada
[2] Department of Civil & Environmental Engineering, Western University, ON, Canada
[3] Department of Civil & Environmental Engineering, Western University, ON, Canada
[4] Email: aelshae@uwo.ca

Abstract: Low-rise buildings are vulnerable structures to wind damage during hurricanes, typhoons and extreme wind events. Various experimental and numerical studies were conducted on low-rise buildings to evaluate and control the wind-induced loads. These studies considered wind to be acting on the building external walls. This assumption can only be applicable for closed building envelops. However, during extreme events, buildings may lose some non-structural components (e.g. windows and doors), which will allow wind to enter the building envelop leading to alteration of flow field and redistribution of wind loads. Consequently, this transfer may subject the internal walls to additional lateral loads exceeding their typical load resistance capacities (i.e. internal walls are typically of lower capacities compared to external walls). Furthermore, Failure of windward façade may expose the structure to higher wind loads due to the increase in the total subjected area to wind. On the other hand, as the collapse of components progresses to leeward faces, the channeling flow through the building may distract the wake formation reducing loads on exterior walls. The current study examines a four-story gable roof house during a progressive collapse scenario. Computational Fluid Dynamic (CFD) simulations were used to study the progressive stages of building damage for wind azimuth (0°). In addition to the undamaged stage, three damage stages were assumed. In the first two stages, building components in the windward direction were damaged allowing air to enter the internal spaces. While in the final stage, the damage reached the leeward components allowing the trapped air to channel through the building, which was found to decrease the overall load on the building.

Keywords: Low-rise building; wind load; aerodynamics, internal pressure; progressive collapse; turbulence, Large Eddy Simulation (LES); Computational Fluid Dynamics (CFD)

1 INTRODUCTION

Post-Hurricane investigations have stated that severe damage took place among low-rise buildings as a result of wind in extreme weather conditions. For instance, according to the report issued by NOAA (Smith et al. 2018) hurricane Irma - September 2017 had a serious impact on Florida's built-up area where more than 25% of the buildings were destroyed, 65% were significantly damaged, and 95 fatality incidents occurred. However, economically, such disasters affected the total loss cost to exceed 1.2 trillion dollars for the time between 1980 to 2017 (Smith et al. 2018). Various experimental and numerical studies have been performed on low-rise buildings to examine the behavior of building envelops during excessive wind events in order to assess and restrict the wind-induced loads. Earlier in the mid 70's, (Davenport 1977) managed to conduct a chain of wind tunnel tests for different low-rise buildings with distinct boundary layer wind profiles. Later-on, Pressure distribution have been expansively examined on low-rise building roofs by several researchers. Validation was performed by(Lin et al. 1995) through evaluating the crucial corner regions via comparing with existing full-scale measurements for different constructing heights and plan sizes. (Uematsu and Isyumov 1999) also reported several wind tunnel and field pressure measurements for building roofs. On the same route, several researchers adopted both experimental ((Kopp et al. 2012), (Tecle et al. 2015)) and numerical ((Nozawa and Tamura 2002), (Montazeri and Blocken 2013)) techniques to investigating wind loads on low rise buildings. Aerodynamic mitigation approaches was also introduced by others as a way of reducing wind-induced loads on building exterior including ((Kopp et al. 2005), (Bitsuamlak et al. 2012)). Most of these studies focused intensively on examining the wind loads on the external walls assuming intact building with perfectly sealed envelop.

From a different perspective, Investigations have been made around examining the mean and fluctuating internal pressures in buildings with nominally sealed envelops and dominant openings. Internal pressure investigations were highlighted by (Stathopoulos et al. 1979), (Holmes 1980), who performed various model and full-scale studies. Subsequently in 2008, a cohesive relationship between internal pressures and external pressures was developed by (Ginger et al. 2008) at a dominant opening in terms of sizes and volume of the opening. Furthermore, (Ginger et al. 2010) studied the effect of roof suction with respect to the internal pressure on a dominant windward opening. Aerodynamics of low-rise buildings with opening was also covered intensively through a literature review presented by (Holmes and Ginger 2012) in the light of previous theories. In addition to that, a wind tunnel test was conducted by (Pan et al. 2013) on a one-story gable house model analyzing the effect of internal pressure on the successive failure of non-structural elements.

During wind events, there is a significant possibility for wind to breach through the building envelop due to sudden impact of wind-carried debris on non-structural components (e.g. window, door, roof tile) or overloading these components' capacities in extreme wind conditions. As a result, it is essential to consider the influence of internal walls along with external walls for wind load resistance. Various damage states may result in (1) altering the wind flow field internally and externally, (2) redistributing wind loads on the external walls and roof, (3) subjecting the internal walls to additional lateral loads, which are not typically considered in their structural design, and (4) exposing building surfaces (walls and roof) to a combination of both the internal and external pressures (i.e. net forces), which is the main concern of the current study.

The purpose of the current work is to study the behaviour of wind flow field and it's influence on the external and internal surfaces of the building, assuming a predicted scenario for a progressive collapse of non-structural elements. These damage stages are predetermined based on a logical sequence of successive failure from one zone to another.

For further realistic scenarios, this work can be further investigated through coupling Computational Fluid Dynamic (CDF) simulations along with structural modeling techniques such as Finite Element Methods (FEM) to assess the exact spots of failure. The study model is a four-story gable roof house examined under 4 damage stages including the intact form of the building envelop. Computational Fluid Dynamic (CFD) simulations are used to study wind effect at different damage stages for a single wind azimuth (0^o). Apart from the undamaged stage, the successive 2^{nd} and 3^{rd} stages address an assumed failure of non-structural components (i.e. windows and doors) of the windward face results in breaching of wind through the building envelop allowing air to get trapped in primarily zones. While along the final stage, failure propagates to reach the leeward openings allowing channeling of trapped air through the building. Wind-induced pressures and forces acting on walls (internal and external) and roof are evaluated. The paper is organized into four sections. Section 1 (this section) presents an introduction and literature review on the previous studies examining the wind effect on low-rise buildings. In Section 2, a description of the adopted CFD model is provided. Section 3 presents the results and discussion. Finally, Section 4 summarizes the conclusions and main findings of the study.

2 NUMERICAL STUDY DETAILS

2.1 Study case

In this study the examined building has an overall area of 400 m2 consisting of four stories with an equal height of 3 m Figure 1. The typical plan includes 7 windows and 5 doors, and the story plan is divided into 5 regions. A predefined progressive failure scenario is assumed. Four different damage stages are presented (C0, C1, C2 and C3), and the damage stages and flow accessibility are defined in each story as shown in Figure 2. In the initial damage state (i.e. C0) the building is considered intact with no openings allowing the wind flow to enter the building envelop. The failure of window (W1) is assumed in stage (C1) allowing the wind to access Zone 1 of Story 2. As the damage progresses to (C2), wind flow accesses Zones 1 and 2 in all stories due to the damage of windows (W1, D1 and roof window), while for Story 2, Zone 3 and 4 become accessible to wind due to the failure of (W2, W3, D2 and D3). Finally, in the last damage stage (C3), 83% of windows and 90% of doors are assumed to be damaged allowing the wind to reach all zones of the examined building. Table 1 provides a detailed summary for the damage stages and failed components.

Table 1 Summery for cases naming and damage details

Damage stage	Failed windows	Failed doors
C0	--	--
C1	W1 in Story 2 (3.5% of total windows)	D1 in Story 2 (5% of total doors)
C2	W1 in all stories W2, W3 in Story 2 and roof window (24% of total windows)	D1 in all stories D2, D3 in Story 2 (30% of total doors)
C3	All in Stories 2, 3 and 4 W1, W4 in Story 1 and roof window (83% of total windows)	All in Stories 2, 3, 4 D1, D2, D3 in Story 4 (90% of total doors)

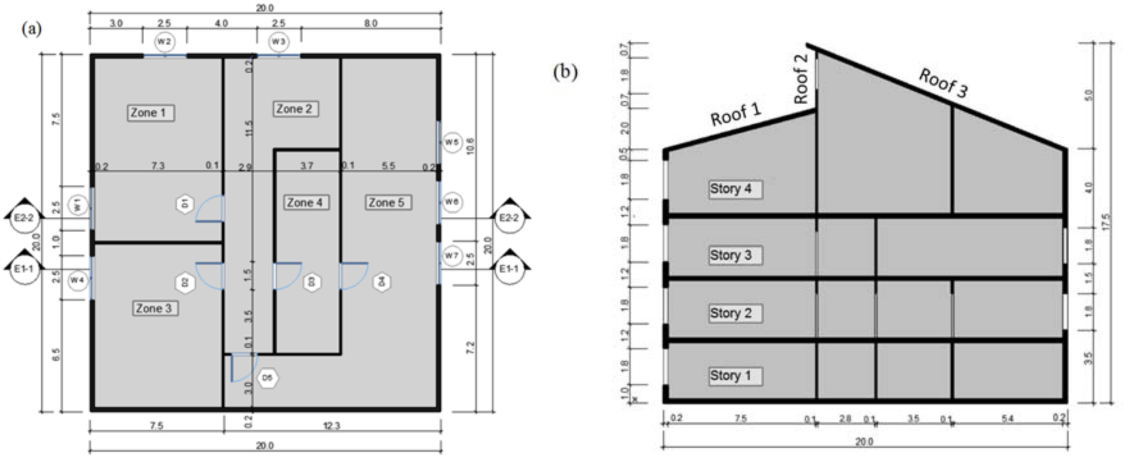


Figure 1 (a) Typical Plan and (b) Section Elevation (E 1-1) dimensions (in meters) for the study building

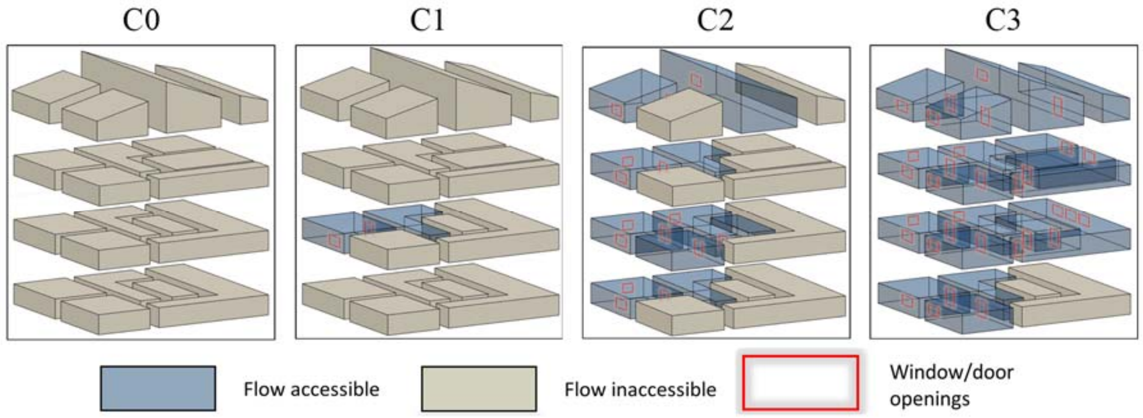


Figure 2 Wind accessibility zones through damage stages

2.2 Numerical simulation details

CFD simulations were performed on full scale models to assess the different failure stages. Large eddy simulation (LES) models are utilized and the computational domain properties and dimensions are defined based on the procedure recommended by (Franke et al. 2007) and (Elshaer et al. 2016). A no-slip wall boundary condition is assigned to the ground and all walls of the building, while symmetry plane boundary condition is assigned for top and side faces of the computational domain. The inflow generation is performed based on the Consistent Discrete Random Flow Generation (CDRFG) technique developed by (Aboshosha et al. 2015), while the outflow of the computational domain is defined as a pressure outlet. The computational domain dimensions and the boundary conditions assigned for the LES are shown in Figure 3. An urban terrain exposure is considered, the profiled for the mean, turbulence intensity and turbulence length scales are generated following (ESDU 2001) guidelines as shown in Figure 4. The computational domain consists of hexahedral meshes with a total number of 1.6M cells. For the region away from the studied area (i.e. Mesh Zone 1) a mesh size of 4.0 m is selected. To capture the generate turbulence from the inflow boundary condition, the computational domain is refined near the building area (Mesh Zone 2), having a mesh size of 0.2 m (Figure 5). The time used in the simulations is 0.05 seconds maintaining the Courant number below 1.0 to ensure numerical convergence of the solver (Courant et al. 1928). The numerical simulations are conducted for 2,000 time-steps, which represent 100 seconds. CFD simulations are conducted using the commercial software (Star CCM+ v.10.02.011 2016) using a dynamic sub grid model suggested by (Smagorinsky 1963).

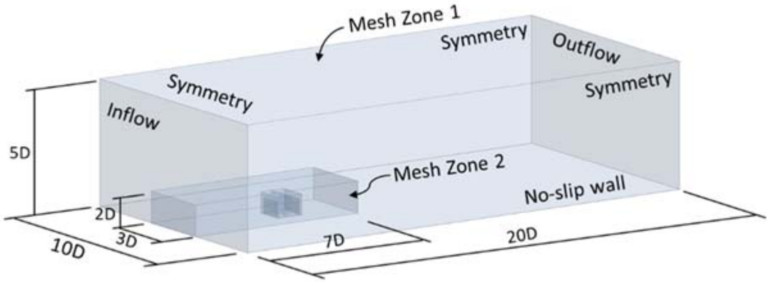
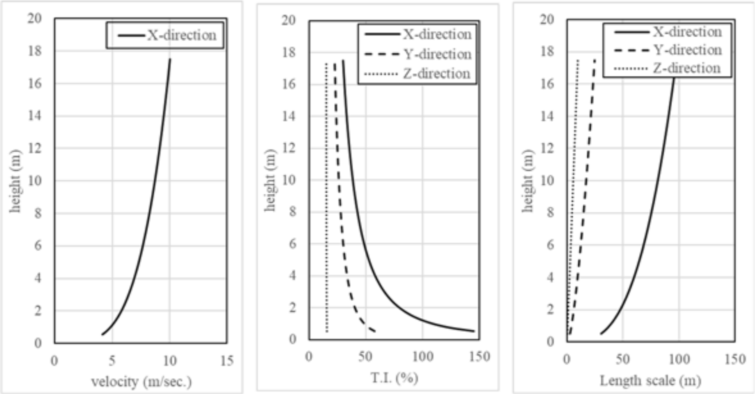


Figure 3 Computational domain dimensions and boundary conditions



(a) (b) (c)

Figure 4 (a) mean velocity, (b) turbulence intensity and (c) turbulence length scale profiles used for inflow generation using CDRFG technique

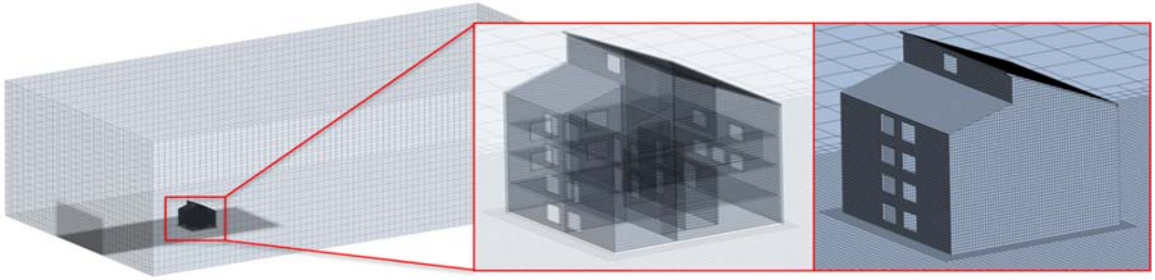


Figure 5 Mesh grid resolution utilized in the CFD simulations

3 RESULTS AND DISCUSSIONS

3.1 Wind flow field and pressure distribution

Figure 6 shows the mean wind velocity field and mean velocity streamlines. Minor differences are observed in the wind flow structure surrounding the building especially for damage stage (*C3*), as the flows channel through the study building, they started opposing the flow in the wake behind the building. However, the internal mean flows vary significantly along different damage levels. For instance, at Case (*C1)*, the inward wind flows at Story 2 was trapped forming a recirculation in Zone 1 and Zone 2 due to the opening of *W1* and *D1*. This trapped flow is expected to cause high values of fluctuating forces on the internal walls surrounding it. As the damage progresses to (*C2*), the wind flow channeled through the building reaching the leeward face of the building and escaping to outside through *W3. While in* (*C3*), both story 1 and story 2 witness a channeling wind flow entering from *W1* and *W4* and exiting from *W3* and *W7,* respectively*.* The mean pressure coefficient (*Cp*) distributions is shown in Figure 7. It is noticed that the mean *Cp* distributions on the external walls did not significantly change over the damage stages (i.e. less than *3.5%*)*.*

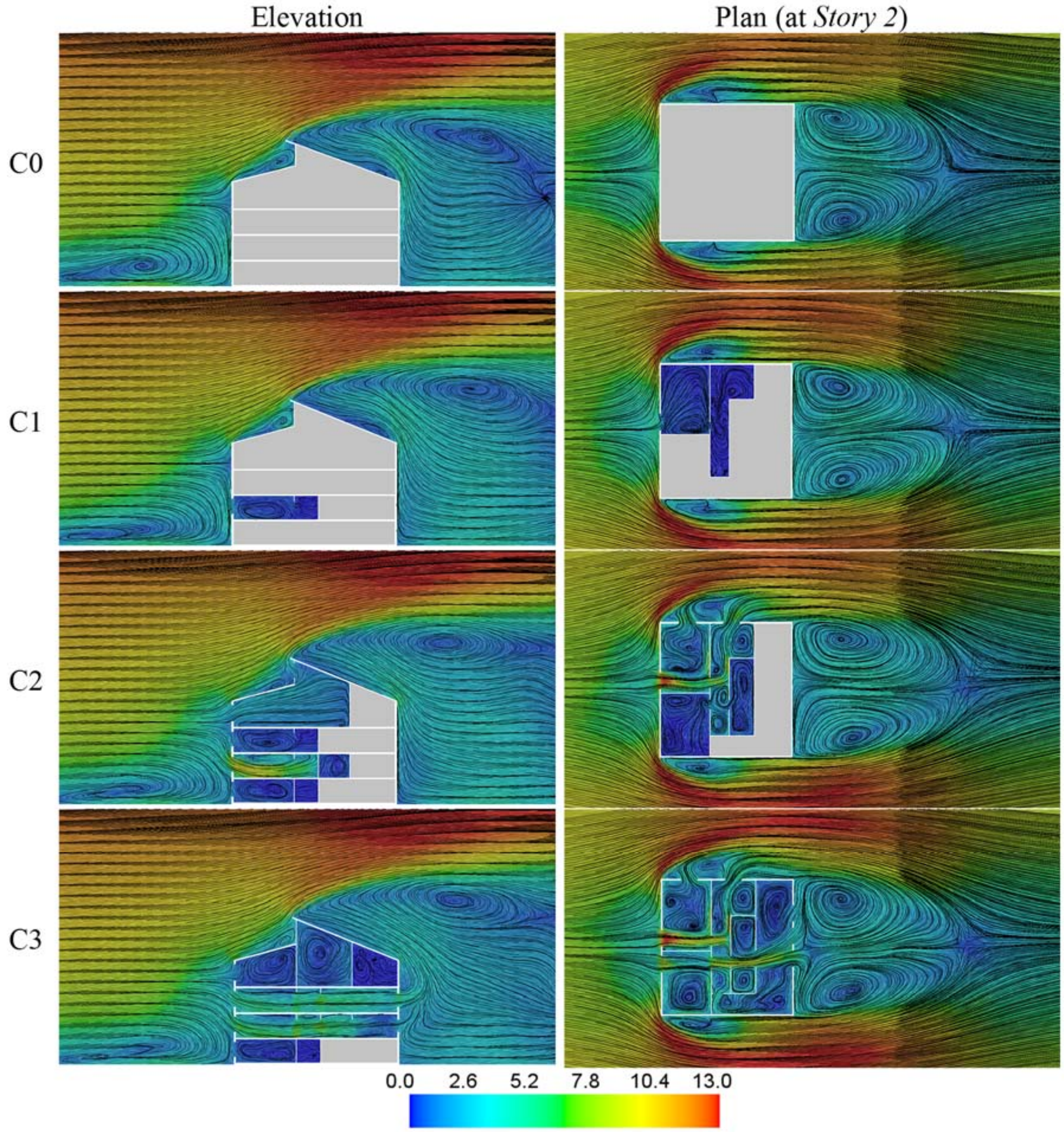


Figure 6 Mean velocity contours and wind flow streamlines for different damage stages

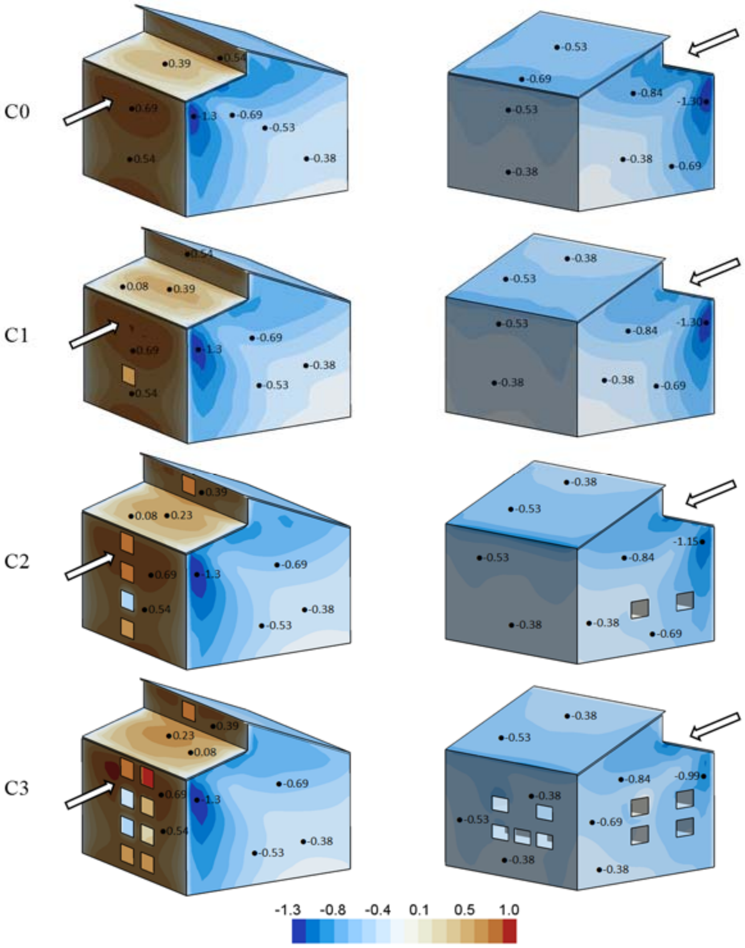
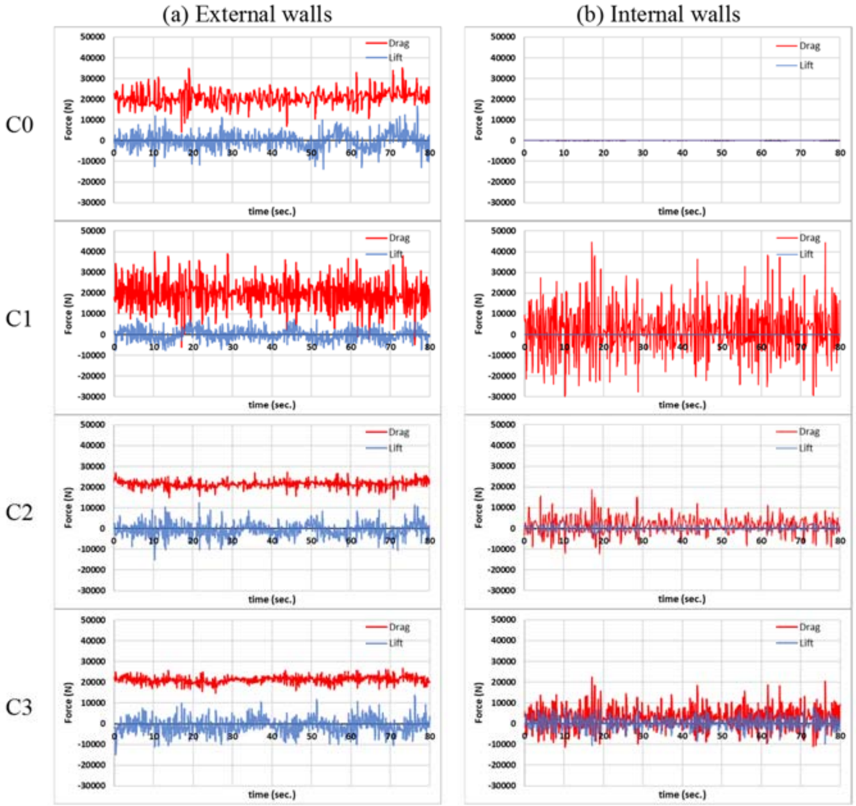


Figure 7 Mean of *Cp* on external walls of the study building for different damage stages

3.2 Wind forces on walls and roof

The total foundation level wind forces (drag and lift) have been evaluated by integrating the wind pressures on both external and internal walls of the building. Figure 8 shows the total drag and lift forces acting on the building walls externally and internally. It is observed that the mean forces on the external walls of the building has a quite insignificant change (less than 3.0%). However, there was a notable variation in the fluctuating component of wind forces at the early stage of failure (C0) and supressed gradually (i.e. up to 25% compared C0) as the building progresses in damage. This can be due the channeling effect of wind flow through the building in the opposition of wake formation. As for the internal walls, a significantly high fluctuating component in the drag forces is witnessed for stage C1, almost 1.5 times the corresponding external forces. These internal wind forces initiated an amplification of the fluctuating component due to a flow resonance known by Helmholtz resonance (Holmes 1980). As the building progresses in damage, this amplification gradually decreases as wind channels through the building allowing the trapped air to escape from the leeward openings, thus interfering with the flow circulation zones. On the contrary, the fluctuating lift forces on the internal walls increased significantly in cases C2 and C3 especially at the damage of the side openings of the building (W3 and W4).

Over the damage stages, time histories of roof forces (*F1*, *F2* and *F3*) are to be calculated as shown in Figure 9*.* Once the building progresses to stages *C2* and *C3*, an alteration of the mean wind forces on *Roof 1* and *2* occurred due to the internal pressure changes. This alteration changed the forces (F1 and F2) from being typically positive to negative uplift forces. Moreover, the internal pressure inside the building is found to increase the total uplift forces on *Roof 3* (*F3*) with the increase in building damage (i.e. up to ~1.9 times compared to the undamaged case C0). This significant increase in the total uplift forces is due to both the internal and external wind forces that are acting in the same direction. As a result, roof parts contribute in the increase of the potential wind risks with the progression of building damage.


(a) External walls

(b) Internal walls

Figure 8 Drag and lift forces time histories on the (a) external and (b) internal wall for different damage stages

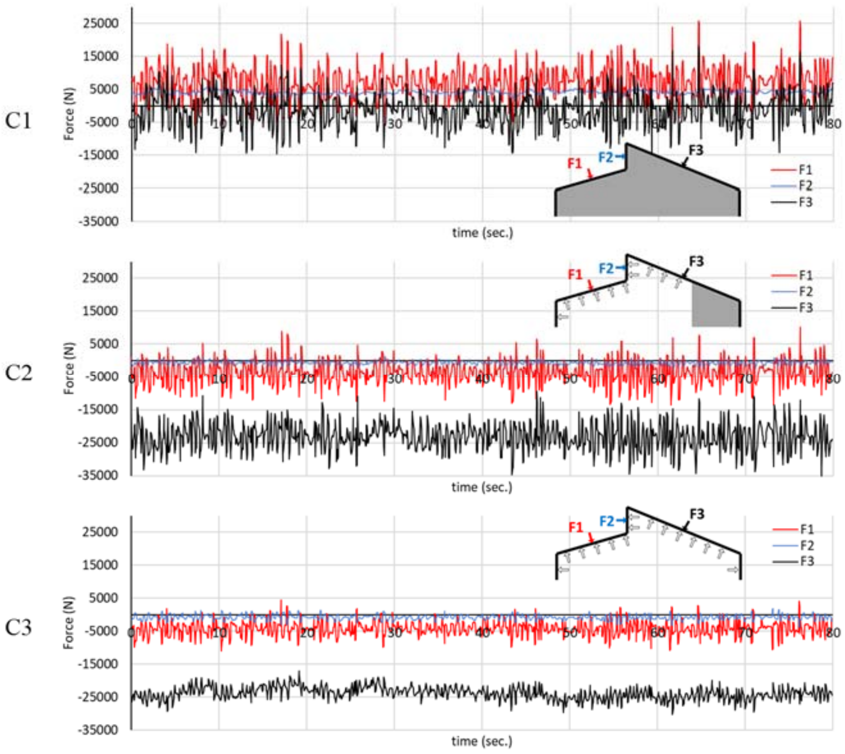


Figure 9 Time histories of roof forces for different damage stages

4 CONCLUSION

The current work investigates the variation in aerodynamics and their consequences with respect to the progression in damage of non-structural components (i.e. windows and doors) for a typical low-rise building. A comparison between an undamaged(intact) building and three different damage levels of failure is highlighted to examine the change in wind flow and wind-induced load though out the predetermined damage scenario for a wind azimuth of *0°*. A CFD based approach is used to simulate the alteration in wind flow and assess the change in wind pressure, internal and external loads on walls and roof surfaces. Since wind breach through the building envelop the failure starts to progress subjecting the internal walls to an unsuspected design load case. This additional load case is not typically considered in the design of internal walls, thus increasing the risk of wall failure as they exceed their load capacities. This can be attributed to the increase in both the mean and fluctuating components of the wind forces on the internal walls (i.e. up to 1.5 times the corresponding external wind forces) and roof (i.e. ~1.9 times the maximum uplift force compared to the undamaged case C0). On the contrary, the development in building damage has a minor effect on both the wind flow around the building and the wind pressure on the external walls. In conclusion, the local damages of non-structural elements during wind events is found to increase the wind risk on the overall structural elements (walls and roof), which illustrates the necessity of accounting for progressive collapse scenarios in the structural design process.

Acknowledgement

The authors would like to acknowledge the financial support from Ontario Center of Excellence (OCE), National Science and Engineering Research Center (NSERC), the Southern Ontario Smart Computing Innovation Platform (SOSCIP), and Canada Research Chair. The authors are grateful for access to SciNet and SHARCNET for the support received from their excellent technical staff.

References

Aboshosha, H., Elshaer, A., Bitsuamlak, G. T. G. T., and El Damatty, A. (2015). “Consistent inflow turbulence generator for LES evaluation of wind-induced responses for tall buildings.” *Journal of Wind Engineering and Industrial Aerodynamics*, 142(JULY), 198–216.

Bitsuamlak, G. T., Warsido, W., Ledesma, E., and Chowdhury, A. G. (2012). “Aerodynamic mitigation of roof and wall corner suctions using simple architectural elements.” *Journal of Engineering Mechanics*, American Society of Civil Engineers, 139(3), 396–408.

Courant, R., Friedrichs, K., and Lewy, H. (1928). “Über die partiellen Differenzengleichungen der mathematischen Physik.” *Mathematische annalen*, Springer, 100(1), 32–74.

Davenport, A. G. (1977). *Wind Loads on Low Rise Buildings: Final Report of Phases I and II. Part I: Text and Figures*.

Elshaer, A., Aboshosha, H., Bitsuamlak, G., El Damatty, A., and Dagnew, A. (2016). “LES evaluation of wind-induced responses for an isolated and a surrounded tall building.” *Engineering Structures*, Elsevier, 115, 179–195.

ESDU. (2001). *Engineering Sciences Data Unit. Characteristics of atmospheric turbulence near the ground. Part II: single point data for strong winds*.

Franke, J., Hellsten, A., Schlünzen, H., and Carissimo, B. (2007). “Best Practice Guideline for the CFD Simulation of Flows in the Urban Environment. COST Action 732: Quality Assurance and Improvement of Microscale Meteorological Models.” *Hamburg, Germany*.

Ginger, J. D., Holmes, J. D., and Kim, P. Y. (2010). “Variation of Internal Pressure with Varying Sizes of Dominant Openings and Volumes.” *Journal of Structural Engineering*, 136(10), 1319–1326.

Ginger, J. D., Holmes, J. D., and Kopp, G. A. (2008). “Effect of building volume and opening size on fluctuating internal pressures.” *Wind and structures*, Techno-Press, 11(5), 361–376.

Holmes, J. D. (1980). “Mean and fluctuating internal pressures induced by wind.” *Wind Engineering*, Elsevier, 435–450.

Holmes, J. D., and Ginger, J. D. (2012). “Internal pressures–The dominant windward opening case–A review.” *Journal of Wind Engineering and Industrial Aerodynamics*, Elsevier, 100(1), 70–76.

Kopp, G. A., Mans, C., and Surry, D. (2005). “Wind effects of parapets on low buildings: Part 4. Mitigation of corner loads with alternative geometries.” *Journal of Wind Engineering and Industrial Aerodynamics*, Elsevier, 93(11), 873–888.

Kopp, G. A., Morrison, M. J., and Henderson, D. J. (2012). “Full-scale testing of low-rise, residential buildings with realistic wind loads.” *Journal of Wind Engineering and Industrial Aerodynamics*, Elsevier, 104–106, 25–39.

Lin, J.-X. X., Surry, D., and Tieleman, H. W. (1995). “The distribution of pressure near roof corners of flat roof low buildings.” *Journal of wind engineering and industrial aerodynamics*, Elsevier, 56(2–3), 235–265.

Montazeri, H., and Blocken, B. (2013). “CFD simulation of wind-induced pressure coefficients on buildings with and without balconies: validation and sensitivity analysis.” *Building and Environment*, Elsevier, 60, 137–149.

Nozawa, K., and Tamura, T. (2002). “Large eddy simulation of the flow around a low-rise building immersed in a rough-wall turbulent boundary layer.” *Journal of Wind Engineering and Industrial Aerodynamics*, Elsevier, 90(10), 1151–1162.

Pan, F., Cai, C. S., and Zhang, W. (2013). “Wind-induced internal pressures of buildings with multiple openings.” *Journal of Engineering Mechanics*, 139(3), 376–385.

Smagorinsky, J. (1963). “General circulation experiments with the primitive equations: I. the basic experiment.” *Monthly weather review*, 91(3), 99–164.

Smith, A., Lott, N., Houston, T., Shein, K., Crouch, J., and Enloe, J. (2018). “US billion-dollar weather & climate disasters: 1980-2017.” *NOAA National Centers for Environmental Information, accessed Jan 2018*.

Star CCM+ v.10.02.011. (2016). “CD-ADAPCO product. <www.cd-adapco.com/products/star-ccm>.” CD-ADAPCO Product.

Stathopoulos, T., Surry, D., and Davenport, A. G. (1979). “Internal pressure characteristics of low-rise buildings due to wind action.” *JE Cermak, Wind Engineering*, 1.

Tecle, A. S., Bitsuamlak, G. T., and Chowdhury, A. G. (2015). “Opening and Compartmentalization Effects of Internal Pressure in Low-Rise Buildings with Gable and Hip Roofs.” *Journal of Architectural Engineering*, 21(1), 4014002.

Uematsu, Y., and Isyumov, N. (1999). “Wind pressures acting on low-rise buildings.” *Journal of Wind Engineering and Industrial Aerodynamics*, Elsevier, 82(1), 1–25.