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WIND SAFETY ASSESSMENT DURING HIGH RISE BUILDING CONSTRUCTION

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Abstract: The interactions between buildings and wind affect the safety and comfort of people in many places, including streets and outdoor accessible levels of buildings. However, these effects are only studied prior to and post construction, while the safety of the workers during the construction process is often overlooked. In this study, the changing wind environment, due to new construction is assessed numerically, targeting the safety and capabilities of construction workers to accomplish their tasks. A CFD based study utilizing a RANS turbulence modeling scheme is conducted on the widely referenced CAARC building. This study gives insight on the possible complexities arising in the wind microclimate at different construction stages and links these affects to the safety, operation, and comfort of construction workers. The study also illustrates the possible risks associated with wind-borne debris and the impacts it has on construction workers and most importantly the neighbouring community. Finally, some recommendations for future studies are provided, emphasizing the appropriate mitigation measures necessary to increase safety and comfort on and around construction sites.

1 Introduction

In the recent years, the increase in tall building construction has introduced high speed wind that has caused several problems at pedestrian levels. Several building codes have begun to recommend the assessment of pedestrian level winds during the design phases, however, the wind environment that changes during the construction of the building itself is often disregarded. These changes to the wind microclimate play a considerable role in the safety of the workers and the surrounding community. This is an issue because there are many risks associated with the construction of high-rise structures due to increased wind speed. For example, in January of 2017 in Saanich, B.C, Canada, the Times Columnist reported that a piece of plywood, picked up by a gust of wind, knocked a worker off one of the exposed upper levels of a building which resulted in a fatal injury (Dedyna, 2017). Similarly, in February of 2016 in Chicago, USA, ABC news reported that buildings were evacuated and streets shut down after debris from a nearby construction site flew into the facade of an occupied neighbouring building (WLS,2017). Currently, construction workers have general guidelines specifying the wind speed limits for safe working environments. For example, it is suggested that when the wind speed exceeds 14m/s, work at higher elevations must cease (PSP,2017). High speed wind can cause workers to lose balance resulting in fatal injuries. In addition, high speed wind can also blow loose materials that can injure workers or individuals on or near the construction site.

To the knowledge of the authors, there are a limited number of studies that deal with the impact that high wind speed has on the construction safety of high-rise buildings. In this study, the primary concern is the safety of the construction workers rather than their comfort. However, the same methodology used to study pedestrian level wind can be used to evaluate the safety of the construction workers by using different criteria.

The topic of pedestrian level wind has been studied by many researchers using experimental as well as computational methods in the past. In general, wind comfort only refers to the mechanical effects of wind on people, and excludes thermal comfort, humidity, solar radiation, and precipitation. Stathopoulos (2006), Wu and Kriksic (2012), Stathopoulos and Wu (1995), and several other researchers, outlined the methods to investigate pedestrian level winds in urban areas. Studies have also been conducted that outline how there are physiological symptoms of working at higher elevations that can alter the standard comfort levels of workers on site (Hsu et al., 2008). For instance, Blocken et al. (2008) conducted a study to examine the wind effects on accessible balconies at higher elevations, using computational methods. The study of wind on balconies is similar to wind at exposed floors at higher elevations, but the criteria used for assessing the safety of construction workers at these levels, would be different from the criteria used to determine the comfort of pedestrians. This research uses the criteria proposed by Isyumov and Davenport (1975) to determine the wind speed that produces unsafe environments for workers.

Researchers have used CFD to study pedestrian level winds due to the cost benefits over experimental methods. Many studies have been performed to demonstrate the usefulness of Reynolds-Averaged Navier-Stokes (RANS) or Large Eddy Simulation (LES) computational fluid dynamic (CFD) simulations compared to wind tunnel methods. Recently, the Architectural Institute of Japan has created benchmarks for the validation of CFD simulation applied to pedestrian wind environments around buildings using both RANS and LES models (AIJ, 2016). Although LES models can provide the most reliable result, Blocken et al. (2016) demonstrated that steady RANS simulations can provide reasonably accurate results for high amplification factors (i.e. when the ratio of velocity with and without the structure is above 1). Since wind speeds at high amplification factors (>1) have the highest contribution to the probability of exceedance in the comfort/safety criteria (Blocken et al. ,2016), the current study has adopted the RANS turbulence model.

In addition to the safety and comfort of workers, wind-borne debris set in motion by high velocities of wind, affect the safety of the workers on site, pedestrians in the surroundings and occupants of neighbouring buildings. Studies on wind-borne debris have been performed by Baker (2007) that consider the flight equations for compact and sheet debris. Wind tunnel experiments that measure debris trajectories and velocities have been carried out by Wang and Letchford (2003), Holmes et al. (2004) and Lin et al (2004). This is especially significant as materials are stored and used at higher elevations where they may be subjected to these effects. In this study, the take-off velocity (the velocity at which the construction material becomes airborne) is calculated for different types of materials and the results are compared with the maximum velocity found from the CFD simulations.

2 Building Geometry and Configuration

The CAARC (Commonwealth Advisory Aeronautical Research Council) building has been widely studied in the wind engineering community both experimentally and numerically. The dimensions of the building are 30.58 × 45.72m ×182.88m. For the current study, the building is divided into 50 floors, with a center to center story height of 3.5m, a slab thickness measuring 0.25m and a column dimension of 0.5m×0.5m. Typically, the construction of a building begins with the completion of the structure, followed by the installation of the cladding from the bottom to the top. This study focuses on the stage when 80% of the cladding is installed as seen in Figure 1. This is because the wind speed would be greater at these higher elevations, leading to increased safety issues and risks of debris becoming wind-borne.

2.1 Wind Safety

To assess wind safety, the comfort criteria by Isyumov and Davenport, (1975) and the evaluation of the wind interaction with the building (aerodynamic data) as discussed by Blocken and Carmeliet (2008) are used. Once the aerodynamic interactions are determined, the specific meteorological information of a location can be applied to establish the conditions affecting workers.

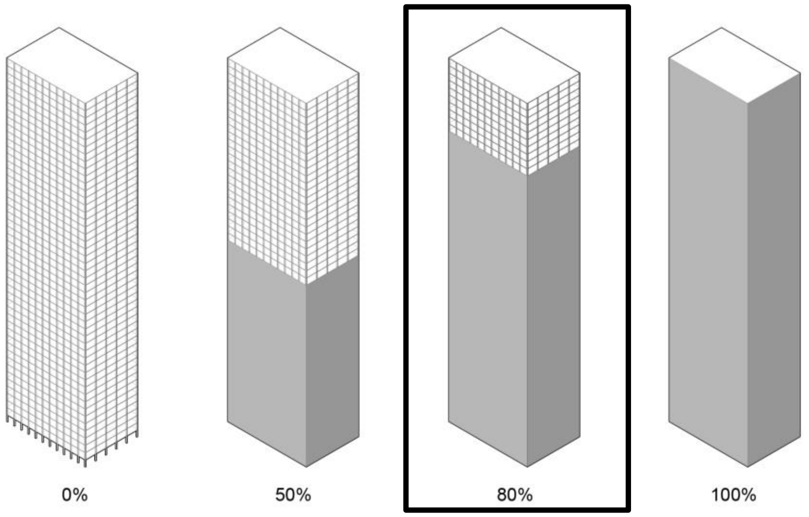


Figure 1: Stages of construction from exposed structure to fully clad

2.1.1 Wind Danger Criteria

In typical pedestrian level wind criteria, wind speeds and their associated activities such as sitting or walking are included in the comfort criteria. However, since workers are constantly moving and adapting to the conditions from a comfort perspective, the values referring to unacceptable, poor wind climate are the only values included in this study. To determine areas of danger due to wind speeds, the portion of the Isyumov and Davenport criteria that focuses on the unacceptable conditions is selected as depicted in Table 1 (Blocken et al.,2016).

Table 1: Different wind danger criteria

Unacceptable, poor wind climate	Wind speed threshold	P_{min} Minimum allowed exceedance probabilities	Description
Isyumov & Davenport	U>15.1 m/s (U>8Bft)	0.01% (1/year)	“Dangerous”
Melbourne	$U+3.5\sigma_u>23$ m/s	0.022% (2h/year)	“Completely unacceptable – the gust speed at which people get blown over”
NEN 8100	U>15 m/s	0.05%	“limited risk” and “dangerous”

2.2 Computational Set Up

2.2.1 Computational Domain Dimensions and Boundary Conditions

All simulations are conducted using a commercial CFD package (STAR-CCM+ v.10.06.010) employing a RANS turbulence model. The simulations are conducted using the SharcNet high performance computer facility at Western University.

Preliminary study:

A preliminary investigation was performed to determine the effect of the geometric parameters on the wind flow, by isolating one floor at the center of the entire tower. The center of the selected floor (Figure 2b) is located at 91.44m above the ground. The boundary conditions (average velocity, U_{av}, turbulence intensity, I and turbulence length scale, L) are calculated at a height of 91.44m based on the power law and are applied to the inlet as a uniform flow. The dimension of the computational domain and boundary conditions used are chosen based on the recommendations of COST (2007), Franke (2006) and Dagnew and Bitsuamlak (2013), as shown in Figure 2. The sides, top and bottom of the computational domain are assigned as symmetry plane boundary conditions, (assuming the effect of shear flow is negligible). The faces of the building are defined as no-slip boundary conditions. The parameters used in the simulations to handle the flow quantities and the solution methods are summarized in Table 2. All the simulations ran until a satisfactory convergence was reached.

Table 2: Parameters used to setup inlet boundary conditions

Parameter	Definition	Value(s)
Exposure	Urban Terrain	$U_{avref} = 40m/s$
Mean velocity U_{av}	$U_{av} = U_{av,ref}\left(\frac{z}{z_{ref}}\right)^{\alpha}$	$z_{ref} = 182.88$ $\alpha = 0.326$
Turbulent Intensity I	$I_j = I_{refj}\left(\frac{z}{z_{ref}}\right)^{-d_j}$	$I_{refj} = 0.208, \quad d_j = 0.191$
Length Scale	$L_j = L_{refj}\left(\frac{z}{z_{refL}}\right)^{\varepsilon_j}$	$L_{refj} = 0.302\ m, \varepsilon_j = 0.473,$ $z_{refL} = 127.0m$

*(Zhou, 2003), **(ESDU, 2001).

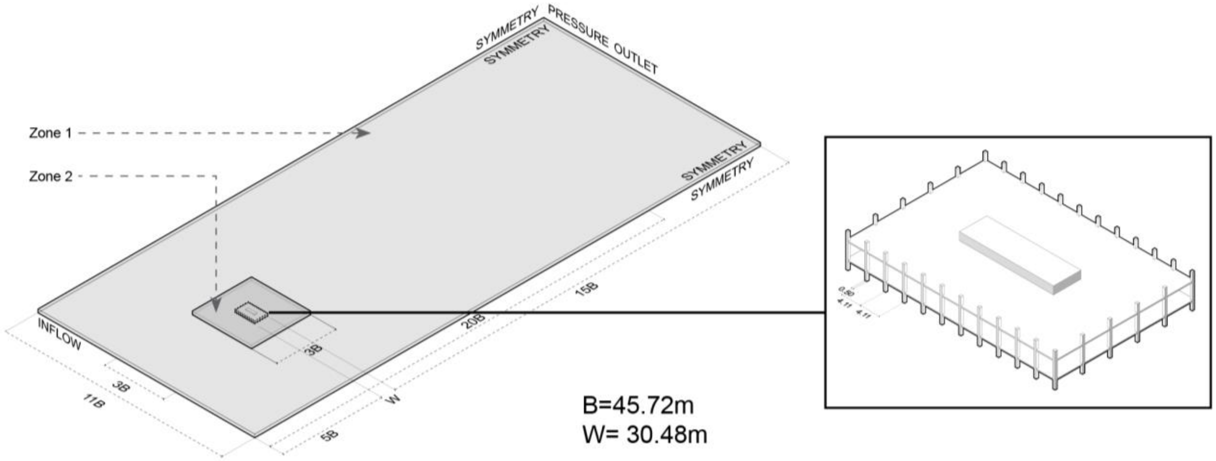


Figure 2: a) Computational domain and boundary conditions, b) isolated geometry

Full Building:

The building is modeled in full scale and a mean wind velocity of 40 m/s at the building height is used. The computational domain and boundary conditions used for the RANS model are chosen based on the recommendations of COST (2007), Franke (2006) and Dagnew and Bitsuamlak (2013), as shown in Figure 3. The sides and top of the computational domain are assigned as symmetry plane boundary conditions, while the faces of the building and the ground are defined as no-slip walls. The simulation ran until a satisfactory convergence was reached.

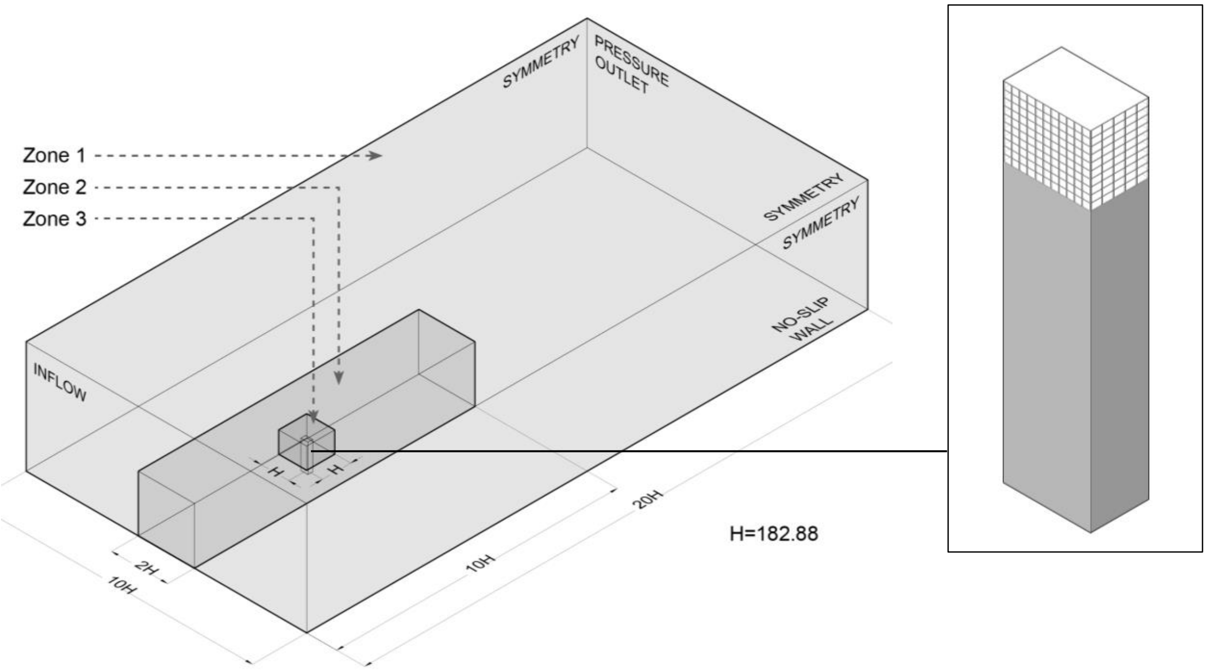


Figure 3: Building test computational domain and boundary conditions

2.2.2 Grid Discretization

The computational domain is discretized using polyhedral control volumes. The computation domain is divided into different zones that are each refined using different mesh sizes as shown in Figure 4. In zone 1 a maximum grid size of H/10 is used and zone 2, which is located closer to the section of the building, a mesh size of 30/H is used to help capture important details of the flow. At the walls, ten prism layers parallel to the building surfaces with a stretching factor of 1.05 are used, as recommended in Murakami (1997), COST(2007) and Tominaga et al. (2008).

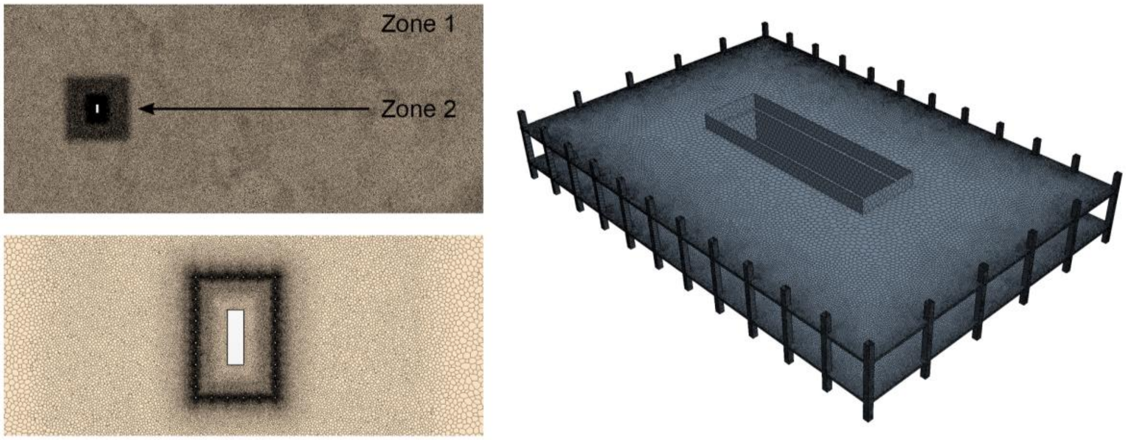
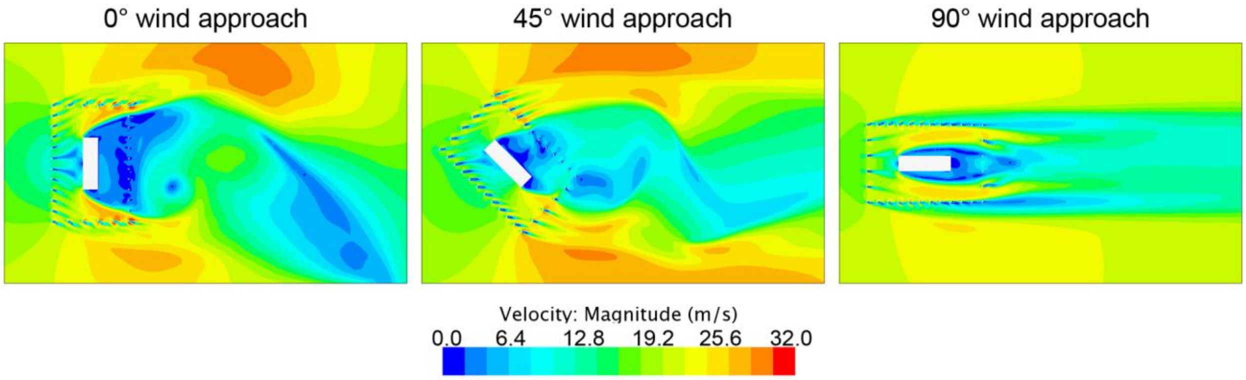


Figure 4: Mesh details

3 Results and Discussion

3.1.1 Wind Flow Field

Figure 5 shows the mean velocity contour plots for 0°, 45° and 90° wind angles of attack. For an angle of attack of 0°, low velocities are seen (blue) in the wake zone as well as areas upwind of the core. Wind can be seen to separate at the edges of the columns, but dominantly separates around the central core, accelerating around and outward from the building. When the angle of attack is rotated 45°, the size of the wake region is reduced and the wind is accelerated greatly between the columns downwind of the core. When winds approach the short end of the structure from an angle of 90°, they are funneled between the core and the columns and accelerate as they move downwind of the core. Compared to the 0° and 45° angles of attack, when the wind approaches from 90° the smallest wake is produced.


0° wind approach

45° wind approach

90° wind approach

Figure 5: Sensitivity test of column layout for different wind angles of attack

Depending on the wind direction, workers can move to the wake region (marked by the blue regions) that would be safe locations to work or store materials. When winds approach from angles in line with the structure (0° and 90°), higher velocities occur between the interior core and the exterior rows of columns due to the channeling effect. These higher velocities can cause workers to lose their balance and make loose materials airborne. According to the safety criteria created by Isyumov and Davenport that specifies wind speeds over 15.1 m/s as dangerous, much of the floor area of each of the three angles of wind attack seem to be subjected to unsafe conditions.

3.1.2 Calculation of the amplification factor, K

For a better comparison of the simulation results, a local amplification factor, defined as the ratio of the local wind speed to the wind speed that would occur at the same location in the absence of buildings (Blocken et al., 2016) is used. In the current case, since we have studied an isolated building, the amplification factor, K (at any location), is determined by dividing the local wind speed by the mean velocity profile as,

$$K = \frac{U}{\overline{U}(z)} \qquad (1)$$

,where U is the magnitude of the velocity at any location and $\overline{U}(z)$ is the mean velocity profile calculated using Table 2.

Figure 6(a) shows the amplification factors for the longitudinal lateral sections of the exposed portion of the 80% cladded building while Figure 6(b) shows the amplification factors in plan of each floor (taken at mid-height of each storey) for the top ten storeys.

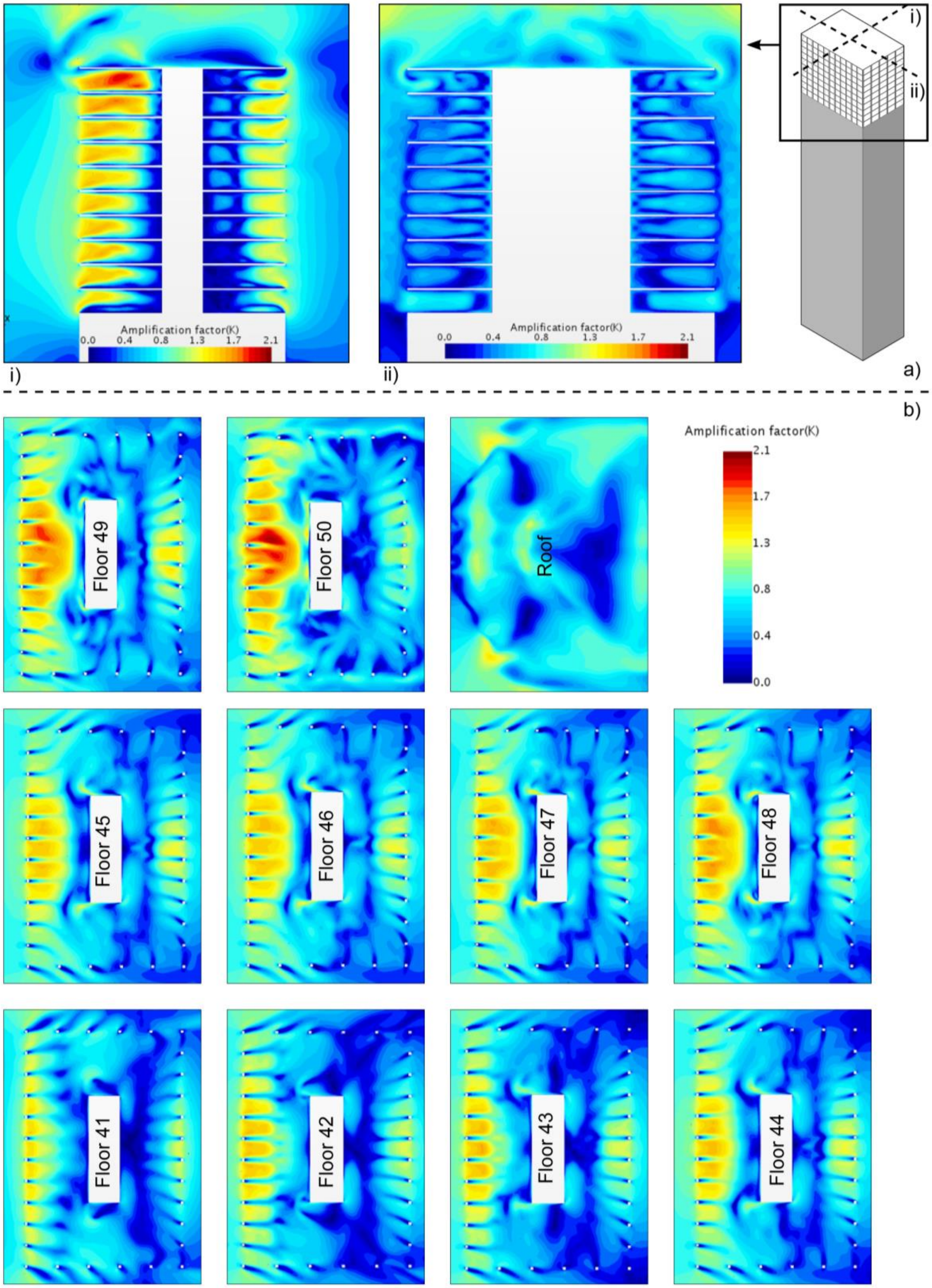


Figure 6: Amplification factor of (a) longitudinal sections of exposed structure and (b) section of each floor plan exposed

The amplification factor of 2.1 (as shown in Figure 6(b)) is equal to 81.7m/s. This value is most evident on the 50th floor in the red areas. In many of the floors, this value exceeds the 15.1 m/s maximum safe criteria for construction workers given in Table 1, which means that many of these areas can potentially endanger workers at higher elevations.

3.1.3 Wind borne debris and construction safety

On construction sites, in addition to the safety risk due to high wind speeds, there is also a risk associated with wind born debris (i.e. wind can blow some construction materials and tools off the site creating a risk for injury). If construction materials and tools are not properly stored, they can easily be picked up by wind to become missiles. This significantly impacts the safety of both construction workers and the nearby community. The lift-off velocity(U_f) of an object is the velocity required to make an object become airborne and dangerous. The lift-off velocity for any object depends on its mass, shape, and initial placement on the surface. The lift-off velocity as it is given in Holmes (2007) can be expressed as:

$$U_f = \sqrt{\frac{I\rho_m g l}{\alpha \rho_a C_F}}$$

where, l is the characteristic dimension of the object as shown in Figure 9; ρ_m is density of the object; C_F represents the force coefficient which reflects the aerodynamics; α represents a constant which depends on the shape of the object and it is given in Table 3; ρ_a is the density of the air, and a value of 1.25kg/m^3 is used and g stands for the gravitations acceleration. For objects resting on the ground $I \approx 1.0$.

In this study, three types of construction materials, i.e. compact, sheet and rod (see Figure 8) are considered. A range of lift-off velocities for different construction materials are calculated and summarized in Table 3. Comparing the lift-off velocity with the maximum velocity found in the CFD study, the analysis shows that materials would be blown over, causing dangerous situations for construction workers.

Table 3: Lift-off velocities for different types of construction materials

	Examples	$l(mm)$	$\rho_m\left(\frac{kg}{m^3}\right)$	C_F	α	$U_f\left(\frac{m}{s}\right)$
Compact	Bricks, concrete blocks, etc.	75-400	400-2500	1.0	$1/2$	21.7-125.3
Sheet	Glass sheet, plywood, tiles, aluminium sheets, etc.	0.5-15	400-2800	0.3	$1/2$	*3.2-46.9*
Rod	Rebar, metal rods, metal conduits, etc.	5-170	2720-7850	1.0	$2/\pi$	12.9-127.9

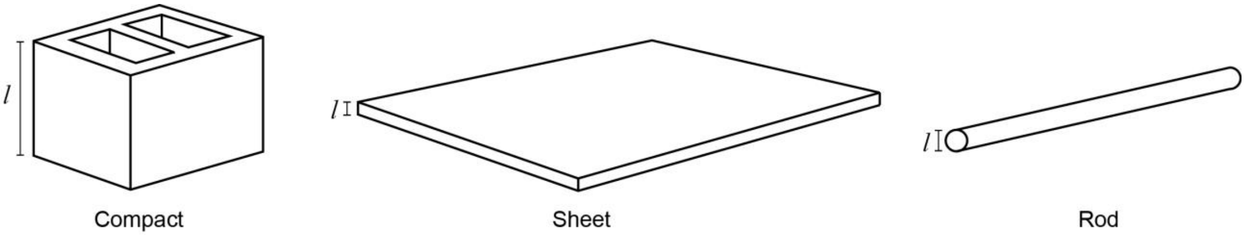


Figure 8: Categories of wind borne debris

4 Conclusion

This study focuses on numerically evaluating the changing wind environment during construction and its effects on the safety of workers using CFD. The Commonwealth Advisory Aeronautical Research Council (CAARC) building is modeled and used as a case study. Results obtained from the RANS simulations are evaluated with the safety criteria and lift-off velocities which cause wind-borne debris and the following conclusions can be extracted.

- During the construction of tall buildings, the top floors are exposed to a high wind speed that could potentially affect the safety of construction workers on site. In certain locations, the wind velocities are magnified by a factor of 2.1. The amplification increases and penetrates closer to the core of the building with an increase in elevation. Without a doubt, the velocities exceed the safety margin, creating high risk zones that are unsafe for workers. Through this study, it is clear that construction safety is influenced by the wind, and proper attention should be given to mitigate those issues either within the design phase or during construction. Further studies focusing on the mitigation strategies should be carried out.
- The comparison of the maximum wind speed found from the CFD simulation with the lift-off velocity for different construction materials shows that materials that are not fastened properly will lift-off and become dangerous wind-born debris that threaten the safety of workers and nearby pedestrians. This risk can be alleviated by storing materials near the core where the wind speed is relatively low.
- Further studies that could be carried out could focus on: the different construction stages (Figure 1), the inclusion of the installation of the cladding, a study of the CAARC building structure with surroundings, incorporation of local meteorological information to make results site specific as well as a more detailed study of wind borne debris.

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