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WIND DAMAGE ANALYSIS OF DEBRIS IMPACTING ON HIGH-BUILDING CURTAIN WALLS CONSIDERING LOCAL WIND ENVIRONMENT

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The security risks of glass curtain wall of high-rise building have become increasingly important. Taking into account the local wind environment, the wind damage caused by debris impacting on glass curtain walls is studied in this paper. The factors influencing the flight characteristics of spherical debris are analyzed. The three-dimensional flight trajectories of debris are investigated for different initial parameters and wind flow. The results show that the influence of the material properties, the size of debris and the initial wind flow are significant on the flight characteristics of debris. Incorporated by the numerical simulation of local wind environment in urban area by CFD, the flight trajectories of debris can be simulated according to the local wind field. Furthermore, a new method is presented to analyze the wind damage of high-rise buildings caused by debris impacting in strong wind. An example is given to show that for the wind damage analysis of debris impacting on curtain walls of high-rise buildings, it is necessary to consider the local wind environment and the three-dimensional flight characteristics of debris.

Keywords: Glass curtain wall, local wind environment, windborne debris, flight trajectory, damage assessment.

1 Introduction

There are many factors that cause the damage of the glass curtain wall, such as material properties, seismic action, wind, temperature stress, deformation of the main structure and so on. Research (Minor, 2005) reveals that all kinds of debris is caused by high-rise building glass curtain wall damage one of the important reasons. Hurricane Alicia (1983), Hurricane Hugo (1989), Hurricane Andrew (1992), Typhoon York (1999) and other post-disaster reports (Wills & Lee, 2002; Song & Ou, 2010) pointed out that many glass curtain walls of high-rise buildings damaged seriously due to the impact of windborne debris in the strong wind. For example, Typhoon York caused the destruction of a number of glass curtain walls of super high-rise buildings in Central Plaza, Hong Kong (Song & Ou, 2010). Over the past two decades, the windborne debris flying characteristics have been focused on. Much research work has been carried out on wind damage of building envelope caused by the impact of windborne debris, but the windborne debris damage and assessment of high-rise buildings glass curtain wall are researched rarely.

Related research began in 1970s and 1980s. The flight characteristics of plate-like debris are systematically studied by numerical simulation and wind tunnel test by Tachikawa (1983). Then, Holmes (2004, 2006b) and Lin et al (2006, 2007) carried out a series of theoretical studies and experimental tests on the flight trajectories of different types debris, but the research on the three-dimensional flight characteristics of windborne debris was not deep enough. In recent years, windborne debris risk assessment analysis for urban areas has been conducted. Twisdale et al. (1996) implemented the risk analysis of the windborne debris in the residential area, and gave a reliability curve for the analysis of the impact risk of windborne debris. Wills et al. (2002) established the windborne debris damage model of the city in the Pacific Rim Pacific region under the typhoon wind. Lin and Vanmarcke (2010a, b) gave a windborne risk assessment model based on the Poisson stochastic measure theory. Song and Ou (2010) analyzed the damage of the buildings envelope based on the windborne debris flight trajectory. On the other hand, the post-disaster investigation of typhoon Morandi in Xiamen in 2016 showed that the local wind environment could have a significant effect on the destruction of glass curtain wall. For the phenomenon, Brewick et al. (2009) also suggested that the consideration of the local wind environment would allow for more accurate assessment of the flight behavior of the debris around the building and the wind damage of the building glass curtain wall.

In this context, this paper focuses on the wind damage caused by windborne debris impacting the glass curtain wall. According to the gravel and stone of the building roof (i.e. spherical debris, Wills et al, 2002), based on the numerical solution of the three-dimensional motion equation of the debris, this paper presents a method to analyze the impact damage of debris in consideration of the influence of wind environment around buildings.

2 Windborne debris flying characteristics

In this paper, the gravel and stones on the building roof are assumed as spherical debris (Wills et al, 2002). At the time instant T, the wind speed is denoted as $\boldsymbol{U} = (U_x, U_y, U_z)^{\mathrm{T}}$, and the flying velocity of the spherical debris in the wind is denoted as $\boldsymbol{u} = (u_x, u_y, u_z)^{\mathrm{T}}$. Consequently, the three-dimensional equation of motion of spherical debris can be written as

$$\ddot{x} = \frac{\rho_a C_D}{2\rho l} v_x \sqrt{{v_x}^2 + {v_y}^2 + {v_z}^2} \tag{1a}$$

$$\ddot{y} = \frac{\rho_a C_D}{2\rho l} v_y \sqrt{{v_x}^2 + {v_y}^2 + {v_z}^2} \tag{1b}$$

$$\ddot{z} = \frac{\rho_a C_D}{2\rho l} v_z \sqrt{{v_x}^2 + {v_y}^2 + {v_z}^2} - g \tag{1c}$$

Where ρ_a is air density; g is gravity acceleration; C_D is aerodynamic drag coefficient of the spherical debris, which is generally taken as 0.5 (Talay,1975); l is characteristic length of the spherical debris, which is defined as the ratio of volume to windward area of the spherical debris, namely

$$l = \frac{2}{3} d \tag{2}$$

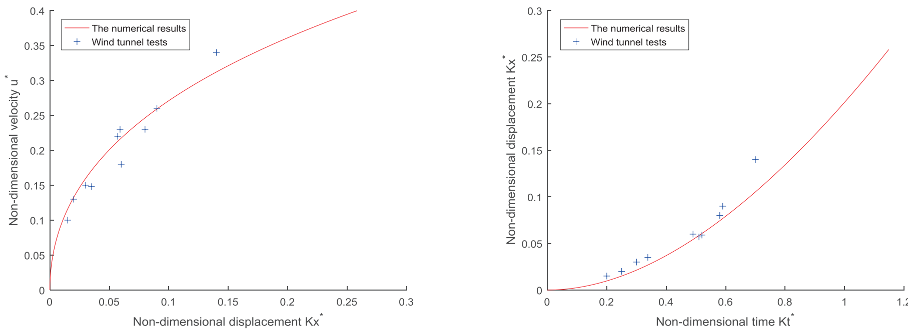
Here d is the diameter of the spherical debris.

According to Eq. (1), once the initial parameters of debris and wind environment are known, the flight trajectory of the spherical debris can be solved. In this paper, the equation of motion is solved by the fourth order Runge-Kutta-Felhberg (RKF45) method. For the spherical debris, the initial parameters required to define include the diameter d (or characteristic length l), the density ρ, and the wind speed $\boldsymbol{U}$ which can be the average wind speed, wind velocity time process, or wind velocity matrix at different spatial locations. Lin et al. (2007) conducted wind tunnel tests on the flight characteristics of spherical debris with different initial parameters. The numerical simulation results of this paper are compared with the test results herein Lin et al. The results are shown in Figure 1. It can be seen from Figure 1 that the numerical simulation results in this paper are in good agreement with wind tunnel tests.Where

$$\bar{x} = \frac{gx}{U^2}, \bar{u} = \frac{u}{U}, \bar{t} = \frac{gt}{U} \tag{3}$$

are the non-dimensional displacement, velocity and time along the horizontal direction of wind velocity, respectively. K is the ratio of aerodynamic and gravity of debris, which is known as Tachikawa number (Holmes et al, 2006a), i.e.

$$K = \frac{\rho_a U^2 A}{2mg} = \frac{\rho_a U^2}{2\rho g l} \tag{4}$$



(a) The relationship between $K\bar{x}$ and $K\bar{t}$ (b) The relationship between $\bar{u}$ and $K\bar{x}$

Figure 1. The comparation between the numerical results and wind tunnel tests of Lin et al.

3 Numerical simulation of wind environmental conditions around buildings

In this paper, numerical simulation of wind environmental conditions has been done about the central building of Concordia University and buildings around it in Montreal, Canada (Stathopoulos & Baskaran, 1996). Figure 2 shows the area under consideration, in which there are 7 buildings. The height of the central building (i.e. building X) is 40m, and the heights of others are 12.5m.

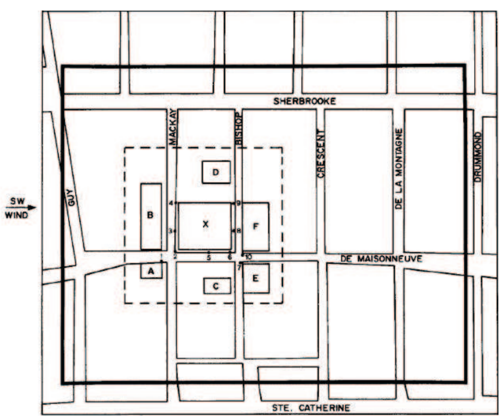


Figure 2. The area under consideration

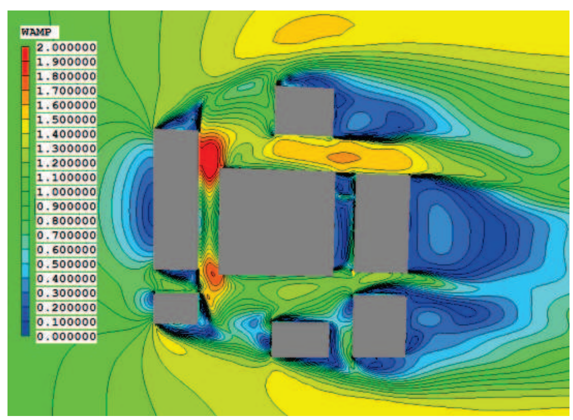


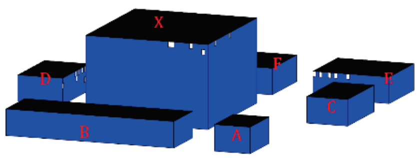
Figure 3 The result of WAMP at 2m height

It is assumed that the average wind speed at the height of 10m is 50m/s, and the wind profile is given according to logarithm law (Simiu & Scanlan, 1977). Wind direction is from southwest which is from left to right in Figure 2. The area enclosed by thick lines in Figure 2 is the calculation area for numerical simulation. The numbers 1-10 are points selected to measure wind speed in the wind tunnel test by Stathopoulos and Baskaran (1996). In this paper, CFD software PHEONICS is used to simulate the wind field in the building area, and the result of wind speed amplification factor (WAMP) at 2m height is shown in Figure 3.

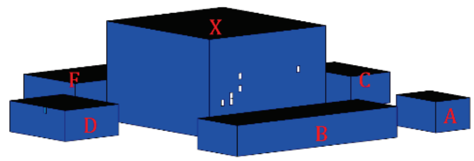
4 Numerical analysis of debris impact damage prediction model

In order to analyze the impact and damage to the glass curtain wall by the gravel under the strong wind, it is assumed that the building is surrounded by glass curtain walls, of which the size of the single glass is $1.5\text{m} \times 2.5\text{m}$ with 6mm thickness, and the impact resistance capacity is $0.05\text{kg} \cdot$

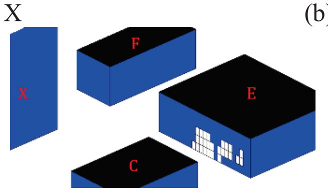
m/s. Then it is assumed that the spherical debris comes from the roof of each building. The density of debris is $\rho = 2000\text{kg/m}^3$, and the diameter d is in the range of $5 - 15\text{mm}$, which is uniform distribution. The number of debris on the roof is 0.5 per m^2. Figure 4 shows the damage of the glass curtain wall of the buildings by calculating the trajectory and the impact of debris. In Figure 4, the white rectangular area of the building surface indicates the curtain wall glass that is damaged by the impact of the debris. The number of times impacting on the building and the amount of glass damaged are shown in Tables 1 and 2.



(a) Debris from Building X



(b) Debris from Building B



(c) Debris from Building C

Figure 4 Glass curtain wall destruction impacted by debris

Table 1 The number of times impacting on the building

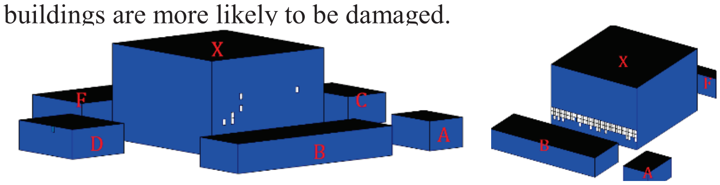
Impacting time	Building X	Building A	Building B	Building C	Building D	Building E	Building F
Building X	819	0	0	0	13	28	11
Building A	0	0	0	0	0	0	0
Building B	78	0	505	0	19	0	0
Building C	0	0	0	0	0	226	0
SUM	897	0	505	0	32	254	11

Table 2 The number of destruction of glass damaged

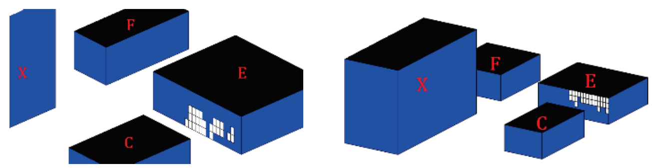
Number of destruction	Building X	Building A	Building B	Building C	Building D	Building E	Building F
Building X	6	0	0	0	10	25	0
Building A	0	0	0	0	0	0	0
Building B	6	0	2	0	1	0	0
Building C	0	0	0	0	0	60	0
SUM	12	0	2	0	11	85	0

It can be seen from Figure 4 that the damage caused by the impact of debris in the curtain wall glass of Building E is most serious. It is due to Building C close to Building E that the most of the debris from the roof of Building C flying impact on Building E cause the destruction of curtain wall glass of Building E. In contrast, for Building X that is close to Building B, curtain wall glass is significantly less damaged. It is because Building X is much taller than the buildings around it and the wind pressure is higher in front of it (i.e. above Building B) that it makes the wind speed around it smaller and air flows around both sides of the Building X, resulting in the large part of debris from the roof of Building B fails on the road on both sides of Building X. Therefore, the speed of debris hitting Building X is not large, and momentum of many debris cannot reach the critical momentum to cause glass curtain wall of Building X damage.

For further comparison, regardless of the influence of buildings on wind speed and wind direction, the wind speed around the building is taken as 50m/s, and the damage of the glass curtain wall on the building surface can be obtained as shown in Figures 5 and 6. The number of impacts on the building and the amount of damage to the glass are shown in Tables 3 and 4. By comparison, we can see that whether the difference of wind environment around the buildings is considered or not, the assessment result of the curtain wall damage caused by the impact of the fragments has a significant impact. When considering changes in the local wind environment around the buildings, debris trajectories are more disorganized. Therefore, damage to the glass curtain wall directly behind the debris source building may be lessened rather than considered, and the surrounding buildings are more likely to be damaged.



(a) Considering changes in local wind environment (b) Regardless of changes in local wind environment
Figure 5 The comparation of destruction of the glass curtain wall impacted by debris from Building B



(a) Considering changes in local wind environment (b) Regardless of changes in local wind environment
Figure 6 The comparation of destruction of the glass curtain wall impacted by debris from Building C

Table 3 The number of times impacting on the building regardless of changes in local wind environment

Impacting time	Building X	Building A	Building B	Building C	Building D	Building E	Building F
Building X	0	0	0	0	0	0	0
Building A	0	0	0	0	0	0	0
Building B	754	0	0	0	0	0	0
Building C	0	0	0	0	0	350	0
SUM	754	0	0	0	0	350	0

Table 4 The number of destruction of glass damaged regardless of changes in local wind environment

Number of destruction	Building X	Building A	Building B	Building C	Building D	Building E	Building F
Building X	0	0	0	0	0	0	0
Building A	0	0	0	0	0	0	0
Building B	409	0	0	0	0	0	0
Building C	0	0	0	0	0	202	0
SUM	409	0	0	0	0	202	0

5 Conclusion

In this paper, according to the flight characteristics of spherical debris, the three-dimensional equation of motion is established and numerically solved. The flying characteristics of the debris are analyzed and the main factors affecting the flying characteristics of the spherical debris are studied, including wind speed, material properties and debris size. Based on the numerical simulation of the local wind environment in the urban area, the flight trajectory of the debris was analyzed according to the local flow field conditions, and then the damage caused by the windborne debris was analyzed. The analysis shows that the local wind environment around the urban buildings will cause a direct impact on the trajectory of debris. In the analysis of damage of urban building glass curtain wall impacted by debris, it is necessary to consider the influence of the local wind environment.

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