Wind Tunnel Experiments on Flight Characteristics of Windborne Debris upon Low-Rise Building

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Abstract. In strong wind events such as hurricanes and tornadoes, windborne debris is the main cause of disasters and buildings destruction. Roof slabs, tiles, and other enclosure components may become potential windborne debris. In the present research, a series of wind tunnel experiments were carried out to investigate the flight characteristics (i.e., the trajectory distribution and the flight speed) of debris released at different positions on the windward roof of a low-rise building. The results show that the initial position of debris has an important influence on the trajectory distributions and flight speed. Along the Y-axis, the trajectory distribution of debris released near the central axis of the roof is wider than those of debris whose initial positions lying closer to the side. As for debris which is closer to the central axis of the roof, a wider trajectory distribution in the vertical direction and higher flight speed are observed when the debris is released closer to the windward eave. And for debris whose initial positions have the same distance from the windward eave, the closer the initial positions to the central axis, the lower the total speed is. The total speed of the debris is mainly composed of the vertical (Z-axis) speed component at the beginning of the flight, and gradually, the proportion of horizontal (X-axis) speed keeps increasing with time passing by.
Keywords. Low-rise building, wind tunnel, debris, flight characteristics.

1. Introduction
The Chinese southeast coastal is a typhoon-prone area, and the damage caused by the destruction of low-rise buildings exceeds more than half of the total loss of the wind disaster. Particularly, for low-rise buildings, windborne debris is the main cause of disasters and buildings destruction. Based on wind tunnel experiments, Wills [1] established a model that can be used to estimate the initial wind speed and damage energy of flying debris. The characteristic parameter is the density of materials, the size, and the shape of the debris. Holmes [2] used numerical simulation to calculate the trajectory of flat-plate debris and compared them with experimental data from Texas Tech University (TTU). Ning L. [3] investigated the aerodynamic characteristics of plate-type debris through experiments in wind tunnel and full scale. Visscher and Kopp [4] established a 1:20 scale model of a house in the Wind Tunnel Laboratory of the University of Western Ontario in Canada to simulate the failure limit and flight characteristics of the roof panel under strong wind and turbulent atmospheric boundary layer conditions. Fu A. M. [5] proposed a numerical model of three-dimensional motion of plate-type windborne debris in uniform wind field based on quaternions. This model can simulate the complex 3D spinning flight robustly and efficiently with rotational quaternions, which are also free from the gimbal lock that is associated with Euler rotational matrix. Most of the recent researches focused on the simulation of the flat-plate debris trajectory [6-9], while limited studies on the impacts of initial
positions of debris on its trajectory distribution and flight speed are performed. In the present research, a wind tunnel experiment relating to the flying debris generated from a low-rise building roof was conducted under the simulated Chinese standard B-type wind field. Subsequently, the influences of different initial positions and wind speeds on the trajectory distribution and flight speed of debris are scrutinized.

2. Experimental Overview and Data Processing

2.1. Wind Tunnel
Model experiments were carried out in the TJ-5 multi-fan active control wind tunnel of State Key Laboratory of Disaster Reduction in Civil Engineering at Tongji University. The size of the experiment area is 1.5 m in width, 1.8 m in height, and 10 m in length. The maximum wind speed in the uniform flow field is 18 m/s corresponding to a fan rated speed of 6000 rpm, with turbulence intensity less than 1%.

2.2. Experiment Model
The low-rise building selected to be the benchmark building is a classic double-slope roof building having a geometric size of 6 m in length, 6 m in width, and 6.4 m in height. The slope of the roof is 1:3. Considering the factors of blocking ratio and maximum flow velocity generated by the wind tunnel, the geometric scale ratio \( \lambda_L \) of this experiment is determined to be 1:20. Therefore, the size of the experiment model is 0.3 m × 0.3 m × 0.3195 m, and the corresponding blocking ratio is 4.11%.

The debris model is made by roof panel sharing the same specifications as those in Bahareh Kordi [9]. To be more specific, the model in reference [9] has a size of 419 mm × 343 mm × 31.7 mm, and a mass of 4.86 kg. To properly scale the mass of the model, the mass scale formula of the debris model is introduced in equation (1).

\[
\lambda_m = \lambda_p \lambda_L^3
\]

Where \( \lambda_m \) is the mass scale ratio of the model, and \( \lambda_p \) is the gas density scale ratio. Since the fluid in the full-scale experiment, i.e. the air, is the same as that in the wind tunnel, the gas density scale ratio is fixed to be 1:1. Therefore, the mass scale ratio of the debris model can be calculated as (1:1) × (1:20)³ = 1:8000. Based on the \( \lambda_L \) reported above, the geometric size of the debris model is determined to be 21.0 mm × 17.1 mm × 1.6 mm. To meet the scaling requirement of both size and mass, the debris models are made of the pearl cotton board clamped between a galvanized iron board and a carbon board, as shown in figure 1.

![Carbon board and galvanized iron board](image1)

**Figure 1.** Windborne debris front (left) and back(right).

**Figure 2.** Schematic diagram of debris initial positions, wind direction and trajectory coordinates.

Figure 2 shows the debris initial positions 1-6, the coordinate system of the debris flight trajectory, and the 0° wind direction. The electromagnet is buried under the initial position to hold the debris in the wind flow. When the wind speed in the wind tunnel reaches target speed, the DC power is cut off to release the debris. For convenience, the debris released at initial positions 1-6 are numbered to be debris D1-D6 in the following contents.
2.3. Wind Field Simulation

The time ratio $\lambda_T$ and speed scale ratio $\lambda_U$ are expressed in equation (2) and equation (3),

$$\lambda_U = \frac{U_m}{U_p} = \sqrt{\frac{T}{20}}$$

(2)

$$\lambda_T = \frac{T_m}{T_p} = \sqrt{\frac{T}{20}}$$

(3)

where $U_m$ and $T_m$ are wind tunnel experiment wind speed and time duration respectively, and $U_p$ and $T_p$ are the full-scale model wind speed and time respectively. The wind speed and time duration of the full-scale model are 4.47 times those of the wind tunnel experiment.

This experiment was performed under Chinese standard B-type (open terrain) wind field. The profiles of wind speed and turbulence are shown in figure 3. To compare the flight parameters of debris under different wind speeds, the wind tunnel experiment planned to be conducted under two wind speeds: $U_1=$10.89 m/s (fan speed at 3450 rpm) and $U_2=$12.78 m/s (at fan speed 4000 rpm). Two time-histories under two wind speeds are shown in figure 4 and figure 5 respectively.

![Figure 3](image1)

**Figure 3.** Profiles of wind speed and turbulence intensity.  
**Figure 4.** Time history of wind speed, $U_1=$10.89 m/s.  
**Figure 5.** Time history of wind speed, $U_2=$12.78 m/s.

2.4. Experiment Processing Method

In the experiment, two cameras were used to simultaneously record the moving trajectories of the flying debris with 1080p resolution and 120 Hz capture frame rate. In the experiment, one of the cameras captures the trajectories of debris in the X-Z plane, and the other one captures the image from the top where the debris trajectories in the X-Y plane can be recorded. To ensure that the images of flying debris can be captured by two cameras at the same time, two cameras were connected to the same remote control which rationally improves the accuracy of experimental data. However, due to the effect of lens distortion, the images captured by the camera will distort and cannot be analyzed directly. Thus, the distortion is corrected before the data processing by adopting the paradox modification. Lastly, based on the modified pictures, the flight parameters, i.e., trajectories and flight speed, of the debris can be obtained and further analyzed.

3. Result Analysis

3.1. Trajectory Analysis at 0° Wind Direction

The initial point on the X-axis is selected as the outer wall on the windward side, the initial point on the Y-axis is selected as the central axis of the building model on the windward side, and the initial point on the Z-axis is selected on the windward cave, as shown in figure 2. The coordinates of the initial positions where the debris is released are shown in table 1.
Table 1. Coordinate of the initial positions.

| Coordinate | 1   | 2   | 3   | 4   | 5   | 6   |
|------------|-----|-----|-----|-----|-----|-----|
| X/m        | 0.50| 0.50| 1.50| 1.50| 2.50| 2.50|
| Y/m        | 2.49| 0   | 2.49| 0   | 2.49| 0   |
| Z/m        | 0.17| 0.17| 0.50| 0.50| 0.83| 0.83|

At 0° wind direction, the flying trajectory in the X-Y plane is shown in figure 6 and figure 7. Under the wind speed of 10.89 m/s, the trajectories of the debris D2, D4, D6 distribute from -2.0 m to 2.0 m along the Y direction, and the trajectories are approximately symmetric with regard to the X-axis. The trajectories of the debris D1, D3, D5 distribute between 2.0 m and 7.0 m along the Y direction, and is slight increases compared with that measured under the speed of 10.89 m/s.

Figure 6. Trajectories in X-Y plane, $U_1=10.89$ m/s.  
Figure 7. Trajectories in X-Y plane, $U_2=12.78$ m/s.

The trajectories in the X-Z plane are shown in figures 8-11. The results show that the trajectory distributions of the debris D1, D2 are significantly wider than debris D5, D6 along the X-axis in the vertical direction. This may be attributed to the fact that the velocity components along the positive Z-axis of D1, D2 increases gradually during the flight along the sloping roof due to the lift force, while the debris D5, D6 are affected by the small lift and start to fall due to the gravity. Comparing the results obtained under wind speeds of 10.89 m/s and 12.78 m/s, it can be seen that, under higher wind speed, the trajectory distributions in the Z-axis direction become wider, and the distance from the setting point to the initial point increases along the X-axis. When the distance from the initial positions of the debris to the windward eave is the same, the distance from the central axis to the initial position has little influence on the trajectory distribution along Z-axis. Differently, the closer the initial position to the windward eave, the wider the distribution range of the flying trajectory in the Z direction.

Figure 8. X-Z plane trajectory of debris D1\D3\D5, $U_1=10.89$ m/s  
Figure 9. X-Z plane trajectory of debris D1\D3\D5, $U_2=12.78$ m/s.
Comparing these results with those shown in figure 13, the total speed shown in figure 13 is always between 4 m/s and 10 m/s. At T = 0.15 s, the total speed of the debris in figure 14 is in the range from 1 m/s to 3 m/s. The total speed range in figure 14 is between 4 m/s and 10 m/s. The acceleration of the debris increases continuously from T = 0 s to 0.15 s.

Under different wind speeds, the ratio of the three-speed components (i.e., along X, Y, and Z-axis) to the total speed at different time t (i=1, 2, 3, 4) is shown in table 2. When the debris flies upwards along the slope of the roof, the initial speed is mainly composed of the Z-direction speed due to the effect of the lift. Afterward, the speed in the X and Y directions increases gradually, and correspondingly, their proportion in the total speed increases. As the X direction is parallel to the wind direction, the flight speed in the X direction increases faster than the speed in the Y direction, and the ratio of the speed in the X direction to the total speed is much larger than that in the Y direction (V_x^2/V_z^2 > V_y^2/V_z^2).

The variation of the total speed of the debris D1, D5, D6 along time under the wind speed of 12.78 m/s is shown in figure 13-15. Comparing the curves in figure 13 and figure 14, when T_m = 0.1 s, the total speed of the debris in figure 14 is in the range from 1 m/s to 4 m/s. At T = 0.15 s, the total speed range in figure 14 is between 4 m/s and 7 m/s. Comparing these results with those shown in figure 13, the total speed shown in figure 13 is always

3.2. Speed Analysis at 0° Wind Direction

In figure 12 and figure 13 taking position 1 as an example, the total speed and acceleration of the debris under wind speed of 12.78 m/s are significantly higher than those under the wind speed of 10.89 m/s at most time. At T_m=0.1 s (corresponding to T_p=0.45), the total speed of the debris under the wind speed of 10.89 m/s range from U_p= 0.5 m/s to 3 m/s (corresponding to U_p=2.24 m/s-13 m/s). The total speed under 12.78 m/s ranges from 2.5 m/s to 4 m/s (U_p=11.18 m/s-17.89 m/s). At T_m=0.15 s (corresponding to T_p=0.67 s), the range of total speed of debris under 10.89 m/s is from 3 m/s to 6 m/s. The total speed under the wind speed of 12.78 m/s is between 6 m/s and 10 m/s (U_p=26.83 m/s-44.72 m/s). The acceleration of the debris increases continuously from T_m=0 s to 0.15 s.

Under different wind speeds, the ratio of the three-speed components (i.e., along X, Y, and Z-axis) to the total speed at different time t (i=1, 2, 3, 4) is shown in table 2. When the debris flies upwards along the slope of the roof, the initial speed is mainly composed of the Z-direction speed due to the effect of the lift. Afterward, the speed in the X and Y directions increases gradually, and correspondingly, their proportion in the total speed increases. As the X direction is parallel to the wind direction, the flight speed in the X direction increases faster than the speed in the Y direction, and the ratio of the speed in the X direction to the total speed is much larger than that in the Y direction (V_x^2/V_z^2 > V_y^2/V_z^2).

The variation of the total speed of the debris D1, D5, D6 along time under the wind speed of 12.78 m/s is shown in figure 13-15. Comparing the curves in figure 13 and figure 14, when T_m = 0.1 s, the total speed of the debris in figure 14 is in the range from 1 m/s to 4 m/s. At T = 0.15 s, the total speed range in figure 14 is between 4 m/s and 7 m/s. Comparing these results with those shown in figure 13, the total speed shown in figure 13 is always

![Figure 10](image1.png)  
**Figure 10.** X-Z plane trajectory of debris D2\D4\D6, U_1=10.89 m/s.

![Figure 11](image2.png)  
**Figure 11.** X-Z plane trajectory of debris D2\D4\D6, U_2=12.78 m/s.

![Figure 12](image3.png)  
**Figure 12.** Total speed of debris D1, U_1=10.89 m/s.

![Figure 13](image4.png)  
**Figure 13.** Total speed of debris D1, U_2=12.78 m/s.
higher than the speed in figure 14 at an arbitrary time. Comparing figure 14 and figure 15, the total speed of the debris D6 distribute from 1 m/s to 3 m/s at Tₚ=0.1 s. When Tₚ=0.15 s, the total speed of the debris D6 lies between 2 m/s and 5 m/s, and the total speed of the debris D5 is higher than that of debris D6. From the above analysis, it can be seen that, when the distance from the windward eave to the initial positions keeps stable, the debris is prone to lower flight speed when it is released closer to the central axis. And a slower flight speed is expected when the initial positions of debris lie further from the windward eave.

### Table 2. Portion of three flight speed components to the total speed under different wind speed.

| Percentage | U₁-t₁ | U₁-t₂ | U₁-t₃ | U₁-t₄ | U₂-t₁ | U₂-t₂ | U₂-t₃ | U₂-t₄ |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|
| V₁²/Vₚ²   | 16.0% | 76.2% | 88.3% | 91.7% | 50.2% | 87.2% | 92.8% | 95.6% |
| V₂²/Vₚ²   | 9.2%  | 6.3%  | 5.1%  | 5.7%  | 15.4% | 21.5% | 18.5% | 16.3% |
| V₃²/Vₚ²   | 74.8% | 17.5% | 6.6%  | 2.6%  | 83.5% | 38.4% | 28.0% | 18.6% |

**Figure 14.** Total speed of debris D5, **Figure 15.** total speed of debris D6, U₂=12.78m/s.

### 4. Conclusion

In this paper, the trajectory distribution and flight speed of debris were investigated through wind tunnel experiments under different wind speeds considering different initial positions. The main conclusions can be summarized as follows.

1. When the distance from the initial position to windward eave is the same, the trajectory distribution of debris released near the central axis is wider than that of the side in the Y direction. A wider distribution range of the trajectory in the Y direction is observed under higher wind speed.

2. When the distance from the initial positions of the debris to the windward eave keeps stable, the distance from the central axis to the initial position has little influence on the trajectory distribution along Z-axis. Differently, the closer the initial position to the windward eave, the wider the distribution range of the flying trajectory in the Z direction. And a slower flight speed is expected when the initial positions of debris lie further from the windward eave.

3. The trajectory distributions in the Z-axis direction become wider under higher wind speed, and the distance from the setting point to the initial point increases along the X-axis.

4. When the debris flies upwards along the slope of the roof, the initial speed is mainly composed of the Z-direction speed. Afterward, the speed in the X and Y directions increases gradually, and the ratio of the speed in the X direction to the total speed is much larger than that in the Y direction.

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