Abstract  Windborne debris is one of the most important causes of the envelope destruction according to the post-damage investigations. The problem of windborne debris damage could be summarized as three parts, including windborne debris risk analysis, debris flying trajectories, and impact resistance of envelope analysis. The method of debris distribution is developed. The flying trajectories of compact and plate-like debris are solved by using a numerical method according to the different aerodynamic characteristics. The impact resistance of the envelopes is also analyzed. Besides, the process of windborne debris damage analysis is described in detail. An example of industrial building is given to demonstrate the whole method by using the observed data of typhoon Chanchu (2006). The method developed in this paper could be applied to risk assessment of windborne debris for structures in wind hazard.

Keywords  typhoon, windborne debris, structural envelopes, damage estimation

1 Introduction

Lots of wind disaster investigations have revealed that the typhoon-induced debris is the main reason for damage of structural envelopes. According to the damage reports of hurricane Alicia (Houston, Tex., 1983), hurricane Hugo (Carolina, 1989) and hurricane Andrew (Florida, 1992), the loss caused by windborne debris is the important part of the total loss [1]. And debris of typhoon York (Hong Kong, 1999) has destroyed tremendous glass curtain walls of high-rise buildings in Central Plaza in Hong Kong [2].

Fast-flying debris may penetrate envelopes and threaten human life and property. Debris penetration also induces internal pressurization, approximately doubling the net loading on roofs, side walls, and leeward walls. Consequently, failed roofing structures, damaged wall cladding panels, and broken glass may become debris sources, starting a “chain reaction” of failures [3]. The problem of windborne debris damage could be summarized as three parts, including windborne debris risk analysis, debris flying trajectories, and impact resistance of envelope analysis. Potential debris includes roof gravel, roof members, and other building components, as well as tree limbs and vehicles.

2 Windborne debris risk analysis

The number of the windborne debris could be calculated by using Eq. (1), where \( N_{\text{deb}} \) is the total number of the debris, \( A_{\text{deb}} \) is the area of the debris source region, and \( \rho_{\text{deb}} \) is the distribution density of the debris region. A schematic drawing of the dimensions of the debris source region and structure is shown in Fig. 1, where \( L_s \) is the length of the structure, \( W_s \) is the width of the structure, \( R \) is the radius of the debris region, and \( \alpha_{\UH} \) is the wind direction angle. For wind direction, \( \alpha_{\UH} \) varies with time, and then \( N_{\text{deb}} \) is not a constant but a variable.

\[
N_{\text{deb}} = \frac{A_{\text{deb}} \cdot \rho_{\text{deb}}}{\cos \alpha_{\UH}}
\]

Received July 20, 2009; accepted December 12, 2009

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Fig. 1  Debris distribution around the structure
\[ N_{\text{deb}} = \rho_{\text{deb}}A_{\text{deb}}. \]  

(1)

3 Windborne debris flying trajectories

Wills et al. [4] classified debris into three generic types: compact, plate-like, and rod-like. The different shapes of debris have different flying trajectories because of their different dynamical characteristics. Windborne debris flying trajectories depend on the shape, density and dimension of the debris, the constraint form, the initial wind attack angle, the wind speed and the air density, etc.

1) Plate-like debris flying trajectories

The forces acting on the plate-like debris include wind load, gravity, and frictional drag of the air. Through calculating the dynamical trajectory Eqs. (2)-(4) of the debris by a numerical method, both velocities and distances of horizontal and vertical could be achieved [5]:

\[
\frac{d^2 x}{dt^2} = \frac{m}{l} \frac{d v_m}{dt} = \frac{1}{2} \rho_{\text{a}} A [(U - u_m)^2 + v_m^2] (C_D \cos \beta - C_L \sin \beta),
\]

(2)

\[
\frac{d^2 z}{dt^2} = \frac{m}{l} \frac{d v_m}{dt} = \frac{1}{2} \rho_{\text{a}} A [(U - u_m)^2 + v_m^2] (C_D \cos \beta) - mg,
\]

(3)

\[
I_{\text{m}} \frac{d^2 \theta}{dt^2} = \frac{1}{2} \rho_{\text{a}} A [(U - u_m)^2 + v_m^2] C_M,
\]

(4)

where \( m \) is the debris mass; \( l \) is the reference length (alongwind dimension for a plate or rod); \( A \) is the reference debris area (usually taken as the largest face area); \( I_m \) is the mass moment of inertia; \( x \) is the horizontal displacement of debris; \( z \) is the vertical displacement of debris; \( \theta \) is the angular rotation; \( u_m \) is the horizontal debris velocity; \( v_m \) is the vertical debris velocity; \( U \) is the wind speed; \( \rho_{\text{a}} \) is the air density; \( C_D \), \( C_L \) and \( C_M \) are drag, lift, and moment force coefficients, respectively; \( \beta \) is the angle of the relative wind vector to the horizontal; \( g \) is the acceleration due to gravity; and \( t \) is the time.

2) Compact debris flying trajectories

The kinematics of compact debris accelerated in a steady horizontal wind stream is assumed to have drag forces and gravity given by Eqs. (5) and (6):

\[
\frac{d^2 x}{dt^2} = \frac{\rho_{\text{a}} C_D (U - u_m) \sqrt{(U - u_m)^2 + v_m^2}}{2 \rho_{\text{m}} I} - g,
\]

(5)

\[
\frac{d^2 z}{dt^2} = \frac{\rho_{\text{a}} C_D (v_m \sqrt{(U - u_m)^2 + v_m^2}}{2 \rho_{\text{m}} l} - g,
\]

(6)

where \( \rho_{\text{m}} \) is the debris density, and \( l \) is the characteristic length of the object equal to the ratio of the volume to the frontal area, which, in the case of a sphere, is equal to two-thirds of the diameter [6].

On the purpose of validating the accuracy of the trajectory method, a compact debris example is given. The compact debris is a sphere of 8-mm diameter with a density of 2000 kg/m³ starting from a height of 10 m above the ground level. The mass of this object, which approximates a piece of roofing gravel, is 0.54 g. The wind speed for initiation of flight for a sphere resting under its own weight is approximately 20 m/s. The drag coefficient is assumed to be independent of Reynolds Number with a constant value of 0.5. The results of comparison of the numerical method and the literature value are listed in Table 1.

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<th>Flight time /s</th>
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