Computational methods of windborne debris trajectories in a near-surface tornadic field

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ABSTRACT:
In a tornado, windborne debris is the main source of residential building envelope damage. In an estimated tornadic field based on post-damage survey data, the windborne debris can act as a particle in the pressure field. To consider the debris risk analysis, the flying trajectories of the debris need to be analyzed for a specific tornado scenario. This paper raises a novel model which simulates compact, rod-like, and plate-like windborne debris trajectories with a simplified coupled computational fluid dynamics rigid body (CFD-RBD) method. A translational vortex field generates a windborne debris distribution map around the target building. Thus, the in-situ debris distribution map, which can be accessed from the post damage survey, will be compared with the CFD-RBD result and then provides the estimation of the tornadic wind and pressure fields. An example of a windborne debris distribution map is given to demonstrate the whole method by using the post damage survey data of the 2011 Joplin, MO tornado.

Keywords: Tornado, Debris, Near-surface, post-disaster data, Trajectories

1. INTRODUCTION

A tornado is an extreme and complex wind event that is composed of a violently rotational wind field and a persistently translational wind field, and it cause nearly one-fifth of all-natural hazard fatalities based on 10-year average data in the United States (NWS Analyze, 2020). To understand and replicate the complex near-surface tornadic field, some numerical vortex models have been proposed such as Rankine vortex model (Rankine, 1882, p. 1), Burgers-Rott Model (Burgers, 1948; Rott, 1958), and Baker-Sterling model (Baker and Sterling, 2017). These models have been proposed for use in numerous actual tornadoes (Refan and Hangan, 2018; Bluestein et al., 2018, Chen and Lombardo, 2019) based on radar data and tree-fall/damage patterns as *in-situ* data are challenging to obtain.

In a tornado, windborne debris is commonplace. The debris will obtain massive kinetic energy as missiles during the motion in the near-surface tornadic field (Lin et al., 2007). Hence, it is possible to consider the windborne debris landing points as evidence for evaluating the near-surface tornadic field. Thus, this paper puts forward a method for applying translational numerical vortex models into a real tornado event by adopting the windborne debris distribution map around the damaged building to replicate the near-surface tornadic field in the real case.

As for replicating the near-surface tornadic field from previous tornado cases, this paper adopting the estimated tornado path from satellite images and applying a translational vortex model with pre-set parameters combination along the path. Then, the computed debris flying trajectories in the replicated tornadic field can be described through theoretical formula results (Twisdale et al., 1979) and the fitting aerodynamic coefficient result from CFD-RBD test data.

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Then, The estimated landing points of windborne debris generated from the footprint of the damaged building during a tornado case are recorded to generate a distribution cluster map. Comparing the cluster with the real debris landing point from post damage survey data, an evaluation score for the matching degree between the numerical replicated near-surface tornadic field and the in-situ situation is given, and the best-fit model parameters combination can be found.

In this paper, Section 2 introduces the acquisition process of the in-situ debris distribution data from post damage survey as the source data of this method; Section 3 introduces the numerical models of a translational one-cell vortex and plate debris trajectories in the simulated wind field coupled with CFD-RBD simulation for wind coefficient; the model fitting and approximation process with the 2011 Joplin, MO tornado is shown in Section 4 and the possible improvement is developed in Section 5.

2. DATA COLLECTION

During a post damage survey, orthogonal photos containing building damage and windborne debris are generated from aerial imagery. As an illustration, Figure 1 shows an extracted building footprint and nearby windborne debris from that footprint. After the image analysis process, the coordinates of debris landing points and the aspect ratio for each piece of debris are recorded as the input data.

Figure 1. An aerial photo of a rectangular residential building with yellow marked plate debris and blue marked rod debris

3. MODELS

3.1. Estimated near-surface tornadic field

Considering the previously mentioned stationary vortex models along a tornado path to reproducing a real tornado case, a modified near-surface tornadic field can be generated as a combination of a numerical stationary vortex field and a translation field (Chen and Lombardo, 2019). To consider the debris flight trajectories in the estimated translational near-surface tornadic field, a three-dimensional vortex model (e.g. Burgers-Rott Model; Baker Sterling model) is able to describe the debris motion.

3.2. Computed trajectories in the estimated near-surface tornadic field

Previous studies have built exhaustive theoretical formulas to describe the aerodynamic behaviors of different types of debris. Windborne debris is classified into three types: compact, sheet, and rod based on its shape (Wills et al., 2002). In the beginning, basic equations of motion (EOM) for debris were established only considering the drag force of spherical particles (McDonald, 1976). Then, a three-dimensional trajectory model with lift, drag, and side force impact under relative wind vector was generated (Twisdale et al., 1979). Finally, a six-dimensional model with overall consideration of lift, drag, side force, pitch moment, rolling moment, and deflection torque coefficients is established (Redmann et al., 1978). The computed solution of debris flight trajectories matured gradually from the theoretical model to the wind tunnel test validation and modified models with considering Magnus and turbulence effects (Lin et al., 2007; Richards et al., 2008). Computational Fluid Dynamics (CFD) is also applied in recent studies of simulating the windborne debris trajectories, and unsteady/ quasi-steady flow methods are the two main simulation methods applied. In the unsteady flow simulation method, the debris motion in the wind field is considered as a Fluid-Structure Interaction (FSI) problem, and Large Eddy Simulation (LES) with dynamic mesh technique is applied for solving the time-varying debris spatial position (Liu et al., 2021). As for the quasi-steady simulation method, the debris aerodynamic force is assumed only related to the relative rigid body motion in the current time step, and RANS could be applied to solve the trajectories (Kakimpa et al., 2012). Since the traditional EOM method usually describes the specific debris used in wind tunnel experiment and inconvenient to be applied for the debris real cases, and the unsteady CFD method requires a huge computer source, this paper couples a 3-DOF debris EOM with a quasi-steady CFD method for determining the aerodynamic coefficient for the debris from the real case under the variance of wind attack angle and debris' aspect ratio. As an illustration, 3-DOF EOM under a steady flow (U and V are computed from the wind field model) for plate debris are shown in Eq (1)-(3), and the small-time step simulation method is shown in Eq (4)-(6):

$$\frac{d^2x}{dt^2} = \frac{dU_m}{dt} = \frac{\rho_a A\left[(U-U_m)^2+(V-U_m)^2\right](C_D\cos\beta - C_L\sin\beta)}{2m} \quad (1)$$

$$\frac{d^2z}{dt^2} = \frac{dV_m}{dt} = \frac{\rho_a A\left[(U-U_m)^2+(V-U_m)^2\right](C_D\sin\beta + C_L\cos\beta)}{2m} - \mathrm{g} \quad (2)$$

$$\frac{d^2\theta}{dt^2} = \frac{d\omega_m}{dt} = \frac{\rho_a A l\left[(U-U_m)^2+(V-U_m)^2\right]C_M}{2I_m} \quad (3)$$

$$x_i = x_{i-1} + U_{m,i-1}\Delta t + 0.5a_{x,i-1}\Delta t^2 \quad (4)$$

$$y_i = y_{i-1} + V_{m,i-1}\Delta t + 0.5a_{y,i-1}\Delta t^2 \quad (5)$$

$$\theta_i = \theta_{i-1} + \omega_{m,i-1}\Delta t + 0.5a_{\theta,i-1}\Delta t^2 \quad (6)$$

In these equations, C_D, C_L and C_M for a single time step with are determined by CFD under the wind attack angle β, which can be denoted by rotation angle θ as Eq (7):

$$\sin\beta = \frac{V_i - V_{m,i}}{\sqrt{(U_i - U_{m,i})^2 + (V_i - V_{m,i})^2}} \quad (4)$$

4. RESULTS

For the case shown in Figure 1, a plate debris with a length of 1.92 meters and a width of 0.84 meters, which were obtained from image analysis, is selected as the target plate. Then, the aerodynamic coefficients under different wind attack angles for this debris are simulated in ANSYS Fluent software with Spalart-Allmaras viscous equation under second-order upwind solution format. The source building footprints are meshed based on the debris area information and for each mesh grid point, flying debris is generated once a critical wind speed V_c=70 mph is reached. As for the illustration case, a Rankine vortex field with parameters ($\eta = 3.69$, $G_{max} = 5.13$, $\alpha = 24.9°$, R_{max}=380m, $\varphi = 0.821$) (Chen and Lombardo, 2019) is applied for the near-surface tornadic field.

Then for each piece of flying debris, a trajectory is computed under the pre-defined wind field model coupled with the 3-DOF equations with CFD-generated aerodynamic coefficients. As a result, the clustering degree of the simulated debris' landing points represents the accuracy of the whole model. As shown in Figure 2, the Euclidean Distance for the landing point cluster to the target plate debris is 7.07 meters.

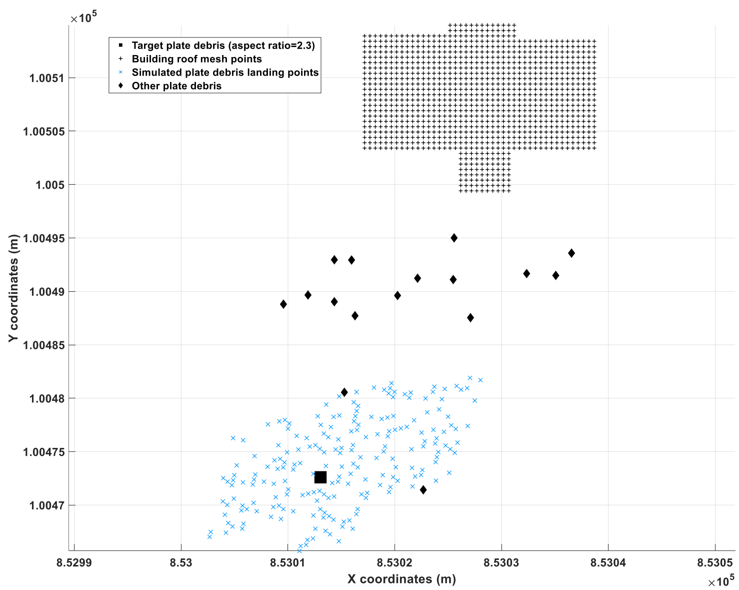

Figure 2. An illustration for simulated debris landing point cluster map

5. CONCLUSION AND IMPROVEMENT

This numerical debris model, which couples a tornado vortex model and 3-DOF equations with CFD-RBD simulated coefficients, makes it possible to rapidly simulate and evaluate the debris distribution from actual tornado cases. The estimated debris trajectories and distribution map will help to calibrate the near-surface wind field. As for improvements, a joint evaluation method for various debris with different types will be considered.

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