# Reproducing the Community Damage Induced by the 2021 Midwest Tornado Outbreak using Combined CM1 and CFD Simulations

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**SUMMARY:**
In this study, Bowling Green is taken as an example to demonstrate the potential of the coupled meteorological model (CM1 here) and CFD to reproduce the realistic tornadic wind field of the intensive 2021 Midwest tornado outbreak and the induced damage condition. The simulation results demonstrate that the coupled approach can reasonably generate a translating tornado in the CFD domain closer to the real-world situation with asymmetry tangential velocity field and tilting vortex structure. And complex terrain can alter the tornado flow structures and translating path in the near-ground region. Even though the current simulation setup overestimates the damage condition, the combined CM1 and CFD simulation approach has a high potential reproduce the structural damage induced by tornadoes with the temporal and spatial varying boundary conditions.

*Keywords: 2021 Midwest tornado Outbreak, tornado-community interaction, CFD*

## 1. GENERAL INSTRUCTIONS

On December 10th and 11th in 2021, a tornado outbreak with three tracks struck many communities across the Midwest of the United States, resulting in 89 deaths, 667 injuries, $3.9B in damages and significant destruction to portions of the region (e.g., Mayfield, KY and Bowling Green, KY). To reduce tornado impact, it is essential to understand tornado-structure and tornado-community interactions. The existing tornado numerical simulation cannot reflect the real-world situation of the temporal and spatial variation in velocity input at velocity inlet (Li et al., 2019; Zhao et al., 2022), due to the lack of field-measured data. Combined mesoscale weather model with CFD is a promising approach to provide temporal and spatial varying boundaries for the wind engineering CFD simulation (Chen et al., 2022; Hiromasa Nakayama et al., 2011; Kadaverugu et al., 2021; Kawaguchi et al., 2019; Kwak et al., 2015). Therefore, the present authors employ the coupled meteorological model with CFD to reproduce real-world tornado events to encourage the knowledge of tornado-community interaction and determine the community-level damage state, with Bowling Green, KY, as an example community.

## 2. METHODOLOGY

The one-way coupling simulation between CM1 and CFD can produce physically driven, realistic tornadoes to analyze the unsteady flow behavior and tornado-induced damage on the structures, as shown in Fig. 1. A rectangular domain $4km \times 4km \times 2km$ $(L \times W \times H)$ is nested in CM1 domain at the near-ground region, where the horizontal and vertical grid spacing is even at 10m (the lowest scalar level is at $z = 5m$). Then, 3D linear interpolation is used to map the output of CM1 to CFD domain, while interpolation for time is also linear. The flow behavior and pressure distribution, especially surrounding the community, are analyzed using CFD with the geometry model inside, which has a finer mesh structure to capture more turbulence and characteristics of the tornadic field. Large Eddy Simulation is applied in this study, which is governed by filtered time-dependent Navier-Stokes equations. Both momentum and mass are assumed to be mainly transported by large eddies, which are directly solved from the equations, while small eddies are numerically modeled with the Smagorinsky-Lilly subgrid model ( $C_s = 0.1$ in CFD). The segregated implicit solver with a SIMPLEC (Semi-Implicit Method for Pressure Linked Equation-Consistent) method is applied for Pressure-velocity Coupling. The time step interval is 0.01s. The CFD computational domain is a cylinder with a height of 1100m and a radius of 800m, which can eliminate the effect of blocking.

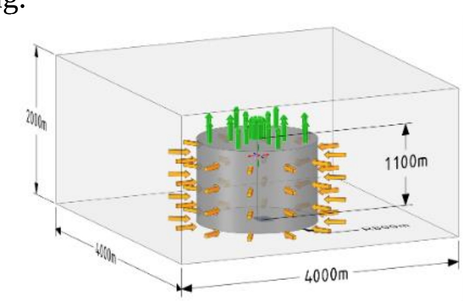
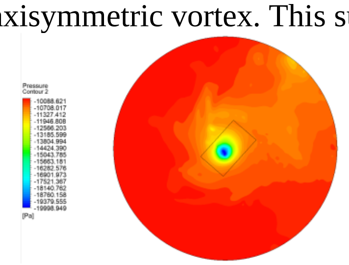


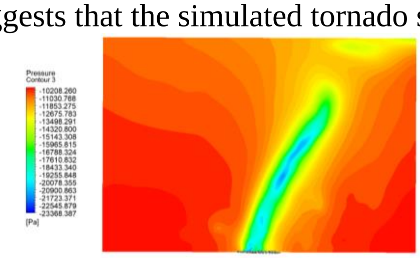

Figure 1. Schematic diagram of the calculation process

## 3. RESULTS AND DISCUSSION

### 3.1 Characteristics of Translating Tornadic wind field

Figure 2 presents the pressure distribution at the elevation of 50m at $T = 12s$ when the tornado vortex is fully within the community area. The pressure distribution on a vertical plane is shown in Figure 3, which corresponds to the location of the minimum pressure in Figure 2. It indicates that a tilting vortex structure is generated, which is attributed from the proper setup, that is, the temporal/spatial varying boundary conditions and initial conditions. Figure 4 presents the tangential velocity contour, which is not a perfect red circular strip as observed in an ideal axisymmetric vortex. This suggests that the simulated tornado structure is asymmetric.





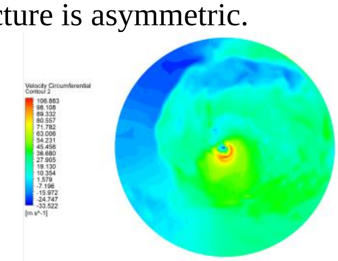


Figure 2. Pressure contour on the horizontal plane at 50m height (T=12s)

Figure 3. Pressure contour on a vertical plane (T=12s)

Figure 4. Tangential velocity contour on the horizontal plane at 50m height (T=12s)

Figure 5 presents the tangential velocity along the X direction and the corresponding pressure contour on the horizontal plane at the height of 50m ($T = 12s$). The core radius at this moment is 35.54m and the corresponding pressure is $-15000Pa$ that is used to plot the iso-surface in Figure 6. The tornado translating is represented by three vertices at $T = 5s, 15s\ and\ 25s$, respectively, as shown in Figure 6. The iso-surfaces exhibit some extent of overall rotation and distortion along the height.

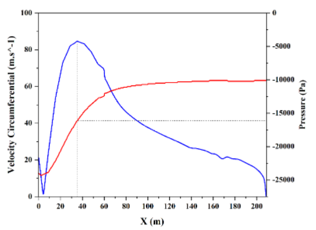



Figure 5. Tangential velocity profile with Pressure profile along the X direction at 50m height (T=12s)

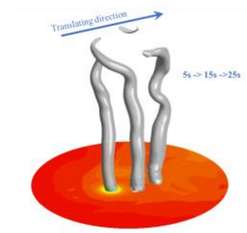



Figure 6. Vortex at three time instant (T=5s, 15s, 25s)

### 3.2 Tornado-Community Interaction

To reproduce the tornado damage observed in the Bowling Green community, two cased are simulated. Case 1 is pure wind field, and does not include the community. The obtained tornado path is presented as the green graph in Figure 7, and the relative location of the path and community is modified to be consistent with the real damage path in Figure 8. Then, Case 2 is to explore the tornado-community interaction with the whole community geometries. And the red line in Figure 7 is the corresponding path from Case 2. It implies that the complex terrain has significant affected the tornado translating directions and vortex flow structurenear ground. Figure 9 presents the surface pressure of a building when the tornado center hit it. Extreme negative pressure appears at the roof edges and corners, which makes the roof component and roof connections vulnerable.

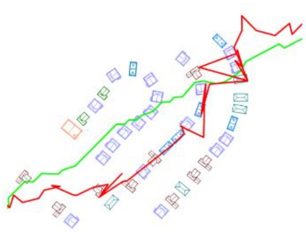


Figure 7. Tornado translating path


Figure 8. Post-storm obervation in the damaged Bowling Green community

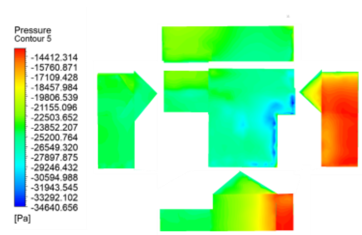



Figure 9. Surface pressure when the tornado center hits the building

### 3.3 Determination of the community-level damage state

To estimate the damage condition of the whole community caused by the simulated tornado, the obtained surface pressure on each building is compared with the structural resistance to find the total area beyond the material capacity. Then, referring to HAZUS, the damage state is determined. Figure 10 shows the damaged results that all buildings are completely destroyed, which indicates that the raw data from the CM1 model is so intense that needs to be scaled to reproduce the real-world damage state obaserved in the Bowling Green community under the 2021 Midwest tornado outbreak.

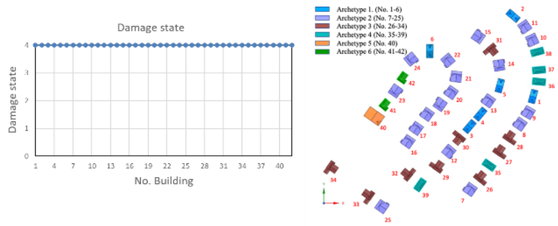



Figure. 10 Damage states for each building in the Bowling Green community based on the current CM1 data

## 4. CONCLUSION

In this study, the combined CM1 and CFD approach is employed to reproduce the real-world tornado event and the damage conditions for a community. With the temporal and spatial varying boundary conditions, the generated tilting translating tornado is closer to a real-world situation. In the near-ground region, the complex terrain has a significant influence on the tornado structure and translating path, and this influence decreases as the elevation increases. And the existing CM1 data is too intense to reproduce real damage. In the future, the authors will modify the raw CM1 data, which can facilitate the simulation for damage reproduction, and also gaining knowledge about the relationship between the coupled velocity and pressure field.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