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Simulated aeroelastic testing in the proposed NEWRITE facility: tower structures under tornado flows

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SUMMARY:
This study investigates the stochastic response of a scale model of a benchmark tall building, subjected to tornado-like wind fields. A numerical model is used to simulate a typical aeroelastic test in the "NEWRITE" facility, the largest experimental facility of its kind currently under design. The synthetic wind field, which replicates the tornado flow in this facility, is based on a stochastic model, combining mean velocity profiles from established tornado models with non-stationary turbulence and time-dependent modulation functions. A Monte Carlo simulation framework is used to account for the aleatory variability of wind loading, introducing randomness in the aerodynamic coefficients and velocity fluctuations, while keeping the structural properties of the aeroelastic model deterministic. A set of repeated time-history analyses is performed for each tornado model. Results are interpreted through a conditional probability approach, based on key intensity measures, enabling a mapping between laboratory input parameters (i.e., geometric scale, velocity scale, etc.) and model's structural response.

Keywords: Tornadoes, Monte Carlo simulations, Aeroelastic tests

1. INTRODUCTION

In the past years, non-stationary wind events grew in occurrence and severity. Among all of these extreme wind hazards, this paper will focus on tornado loads. Despite their low probability of occurrence, this kind of event costs the USA many billions of dollars (Wurman and Gill, 2000). Due to the severe loading mechanisms and the potential damage, associated with tornadoes and other non-synoptic wind events, the need for advanced testing facilities capable of reproducing these phenomena has grown in importance. The "National Testing Facility for Enhancing Wind Resiliency of Infrastructure in Tornado–Downburst–Gust Front Events" (NEWRITE) is a university-based research infrastructure, currently under design, with the goal of enabling physical testing of civil infrastructure, from mid-to-full scale, subjected to realistic non-synoptic wind flows. Within a broad research team, the present study contributes to the design phase of the NEWRITE facility by focusing on the characterization of structural response quantities under simulated tornado-induced wind loads, relevant to: (*a*) laboratory safety during the execution of the tests, (*b*) optimal sensor selection and placement.

2. WIND FIELD AND LOAD SIMULATION

Tornadoes originate from "supercell" thunderstorms and produce short-duration, transient, non-synoptic, high-intensity wind fields near the ground Markowski and Richardson, 2010. A schematic plan view of the fluid-structure system, including the wind velocity components, is shown in Fig. 1. To simulate typical testing conditions in the proposed NEWRITE facility, the storm is assumed to be "frozen", i.e., the translational velocity component of the full-scale tornado is not included. Consequently, the relative radial distance $R = R_0$ does not vary with time.

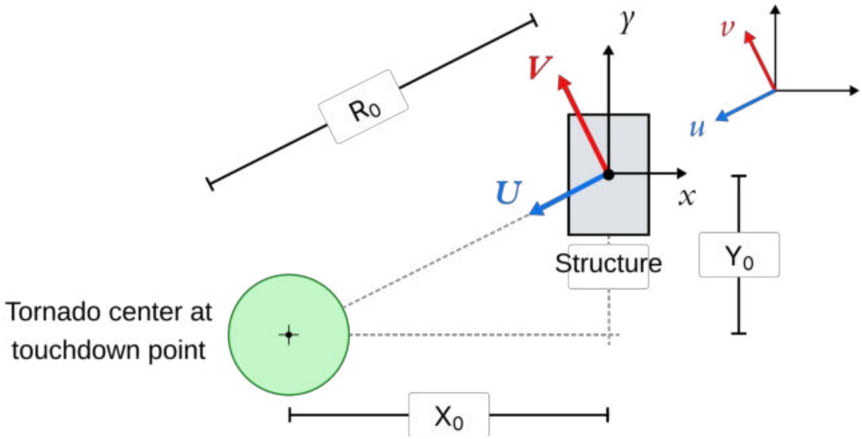

Figure 1. Schematic plan view of the fluid-structure system with the wind velocity component (horizontal plane)

In this work the wind field is generated using a deterministic-stochastic approach (Le and Caracoglia, 2020b). To simulate the time evolution of a tornado simulation in the wind tunnel a trapezioidal, time-dependent modulation function is employed. The non-stationary turbulence is also synthetically simulated. Various models for the formulation of the tangential and radial mean velocity components, induced by a tornado field, are available (Kim and Matsui, 2017). In this study two tornado models are used: (*a*) an empirical model proposed by Fujita (Fujita, 1978), (*b*) a theoretical three-dimensional model by Kuo-Wen (Kuo, 1971). For the sake of brevity, in the following sections, only the essential information is presented.

2.1. Fujita model

The tornadic flow is composed of an inner core and an outer core, which are modeled separately depending on the radial distance from the tornado center (Fujita, 1978). The inner core, having radius r_n is assumed to rotate as a solid body without vertical motion, and it is surrounded by an outer core characterized by a vertical updraft (neglected in this study). Inflow into the outer core occurs only within a shallow layer, referred to as the inflow layer, and the maximum radial and tangential velocities are attained at or near the outer core boundary (Kim and Matsui, 2017). The relationship between the inner and outer radii is, with n being the core ratio:

$$r_n = n \cdot r_0 = 0.9 - 0.7\exp(-0.005 r_0) \cdot r_0 \tag{1}$$

The tangential velocity $V(r,z)$ depends on the cylindrical coordinates r and z; it is defined as the product of two functions, as shown in Eq. (2a), namely the radial and vertical functions, $F(r)$ and $F(z)$, respectively. The radial velocity U is assumed to be proportional to the tangential velocity, as expressed in Eq. (2b), where α is the crossing angle between the flow direction and the tangential direction at the same point.

$$V(r,z) = V_{max} F(r) F(z), \tag{2a}$$

$$U = V_{max} \tan\alpha \tag{2b}$$

2.2. Kwo-Wen model

This model accounts for the boundary layer thickness δ, which is smaller at the tornado center and increases rapidly with increasing radius. The expression for the boundary layer thickness is presented in Eq. (3) where δ_∞ is the boundary layer thickness outside the tornado and r_{co} is the radius where the maximum tangential velocity occurs.

$$\delta = \delta_\infty \left\{ 1 - \mathrm{e}^{\left[-0.5\left(\frac{r}{r_{co}}\right)^2\right]} \right\} \tag{3}$$

To define the radial and tangential velocity components, it is necessary to distinguish whether the flow is inside or outside the boundary layer. Outside the boundary layer, the horizontal, radial velocity U_o is assumed to be zero, while the tangential velocity V_o is given in Eq. (4). The velocity components inside the boundary layer, U_i and V_i, are defined in Eqs. (5a) and (5b).

$$V_o = 1.4 \left(\frac{V_{o,max}}{r/r_{rco}} \right) \left\{ 1 - \mathrm{e}^{\left[-1.256 \left(\frac{r}{r_{co}} \right)^2 \right]} \right\} \tag{4}$$

$$U_i = V_o \left\{ 0.672 \mathrm{e}^{\left(-\pi \frac{z}{\delta} \right) \sin\left[(b+1) \pi \frac{z}{\delta} \right]} \right\}, \quad (5a) \qquad V_i = V_o \left\{ 1 - \mathrm{e}^{\left(-\pi \frac{z}{\delta} \right) \cos\left(2b\pi \frac{z}{\delta} \right)} \right\} \quad (5b)$$

In the previous equations, b is the representation of the velocity fluctuation outside the core.

3. STRUCTURAL MODEL

The structural model analyzed in this study is a scaled-down representation of the CAARC benchmark tall building. The dimensions of the full-scale building are: B = 30.5 m, D = 45.7 m, and H_C = 183 m; the building has uniformly distributed mass per unit height, $m_z(z) = 220,800$ kg/m. The structural system is treated as a shear-type planar building with normalized, continuous, linear mode shapes in bending (lateral planes) and torsion (about z axis). For this system, the quasi-steady aerodynamic theory (Piccardo and Solari, 2000) is adopted to describe the wind-induced loads; this approach is approximately valid to simulate the effects of a short-lived tornado on a tall structure (Le and Caracoglia, 2020a). The dynamic scaling of the model follows the standard principles of aeroelastic dynamic similitude. To ensure similarity between the scale model and the full-scale prototype, the relevant non-dimensional aerodynamic and kinematic parameters must be preserved. The geometric scale ratio $\lambda_L = H_{C,m}/H_{C,p} = \{1 : 25, 1 : 50\}$ (model "m" / prototype "p") and velocity scale ratio $\lambda_V = V_{\mathtt{max},m}/V_{\mathtt{max},p} = 1 : 1.5$. In particular, functional relationships among the following dimensionless quantities, governing the problem, must remain consistent: swirl ratio, dimensionless frequency.

4. NUMERICAL SIMULATIONS

The stochastic analysis is performed using a Monte Carlo simulation framework to account for the inherent aleatory variability of tornado wind loading under laboratory conditions representative of the NEWRITE facility. Uncertainties are introduced in the aerodynamic load parameters and wind fluctuations, while the structural model properties are kept deterministic. A set of $N_{\mathtt{MC}} = 500$ time-history simulations is conducted for each tornado model, considering variability in key parameters such as force coefficients and wind components. The results are analyzed through a conditional approach based on different intensity measures: λ_L, the horizontal components of the offset distance (X_0, Y_0) (Fig. 1) and V_{max}, which characterize the severity of the simulated events. Quantities (X_0, Y_0) and V_{max} are measured at the scales of the NEWRITE facility. Each time-history response is solved by Wavelet- Galerkin method.

5. RESULTS AND FINAL REMARKS

Figure 2 presents the results of the high-fidelity Monte Carlo analysis, simulating $N_{\mathtt{MC}}$ repeated experiments of the CAARC building model in the NEWRITE facility. The figure focuses on the maximum lateral displacement of the model at the geometric scale $\lambda_L = 1 : 50$. The figure panels are organized such that each row corresponds to a different tornado model, while each column corresponds to models located in the same position with respect to the center of the chamber (varying offset distance X_0 with $Y_0 = 0$). In each panel, the boxplots depict the maximum lateral rooftop displacement (e.g., $\delta_{\mathtt{max}}$) as a function of the mean wind velocity $V_{\mathtt{max}}$ in the chamber. The boxplots display median value (central line), 25th and 75th percentiles (the boxes); the "whiskers" extend to the most extreme data points that are not classified as outliers, whereas the outliers (cruciform markers) are outside this range. The overall objective is to provide a simplified mapping between the input parameters (i.e., laboratory test settings ($V_{\mathtt{max}}$, X_0, etc.) and relevant physical quantities that describe the structural response of the aeroelastic model (e.g., base moments, maximum lateral rooftop drift). This framework will support design of the facility and assist NEWRITE researchers in planning future experiments.

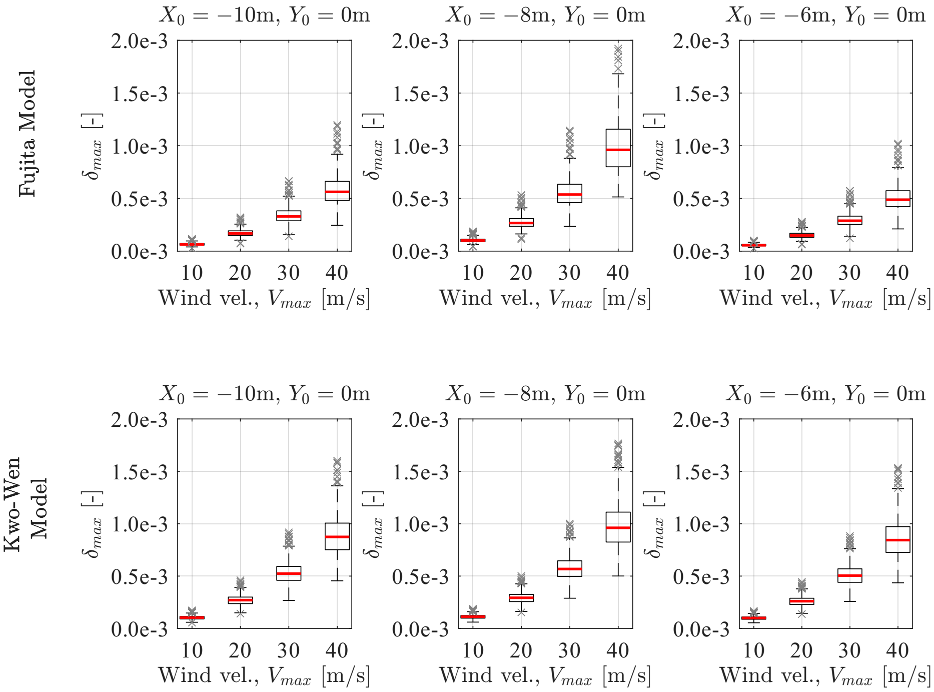

Figure 2. High-fidelity Monte Carlo simulations: normalized lateral rooftop displacement of the CAARC aeroelastic model vs. maximum tangential velocity, with variable offset distance X_0 and two tornado models

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