CWE-8
June 7-11, 2026
London, ON, Canada

Experimental study of aerodynamics of train-bridge system in synoptic and non-synoptic winds

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Abstract: As climate change intensifies the frequency and severity of extreme weather events, understanding the aerodynamic behaviour of train-bridge systems under non-synoptic wind conditions, such as tornadoes, has become increasingly important. In this study, the aerodynamics of a train-bridge system subjected to tornadic winds are investigated experimentally. The side-force coefficients of the leading carriage exhibit trends that closely follow the tangential velocity distribution of the tornado-like flow. Notably, in contrast to uniform-flow conditions, the side-force coefficients in tornadic winds are substantially lower, reflecting the reduced equivalent wind speed acting on the train as a whole.

Keywords: *Aerodynamics, train-bridge system, wind tunnel test, tornado-like vortex, synoptic wind*

1. INSTRUCTIONS

Climate change has led to an increase in the frequency and intensity of extreme weather events, heightening the risk posed by tornadoes to railway systems worldwide. Tornado-induced railway accidents have been reported in multiple regions, including the Uetsu Line accident in Japan and the derailment of 43 carriages in North Dakota, USA (Suzuki and Okura, 2016). With the rapid expansion of high-speed rail networks in China, high-speed trains are increasingly exposed to non-synoptic wind hazards, such as tornadoes.

Previous studies have investigated the aerodynamics of railway vehicles under crosswind conditions using experimental and numerical approaches (Kikuchi and Suzuki, 2015; Premoli et al., 2016; Liu et al., 2020). However, owing to the technical challenges associated with large-scale tornado simulators, experimental investigations of railway vehicle aerodynamics in tornadic winds remain scarce. In this study, the aerodynamic responses of a railway vehicle are measured experimentally in a tornado simulator, and a comprehensive comparison is conducted between aerodynamic characteristics under tornadic winds and those in atmospheric boundary layer flows.

2. WIND TUNNEL TESTS

2.1. Train-bridge system

In this study, a CRH2 high-speed train and a 32 m simply supported beam bridge are examined, as both are widely deployed across China's high-speed railway network. A geometric scale of 1:40 is adopted, and the corresponding models are shown in Figure 1. Aerodynamic forces acting on the leading carriage are measured using a high-frequency force balance, while surface pressure distributions at two cross-sections of the leading carriage are captured using a pressure-scanning system.

Figure 1: The train-bridge system model.

A direct-flow wind tunnel and a tornado simulator were constructed at Central South University in 2022 and 2023, respectively. The direct-flow wind tunnel has a test section 15 m long, 2.2 m wide and 2.0 m high, with a continuously adjustable wind speed from 0 to 35 m/s and a turbulence intensity below 1% Figure 2(a). The tornado simulator, driven by eight fans, provides a 12 m-diameter test area and a 5 m updraft channel, generating a vortex with a core radius of 2 m, a swirl ratio ranging from 0 to 2.0 and a maximum tangential wind speed of 30 m/s. The flow characteristics of the resulting tornado-like vortices have been documented previously (Jing et al., 2025). The configuration of the train-bridge system within the tornado simulator is illustrated in Figure 2(b), with the centre of the leading carriage aligned with the vortex centre.

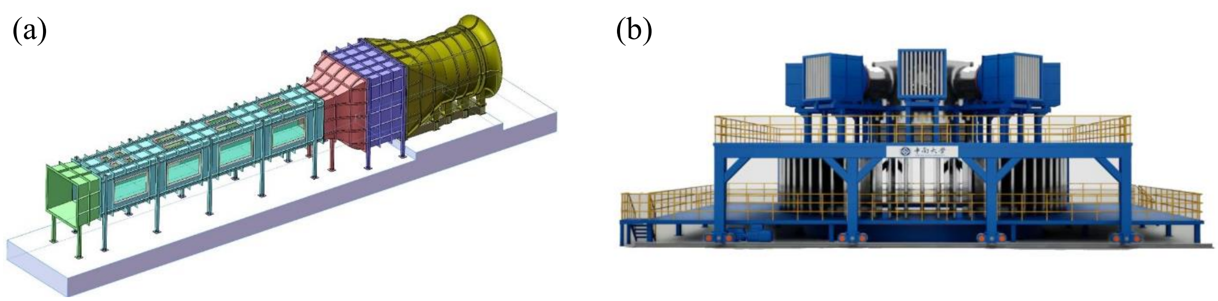

Figure 2: (a) The direct-flow wind tunnel and; (b) tornado simulator at Central South University.

The aerodynamic coefficients are calculated as the following equation:

$$C_{fy} = \frac{2F_y}{\rho A V^2} \tag{1}$$

where F_y is side force, ρ is air density, A is the side area of carriage, V is the inflow wind speed. For aerodynamic investigation, the inflow wind speed at the height of the car-body centre of gravity is used in the direct-flow wind tunnel, whereas the maximum tangential wind speed at the same height is adopted in the tornado simulator.

3. RESULTS AND DISCUSSION

The aerodynamics of the train-bridge system are measured in both a direct-flow wind tunnel and a tornado simulator. In the direct-flow wind tunnel, the incoming wind is oriented perpendicular to the train, corresponding to an angle of attack of 90°, which yields the maximum aerodynamic coefficients and is therefore selected as the representative condition. In the tornado simulator, the train-bridge system is initially positioned at the vortex centre and subsequently displaced radially outward in increments of 0.20 m. As shown in Figure 3, the side force is negligible when the system is located at the vortex centre, owing to the symmetric action of tangential winds on both sides of the train. The side force increases with radial distance and reaches a maximum near the vortex core radius, where the carriage is fully immersed in the tangential flow and the spatially averaged wind speed attains its peak value.

In addition, the train-bridge system is translated along a path parallel to the vortex core radius, corresponding to train motion along a circular trajectory around the tornado. Under this configuration, variations in side force are markedly smaller than those observed along the vortex centreline, reflecting the reduced equivalent wind speed acting on the leading carriage. Differences in side force among positions at the core radius arise from changes in local wind direction.

Compared with the aerodynamic coefficients obtained in the direct-flow wind tunnel, the maximum coefficients measured in the tornado simulator are consistently lower, owing to the smaller equivalent wind speed acting on the carriage under tornadic wind conditions.

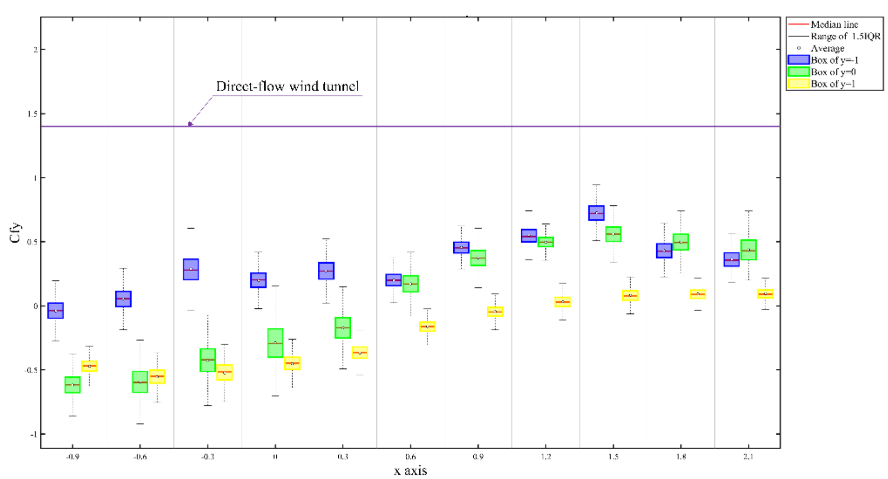

Figure 3: A comparison of aerodynamics of train-bridge system in synoptic and non-synoptic winds.

4. CONCLUSIONS

In this study, the aerodynamic coefficients of a train-bridge system under synoptic and non-synoptic wind conditions are compared experimentally. The side-force coefficients of the leading carriage at different spatial positions exhibit trends that closely follow the tangential velocity distribution of the tornado-like flow. Despite this correspondence, the side-force coefficients measured under tornadic winds are consistently smaller than those obtained in uniform-flow conditions, reflecting the reduced equivalent wind speed acting over the full projected area of the train in non-synoptic wind fields.

ACKNOWLEDGEMENTS
The work presented here was supported by the National Natural Science Foundation of China (U2568215)

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