Experimental Study on Wind Loading Characteristics of Trains under Stationary Tornado-like Vortices

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Abstract: The risk of trains being hit by tornadoes in China continues to increase due to the increasing density of railway lines and the shortening of the train departure intervals and the increasing probability of extreme weather phenomena caused by global climate change. If a train is hit by a tornado, it will cause huge casualties and economic losses, so it is necessary to investigate the tornado-induced effects on trains. A series of rigid-model wind pressure measurement tests on a train car under tornado wind loading were conducted using a tornado-vortex simulator, in order to determine the effects of the distance between the train car and the tornado’s center, the swirl ratio of a tornado-like vortex, and the ground roughness on the wind pressure distributions and wind load characteristics on trains. Apparent discrepancies were observed between tornado-induced wind loading and lateral wind loading obtained from conventional boundary-layer wind tunnel tests. The wind pressure and wind load on the car surface are mainly affected by the combined effects of the aerodynamic flow-structure interaction and the pressure drop accompanying the tornado within 1.5 times the vortex core’s radius, and the impact of tornado-like vortices on the train car is almost negligible as the distance from the train car to the tornado’s center exceeds three times vortex core’s radius. The variation trend of mean/fluctuating pressure coefficients is generally consistent. Large values of fluctuating pressure exist mainly on the top and side surfaces of the train car, especially the side surface proximal to the tornado’s center. The most unfavorable mean sectional side force coefficients were found when the train car is located in the tornado’s core and the largest lift force coefficients at the tornado’s center. The overall side force coefficients peaked when the train car is located at a distance of 1.5 times the tornado’s core radius, whereas the largest lift force coefficients were found when the train car was located at the tornado’s center. The overall distribution patterns of the wind force coefficients of the car under different swirl ratios and ground roughness levels are basically the same. The peak aerodynamic force value increases with increasing swirl ratio, and it decreases as ground roughness increases.

Keywords: physical simulation; tornado-like vortices; train; wind pressure; wind force

1. Introduction

Tornadoes are common all over the world. They have great destructive power, though they normally do not last long. A tornado is a micro-scale and strong convective weather phenomenon: a quickly rotating column of air that extends from a thunderstorm and touches the ground. The number of tornadoes reported in China is lower than that in the United States; nevertheless, the damage caused by them is very great. They caused a total economic loss of more than 9.1 billion CNY from 2007 to 2017, and at least 1772 people died from 1961 to 2011 [1–3]. For example, Yang et al. [4] reported that on 23 June 2016, an EF4 tornado killed at least 99 people and injured 846 others in Yancheng City, Jiangsu Province, China. In addition, more than 3000 buildings were destroyed, and hundreds of high-voltage transmission towers were damaged. According to reported statistics, approximately 17 provinces in China have suffered from tornadoes over the last two decades. Annually,
the number of deaths is more than 10 and the number of injuries exceeds 1000 [5]. The direct economic loss amounts to billions of CNY. The railway infrastructures are also vulnerable to these extreme local strong winds, and trains in Japan are often affected by strong tornadoes [6,7]. For instance, a high-speed train was hit by a tornado on 25 December 2005 near Sakata, and it overturned, killing 5 people and injuring 32 more. Another train encountered a tornado on 17 September 2006 when traveling at a speed of 25 km/h on the Japanese National Railroad. The first two wagons overturned, and six people were injured. In China, to the author’s knowledge, there are few records of extremely strong winds hitting trains, such as tornadoes. On 1 June 2021, a tornado was generated between the Mao’ershan West Railway Station and the Shangzhinan Railway Station along the Harbin–Mudanjiang High-Speed Railway, which caused equipment failure, and many trains were delayed. In recent years, the density of railway lines in China has been increasing. Global warming also leads to higher frequencies of extreme weather phenomena, such as tornadoes. Therefore, it is necessary to evaluate tornado-induced aerodynamic forces and strengthen the meteorological monitoring technology to ensure the operational safety of trains, especially in the areas where tornadoes are most common [8].

Due to the difficulties and dangers associated with field measurements, and the complexity of tornadoes’ boundary conditions, the parameters defining the characteristics of tornadoes have not been well investigated. Physical modeling of tornado-like vortices has become a powerful tool for investigating tornado-induced wind forces on a structure. This modelling approach is similar to boundary-layer wind tunnel experiments, and has advantages such as controllable conditions and repeatability [9]. Ying and Chang [10] designed and developed a tornado-like-vortex simulator based on basic knowledge of tornado structure, and analyzed the tangential and radial velocities of tornadoes. The tornado-vortex simulator was improved by Ward [11], becoming known as the Ward-type tornado-vortex simulator. Haan et al. [12] designed, built, and tested the Iowa State University (ISU) tornado-vortex simulator. Its design and construction were based on two important requirements; i.e., it needed to accommodate physical models of a reasonable size to measure wind loads on different structures, and the tornado needed to be able to move along a path on the ground, enabling the simulation of realistic scenarios.

Most existing studies on the structural wind load caused by tornadoes have been related to building structures, cooling towers, transmission towers, bridges, etc. For example, Haan et al. [13] used the ISU tornado-vortex simulator to investigate the wind loads on a one-story gable-roof structure and compared them to the provisions of the ASCE-7-05 building standard. Yang et al. [14] conducted an experimental study to investigate the characteristics of wake vortex, flow structures, and wind loads acting on a high-rise building model in tornado-like winds. Sabareesh et al. [15,16] used the tornado-vortex simulator of the Tokyo Institute of Technology to study the effects of building location and ground roughness on the surface pressures of a cubic building. Razavi and Sarkar [17] studied the influences of three roof geometries on tornado-induced structural actions on five equally-spaced wood frames of a low-rise building, and the maximum structural actions were calculated and compared with predictions of the ASCE7-16 building standard. Cao et al. [9] and Wang et al. [18] investigated the wind pressure distributions and wind forces on the inner and outer surfaces of a cooling tower structure that was subjected to stationary and translating tornado-like vortices. Ezami et al. [19] tested an aerodynamic, self-supported lattice transmission tower model under tornado-like vortices. The tornado-like wind field was measured using cobra probes, and the aerodynamic structural responses were also measured to understand the dynamic responses of self-supported transmission towers to the tornado-induced loads. Cao et al. [20] conducted wind pressure measurements on a rigid streamlined bridge deck model to determine the tornado-induced surface pressure distributions and aerodynamic load coefficients for each test section, and total force coefficients.

In addition, studies have also been carried out on the wind loads on trains under boundary-layer cross-winds. For instance, Baker et al. [21–23] conducted wind tunnel
tests to study the aerodynamic forces and moments of a train under cross-winds. Using different ground simulation techniques, Kwon et al. [24] performed a large number of wind tunnel tests on Korean high-speed railway trains to investigate the effect of the train shape on wind resistance. Tian [25] studied the effects of wind speed and wall height on the aerodynamic performance and overturning stability of trains.

The available literature concerning tornado-induced wind loads on trains is limited. Suzuki et al. [26–28] and Bourriez et al. [29] conducted preliminary model experiments to investigate the aerodynamic forces acting on a train traveling through a tornado. The results showed that the aerodynamic forces changed magnitude and direction depending on the position of the train in the swirling flow, and the train itself may deform the flow field. In another study, Baker et al. [30] proposed a risk analysis method for the overturning of a train by a tornado, and the probability of overturning was determined based on specified statistical distributions of tornado parameters and vehicle operation parameters. Cao et al. [31] investigated the spatially varied aerodynamic load characteristics of the high-speed train with different locations of the tornado’s center, along with the effects of the viaduct and wind screen on the wind loads. It was found that the wind screen alters the mechanism of the tornado-vortices–train-viaduct interaction, and therefore changes the most unfavorable location of the tornado’s center for total force coefficients. Additionally, some studies have been carried out to investigate the wind loads on train cars under the action of tornadoes via numerical simulation. For example, Xu et al. [32] investigated the interaction between a high-speed train and a tornado-like vortex numerically using detached eddy simulations and model analysis considering the operation path, tornado intensity, and train speed. Kohei et al. [33] conducted a computational simulation for the flow around a train passing through stationary tornado-like vortices and the resulting aerodynamics forces acting on the train, and compared it with the experimental results. However, the research on the wind loading characteristics of a train under the action of tornadoes is in the exploratory stage, and some important parameters related to the tornado airflow, such as the swirl ratio and ground roughness, were not taken into account.

In this study, pressure measurements on a rigid train car model under stationary tornadoes were performed to investigate the effects of the distance between the tornado’s core and the longitudinal axis of the train car, the swirl ratio, and the ground roughness on the wind pressure distributions on the train car’s surface and wind load characteristics. The findings can be helpful to determining the threshold conditions for raising the alarm when safety is compromised. The rest of this paper is structured as follows: Section 2 introduces the experimental setup and the definitions of the main parameters and influential coefficients; Section 3 presents the pressure distributions across the train car under tornado-like flow; Sections 4 and 5 present, respectively, the sectional aerodynamic load coefficients and total force coefficients of the train car under the action of a tornado; finally, Section 6 draws the main conclusions.

2. Experimental Setup

2.1. Tornado-Vortex Simulator

The tornado-vortex simulator of Beijing Jiaotong University, whose design is based on that at the ISU, was used to generate tornado-like airflow. In the simulator, a circular duct 1.5 m in diameter and 0.89 m in height is suspended on a horizontally-movable steel frame (see Figure 1b), consisting of three components: a suspended fan in an updraft hole with a radius of 250 mm \( r_0 \), a set of guide vanes arranged around the duct’s periphery, and a honeycomb mounted at the center of the duct below the fan (see Figure 1a). The fan generates an updraft flow (maximum flow rate 4.8 m\(^3\)/s), which gains some rotational momentum as it passes through the top guide vanes. Subsequently, the airflow is redirected to the surface of the platform through a wide annular duct, and the horizontal airflow gradually converges on the center of the simulator floor and converts into an upward vertical airflow. Consequently, a spiraling tornado vortex is formed between the platform and the honeycomb. The tornado wind field can be adjusted by changing the angle of
the guide vanes (maximum angle 60°), the speed of the fan (maximum rotational speed 3500 rpm), and the height of the simulator over the platform (h = 0–550 mm).

![Schematic and picture of tornado-vortex simulator at Beijing Jiaotong University](image)

**Figure 1.** Schematic and picture of tornado-vortex simulator at Beijing Jiaotong University. (a) The schematic of the TVS. (b) A picture of the TVS.

2.2. Experimental Parameters

One of the important parameters in the experiments is the distance between the tornado’s center and the longitudinal axis of the train car model (R), which is normalized by the radius of the tornado’s core (Rc). The instrumented train car model was installed and fixed to the simulator’s floor, as depicted in Figure 2, with its axis being perpendicular to the tornado’s path. The horizontally movable fan was shifted from the center to the right-hand side of the train car model, in order to adjust the distance between the tornado to the car-model’s center. Measurements were conducted on the model with the fan working at 13 positions which corresponded to R varying from 0.0 to 200 mm with an increment of 20 mm and 200 to 300 mm with an increment of 50 mm. The corresponding dimensionless relative distance R/Rc varied from 0 to 3.75.

![Diagram of the relative positions of the rigid car model and the tornado](image)

**Figure 2.** Diagram of the relative positions of the rigid car model and the tornado.

Another main parameter that controls the structure of the tornado wind field is the swirl ratio, which is a measure of the tornado’s rotational intensity and is defined as the ratio of the tangential circulation flow of the tornado to the updraft flow [12]. However, it is usually difficult to measure both the tangential circulation flow and the updraft flow in the tornado-like wind field induced by the tornado-vortex simulator. Alternatively, the swirl ratio also can be written as $S = \tan \theta / 2a$, which depends on the simulator’s geometrical dimensions only, where $\theta$ is the angle of guide vanes, $a$ is the aspect ratio expressed as $a = h / r_0$, $h$ is the height of the simulator over the platform, and $r_0$ is the updraft hole radius.
In the presented study, \( h \) and \( r_0 \) were fixed to 300 and 250 mm, respectively, corresponding to a constant aspect ratio: \( a = 1.2 \). The fan rotational speed was fixed to 1900 rpm. Three swirl ratios of \( S = 0.15, 0.35, \) and \( 0.72 \) were investigated by adjusting the angle of guide vanes to \( \theta = 20°, 40°, \) and \( 60° \), respectively.

In addition, ground roughness was taken into consideration due to the different terrains of train routes. It was observed that the effects of ground roughness on tornado-like flow characteristics (such as core radius, tangential velocity, and pressure drop) are significant. The interaction between ground roughness and the vortex layer is predominant [34,35]. The ground roughness value \( \lambda \) in the experiments was defined as the ratio of the total windward area of roughness elements to the surface area of the simulator floor. Three ground roughness of \( \lambda = 0, 5\% \), and \( 25\% \), corresponding to roughness categories A, B, and C of the Chinese codes [36], were obtained by changing the density of the 5 mm high cube roughness elements evenly arranged on the simulator floor.

2.3. Physical Train Model and Pressure Tap Installation

The model prototype was a typical wagon for a conventional high-speed train in China with the span of 45 m, 3.75 m width, and 3.83 m height, using CRH380A Electric Multiple Units (EMUs) without the bogie and pantograph (see Figure 3), which is made of ABS material (a rigid model) and is approximately smooth, and the platform plane was varnished plywood which was very smooth. Considering the layout of the measuring points and the limited space underneath the simulator, the geometric scale ratio of the car model was selected as 1:75. Mishra et al. [37] defined the geometric scale ratio as the ratio of the radius of the wind field generated by the simulator to the actual one. The vortex core radius of the tornado generated by the simulator at the height of the car model was about 80–120 mm, corresponding to an actual tornado with a vortex core radius of 6–9 m.

![Figure 3](image.png)

**Figure 3.** Physical train model and pressure tap installation. (a) Actual rigid model of the train car; (b) Pressure tap distribution over one section. (c) Arrangement of pressure tap sections along model axis (unit: mm).

Thus, the train car model was 600 mm long, 50 mm wide, and 51 mm high. Fifteen sections (as the red lines shown) of pressure taps were installed on the central part of the model, and sixteen pressure taps were distributed across each section, so there were 240 pressure taps in total. The arrangement of the pressure taps is presented in Figure 3b,c.
2.4. Tornado-Like Flow Characteristics

In order to better understand the tornado-like flow characteristics induced by the tornado-vortex simulator of Beijing Jiaotong University, the velocities and pressures were measured without the car model by a turbulent flow instrumentation (TFI) Cobra Probe with the total length of 180 mm, of which the prob length is 30 mm with a 4-hole head 2.6 mm in diameter. In the present study, the selected measurement zone of tornado-like wind field in radial and vertical directions was 300 and 200 mm, respectively. Seventeen heights ranged from 10 to 200 mm above the simulator floor (8 heights in 5 mm increments, 5 heights in 10 mm increments, 2 heights in 25 mm increments, and one in a 50 mm increment) were considered in vertical direction. For each height, 25 locations in the horizontal direction from 0 to 200 mm (20 locations in 5 mm increments, 2 locations in 25 mm increments, and 3 locations in 50 mm increments) were considered. The wind speed and air pressure distributions can be obtained from the measurement zone by adjusting the relative position between the TFI Cobra Prob and the center of tornado-vortex simulator. Due to the limitation of the size of the prob itself, wind speed and pressure at altitudes above 10 mm of the simulator floor were measured only. The measurement zone and locations of the measurement points arranged over the vertical plane are exhibited in Figures 1a and 4.

![Figure 4. Distribution of the measurement points in the measuring zone.](image)

Figure 5 illustrates the tangential wind velocity and pressure drop (the difference between the air pressure at the center of the tornado wind field and the outside atmospheric pressure) distributions over the entire measurement region for different swirl ratios ($S = 0.15, 0.35,$ and $0.72$, respectively) under the ground roughness value $\lambda = 0$. The units of tangential velocity and pressure drop are m/s and Pa, respectively. The radius of the tornado’s core ($R_c$) was defined as the radial position with the maximum tangential velocity in the horizontal plane which varies with height, and it is also depicted by the dotted lines in Figure 5.

The vertical profile of wind velocity is one of the key factors in determining the wind loads on a train. The tangential velocity was found to increase with the distance from the vortex center to the vortex core radius, where unfavorable tangential velocities (peak value) were observed, and gradually decreased further away from the core boundary with a relatively smaller gradient compared to that inside the vortex core radius. Both the tangential velocity and vortex core radius increased with increasing swirl ratio. In particular, when the swirl ratio increased from 0.15 to 0.35, the tangential velocity increased notably, whereas it decreased slightly when the swirl ratio increased from 0.35 to 0.72.
The maximum pressure drop was observed at the center of the tornado vortex core. It decreased with the distance from the vortex center, and the maximum gradient was found near the vortex core radius. The pressure drop increased with increasing swirl ratio, and under a higher swirl ratio, the peak pressure drop at the tornado core’s center was significantly larger than that under a small ratio; i.e., the $S = 0.35$ case experienced a 1.5 times higher pressure drop compared to that of the swirl ratio ($S = 0.15$) case.

The variations in the core radius $R_c$ with height $Z$ under swirl ratio $S = 0.35$ for different roughness values are presented in Figure 6. The dotted line indicates the height at the top of train car model. $Z$ and $R_c$ were normalized by the updraft hole radius of 250 mm ($r_0$). An obvious increase in core radius with height was observed under every roughness condition. In particular, the core radius increased significantly at low elevations, whereas the increase slowed down at high elevations, resulting in the formation of a funnel-shaped conical vortex, similarly the real tornadoes in nature. At lower elevations, a decrease in the core radius was observed with increasing surface roughness. In addition, at higher elevations, the core radius over a rough surface became larger than that over a smooth one, although the increase was not significant. Moreover, when the height was large enough, the core radii in three roughness cases were almost the same. Consequently, it is reasonable to conclude that the effects of roughness on core radius are confined to lower elevations.

In Figure 7, the tangential wind speed and pressure drop obtained from the present measurements are compared with the data of the Spencer and Mulhall tornadoes and predictions from the Rankine and modified Rankine models. The tangential velocity and pressure drop were normalized by the maximum tangential velocity $V_{\text{max}}$ and the minimum pressure drop $P_{\text{min}}$, respectively. It can be observed that, in the radial direction, the results obtained from the tornado simulator exhibit the same distribution pattern as a real tornado and the theoretical predictions. This confirmed the validity of the simulation’s performance using the tornado simulator at Beijing Jiaotong University. Thus, it was considered as appropriate for conducting the following studies.

**Figure 5.** Contours of the tangential velocity and pressure drop distributions ($S$ stands for the swirl ratio). (a) Tangential velocity, $S = 0.15$; (b) tangential velocity, $S = 0.35$; (c) tangential velocity, $S = 0.72$; (d) pressure drop, $S = 0.15$; (e) pressure drop, $S = 0.35$; (f) pressure drop, $S = 0.72$. 

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Figure 6. Core radius variation with height ($S = 0.35$).

Figure 7. Comparison of normalized radial profiles of tangential velocity (a) and pressure drop (b) between experimental results, results from empirical models, and data measured from an actual tornado.

2.5. Boundary-Layer Wind Tunnel Test

In order to better understanding the wind characteristics of trains under the action of tornado-like vortices, conventional boundary-layer wind tunnel tests were also carried out in the high-speed section of the closed-circuit wind tunnel in Beijing Jiaotong University (see Figure 8a). The test section was 3 m wide, 2.0 m high, and 15 m long. A wind field of ground roughness category B of Chinese code was simulated by using wedges and roughness elements; the power-low exponent $\alpha$ was approximated as 0.15 (see Figure 8b); $Z$, $Z_r$, $V$, and $V_r$ denote the height, reference height, wind speed, and reference wind speed, respectively. The reference point was set to a height of 25 cm from the ground, with a mean wind speed $V_r$ of 10.5 m/s, and a turbulence intensity of 0.137. The sampling frequency and sampling length were 312.5 Hz and 96 s, respectively.
2.6. Wind Pressure and Force Coefficients

In this study, the sampling frequency of the data and the sampling time for each case under the tornado-like vortices were the same as the boundary-layer wind tunnel tests. The wind pressure values obtained from a multi-channel pressure-measuring system were then converted to pressure coefficients in the following analysis.

The wind pressure coefficient of each pressure tap can be usually defined as:

\[
C_p(t) = \frac{P(t) - P_0}{0.5 \rho u_{max,h}^2}
\]  

(1)

where \(C_p(t)\) is the wind pressure coefficient, \(P(t)\) is the wind pressure, \(\rho\) is the air density, \(u_{max,h}\) is the maximum tangential wind velocity at the top of the model [12,15,38], and \(P_0\) is the reference pressure in a wind tunnel with a conventional boundary layer, and it usually corresponds to the atmospheric pressure. It is noted that the tornado wind field is accompanied by a strong pressure drop and the flow is swirling, which obviously differs from the boundary-layer airflow, resulting in the selection of \(P_0\) being different from in conventional boundary layer experiments. In this case, \(P_0\) can be defined based on two methods: (1) the atmospheric pressure away from the tornado airflow; (2) the maximum tornado pressure drop at the height of the measuring point. In this study, the first method was adopted [12,38].

Figure 9a exhibits the definitions of the sectional load coefficients, and they can be determined by integrating the pressures measured from the pressure taps along the section with a unit width as:

\[
\begin{align*}
C_{fx}(t) &= \frac{F_x(t)}{0.5 \rho u_{max,h}^2 BH} = \frac{\sum_{i=1}^{16} P_i(t)ds_i \cos \theta_i}{0.5 \rho u_{max,h}^2 BH} \\
C_{fy}(t) &= \frac{F_y(t)}{0.5 \rho u_{max,h}^2 BH} = \frac{\sum_{i=1}^{16} - P_i(t)ds_i \sin \theta_i}{0.5 \rho u_{max,h}^2 BH} \\
C_{my}(t) &= \frac{M_y(t)}{0.5 \rho u_{max,h}^2 BH} = \frac{\sum_{i=1}^{16} P_i(t)ds_i \theta_i}{0.5 \rho u_{max,h}^2 BH}
\end{align*}
\]

(2)

where the drag force coefficient \(C_{fx}(t)\) and lift force coefficient \(C_{fy}(t)\) are the sectional load coefficients along the x- and Z-axis, respectively; the rolling moment coefficient \(C_{my}(t)\) is the moment coefficient of the car section around the y-axis. \(F_x(t), F_y(t),\) and \(M_y(t)\) are the sectional drag force, lift force, and rolling moment, respectively. \(u_{max,h}\) is the maximum tangential wind velocity at the top of the model, \(\rho\) is air density, and \(B\) and \(H\) are the width and height of the train car, respectively. \(P_i, ds_i,\) and \(\theta_i\) denote the wind pressure, the
length of differential element around the section, and the angle between wind pressure and the x-axis.

(a) Definitions of force coefficients; (b) Definitions of total force coefficients.

Due to the strongly spatially varying characteristics of the tornado airflow, it is necessary to take the total load effects over the entire train car into consideration. The overall force coefficients of the entire train car can be determined as the integrals of the sectional wind forces over the length of the train car model as (see Figure 9b):

\[
\begin{align*}
C_{FX}(t) &= \frac{F_X(t)}{0.5\rho u_{max,h}HL} = \sum_{j=1}^{15} \frac{F_{xj}(t)ds_j}{0.5\rho u_{max,h}HL} \\
C_{FZ}(t) &= \frac{F_Z(t)}{0.5\rho u_{max,h}BL} = \sum_{j=1}^{15} \frac{F_{zj}(t)ds_j}{0.5\rho u_{max,h}BL} \\
C_{MX}(t) &= \frac{M_X(t)}{0.5\rho u_{max,h}LBH} = \sum_{j=1}^{15} \frac{M_{xj}(t)ds_j}{0.5\rho u_{max,h}LBH} \\
C_{MY}(t) &= \frac{M_Y(t)}{0.5\rho u_{max,h}LBH} = \sum_{j=1}^{15} \frac{M_{yj}(t)ds_j}{0.5\rho u_{max,h}LBH} \\
C_{MZ}(t) &= \frac{M_Z(t)}{0.5\rho u_{max,h}LBH} = \sum_{j=1}^{15} \frac{M_{zj}(t)ds_j}{0.5\rho u_{max,h}LBH}
\end{align*}
\]

where \(C_{FX}(t)\) and \(C_{FZ}(t)\) are the total drag force coefficient and total lift coefficient of the train car, respectively; \(C_{MX}(t)\), \(C_{MY}(t)\), and \(C_{MZ}(t)\) correspond to the total pitching, rolling, and yawing moment coefficients of the train car around the x-, y-, and z-axis, respectively, \(F_X(t)\) and \(F_Z(t)\) are the total wind forces estimated by integrating the surface pressures acting on the train car model along x, y, and z directions (as defined in Figure 3); \(M_X(t)\), \(M_Y(t)\), and \(M_Z(t)\) are the total pitching, rolling, and yawing moment by integrating the sectional wind forces along y direction of the train car model. \(L\) denotes the length of the train car, \(ds_j\) is the width of section \(j\), and \(d_j\) is the distance between section \(j\) and the middle section of train car model; \(\rho\), \(B\), and \(H\) are the same as in Equation (2).

3. Pressure Coefficient Distribution

In this section, the effects of the distance from the train car to the tornado’s center, swirl ratio, and ground roughness on the pressure distribution on the train car surface are investigated. In addition, the results corresponding to the boundary-layer wind are also given for comparison.
3.1. Effect of Distance between Car and Tornado Center

Figure 10 exhibits the mean pressure coefficient contours on the train car surfaces (A represents the lower surface, B the left surface, C the upper surface, and D the right surface) for different distances between the car and the tornado’s center with $S = 0.35$ and $\lambda = 0$ and those under boundary-layer cross-wind conditions. It can be noticed that the mean pressure coefficient distribution under the effect of the tornado is different from that under a boundary-layer cross-wind.

Figure 10. Contours of mean (left sub-figure) and fluctuating (middle sub-figure) pressure coefficient distributions on the car surfaces ($S = 0.35$, $\lambda = 0$). (a) Boundary-layer cross-wind; (b) $R/R_c = 0$; (c) $R/R_c = 1$; (d) $R/R_c = 3.75$. 
Under the boundary-layer cross-wind conditions, the pressure coefficients of the windward side of the train car were found to be positive (see Figure 10a). The pressure coefficients on the upper and lower surfaces of the train car were negative due to airflow separation. The pressure magnitudes on the lower surface were smaller than those on the upper surface due to the roughness of the ground. The pressure coefficients on the leeward side of the car were negative, and their distribution was relatively smooth compared to those on the other surfaces.

Due to the pressure drop and the spirally developing wind field, all the mean pressure coefficients of the train car under tornado wind loading were negative. Large values of the fluctuating pressure exist mainly on the top and side surface of the train car, especially the side surface proximal to the tornado’s center. When the train car was at the center of the tornado vortex core ($R/R_c = 0$, see Figure 10b), the mean pressure distributions on the upper and lower surfaces were symmetric; on the side surfaces, they were antisymmetric. The same pattern was found in the distribution of fluctuating pressure coefficients. This is attributed to the axisymmetric structure and rotation characteristics of the tornado vortex. Due to the strong pressure drop at the tornado’s core, significant differences in wind pressure distributions were measured between the upper and lower surfaces of the train car. The absolute pressure value on the upper surface of the train car was relatively high, at around 1.2, and that on the lower of the train car was low, at around 0.3.

When the train car was at the vortex core ($R/R_c = 1.0$; see Figure 10c), the symmetric wind pressure distribution disappeared. The mean pressure on the surface proximal to the tornado increased, since the tangential velocity was at its maximum, and the radial and vertical velocities were also larger. Unfavorable values of fluctuating pressure were also found. On the other hand, the mean pressure on the side of the train car away from the tornado was small, indicating that the pressure difference between the two sides of the train car was larger compared to that when $R/R_c = 0$. Moreover, the pressure difference between the upper and lower surfaces decreased, since the pressure drop decreases with increasing distance between car and the tornado’s center (see Figure 7b).

When the train car was at a distance of 3.75 times the vortex core radius from the tornado’s center ($R/R_c = 3.75$, see Figure 10d), the absolute values of the surface mean pressure coefficients were small. This is attributed to the relatively small tangential velocity and pressure drops in the tornado when the train car is far away from the vortex core. Meanwhile, the fluctuating pressure coefficients were also near to zero.

Figure 11 illustrates the mean pressure distributions measured at the middle section of the train car for seven different radial locations when $S = 0.35$ and $\lambda = 0$. The pressure coefficients on the side surface proximal to the tornado increased first and then decreased with increasing distance from the vortex center. The maximum values were observed when $R/R_c = 1.5$. On the other hand, the pressure coefficients on the side surface of the train car away from the tornado decreased with increasing distance from the tornado’s center. On the upper surface, the pressure coefficients increased first and then decreased with increasing distance from the vortex center, and they reached the maximal values when $R/R_c = 1$. The variation trend of the pressure coefficient on the lower surface was the same as that on the side surface proximal to the tornado; however, the values were lower.

When the train car was at the center of the vortex core ($R/R_c = 0$), the vertical loading was predominant and the side force was near to zero, since the pressure distribution was horizontally symmetrical. The pressure differences between the upper and lower surfaces were the largest under all relative distances. When the distance between the tornado’s center and train car started to increase, the horizontal symmetry of the pressure distributions gradually faded away. When $R/R_c = 1.5$, the absolute pressure coefficients on the side surface proximal to the tornado simulator were distinctly larger than those on the surface far from the tornado, which resulted in a large lateral force on the train car. As the tornado moved away from the train car, the absolute pressure coefficients on a measured section of the car decreased, getting close to zero, when $R/R_c = 3.75$, indicating that the effects of the tornado flow on the lateral wind loading of the train car were small.
Figure 11. Mean pressure coefficients at the middle section as distance from the tornado's center to the train car changes ($S = 0.35$, $\lambda = 0$). (a) $R/R_c = 0$; (b) $R/R_c = 0.5$; (c) $R/R_c = 1$; (d) $R/R_c = 1.5$; (e) $R/R_c = 2$; (f) $R/R_c = 2.5$; (g) $R/R_c = 3.75$.

Fluctuating pressure distributions measured at the middle section of the train car for seven different radial locations when $S = 0.35$ and $\lambda = 0$ are also summarized in Figure 12 in the same form as mean pressure distributions. The fluctuating pressure coefficients’ distributions varied almost the same as the mean pressure coefficients’ distributions illustrated in Figure 11. The values on the side surface proximal to the tornado increased first and then decreased with increasing distance from the vortex center. The maximum values were observed when $R/R_c = 1.5$, whereas the values on the side surface away from the tornado decreased with increasing distance from the tornado’s center and were near to zero when $R/R_c = 3.75$.

Figure 12. Fluctuations in pressure coefficients at the middle section with distance from the tornado’s center to train car ($S = 0.35$, $\lambda = 0$). (a) $R/R_c = 0$; (b) $R/R_c = 0.5$; (c) $R/R_c = 1$; (d) $R/R_c = 1.5$; (e) $R/R_c = 2$; (f) $R/R_c = 2.5$; (g) $R/R_c = 3.75$.

3.2. Effect of Swirl Ratio

The pressure coefficient distributions at the middle section of the train car were measured for three swirl ratios ($S = 0.15, 0.35$, and $0.72$) under $R/R_c = 0, 1.5$, and $3.75$, 

![Diagram](image-url)
respectively, in order to clarify the effect of swirl ratio on train car pressure distributions. In addition, only the results for the ground roughness value of \( \lambda = 0 \) are shown as examples in Figure 10 because the results for other ground roughness levels are very similar.

In Figure 13a–c, the horizontally-symmetric pressure distributions when \( R/R_c = 0.0 \) are shown, where it can be observed that the absolute pressure coefficients at both the upper and lower surfaces increased with increasing swirl ratio. Similarly to the change in pressure drop within this range, the resultant lift force increased significantly when the swirl ratio changed from 0.15 to 0.35, and it decreased slightly when it changed from 0.35 to 0.72. The pressure distributions of \( R/R_c = 1.5 \) presented in Figure 13d–f indicate that the absolute pressure coefficients on the side surface proximal to the tornado increased first and then decreased with increasing swirl ratio, whereas those on the opposite side increased monotonously. The lateral loading on the car mainly originates from the pressure differences between the two sides, which first increase and then decrease with increasing swirl ratio. These changes are the same as those of the tangential velocity with increasing swirl ratio near the vortex core. The pressure distributions when \( R/R_c = 3.75 \) are presented in Figure 13g–i and indicate that the swirl ratio has almost no effect on pressure distributions.

![Figure 13](image_url)

**Figure 13.** Mean pressure coefficients at the middle section for three different swirl ratios (\( \lambda = 0 \)).
(a) \( S = 0.15, R/R_c = 0 \); (b) \( S = 0.35, R/R_c = 0 \); (c) \( S = 0.72, R/R_c = 0 \); (d) \( S = 0.15, R/R_c = 1.5 \); (e) \( S = 0.35, R/R_c = 1.5 \); (f) \( S = 0.72, R/R_c = 1.5 \); (g) \( S = 0.15, R/R_c = 3.75 \); (h) \( S = 0.35, R/R_c = 3.75 \); (i) \( S = 0.72, R/R_c = 3.75 \).

3.3. Effect of Ground Roughness

Similarly to the above subsection, the pressure distributions on the middle section of the train car were measured for three ground roughness levels (\( \lambda = 0, 5\% \), and 25\%) under \( R/R_c = 0, 1.5 \), and 3.75, respectively. The results for swirl ratio of \( S = 0.35 \) are shown as examples and are illustrated in Figure 11.

Figure 14a–c depict the pressure distributions when \( R/R_c = 0 \). It can be observed that the absolute pressure coefficient values on the upper surface increased first and then decreased with increasing ground roughness, and those on the lower surface increased slightly. When the ground roughness changed from 0\% to 5\%, the resultant lift force on the train car increased, whereas it decreased slightly when ground roughness changed from 5\% to 25\%. This effect is similar to the effect of swirl ratio on lift force. The pressure distributions when \( R/R_c = 1.5 \) are presented in Figure 14d–f. It can be seen that the absolute pressure coefficient values on the side surface proximal to the tornado decreased with increasing ground roughness, while those on the opposite side decreased slightly. Moreover, the resultant lateral force on the train car decreased with increasing ground roughness. According to the pressure distributions when \( R/R_c = 3.75 \), shown in Figure 14g–i, the ground roughness had no significant effect on pressure. This suggests that the effect of
roughness on pressure coefficient distribution is mainly limited to a small distance from the vortex core, which is consistent with the effect of roughness on the tornado wind field.

![Figure 14. Mean pressure coefficients at the middle section for three ground roughness levels (S = 0.35).](image)

(a) \( \lambda = 0, R/R_c = 0 \); (b) \( \lambda = 5\%, R/R_c = 0 \); (c) \( \lambda = 25\%, R/R_c = 0 \); (d) \( \lambda = 0, R/R_c = 1.5 \); (e) \( \lambda = 5\%, R/R_c = 1.5 \); (f) \( \lambda = 25\%, R/R_c = 1.5 \); (g) \( \lambda = 0, R/R_c = 3.75 \); (h) \( \lambda = 5\%, R/R_c = 3.75 \); (i) \( \lambda = 25\%, R/R_c = 3.75 \).

4. Sectional Aerodynamic Load Coefficients

In this section, the sectional aerodynamic coefficients of the train car for different distances between train car and the tornado’s center, swirl ratios, and ground roughness values were investigated to better understand the effect of tornado-like vortex-induced wind load along the train’s longitudinal axis.

4.1. Effect of Distance between Car and Tornado Center

Figure 15 illustrates the sectional aerodynamic load coefficients of the train car for \( S = 0.35 \) and \( \lambda = 0 \). The variations in the sectional aerodynamic load coefficients along the longitudinal axis of the train car are reflected from vertical directions, and those under different relative distances are reflected from horizontal directions. When the train car is near \( R_c \), the most unfavorable side force coefficients can be observed due to the largest tangential wind velocities. The distance between train car and the tornado’s center has an apparent impact on the sectional aerodynamic load coefficients when within the vicinity of the vortex core radius, but the impact will be almost negligible when the distance exceeds three times the vortex core radius. The sectional side force coefficients exhibited a sign change along the train car’s axis when the distance was within 1.5 \( R_c \), whereas all values were negative when the distance was above 1.5 \( R_c \). That can be attributed to the rotational nature of tornadoes. As for the lift force coefficients, all values under different relative distances were positive, and the most unfavorable value was found at the tornado core’s center, where the strongest pressure drop takes place. The distributions of the sectional rolling moment coefficients were similar to those of the side force coefficients, indicating that the side force contributes a lot to the rolling moment. The value of the rolling moment coefficient was approximately half that of the side force coefficient.
The variations in the sectional aerodynamic load coefficients, including the side force coefficients and lift force coefficients, along the longitudinal axis of the train car model, are presented in Figure 16. Three swirl ratios ($S = 0.15, 0.35,$ and $0.72$) were considered with $\lambda = 0$. For the side force coefficients $C_{f_S}$, only the results for $R/R_c = 1$ are shown as examples due to the maximum tangential velocity occurring here. Similarly, the results for $R/R_c = 0$ are only discussed for the most unfavorable pressure drop. The general variation trend of the sectional force coefficients along the longitudinal axis of the car under different swirl ratios was the same. With increasing swirl ratio, the peak values of sectional side force coefficients and lift force coefficients increased first and then decreased. For $S = 0.35$, the absolute value of the side force first increased and then decreased, reaching its maximum value at Section 2; the lift force increased first and then decreased, reaching its maximum value at the middle section (Section 2).

![Figure 15. Contours of mean sectional aerodynamic load coefficient distribution ($S = 0.35, \lambda = 0$). (a) $C_{f_S}$; (b) $C_{l_S}$; (c) $C_{nY}$.](image)

![Figure 16. Variations in mean sectional aerodynamic load coefficients across car with swirl ratio ($\lambda = 0$). (a) $C_{f_S}$; (b) $C_{l_S}$.](image)

4.3. Effect of Ground Roughness

Similarly to the previous subsection, the side force coefficients and lift force coefficients of each section under different ground roughness levels ($\lambda = 0, 5\%,$ and $25\%$) when $S = 0.35$ are illustrated in Figure 17.
To this end, this section investigates the effects of the distance between the train car and the tornado’s center when \( \lambda = 0 \), \( \lambda = 5\% \), and \( \lambda = 25\% \). The variation trend of the sectional wind force coefficients along the train car’s axis was basically the same as that on smooth ground. The peak value of side force coefficient decreased with increasing ground roughness. The position of the peak side force coefficient for rough ground differed from that for smooth ground, and reached its maximum value at the middle section (section No. 0). The peak values of the sectional lift coefficients increased first and then decreased with increasing ground roughness. The lift force coefficient reached its maximum value at the middle section, which is similar to the results of swirl ratio.

5. Overall Force Coefficients

Since the sectional aerodynamic loads are not distributed consistently along the car’s axis due to the tornado flow characteristics, it was necessary to propose overall force coefficients for the train car, in order to thoroughly assess the effects of tornadoes on trains. To this end, this section investigates the effects of the distance between the train car and the tornado’s center, swirl ratio, and ground roughness on the overall force coefficients of the train car.

5.1. Effect of Distance between Car and Tornado Center

Figure 18 depicts the overall force coefficients as functions of the distance between train car and the tornado’s center when \( S = 0.35 \) and \( \lambda = 0 \), and under boundary-layer cross-wind conditions represented by the dashed lines.
For the results of boundary-layer cross-wind, all the five overall force coefficients do not change with the distance, because the boundary-layer cross-wind field remained constant with horizontal distance. The side force coefficient $C_{FX}$ of the train car was the largest; the rolling moment coefficient $C_{MY}$ and lift coefficient $C_{FZ}$ were relatively small—i.e., $-0.37$ and $0.16$, respectively; and the pitching moment coefficient $C_{MX}$ and yaw moment coefficient $C_{MZ}$ were almost zero.

As for tornado-like wind, the overall force coefficients are significantly affected by the distance between the car and the tornado’s center. Near the tornado’s center, at which the tangential wind velocities were extremely small, the side force coefficient $C_{FX}$ was close to zero. As the distance between the train car and the tornado’s center increased, the side force coefficient $C_{FX}$ of the car increased due to the combined effects of pressure drop and tangential wind velocity. When $R/R_c = 1.5$, the side force coefficient $C_{FX}$ reached its maximum value, and then it decreased with increasing distance. The changes in the rolling moment coefficient $C_{MY}$ were the same as those of the side force coefficient, though its values were approximately half those of the side force coefficient. The absolute value of the pitching moment coefficient $C_{MX}$ increased first and then decreased with increasing distance; i.e., it reached its maximum value when $R/R_c = 1.5$, and became almost zero when $R/R_c > 2$.

Under the tornado wind loading, the lift coefficient $C_{FZ}$ and yaw moment coefficient $C_{MZ}$ of the train car exhibited the most unfavorable values near the tornado’s center ($R/R_c = 0$). This is mainly attributed to the strong rotation effect of the tornado and the large pressure drop at the tornado’s center, due to which the train car is subjected to strong upward suction and counterclockwise torque. As the radial distance increased, the absolute value of the pressure drop decreased, resulting the lift and yaw moment coefficients of the car decreasing as well.

5.2. Effect of Swirl Ratio

Figure 19 demonstrates the variations in overall force coefficients with the distance between the train car and the tornado’s center under three different swirl ratios ($S = 0.15$, $S = 0.35$ and $S = 0.72$) when $\lambda = 0$. It can be observed that the general variation trends of the wind force coefficients with the radial position under different swirl ratios are basically the same; however, there are apparent differences in the values.

(1) Side force coefficient $C_{FX}$ and rolling moment coefficient $C_{MY}$

When the swirl ratio increased from 0.15 to 0.35, the peak value of the side force coefficient $C_{FX}$ increased significantly. Inconspicuous variation was observed when it was increased from 0.35 to 0.72. Under different swirl ratios, the positions of the peak $C_{FX}$ value were different. The side force coefficient $C_{FX}$ reached its maximum value at around $R/R_c = 2.5$ when the swirl ratio was 0.15, and at around $R/R_c = 1.5$ when the swirl ratio was 0.35 or 0.72. The effect of swirl ratio on the rolling moment coefficient $C_{MY}$ was the same as that on the side force coefficient $C_{FX}$, indicating that the side force contributed a lot to the rolling moment. The value of the rolling moment coefficient was approximately half that of the side force coefficient. This tendency agrees well with the results of sectional side force coefficients and rolling moment coefficients in Figure 15.

(2) Lift force coefficient $C_{FZ}$

When $R/R_c < 1.5$, the lift force coefficient $C_{FZ}$ increased first and then decreased with increasing swirl ratio. When $1.5 < R/R_c < 3$, the lift coefficient decreased with increasing swirl ratio. When $R/R_c > 3$, the lift coefficient was almost unaffected by the swirl ratio. Moreover, for higher swirl ratios, the lift force coefficient $C_{FZ}$ attenuated rapidly with increasing distance between car and the tornado’s center within a certain range.

(3) Pitching moment coefficient $C_{MX}$

The peak value of the pitching moment coefficient $C_{MX}$ increased significantly when the swirl ratio increased from 0.15 to 0.35, whereas it was slightly decreased when the
swirl ratio increased from 0.35 to 0.72. In general, the higher the swirl ratio, the closer the position of the peak $C_{MX}$ value appears to the center of the vortex core.

(4) Yawing moment coefficient $C_{MZ}$

When $R/R_c < 1.5$, the yawing moment coefficient $C_{MZ}$ increased with increasing swirl ratio. When $1.5 < R/R_c < 3$, the yawing moment coefficient decreased with increasing swirl ratio. When $R/R_c > 3$, the yawing moment coefficient was nearly not affected by the swirl ratio.

![Graphs showing variations in wind force coefficients](image)

Figure 19. Variations in the wind force coefficients with $R/R_c$ under different swirl ratios ($\lambda = 0$). (a) $C_{FX}$; (b) $C_{FY}$; (c) $C_{MX}$; (d) $C_{MY}$; (e) $C_{MZ}$.

In summary, when the swirl ratio increased from 0.15 to 0.35, the absolute values of the force coefficients of the car increased significantly, which was mainly observed within $R/R_c < 1.5$. When the swirl ratio increased from 0.35 to 0.72, the lift force coefficient $C_{FZ}$ and yawing moment coefficient $C_{MZ}$ changed significantly when $R/R_c < 1.5$, whereas the other wind force coefficients remained rather unaffected.

5.3. Effect of Ground Roughness

Similarly to the analysis in the previous subsection, Figure 20 demonstrates the variations in the overall force coefficients with the distance between the train car and the tornado’s center under three different ground roughness levels ($\lambda = 0.15$, $\lambda = 0.35$, and $\lambda = 0.72$) when $S = 0.35$. It can be observed that the general variation trends of the wind force coefficients with the radial position under different ground roughness levels were essentially the same. Generally, when within the vicinity of the vortex core radius (i.e., $R/R_c < 1.5$), there is uncertainty about the trends of overall force coefficients with different ground roughness values, which may be caused by the uncertainty from the combined effect of pressure drop and aerodynamic effects, though the overall force coefficients decrease with the increasing of the ground roughness further away from the core boundary (i.e., $R/R_c > 2$) as the aerodynamic effects become primary. Additionally, the peak values of all force coefficients decrease as roughness increases, implying that a train exposed to roughness will suffer less damage. On the other hand, the extent of the effect of roughness on different force coefficients is not consistent.
(1) **Side force coefficient** $C_{FX}$ and rolling moment coefficient $C_{MY}$

It can be observed that as the ground roughness increased, the peak value of the side force coefficient $C_{FX}$ decreased. The positions of the peak $C_{FX}$ value under different ground roughness levels were different. The side force coefficient $C_{FX}$ reached its maximum value at about $R/R_c = 1.5$ when on smooth ground, and at about $R/R_c = 1.2$ when the roughness was 5% or 25%. The effect of ground roughness on the rolling moment coefficient $C_{MY}$ was the same as that on the side force coefficient $C_{FX}$.

(2) **Lift force coefficient** $C_{FZ}$

When near the tornado’s center, the lift force coefficient $C_{FZ}$ with rough ground was larger than that with smooth ground. In addition, at other positions, the lift coefficient decreased with increasing roughness. When $R/R_c > 3$, the lift coefficient was almost unaffected by the ground’s roughness.

(3) **Pitching moment coefficient** $C_{MX}$

When the car was located within the vortex core radius, the pitching moment coefficient $C_{MX}$ increased first and then decreased with increasing roughness. When $1.5 < R/R_c < 2$, the pitching moment coefficient $C_{MX}$ decreased with increasing roughness. In general, the higher the ground roughness, the closer the position of the peak pitching moment coefficient $C_{MX}$ to the center of the vortex core.

(4) **Yawing moment coefficient** $C_{MZ}$

When $R/R_c < 3$, the yawing moment coefficient $C_{MZ}$ decreased with increasing ground roughness. When $R/R_c > 3$, the yawing moment coefficient remained unaffected.

6. Conclusions

In this study, the wind loading characteristics of a train model under tornado-like vortices were investigated through wind pressure measurements using a tornado-vortex simulator. Aerodynamic parameters, including the surface pressure distributions, aerodynamic load coefficients for different sections, and the force coefficients of a train car affected by the tornado-like vortices were identified. Furthermore, the effects of distance
between the train car and the tornado’s center, swirl ratio of tornado-like vortices, and ground roughness were taken into consideration. The main conclusions are as follows.

The mean wind pressure coefficients across the train car are negative regardless of the position of the pressure taps. This is attributed to the combined effects of the pressure drop accompanying a tornado and the aerodynamic flow–structure interaction. The mean and fluctuating pressure distribution across the train car varies with the horizontal distance from the tornado’s center to the centerline of the train car model, and the variation trends of them are almost the same. When the train car is at the center of the tornado vortex core, the pressure drop is the main factor. When the train car is located at a distance equal to 1.5 times the vortex core’s radius, the tornado airflow and the aerodynamic effects between train car and tornado are the main factors. When the distance from the train car to the tornado’s center exceeds three times vortex core’s radius, the impact of tornado-like vortices on the train car is almost negligible. These features exhibit obvious discrepancies from results obtained through conventional boundary-layer wind tunnel tests.

The mean sectional force coefficients along the train car axis are position-dependent and reach their peak values near the middle section. The sectional side force coefficients and rolling moment coefficients reach their peak values when the train car is located within the tornado’s core, and the largest sectional lift force coefficients are obtained when the train car is at the tornado’s center. The overall distributions of the wind force coefficients of the train car under different swirl ratios and ground roughness levels are basically the same, though their values are different. The peak aerodynamic force value increases with increasing swirl ratio, but this peak value may not change significantly when the swirl ratio is high; on the other hand, this peak value changed little with increasing ground roughness.

The lift force and yawing moment coefficients of the train car decrease with increasing radial distance, and exhibit their peak values at the center of the vortex core. The absolute values of the side force, rolling moment, and pitching moment coefficients increase first and then decrease with increasing radial distance. They reached their maximum values at a radial distance of 1.5 times the vortex core’s radius. The change trends of the overall force coefficients of the train car under different ground roughness levels and different swirl ratios are nearly the same as those of the sectional force coefficients. The peak values of all force coefficients decreased as roughness increased, implying that a train in rough terrain will suffer less damage.

The present investigation revealed some interesting results of wind loading characteristics of a train car model under tornado-like vortices. One limitation of this study was that the simulated tornado did not have translation speed, which needs to be taken into consideration in further research to provide a comprehensive understanding of wind loads of train cars under the action of tornadoes. Additionally, future works considering more statistical measures, such as median and 84.13th percentile of the pressure and force coefficients, may provide better insights into the wind loading characteristics.

**Author Contributions:** Conceptualization, B.L.; methodology, Y.T.; software, R.L.; validation, R.L.; formal analysis, P.L.; investigation, P.L.; resources, X.H.; data curation, P.L., X.H.; writing—original draft preparation, X.H., R.L.; writing—review and editing, P.L.; visualization, P.L., X.H., R.L.; supervision, B.L., Y.T.; project administration, B.L.; funding acquisition, B.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was funded by the National Natural Science Foundation of China (51878041) and the 111 project of the Ministry of Education and the Bureau of Foreign Experts of China (B13002).

**Acknowledgments:** The comments and work of S.S. Law in improving the English of this paper are also gratefully acknowledged.

**Conflicts of Interest:** The authors declare no conflict of interest.
References


