

Review

Key Parameters and Structural Characteristics Governing Tornado and Extreme Wind Loads: A Comprehensive Review

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Abstract

Climate change has been associated with an increasing occurrence of extreme wind phenomena, including hurricanes, tornadoes, and downbursts, with noticeable rises in both their frequency and severity. These events have heightened concerns regarding their devastating impacts on structures, infrastructure, and economies. To provide a comprehensive and reliable review, a large number of previous studies and scientific references were collected and carefully screened. The selection process focused primarily on studies directly related to structural engineering applications, wind-induced structural responses, tornado and hurricane loading mechanisms, and simulation techniques used in wind engineering research. References unrelated to structural behavior, engineering analysis, or wind-resistant design were excluded to maintain the technical relevance and consistency of the review. This review explores parameters influencing wind loads, focusing on tornado flow field characteristics such as swirl ratio, ground roughness, translation speed, and topography. It also examines structural properties such as geometry, material, orientation, and proximity to the tornado path that govern a building's ability to withstand wind-induced forces. The review evaluates experimental techniques, including wind tunnel tests, tornado simulators, and numerical simulations using Computational Fluid Dynamics (CFD) to improve understanding and resilience. These approaches are compared for effectiveness in replicating real-world scenarios and enhancing predictive accuracy. Furthermore, key engineering standards, such as ASCE 7-22 and FEMA guidelines, are highlighted, showing their role in improving structural design, identifying gaps in research, and advocating for future studies. It emphasizes integrating emerging computational technologies, including machine learning, to enhance structural design efficiency and disaster response performance. This review aims to guide researchers and engineers toward developing resilient structures capable of mitigating the impacts of extreme wind events.



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Keywords: tornado impacts; hurricane hazards; wind tunnel test; artificial intelligence; CFD; numerical tornado simulation

1. Introduction

The impacts of climate change are increasingly evident in the growing occurrence and strength of extreme wind events worldwide [1–4]. Extreme wind events pose serious threats, often causing severe structural failures and major economic consequences. In 2024, hurricanes Beryl, Helene, and Milton caused widespread destruction, with Beryl being

the earliest Atlantic Category-5 storm and Helene devastating Florida. These storms have resulted in billions of dollars in losses worldwide. Tornado outbreaks also hit the U.S. and Europe, including a deadly EF4 tornado in Mississippi, Arkansas, and Tennessee; and an EF3 tornado in Italy's Veneto region. These events highlighted the vulnerability of infrastructure and the need for better disaster preparedness, mitigation measures, and rebuilding efforts.

The growing trend in construction and development has led to a greater focus on different building construction and design methods. It is important to ensure the safety and structural integrity of buildings against all types of loads to which they may be subjected. Wind-induced loads and windborne debris constitute major sources of damage to civil structures during extreme wind events [1].

Tornadoes rank among the most severe windstorms and can result in substantial damage to structures [2,3]. It is considered one of the most dangerous and destructive natural disasters; it also causes a great deal of human and economic losses. Tornadoes annually cause billions of dollars in damage to life, property, and more. Despite this significant impact, research on damage prediction and mitigation remains a relatively new focus within the field of wind engineering [4]. Due to their intense rotational nature and multi-directional velocity components, tornado flow fields exhibit distinct characteristics compared to traditional straight-line wind profiles [2,5–13].

Tornadoes vary in type, wind speed, and intensity, forming violent, rotating, small-scale atmospheric vortices. While their area of influence is much smaller than that of typhoons, their rotational wind speeds are significantly stronger. In recent years, tornado occurrences have increased in densely populated areas, leading to severe damage or collapse of low-rise township buildings due to insufficient resistance. Therefore, incorporating tornado-resistant design in civil engineering structures is essential for improving disaster preparedness, mitigating damage, and safeguarding lives and structures in tornado-prone areas [14,15].

To mitigate the significant damage caused by tornadoes, it is crucial to conduct in-depth investigations into the mechanisms governing tornado–structure interactions, their formation processes, wind field structure, and evolutionary patterns. Currently, tornado wind fields are predominantly studied through experimental modeling, numerical simulations, and real-world field data. Among these, observations in the field provide the most direct means of studying tornado behavior. Despite its high cost and the challenges of managing various uncontrollable factors, it remains highly valued for its authenticity and reliability. However, the presence of a debris wall inside tornadoes further complicates field observations, making them even more challenging [3,16–19].

Measuring tornadoes in the field is a challenging task. This has led to the development of tornado generators in the laboratories, providing researchers with an opportunity to study and gain a better understanding of tornadoes [20,21].

There was no dedicated chapter for tornado loads in previous editions of the American Society of Civil Engineers (ASCE 7) standard [22]. However, the most recent ASCE 7-22 edition guides tornado-related structural loads through a newly incorporated chapter [22]. This chapter provides detailed procedures for assessing and designing for tornado loads, including determining tornado wind speeds, pressure coefficients, and other related factors. Earlier versions of the standard primarily focused on wind loads from hurricanes or general high-speed winds, without detailed consideration for the unique characteristics of tornadoes. The Federal Emergency Management Agency (FEMA) [23] has also published guidance on the design, planning, and construction of safe rooms and tornado shelters to enhance protection against extreme wind events.

These publications include FEMA 320 [23], which offers prescriptive guidance for the design of safe rooms, and FEMA 361 [24], which offers more detailed standards for building tornado and hurricane shelters. These documents address key issues such as wind-induced forces, atmospheric pressure changes, and debris impact that are crucial for designing buildings capable of withstanding tornadoes. These guidelines help engineers design more resilient buildings and shelters, ensuring that structures and occupants can better withstand the devastating effects of tornadoes. The growing awareness of tornado risks and their severe localized impacts has led to the introduction of these guidelines for designing buildings to better withstand tornado-related forces.

This comprehensive review investigates the critical parameters influencing wind loads on structures, focusing on tornado flow field characteristics and structural properties that dictate a building's resilience against these forces. Furthermore, the review explores experimental and numerical simulation methods that advance the understanding of tornado-induced pressures. Recent advancements in engineering codes, including ASCE 7-22 [22] and FEMA guidelines [23], are also analyzed, highlighting their role in designing more resilient structures. Despite the growing body of literature on wind engineering and tornado effects, there is still a lack of studies that provide a fully integrated synthesis of the diverse aspects of the problem, including tornado aerodynamics, structural response, experimental and numerical approaches, and modern design codes within a unified framework, as most existing research addresses these components separately. By consolidating existing knowledge and identifying research gaps, this review emphasizes the potential role of emerging computational technologies, such as machine learning, in advancing predictive capabilities and structural engineering practices. By providing insights into the interaction between wind events and structures, it aims to mitigate the impacts of extreme wind events and enhance the safety and sustainability of buildings.

2. Wind Events

Wind events are natural atmospheric phenomena characterized by strong and often destructive winds. These events include downbursts, hurricanes, and tornadoes, each varying in scale and impact. Tornadoes and downbursts are localized, high-intensity wind events, while hurricanes are large-scale systems affecting vast areas. Extreme wind events can inflict substantial damage on both built structures and the natural environment, highlighting the importance of studying them for improving prediction methods and developing effective mitigation strategies. Understanding their formation, wind field dynamics, and behavior is essential for reducing the risks associated with these powerful forces of nature.

Tornadoes, hurricanes, and downbursts are intense wind events with distinct differences. Tornadoes and hurricanes differ significantly in size, duration, and origin. Tornadoes are small-scale phenomena, typically hundreds of meters wide, lasting from minutes to a few hours, causing localized destruction, and forming from thunderstorms. Hurricanes, on the other hand, are massive systems spanning hundreds of kilometers, lasting for days or weeks, impacting vast areas with strong winds, heavy rains, and flooding, and developing over warm oceans. Downbursts, like tornadoes, are localized events and cause localized destruction [25]. A downburst, as defined by Fujita [26], involves the rapid descent of cold, moist air from a storm cloud, striking the ground and radiating outward horizontally, caused by a sudden downward rush of air during a thunderstorm [27]. A defining feature of downbursts is their 3D wind structure combined with a distinctive nose-shaped velocity profile, marked by highly non-stationary and non-Gaussian properties [28–32]. Extensive attempts have been made using field measurements [33–36], experimental testing [37–39], and computational simulation [40–42].

3. Characteristics of Extreme Wind Events

This section outlines the most critical characteristics influencing structure loading, along with comparisons to previous studies. Haan et al. [43] identified essential characteristics, including tornado core radius, path, swirl ratio, and translation speed.

Tornado-induced wind loads are governed by several critical parameters, including the swirl [44–48], translation speed [14,45,49–52], ground roughness [45,53,54] and topography [55–57] or building-related parameters, including geometry [58], proximity to the tornado mean path [11,59–61], and orientation [2,10,60,62].

3.1. Maximum Horizontal Wind Speed

The Fujita (F) Scale [63] and Enhanced Fujita (EF) Scale [64] provide tornado classifications according to wind speeds and damage, but they differ in accuracy and methodology. The F-Scale, introduced in 1971, categorizes tornadoes from F0 to F5 with wind speeds estimated subjectively, often overestimating stronger tornadoes. In 2007, the EF-Scale replaced it in the U.S., refining wind speed estimates (EF0 to EF5) using standardized damage indicators and engineering analysis. The EF-Scale corrects F-Scale inaccuracies, with EF0 starting at 65 mph (105 km/h) and EF5 exceeding 200 mph (322 km/h), ensuring more precise assessments. This study will examine both classifications. Additionally, the Saffir-Simpson Scale is a five-level system used to measure hurricane intensity according to sustained wind speeds, ranging from Category 1 (least intense) to Category 5 (most severe) [65].

The ranges of wind speed for the Saffir-Simpson, Fujita (F), and Enhanced Fujita (EF) scales provide essential insights into categorizing wind events, as shown in Figure 1. It compares EF-scale 3 s gust wind speeds with Saffir-Simpson 1 min sustained wind speeds. However, it should be noted that these two scales are based on different wind-averaging periods (gust versus sustained), which makes a direct quantitative comparison inappropriate. It may be more accurate to state that the EF scale begins at lower wind speeds and extends to higher values, rather than implying fundamentally different or non-comparable ranges. Each scale serves a specific purpose and is based on unique criteria:

- **Saffir-Simpson Scale:** Focuses on hurricanes, categorizing them by sustained wind speeds and potential for damage. Its straightforward ranges make it practical for storm surge and evacuation planning. The Saffir-Simpson Scale has a relatively narrow range, as it is specifically designed to classify tropical hurricanes based on their sustained wind speeds, focusing on the most intense and destructive storms. These storms typically exhibit a narrower range of wind speeds compared to tornadoes, which are evaluated using the Fujita (F) and Enhanced Fujita (EF) scales.
- **Fujita Scale (F):** Primarily used historically for tornadoes, it estimates wind speeds based on observed damage. While useful, its reliance on post-event damage assessment made it less precise. The Fujita scale (F-scale) has a larger wind speed range compared to the Enhanced Fujita scale (EF-scale). This is because the EF scale was introduced as an enhancement of the Fujita scale, with more precise wind speed estimates based on observed damage.
- **Enhanced Fujita Scale (EF):** Introduced to improve the accuracy of tornado intensity estimation by providing a more reliable, engineering-based relationship between observed damage and wind speed, addressing limitations and overestimation issues in the original Fujita Scale.

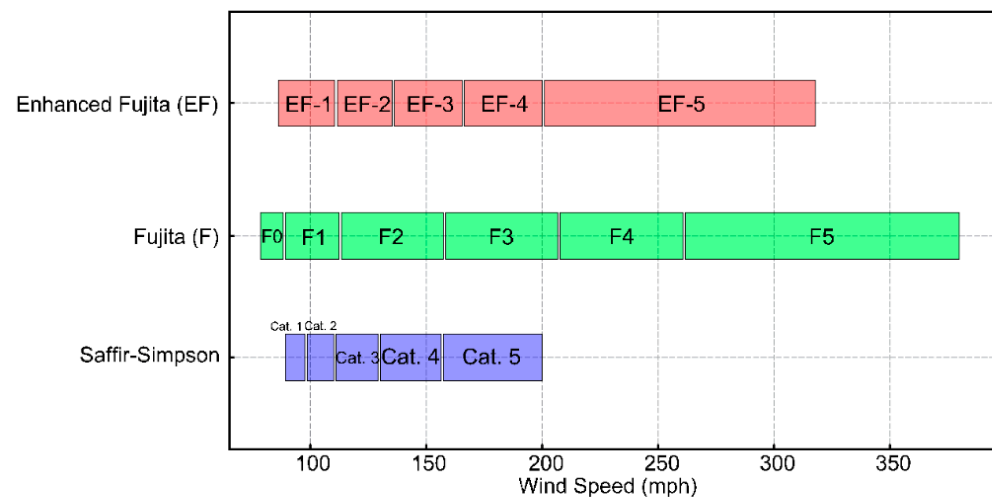


Figure 1. Wind speed range (mph) for Saffir-Simpson, Fujita (F), and Enhanced Fujita (EF) scales.

As observed in Table 1, many scientific researchers historically used the Fujita (F) scale more frequently than the Enhanced Fujita (EF) scale because of historical usage and data availability, and studied tornadoes rated F2 because approximately 90% of all tornadoes are classified F2 or lower [66], and to balance between frequency, damage potential, and practicality for research purposes.

Table 1. Wind events studied and their scale or category.

Scale	Frequency	References
Category 4	2	[67,68]
Category 5	4	[69–72]
F2	7	[8,47,48,73–76]
F4	3	[15,47,77]
EF-3	1	[58]
EF-5	1	[4]

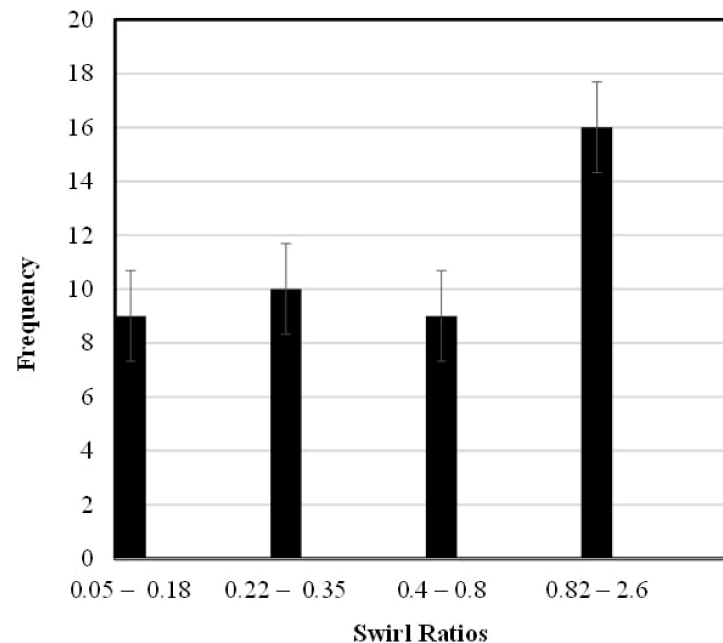
3.2. Swirl Ratio

Swirl ratio, a key parameter in numerical and experimental tornado simulations [43,78], quantifies the ratio of tangential momentum to the vortex inflow rate at a specific radius [58]. Previous studies have identified it as the primary factor influencing tornado flow characteristics [44,78]. According to Davies-Jones [79], the core radius of a tornado vortex depends on the swirl ratio, and larger swirl ratios make the vortex more prone to fragmenting into multiple vortices. Iowa State University's tornado simulator replicates tornado wind fields to study their impacts on structures and environments, contributing to the advancement of safer, tornado-resistant designs. The simulator uses advanced technology to generate controlled vortices, enabling researchers to study tornado dynamics and their impact on structures and the environment. By altering the vane angle, the swirl ratio of the vortex can be controlled [43]. Table 2 shows the ranges applied in earlier studies.

A swirl ratio range of (0.82–2.60) is commonly used because it aligns with natural tornado dynamics, provides a critical transition point for vortex structures, and offers practical advantages for experimental studies, as shown in Figure 2.

Table 2. Used swirl ratio(s) in previous research.

	Used Swirl Ratio(s)			
	0.05–0.18	0.22–0.35	0.4–0.8	0.82–2.6
References	[8,47,48,52,62,73,77]	[10,45,47,48,52,62,73,77,80]	[45,47,48,77]	[4,7,10,44–48,58,62,73]
Frequency	9	10	9	16

**Figure 2.** Used swirl ratios frequency.

Swirl ratio S was calculated in some previous studies according to the following equation [10,46,62]:

$$S = \pi V_{\theta\max} \frac{r_c^2}{Q}$$

where $V_{\theta\max}$ denotes the peak tangential velocity at the radius of peak wind speed, r_c represents the vortex core radius, and Q is the flow rate.

Razavi and Sarkar [52] explored the impact of tornado characteristics, particularly the swirl ratio, in determining wind loads acting on low-rise structures, using laboratory-simulated tornadoes as illustrated in Figure 3, with two swirl ratios given in Table 2, and three translation speeds, peak forces were evaluated using a scaled gable-roof low-rise structure model, and they discovered that lower swirl ratio tornadoes cause higher peak loads and considerably higher peak load coefficients, which were similar to their peak pressure drop observed at the ground surface. Structures situated on the tornado's mean path experience a decrease in peak roof uplift of 6–19% for lower swirl ratios and up to 16% for higher swirl ratios.

Swirl ratio tests of Kuai et al. [46] demonstrated that higher swirl ratios increase the vortex core radius while decreasing peak tangential velocity, and that larger swirl ratios expand the turbulent radial flow near the ground.

Most previous research [11,59,60] examined tornado-induced wind pressures using a single swirl ratio, except for the work by Sengupta et al. [10], and Haan et al. [62], who investigated multiple swirl ratios for buildings located along the tornado's mean path.

Kumar et al. [73] developed full-scale numerical Finite Element models using ANSYS software (Release 11.0) [81] of gable roof buildings to study tornado-induced wind loads

and stress distribution. The results indicated that lower swirl ratio tornadoes (0.08) generate higher peak stresses on buildings than tornadoes with higher swirl ratios (0.24 and 1.14).

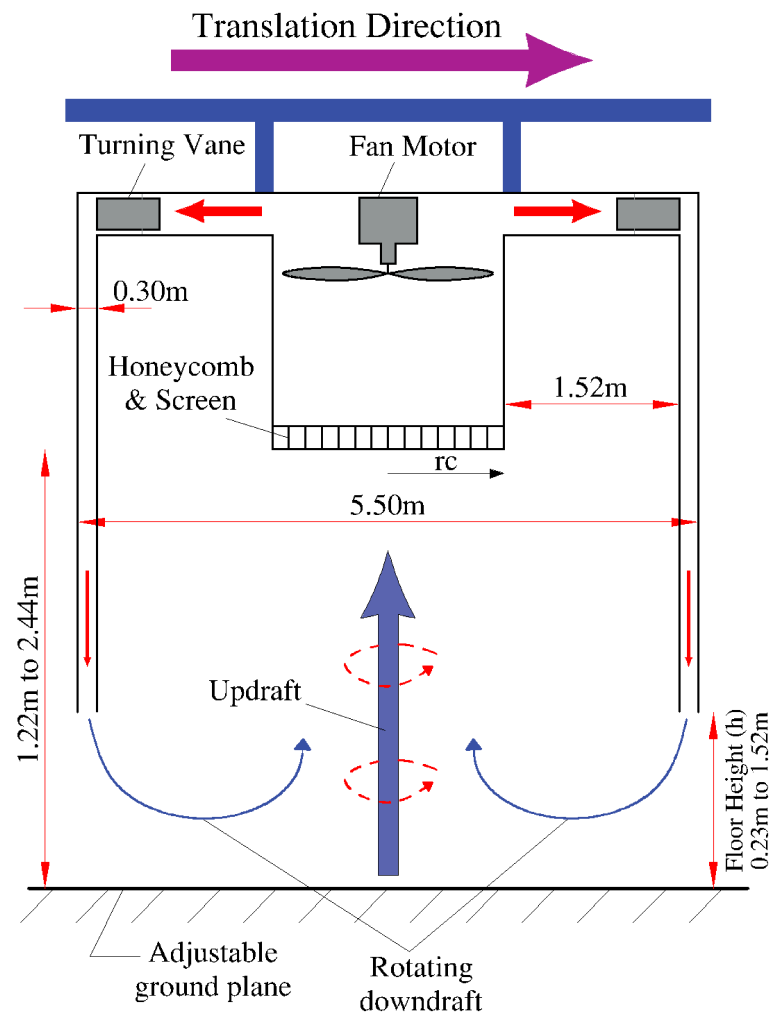


Figure 3. Illustration of the Iowa State University Tornado Simulator (ISU-TS).

3.3. Translation Speed

The translation speed of full-scale tornadoes refers to the speed at which the tornado moves across the ground. This speed significantly affects the wind field dynamics and the resulting damage, with higher speeds amplifying wind asymmetry across the tornado path. Full-scale tornadoes have been recorded moving at translation speeds of 13 m/s, 16.5 m/s, and 23 m/s, as reported by Lee and Wurman [82], Thampi et al. [4], and Haan et al. [43], respectively.

Razavi and Sarkar [52] reported that, under low-swirl conditions, increasing tornado translation speed elevates peak roof uplift along the tornado's mean path but reduces it elsewhere; for high-swirl tornadoes, translation speed has a negligible impact on maximum uplift.

Feng and Chen [8] used wavelet-based techniques to analyze dynamic pressures and internal forces on a low-rise structure during tornado exposure, showing a decrease in peak loads as tornado translation speed rises.

A laboratory investigation conducted by Razavi and Sarkar [14] utilized the ISU Tornado Simulator (Figure 3) to investigate the impact of tornado translation on near-ground flow fields. Unlike stationary vortices, translating tornadoes affect the pattern and intensity of horizontal wind speeds, causing earlier radial inflow reversal and expanding

the core radius. The highest horizontal velocities appeared behind the tornado center, with higher translation speeds further decreasing peak velocities at all heights.

3.4. Surface Roughness and Topographic Effects

Terrain roughness is an important factor that significantly influences the behavior of the near-surface wind field of tornadoes [83]. Table 3 shows previous research attempts to represent the ground roughness.

Table 3. Ground roughness attempts for simulation.

Ground Roughness Attempts for Simulation	Frequency	References
Smooth and rough surface	5	[45,61,77,83,84]
Smooth surface only	2	[48,58]
Open terrain	4	[58,62,85,86]

Most researchers assume both smooth and rough surfaces, as shown in Figure 4, because that allows them to study the extremes of terrain effects on tornado dynamics, providing a comprehensive understanding of wind interactions with the ground and structures. Also simplifies experimentation, enhances comparability, and aligns with real-world scenarios where tornadoes impact diverse terrains.

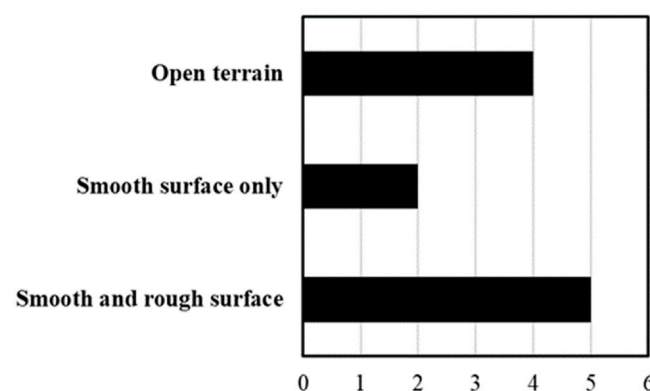


Figure 4. Ground Roughness Frequency.

Ground roughness significantly influences tornado strength and characteristics, directly impacting their effects on structures. Wang and Cao [77] found that ground roughness significantly affects internal pressures, particularly for openings on windward walls. Razavi and Sarkar [58] regarded open terrain and smooth surfaces as valid and useful exposure conditions for their study. Diamond and Wilkins [49] investigated how terrain roughness influences the wind field. They discovered that increasing surface roughness reduces the core radius and decreases internal pressures regardless of swirl ratio [61,84], and lowers external pressures [61]. Sabareesh et al. [84] further demonstrated that introducing roughness increases net local roof forces.

The tests of Kuai et al. [46] revealed that surface roughness significantly affects tornado dynamics. It decreases peak tangential speed near the ground while having less effect at higher altitudes. Razavi and Sarkar [57] investigated the topographic effects on the near-surface flow of a translating tornado. The tornado simulation included three different topographies, with the ridge producing the highest wind amplification, speed-up ratios (+14%), and maximum exposure factors for EF2 and EF3 wind speeds. Topography

strongly affected wind velocity, drag, and exposure, making low-rise buildings on ridges particularly susceptible.

Wang et al. [54] examined tornado-like vortex flow properties by measuring three-dimensional wind velocity and dynamic pressure over varying ground roughness and swirl ratios. They showed that rough ground surfaces induced higher axial velocity within the vortex core, like the effect of a reduced swirl ratio. Pressure drops near the ground were more significant over rough surfaces than over smooth ones. The impact of ground roughness was primarily confined to lower elevations, influencing the near-ground vortex structure in a manner largely dependent on the swirl ratio.

Razavi et al. [83] studied the effect of ground roughness on tornado-like vortices through laboratory simulations of both stationary and translating tornadoes. Using a scaled-down ISU tornado simulator and advanced measurement tools for stationary and translating tornadoes. Near-surface flow characteristics were examined over both rough and smooth terrains. They revealed that for both stationary and translating tornadoes, rough terrain led to smaller core radii, lower tangential velocities, stronger radial and vertical flows, and reduced local swirl ratios.

4. Structure Properties

The impact of wind events on structures is influenced not only by the intensity and characteristics of the wind but also by the structural properties of buildings that significantly affect structural loading and endurance. A building's response to wind forces is primarily influenced by its structural properties [87]. Key factors include Structure type, geometry, material, orientation, and relative distance to the tornado's mean path. These characteristics determine how a building interacts with wind loads and its capacity to withstand extreme events.

4.1. Structure Type and Geometry

Structural geometry plays a crucial role in wind load distribution. Common geometrical factors affecting wind loads include building dimensions (plan shape and height) and roof geometry.

Figure 5a,b show the approximate proportions of the type and plan shape of structures examined during wind events in previous studies, respectively. As shown, approximately half of the structures examined in previous studies are classified as low-rise buildings. Compared to high-rise structures, low-rise buildings are more prone to tornado damage because of lighter weight, weaker construction, and greater exposure to uplift forces. Table 4 illustrates how previous studies have investigated various wind events across various structures.

Table 4. Structures studied by previous researchers during wind events.

Structure Type	Frequency	References
Low-rise building	33	[4,8,9,15,52,58,62,69,71–73,77,88–108]
High-rise building	4	[7,76,86,109]
Transmission tower	8	[47,67,85,110–114]
Other Structures	9	[2,48,74,115–120]

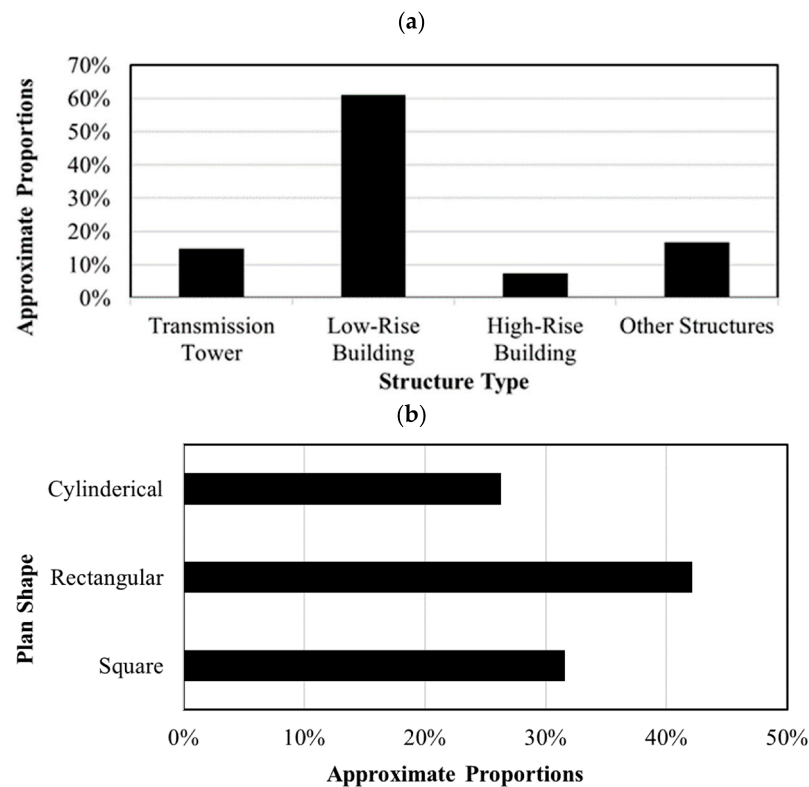


Figure 5. Previously studied structures during wind events: (a) Structure type, and (b) Structure plan shape.

Case et al. [58] examined the influence of varying building geometries on the pressures experienced by low-rise structures during tornadoes, as shown in Figure 6. By analyzing different structural shapes and dimensions, the study revealed that peak loads are strongly affected by various building characteristics, including eave height, roof slope, building plan area, aspect ratio, and architectural features such as attached garages, roof overhangs, and soffits.

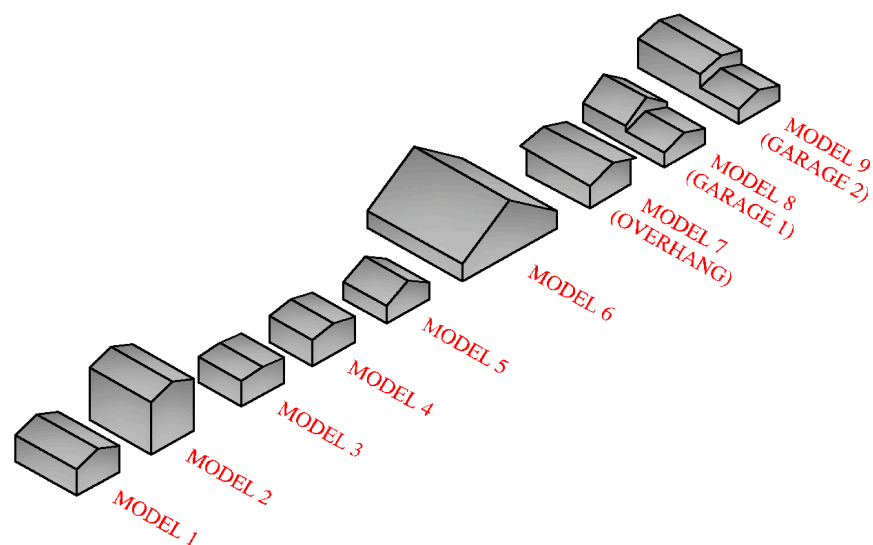


Figure 6. Models used in [58].

Wang et al. [121] examined how opening ratio, central opening orientation, and distance from the tornado-like vortex affect wind pressures on and within the building, showing that internal pressures are strongly influenced by the opening-to-leakage ratio.

Roof Inclination

Razavi and Sarkar [90] analyzed how flat, gable, and hip roofs influence uplift, shear, and moment on low-rise buildings under simulated tornadoes, as shown in Figure 7, showing that flat roofs sustained the highest forces, gable roofs resisted shear better, hip roofs resisted uplift more, and experimental results aligned with ASCE 7-16 standard [22].

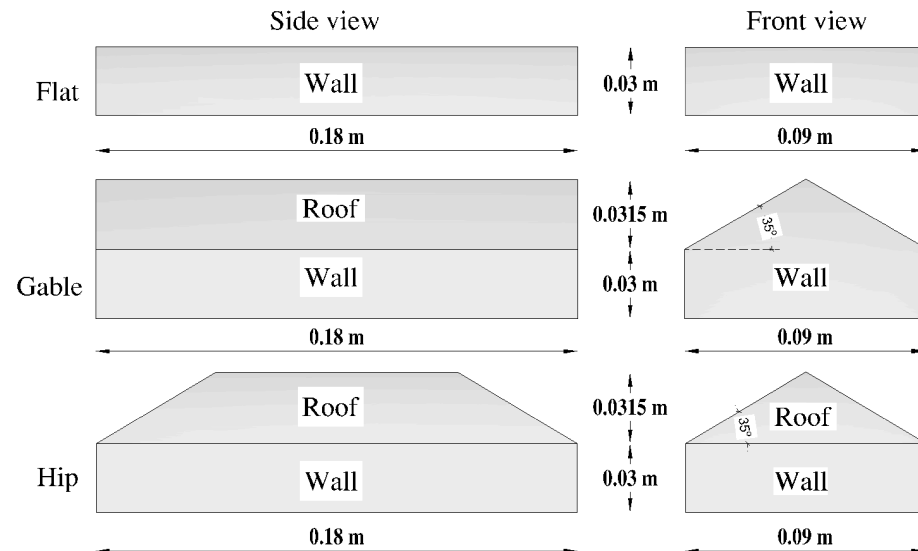


Figure 7. Illustration of three building models and their dimensions used in Razavi and Sarkar [90].

Kumar et al. [73] involved creating full-scale finite element models of gable roof buildings with various roof angles of 13.4° , 25.5° , and 35.1° . They found that the 25.5° roof angle produced the highest peak stresses, followed by the 13.4° and 35.1° roofs. Maximum stresses occurred at the roof-wall junctions and the ridge, with high stress concentrations near the roof's center. As roof angle increases, stress and pressure on the roof also increase. The roof's damage started earlier with higher roof angles, even when the tornado was farther from the building. The analysis revealed early failure of the corner joints and plywood, followed by disintegration of the front and rear walls, especially for the 35.1° roof.

4.2. Structure Material

Structural material selection plays a key role in a building's resistance to extreme wind events, including hurricanes, tornadoes, and downbursts. Materials like steel and reinforced concrete offer high strength and durability, making them ideal for withstanding intense wind forces due to their resistance to bending or deformation. Lighter materials, such as wood, while flexible, are more susceptible to high wind damage and may not withstand the extreme forces of tornadoes or hurricanes. The aerodynamic properties of materials also influence how a structure responds to wind, with heavier materials generally reducing sway but potentially requiring more robust foundations. Additionally, the long-term effects of exposure to wind, moisture, and storms can degrade certain materials, such as wood or untreated metals, compromising their strength. Ultimately, the choice of material affects a building's ability to endure wind events, with proper selection playing a key role in ensuring safety and minimizing damage during such extreme conditions. Figure 8 shows the materials of structures studied in previous research.

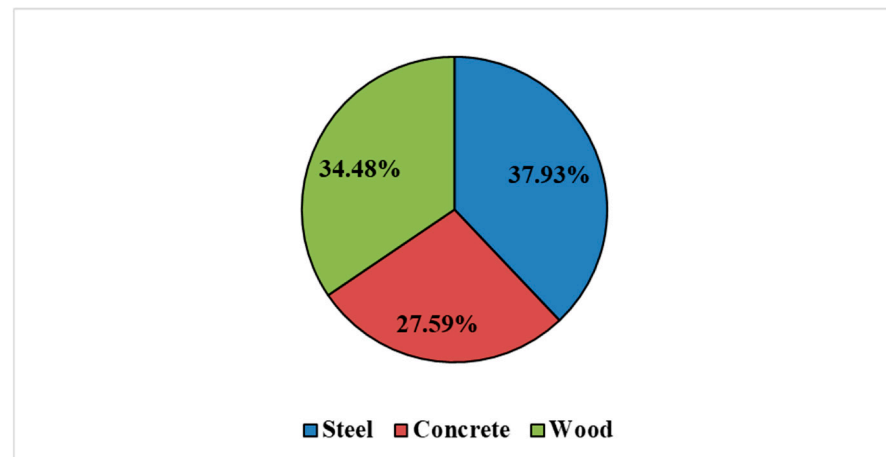


Figure 8. Structure material of previously studied structures during wind events.

4.3. Relative Distance to Tornado's Mean Path and Building Orientation

Due to the distinct nature of tornado winds compared to straight-line winds [2,5–13], Mishra et al. [11] analyzed the pressure distribution of a stationary tornado, and they found that the distance from the tornado center governs external pressures on cubic buildings. Amirinia and Jung [86] demonstrated that hurricane surface wind characteristics differ from those of non-hurricane surface winds.

Low-rise buildings are particularly vulnerable to tornadoes, as these events frequently strike suburban areas predominantly consisting of low-rise residential structures [121], Feng and Chen [8] analyzed and characterized dynamic pressures and internal forces on a low-rise structure. They demonstrated that tornado pressure patterns depend on building location within the tornado vortex, with the core region exhibiting more uniform pressures.

Xu et al. [15] developed a numerical tornado model, and found that:

- Negative pressures dominate at the tornado center, producing symmetric structural deformation, with the front and back walls showing somewhat larger displacements.
- At the core radius, displacement is largest at the middle walls of upper floors. Local positive pressure appears on the front wall.
- At $2 \times$ core radius, displacement is smaller, with left and back walls showing more deformation.

Liu et al. [115] investigated the impacts of tornado-induced wind loads on cooling towers using large eddy simulations (LES). They showed that tornado forces on cooling towers are significantly larger and more fluctuating than those from straight-line winds, especially near the tornado core ($r \leq 1.5 r_c$). Fluctuations in aerodynamic forces are attributed to two primary factors: sub-vortices within the tornado core and vortex shedding from the tower. Beyond $r > 3.0 r_c$, the forces resemble those from straight-line winds. Under a stationary tornado with constant swirl, Hu et al. [60] showed that building proximity to the tornado center and orientation strongly affect loads, with peak pressures exceeding those from straight-line winds by a factor of three.

Previous Studies [10,59,60,62] examined the effect of building orientation only at specific locations, which does not ensure the identification of the worst tornado loading scenario. Cao et al. [2] showed that a cooling tower exposed to a stationary tornado experiences both pressure drops and flow–structure interactions, with peak forces near the core radius. Tornado winds differ markedly from straight-line winds, yet few studies have considered translating tornadoes [4,10,58,62], primarily for buildings along the tornado's path or at fixed locations.

Jischke and Light [59] demonstrated that tornado-induced loads surpass those from equivalent straight-line winds, stressing the need to account for building orientation and position relative to the tornado center when evaluating tornado wind effects.

Using a Ward-type tornado simulator, Sabareesh et al. [61] investigated the effects of building locations from the vortex center and terrain roughness on surface pressures experienced by a cube-shaped building model under swirl flow. They revealed that peak pressures occurred at roof corners and leading edges within the vortex core, driven by strong tangential and updraft flows. Buildings near the vortex boundary experienced varied pressure distributions, with windward and leeward faces showing reduced pressures. At greater distances, oblique flow influenced pressure patterns, causing higher suction on side walls.

Wang et al. [121] demonstrated that internal pressures are strongly affected by whether a large wall opening is located on the windward face or a sidewall.

5. Simulation Method

The detailed flow dynamics of tornadoes and downbursts cannot be effectively defined or distinguished by standard wind simulators [122]. Hence, recent studies have utilized arrays of multi-point and sonic anemometers, together with LiDAR technology, to measure non-synoptic wind events in coastal harbors, as demonstrated by [123–127]. Other approaches include using LiDARs alone for canopy and topographic flow assessments, as seen in the works of Mann et al. [128]. Additionally, mobile Doppler radars have been employed for tornado flow measurements [17,82,125,129–134], while Dual Doppler Radar and multi-point measurement techniques have been applied to analyze various gust events (Gunter and Schroeder [129]). However, simulation methods are also essential for studying wind events and their impacts on structures, particularly due to the high costs and challenges associated with managing uncontrollable variables [16,17]. These methods are broadly categorized into experimental approaches, including wind tunnel and tornado simulator tests, and numerical simulations using computational techniques such as CFD. Both approaches offer unique advantages and are often used in complementary ways to gain insights into wind-structure interactions.

Figure 9 summarizes the research methodology adopted in 45 peer-reviewed studies included in this review. The studies were classified according to their primary research approach into three categories: 19 numerical studies, 22 experimental studies, and 4 studies combining both numerical and experimental methods. This classification was conducted to identify the most widely adopted research methodologies in wind engineering and to assess current research trends and methodological developments in the field. As illustrated in Figure 9, approximately 49% of the reviewed studies employed experimental methods, such as wind tunnels and the Iowa State University (ISU) Tornado Simulator, while about 42% relied on numerical simulations, primarily Computational Fluid Dynamics (CFD), and the remaining 9% integrated both approaches. Experimental facilities enable researchers to investigate tornado and hurricane flow characteristics, including swirl ratio, translation speed, and turbulence, while directly observing structural responses under controlled laboratory conditions. The reported percentages represent the distribution of the reviewed studies and are intended to illustrate general research trends rather than provide statistical inference.

Wind Tunnel Tests: These tests simulate straight-line winds or tornado-like vortices, offering insights into pressure distributions and aerodynamic forces on structures. Studies have demonstrated the impact of roof geometry, structure orientation, and terrain roughness on wind-induced loads, for example [14,43,85,92,96,109,111,112,117,135–137] conducted wind tunnel tests in their studies. Wind tunnel tests can be an effective simulation method

for traditional straight-line winds but not for tornadoes, as there are significant differences between them, as mentioned before.

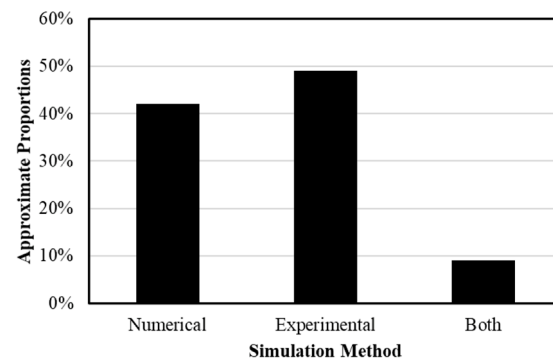


Figure 9. Distribution of the primary research methodologies adopted in the 45 reviewed studies.

Tornado Simulators: These simulators replicate the complex dynamics of tornadoes, enabling the study of swirling wind effects with different components, and their interaction with structures, and analyzing localized effects, which differ significantly from straight-line winds [2].

The ISU Tornado Simulator, a large-scale facility, has been used in multiple studies [4,7,14,52,58,62,76,83,90] to simulate tornadoes and analyze their effects. Wang and Cao [77] and Cao et al. [2] simulated stationary tornado vortices using the Tongji University tornado simulator, China, as illustrated in Figure 10. The widely used Ward-type simulator, originally developed by Chang [20] and later refined by Ward [21], generates tornado vortices via the guide vanes positioned on the test floor [11,138,139].

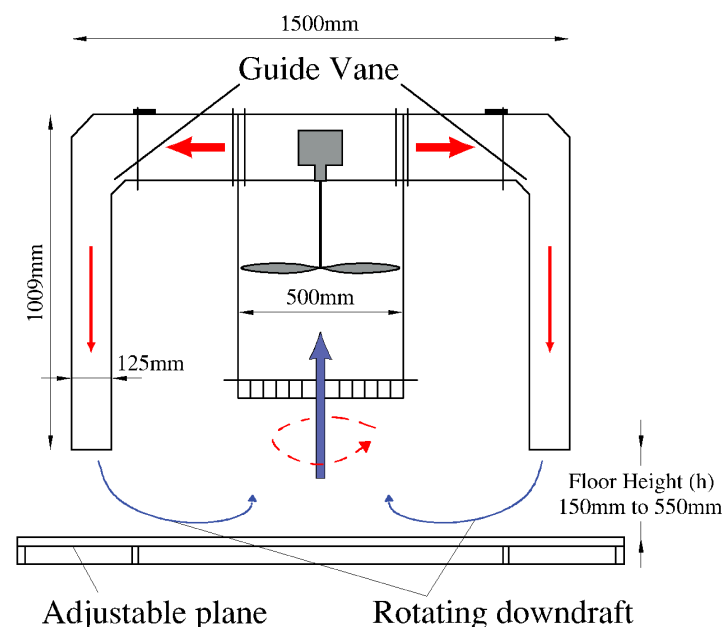


Figure 10. Illustration of tornado vortex simulator at Tongji University.

The Wall of Wind is a large-scale wind tunnel, designed to replicate Category 5 hurricane conditions. Utilizing a matrix of 12 fans, it generates wind speeds of more than 72 m/s [140]. This facility is designed to produce airflow with varying turbulence characteristics through active and passive control mechanisms [141].

Recent developments in tornado simulators involve elevated guide vanes to enhance vertical airflow [43]. The 25 m Wind WinDEEE Dome at Western University offers a

three-dimensional, time-dependent testing environment [122], allowing simulation of tornado-like flows via controlled fan operation [142].

In contrast, some studies have utilized numerical simulation software programs to model wind events, as presented in Table 5.

Table 5. Used software programs in previous numerical simulations.

Used Software Programs	Frequency	References
Ansys (Release 11.0) [81]	5	[4,15,73,143,144]
Abaqus (Version 2021) [145]	4	[67,89,143,146]
SAP2000 (Version 25.78) [147]	1	[113]
ETABS (Version 2021) [148]	1	[97]
FLUENT (Version 19.2) [149]	3	[45,47,150]
FAST (Fatigue, Aerodynamics, Structures, and Turbulence) (Version 2021) [151]	1	[48]
OpenFOAM (Version 7) [152]	4	[80,153–155]

Figure 11 presents the distribution of software packages used in numerical wind engineering studies. The analysis is based on all 19 numerical studies included in this review that explicitly reported the computational software employed for numerical simulation. The software packages were classified by the primary simulation platform used in each study to identify the most widely adopted computational tools in wind engineering research and to highlight current trends in numerical modeling. As illustrated in Figure 11, ANSYS, OpenFOAM, and FLUENT are among the most widely utilized software packages for Computational Fluid Dynamics (CFD) simulations of extreme wind events. These numerical tools provide a cost-effective and scalable alternative to experimental investigations, enabling detailed analyses of tornado and hurricane flow fields, pressure distributions, turbulence characteristics, and wind-induced structural responses. The reported percentages represent the frequency of software use across the 19 reviewed numerical studies and are intended to illustrate general research trends rather than to provide statistical inference.

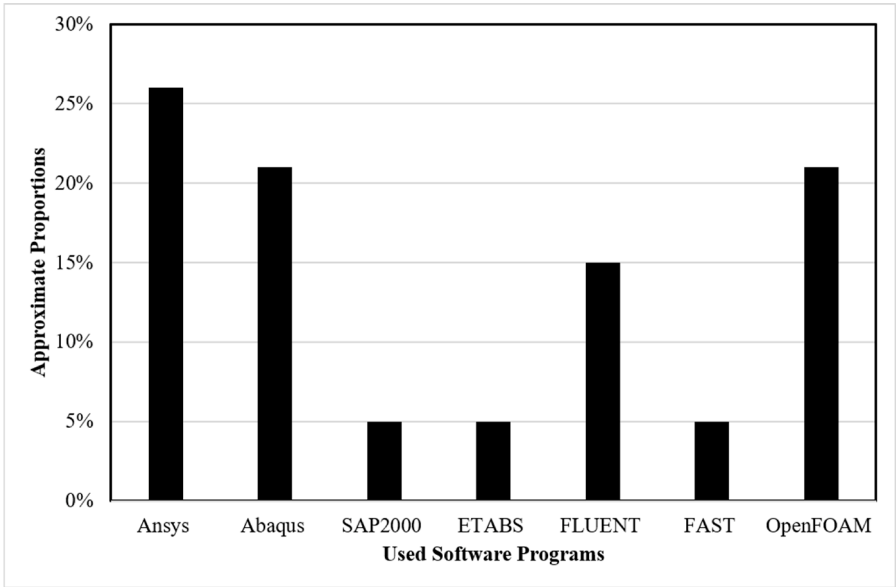


Figure 11. Distribution of software packages used in the reviewed numerical studies.

Some of the advantages of numerical simulation include: High precision in capturing complex flow dynamics, ability to model full-scale scenarios that are challenging to replicate experimentally, flexibility to explore parametric variations, such as ground roughness or building geometry, but there are also limitations, including: Computationally intensive, requiring significant processing power for high-resolution simulations; results depend on the accuracy of input parameters and turbulence models. Hence, some studies tried to combine experimental and numerical simulations to provide robust insights into wind events. For example, experimental data from wind tunnels are often used to validate numerical models, ensuring the reliability of CFD simulations. Similarly, numerical simulations complement experimental methods by exploring a broader range of scenarios and refining design recommendations.

6. Used Codes/Standards for Wind Events

Figure 12 summarizes the engineering codes and standards adopted in the reviewed studies. The classification was conducted based on 40 selected publications that explicitly specified the design codes or standards used in their analyses. This assessment was performed to identify the most frequently adopted codes in wind engineering research and to highlight current trends in structural design and wind load evaluation practices. As illustrated in Figure 12, the ASCE 7 standard is the most widely adopted code among the reviewed studies. This is expected because ASCE 7 provides comprehensive procedures for evaluating wind loads and, in its latest edition (ASCE 7-22) [22], introduces a dedicated chapter addressing tornado loads, including tornado wind speeds, pressure coefficients, and other parameters required for tornado-resistant design. The reported percentages represent the frequency of code adoption within the reviewed publications and are intended to illustrate general research trends rather than provide statistical inference.

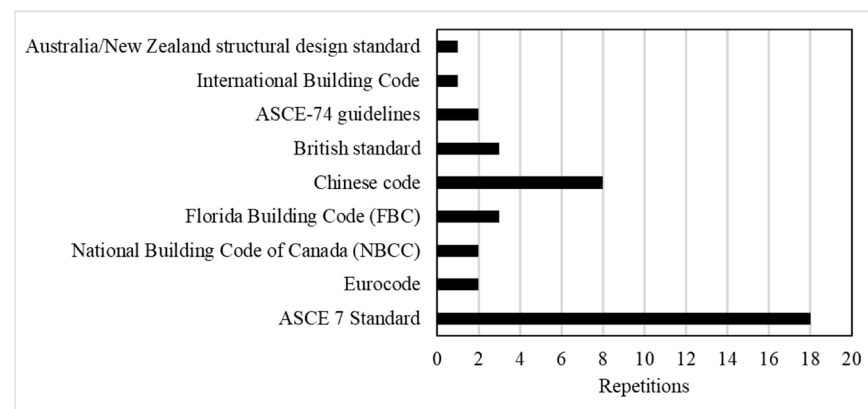


Figure 12. Distribution of engineering codes and standards adopted in the reviewed studies.

European standards such as Eurocode 1 (EN 1991-1-4) [156] and Canada's NBCC [157] also address region-specific wind actions, while the International Building Code (IBC) [158] incorporates wind load criteria globally. These codes improve structural safety, reduce economic losses, and promote sustainability by enabling resilient building designs. Continuous improvements in wind engineering standards, combined with CFD analyses and intelligent construction technologies, bolster readiness for severe wind events and climate impacts. Table 6 illustrates the commonly used codes in previous research articles to address wind and tornado loads on different structures.

Table 6. Previously utilized codes/standards in wind events research.

Utilized Codes/Standards	Frequency	References
ASCE 7 Standard [22]	18	[8,68,71,72,76,77,86,89–92,95,97,114,120,137,159,160]
Eurocode [156]	2	[85,113]
National Building Code of Canada (NBCC) [157]	2	[88,98,100]
Florida Building Code (FBC) [161]	3	[71,120,159]
Chinese Code [162]	8	[2,67,96,109–112,114]
British Standard [163]	3	[2,67,114]
ASCE-74 Guidelines [164]	2	[47,74]
International Building Code (IBC) [158]	1	[68]
Australia/New Zealand Structural Design Standard [165]	1	[114]

7. Structural Damage Caused by Extreme Wind Events

7.1. Tornado-Induced Damage

Tornadoes are among the most destructive localized wind hazards, producing extreme wind speeds, intense pressure gradients, rapidly changing wind directions, and severe windborne debris impacts [62]. Unlike straight-line winds, tornadoes generate highly three-dimensional and non-stationary flow fields that impose complex loading conditions on structures [138]. As a result, buildings are subjected to combined uplift, lateral, torsional, and impact loads that may exceed the design assumptions of conventional wind-resistant structures. Residential buildings are particularly vulnerable due to failures initiated in roof coverings, roof-to-wall connections, garage doors, and wall systems, which often lead to progressive structural collapse [107,108]. The severity of damage is strongly influenced by tornado intensity, building geometry, construction quality, and the presence of openings that increase internal pressure. These characteristics make tornado-resistant design significantly more challenging than conventional wind design [10].

Furthermore, post-disaster investigations have shown that windborne debris is one of the primary causes of structural damage during tornado events [17,166]. Debris impacts frequently penetrate building envelopes, resulting in sudden increases in internal pressure that accelerate roof uplift and wall failures [99,107,167,168]. Critical facilities, including schools, hospitals, and emergency shelters, require enhanced structural detailing and protective measures to withstand these combined hazards. Consequently, recent design standards such as ASCE 7-22 [22] have introduced dedicated tornado load provisions, while FEMA guidelines [23] emphasize continuous load paths, impact-resistant envelopes, and improved connection detailing to enhance structural resilience against tornadoes.

7.2. Hurricane-Induced Damage

Hurricanes are large-scale atmospheric systems capable of producing prolonged high wind speeds, heavy rainfall, storm surge, and flooding over extensive geographical regions [169]. Unlike tornadoes, hurricane winds are predominantly straight-line and persist for several hours, leading to repeated cyclic loading that progressively weakens structural components and connections [170]. Common structural failures include roof covering loss, roof framing damage, cladding failures, glazing breakage, and progressive envelope deterioration, which subsequently increases internal pressure and accelerates structural damage [171]. In coastal regions, these wind effects are often accompanied by storm surge and wave action, resulting in severe foundation erosion, scour, and inundation that further compromise structural stability [72].

Numerous post-hurricane damage assessments have demonstrated that inadequate connection detailing, insufficient load paths, and poor construction practices remain major contributors to structural failures [171]. Buildings designed according to modern wind-resistant codes generally exhibit significantly improved performance compared with older structures, emphasizing the importance of updated design provisions and retrofit strategies. Recent research has also highlighted the increasing use of numerical simulations, wind tunnel experiments, and machine learning techniques to better understand hurricane-induced wind loads, predict damage patterns, and optimize resilient structural design under future climate scenarios [68].

7.3. Comparison Between Tornado and Hurricane Damage

Table 7 presents a comparison between tornadoes and hurricanes based on their wind characteristics and structural impacts. Despite both being extreme wind hazards, they differ significantly in terms of wind field characteristics, spatial extent, duration, loading mechanisms, and damage patterns. Tornadoes primarily cause localized damage through intense rotating winds and debris impacts, whereas hurricanes produce widespread damage due to prolonged straight-line winds, storm surge, and heavy rainfall. Understanding these differences is essential for selecting appropriate structural design criteria and mitigation strategies.

Table 7. Comparison of tornado and hurricane characteristics.

Aspect	Hurricane	Tornado
Duration	Hours to days	Seconds to minutes
Scale	Hundreds of kilometers	Hundreds of meters
Wind speed	Moderate-high	Very high
Wind direction	Relatively consistent	Rapidly changing
Pressure drop	Small	Significant
Debris	Moderate	Extremely severe
Storm surge	Yes	No
Rainfall	Heavy	Limited
Damage path	Wide	Narrow

7.4. Strategies for Improving Structural Resistance to Extreme Wind Events

One of the most effective strategies for reducing wind-induced structural damage is establishing a continuous load path that efficiently transfers wind loads from the roof to the foundation. Post-disaster investigations following major tornadoes and hurricanes have consistently shown that structural failures are frequently initiated at weak connections rather than inadequate member strength [100,159]. In particular, failure of roof-to-wall connections often results in progressive collapse of the roof system, followed by failure of the exterior walls due to the loss of structural integrity. Therefore, ensuring continuity between roof framing, walls, floors, and foundations through properly designed connections is considered a fundamental principle of wind-resistant structural design. Modern design standards, including ASCE 7-22 [22] and FEMA guidelines [23], strongly emphasize the importance of continuous load paths for mitigating wind damage.

Among all structural connections, roof-to-wall connections are widely recognized as one of the most critical components governing building performance under extreme wind loads [168]. Numerous post-event damage surveys have demonstrated that inadequate fastening, insufficient anchorage, and poor construction practices frequently initiate roof

uplift failures during tornadoes and hurricanes [95]. The use of hurricane clips, metal straps, anchor bolts, and improved fastening systems significantly increases the uplift resistance of roof systems by providing a direct load transfer mechanism between roof framing and supporting walls. Studies have shown that strengthening roof-to-wall connections substantially reduces the probability of progressive structural failure, particularly in low-rise residential buildings, where roof failures are often the primary cause of catastrophic damage [15,71].

8. Artificial Intelligence and Machine Learning Applications in Wind Engineering

Artificial intelligence (AI) and machine learning (ML) have recently emerged as promising technologies in wind engineering because of their ability to analyze large datasets, identify complex nonlinear relationships, and significantly reduce computational costs [172]. Traditional approaches, including full-scale field measurements, wind tunnel experiments, and high-fidelity Computational Fluid Dynamics (CFD) simulations, often require substantial time, computational resources, and financial investment [48]. AI-driven models provide efficient surrogate solutions capable of learning from numerical or experimental data and rapidly predicting wind characteristics and structural responses while maintaining acceptable levels of accuracy [173]. Consequently, AI techniques are increasingly being incorporated into wind engineering applications, particularly for hazard assessment, structural reliability analysis, aerodynamic optimization, and real-time decision-making [174].

8.1. Machine Learning-Based Wind Field Modeling

One of the most active research areas involves the application of machine learning for wind field prediction and reconstruction. Deep Neural Networks (DNNs), Convolutional Neural Networks (CNNs), Artificial Neural Networks (ANNs), Long Short-Term Memory (LSTM) networks, and Physics-Informed Neural Networks (PINNs) have been successfully employed to predict complex wind flow patterns around buildings without repeatedly performing computationally expensive CFD analyses [174]. These models have demonstrated the capability to estimate velocity distributions, pressure coefficients, turbulence characteristics, and vortex structures with high accuracy after adequate training. In addition, AI-assisted surrogate models have been used to accelerate parametric studies involving different building geometries, terrain conditions, and wind directions, substantially reducing computational time while preserving reliable predictive performance.

Recent studies have demonstrated the growing potential of Artificial Intelligence (AI) and Machine Learning (ML) for wind field modeling across a wide range of wind engineering applications. Graph Neural Networks (GNNs) combined with UNet architectures have been employed to estimate high-elevation wind speeds in complex mountainous terrain, where the integration of topographic information and physical constraints significantly improved prediction accuracy [175]. Similarly, ML-based surrogate models have been developed for tropical cyclone (TC) wind field prediction, replacing conventional parametric approaches by combining Principal Component Analysis (PCA) with Quantile Regression Forests or deep learning techniques, thereby providing more accurate probabilistic wind field representations and uncertainty quantification [176]. Hybrid physics-informed frameworks integrating numerical models with ML algorithms, such as FVCOM coupled with Long Short-Term Memory (LSTM), Convolutional Neural Networks (CNN), CNN-LSTM, and ConvLSTM, have also demonstrated substantial improvements in storm surge forecasting by reducing the prediction errors associated with traditional numerical simulations [177]. More recently, advanced deep learning models, including Fully Connected Deep Neural Networks (FC-DNNs), CNNs, and Transformer networks,

have been introduced for tropical cyclone wind field reconstruction using multiple meteorological variables [178]. Among these approaches, Transformer-based models achieved the highest prediction accuracy and the lowest prediction errors, outperforming conventional linear models and other deep learning architectures. Overall, these studies demonstrate that integrating AI with physical knowledge and numerical simulations provides a robust and efficient framework for accurately modeling complex wind fields while significantly reducing computational costs.

8.2. Structural Response Prediction

Machine learning has also been widely adopted to predict structural responses subjected to extreme wind events [179]. Instead of performing repeated nonlinear finite element analyses, supervised learning algorithms can estimate key engineering demand parameters such as maximum displacement, base shear, overturning moment, acceleration, and stress distribution directly from structural and wind characteristics. Tahera et al. [180] integrated codal analysis, ETABS simulations, wind tunnel testing, and AI-based models (ANN and LSTM) to evaluate the wind response of a 25-story reinforced concrete building. The wind tunnel results validated the numerical predictions, while the LSTM model outperformed the ANN in predicting storey displacements and drifts. The findings also demonstrated that building orientation significantly affects wind-induced structural response, emphasizing the potential of AI to enhance wind engineering analysis and design.

Beyond structural response prediction, AI has become an effective tool for disaster management and resilience enhancement. Machine learning algorithms have been employed to estimate post-disaster damage, identify vulnerable regions, optimize emergency response strategies, and support rapid recovery planning following hurricanes and tornado outbreaks [181]. Remote sensing imagery combined with deep learning techniques has enabled automated damage detection immediately after extreme wind events. Furthermore, optimization algorithms integrated with machine learning have been utilized to improve aerodynamic building configurations, optimize structural member dimensions, and identify cost-effective design solutions while satisfying structural safety requirements. These capabilities support performance-based design and improve the resilience and sustainability of infrastructure exposed to extreme wind hazards.

Gerolimos et al. [181] proposed an Open World Machine Learning (OWML) framework to enhance decision-making in natural disaster management by integrating machine learning techniques with continuously evolving knowledge. The framework was evaluated across four types of natural disasters, namely earthquakes, floods, wildfires, and hurricanes, demonstrating its capability to process large geospatial datasets and adapt to previously unseen disaster scenarios. The findings indicated that the OWML framework improves predictive accuracy, supports evacuation planning, and enhances disaster response, highlighting its potential as an effective decision-support tool for natural hazard management despite challenges related to data quality and model complexity.

Figure 13 illustrates the general workflow of AI/ML applications in wind engineering. Experimental data, field measurements, and CFD simulations serve as the primary data sources for training AI/ML models, which are subsequently applied to wind field prediction, pressure estimation, structural response prediction, damage assessment, structural optimization, digital twins, and real-time monitoring. This framework highlights the growing role of AI in improving the efficiency and accuracy of wind engineering analyses.

Future research should focus on developing reliable benchmark datasets, integrating physics-based constraints into machine learning models, improving the interpretability of AI predictions, and combining experimental, numerical, and field measurements to establish robust digital twins for structural systems subjected to extreme wind events. Such

developments are expected to improve predictive capability, reduce computational costs, and facilitate real-time structural assessment and resilient infrastructure design.

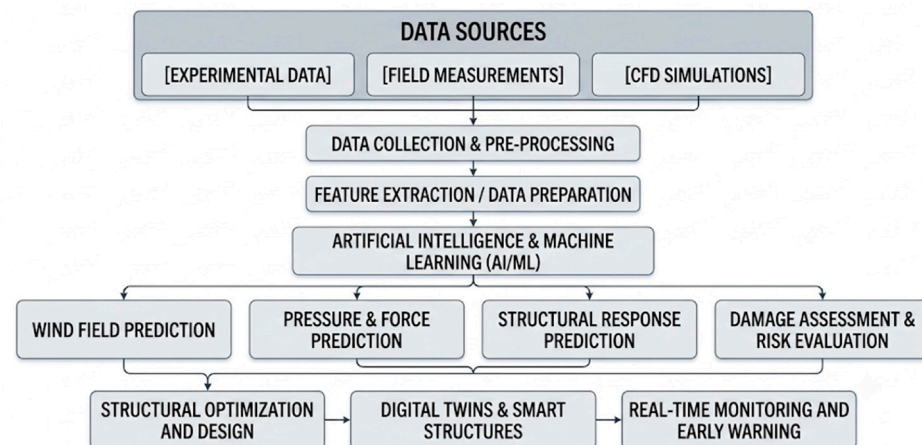


Figure 13. Conceptual Framework of Artificial Intelligence and Machine Learning Applications in Wind Engineering.

9. Conclusions and Recommendations for Future Work

Climate change has increased extreme wind events, causing severe structural and economic losses. Tornadoes, among the most destructive, generate complex wind fields that differ from straight-line winds, making their study crucial for building resilience.

This review provides an in-depth analysis of how extreme wind events, especially tornadoes, impact structural performance, focusing on the critical parameters that govern wind loads and structural resilience. Key findings indicate that tornado flow characteristics, including swirl ratio, translation speed, and ground roughness, significantly influence the intensity and distribution of wind-induced pressures on structures. Additionally, structural properties such as geometry, material, orientation, and proximity to the tornado path were identified as decisive factors in determining structural performance under extreme wind loads.

Wind tunnel and tornado simulator experiments, together with numerical techniques like CFD, have played a key role in enhancing knowledge of wind–structure behavior. These methodologies have enabled researchers to simulate complex wind events and identify key parameters that inform design standards. Recent updates in engineering codes have made significant strides in addressing tornado-specific loads and offering design recommendations for safe rooms and resilient structures. However, there are still gaps in current research that need to be addressed to overcome these challenges and some suggestions to help improve the field of wind engineering.

Future work should emphasize the following:

- **Multi-Parameter Analysis:** Investigating the combined effects of tornadoes' parameters to model their full impact on structures.
- **Focus on Translating Tornadoes:** More studies on translating tornadoes and their unique wind field characteristics will help refine simulation accuracy and building codes.
- **Advanced Material Development:** Exploring lightweight, high-strength materials, such as fiber-reinforced composites, that improve structural performance under extreme wind forces.
- **The orientation and placement of a building relative to the tornado center critically affect the resulting wind loads.**

- Interference effects: The impact of translating tornadoes in dense urban areas, including the shielding and funneling effects caused by surrounding buildings.
- Integrating experimental and numerical simulations to better understand wind events and refine design practices.
- Response of specialized structures to dynamic and wind-induced vibrational loads during extreme wind events.
- AI and Machine Learning Integration: Utilizing data-driven approaches to optimize design parameters, enhance predictive accuracy, and improve real-time disaster response.
- Big Data Applications: Leveraging IoT sensors and big data analytics allows continuous monitoring of wind performance and informs effective mitigation measures.
- Field Monitoring: Capturing real-time structural responses to extreme wind events using Internet of Things (IoT-based sensors), to improve the accuracy of simulation validations.
- Climate Adaptation: Assessing how climate change influences the occurrence and severity of wind events to guide updates to design codes.
- Expand high-fidelity CFD simulations: More studies employing Large Eddy Simulation (LES), Detached Eddy Simulation (DES), and Fluid–Structure Interaction (FSI) are needed to accurately capture the complex transient behavior of tornadoes and hurricanes, particularly in urban environments.
- Strengthen experimental validation: Although CFD has become increasingly powerful, wind tunnel experiments and full-scale field measurements remain essential for validating numerical models and ensuring the reliability of simulation results.
- Develop hybrid experimental–CFD frameworks: Future research should focus on integrating experimental testing with numerical simulations to leverage the accuracy of laboratory measurements and the flexibility of CFD analyses.
- Expand the application of AI and Machine Learning in wind engineering: Although AI and ML have shown promising capabilities in wind field modeling, pressure prediction, and structural response analysis, their application in wind engineering remains relatively limited compared with traditional numerical and experimental approaches.
- Develop standardized benchmark datasets for AI training: The lack of comprehensive, high-quality datasets integrating experimental measurements, field observations, and CFD simulations limits the development, validation, and generalization of AI models.
- Enhance roof-to-wall connection systems: Since roof-to-wall connection failure is one of the primary causes of structural collapse during extreme wind events, further research is required to develop more efficient and resilient connection details, validate their performance experimentally and numerically, and establish practical design recommendations for future wind-resistant construction.

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References

1. Zhao, J.; Yan, G.; Han, D. A review of approaches to simulate windborne debris dynamics in wind fields. *J. Wind Eng. Ind. Aerodyn.* **2021**, *212*, 104597. [CrossRef]
2. Cao, S.; Wang, J.; Cao, J.; Zhao, L.; Chen, X. Experimental study of wind pressures acting on a cooling tower exposed to stationary tornado-like vortices. *J. Wind Eng. Ind. Aerodyn.* **2015**, *145*, 75–86. [CrossRef]
3. Kim, Y.C.; Matsui, M. Analytical and empirical models of tornado vortices: A comparative study. *J. Wind Eng. Ind. Aerodyn.* **2017**, *171*, 230–247. [CrossRef]
4. Thampi, H.; Dayal, V.; Sarkar, P.P. Finite element analysis of interaction of tornados with a low-rise timber building. *J. Wind Eng. Ind. Aerodyn.* **2011**, *99*, 369–377. [CrossRef]
5. Wang, J.; Cao, S.; Pang, W.; Cao, J.; Zhao, L. Wind-load characteristics of a cooling tower exposed to a translating tornado-like vortex. *J. Wind Eng. Ind. Aerodyn.* **2016**, *158*, 26–36. [CrossRef]
6. Yang, Z.; Sarkar, P.; Hu, H. Visualization of flow structures around a gable-roofed building model in tornado-like winds. *J. Vis.* **2010**, *13*, 285–288. [CrossRef]
7. Yang, Z.; Sarkar, P.; Hu, H. An experimental study of a high-rise building model in tornado-like winds. *J. Fluids Struct.* **2011**, *27*, 471–486. [CrossRef]
8. Feng, C.; Chen, X. Characterization of translating tornado-induced pressures and responses of a low-rise building frame based on measurement data. *Eng. Struct.* **2018**, *174*, 495–508. [CrossRef]
9. Kopp, G.A.; Wu, C.H. A framework to compare wind loads on low-rise buildings in tornadoes and atmospheric boundary layers. *J. Wind Eng. Ind. Aerodyn.* **2020**, *204*, 104269. [CrossRef]
10. Sengupta, A.; Haan, F.L.; Sarkar, P.P.; Balaramudu, V. Transient loads on buildings in microburst and tornado winds. *J. Wind Eng. Ind. Aerodyn.* **2008**, *96*, 2173–2187. [CrossRef]
11. Mishra, A.R.; James, D.L.; Letchford, C.W. Physical simulation of a single-celled tornado-like vortex, Part B: Wind loading on a cubical model. *J. Wind Eng. Ind. Aerodyn.* **2008**, *96*, 1258–1273. [CrossRef]
12. Huo, S.; Wang, J.; Haan, F.L.; Kopp, G.A.; Sterling, M. A Study of the Effects of Tornado Translation on Wind Loading Using a Potential Flow Model. *Front. Built Environ.* **2022**, *8*, 840812. [CrossRef]
13. Chen, Q.; Tang, Z.; Wu, X.; Zuo, D.; James, D. Laboratory study of tornado-like loading on a low-rise building model. *J. Wind Eng. Ind. Aerodyn.* **2023**, *238*, 105443. [CrossRef]
14. Razavi, A.; Sarkar, P.P. Laboratory investigation of the effects of translation on the near-ground tornado flow field. *Wind Struct. An. Int. J.* **2018**, *26*, 179–190. [CrossRef]
15. Xu, F.; Ma, J.; Chen, W.L.; Xiao, Y.Q.; Duan, Z.D. Analysis of load characteristics and responses of low-rise building under tornado. *Procedia Eng.* **2017**, *210*, 165–172. [CrossRef]
16. Alexander, C.R.; Wurman, J. The 30 May 1998 Spencer, South Dakota, Storm. Part I: The Structural Evolution and Environment of the Tornadoes. *Mon. Weather Rev.* **2005**, *133*, 72–97. [CrossRef]
17. Wurman, J.; Alexander, C.R. The 30 May 1998 Spencer, South Dakota, Storm. Part II: Comparison of Observed Damage and Radar-Derived Winds in the Tornadoes. *Mon. Weather Rev.* **2005**, *133*, 97–119. [CrossRef]
18. Pandey, S.K.S. An analytical model of two-cell tornadoes with emphasis on sharpness parameter affecting updrafts and a discussion on debris trajectory in outer cell. *J. Wind Eng. Ind. Aerodyn.* **2024**, *253*, 105862. [CrossRef]
19. Lombardo, F.T.; Zaldivar de Alba, A.; Chen, G.; Rhee, D.M.; Nevill, J.B.; Wienhoff, Z.B. An atmospheric vortex and its induced loading on a bluff body. *J. Wind Eng. Ind. Aerodyn.* **2023**, *243*, 105605. [CrossRef]
20. Chang, C.C. Tornado Wind Effects on Buildings and Structures with Laboratory Simulation. 1971. Available online: <https://cir.nii.ac.jp/crid/1574231875526963328> (accessed on 21 November 2024).
21. Ward, N.B. The Exploration of Certain Features of Tornado Dynamics Using a Laboratory Model. *J. Atmos. Sci.* **1972**, *29*, 1194–1204. [CrossRef]
22. American Society of Civil Engineers. *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE/SEI 7-22); American Society of Civil Engineers: Reston, VA, USA, 2022. Available online: <https://ascelibrary.org> (accessed on 18 July 2026).

23. Federal Emergency Management Agency. *FEMA P-320: Taking Shelter from the Storm—Building or Retrofitting a Safe Room for Your Home or Small Business*, 4th ed.; U.S. Department of Homeland Security: Washington, DC, USA, 2021. Available online: <https://www.fema.gov> (accessed on 18 July 2026).
24. Federal Emergency Management Agency. *FEMA P-361: Safe Rooms for Tornadoes and Hurricanes—Guidance for Community and Residential Safe Rooms*, 4th ed.; U.S. Department of Homeland Security: Washington, DC, USA, 2021. Available online: <https://www.fema.gov/emergency-managers/risk-management/building-science/safe-rooms/resources> (accessed on 18 July 2026).
25. Zhang, Y.; Wang, D.; Sun, C.; Fu, X. Probabilistic study on non-stationary extreme response of transmission tower under moving downburst impact. *Structures* **2024**, *68*, 107179. [[CrossRef](#)]
26. Theodore Fujita, T. Downbursts: Meteorological features and wind field characteristics. *J. Wind Eng. Ind. Aerodyn.* **1990**, *36*, 75–86. [[CrossRef](#)]
27. Zhang, S.; Guo, K.; Yang, Q.; Xu, X. Review of Wind Field Characteristics of Downbursts and Wind Effects on Structures under Their Action. *Buildings* **2024**, *14*, 2653. [[CrossRef](#)]
28. Hu, P.; Cheng, W.; Xu, G.; Han, Y.; Yan, N.; Wang, N. Prediction of buffeting responses of the thin plate under joint action of wave and wind using LSTM and transfer learning. *Appl. Ocean Res.* **2023**, *134*, 103514. [[CrossRef](#)]
29. Choi, E.C. Wind characteristics of tropical thunderstorms. *J. Wind Eng. Ind. Aerodyn.* **2000**, *84*, 215–226. [[CrossRef](#)]
30. Choi, E.C.C. Extreme wind characteristics over Singapore—An area in the equatorial belt. *J. Wind Eng. Ind. Aerodyn.* **1999**, *83*, 61–69. [[CrossRef](#)]
31. Holmes, J.D.; Oliver, S.E. An empirical model of a downburst. *Eng. Struct.* **2000**, *22*, 1167–1172. [[CrossRef](#)]
32. Hjelmfelt, M.R. Structure and Life Cycle of Microburst Outflows Observed in Colorado. *J. Appl. Meteorol. Climatol.* **1988**, *27*, 900–927. [[CrossRef](#)] [[PubMed](#)]
33. Li, S.; Catarelli, R.A.; Phillips, B.M.; Bridge, J.A.; Gurley, K.R. Physical simulation of downburst winds for civil structures: A review. *J. Wind Eng. Ind. Aerodyn.* **2024**, *254*, 105900. [[CrossRef](#)]
34. McCarthy, J.; Wilson, J.W.; Fujita, T.T. The Joint Airport Weather Studies Project. *Bull. Am. Meteorol. Soc.* **1982**, *63*, 15–22. [[CrossRef](#)]
35. Iwashita, H.; Kobayashi, F. Transition of meteorological variables while downburst occurrence by a high density ground surface observation network. *J. Wind Eng. Ind. Aerodyn.* **2019**, *184*, 153–161. [[CrossRef](#)]
36. Lombardo, F.T.; Smith, D.A.; Schroeder, J.L.; Mehta, K.C. Thunderstorm characteristics of importance to wind engineering. *J. Wind Eng. Ind. Aerodyn.* **2014**, *125*, 121–132. [[CrossRef](#)]
37. Butler, K.; Cao, S.; Kareem, A.; Tamura, Y.; Ozono, S. Surface pressure and wind load characteristics on prisms immersed in a simulated transient gust front flow field. *J. Wind Eng. Ind. Aerodyn.* **2010**, *98*, 299–316. [[CrossRef](#)]
38. Romanic, D.; LoTufo, J.; Hangan, H. Transient behavior in impinging jets in crossflow with application to downburst flows. *J. Wind Eng. Ind. Aerodyn.* **2019**, *184*, 209–227. [[CrossRef](#)]
39. Aboutabikh, M.; Ghazal, T.; Chen, J.; Elgamal, S.; Aboshosha, H. Designing a blade-system to generate downburst outflows at boundary layer wind tunnel. *J. Wind Eng. Ind. Aerodyn.* **2019**, *186*, 169–191. [[CrossRef](#)]
40. Chay, M.T.; Albermani, F.; Wilson, R. Numerical and analytical simulation of downburst wind loads. *Eng. Struct.* **2006**, *28*, 240–254. [[CrossRef](#)]
41. Orf, L.; Kantor, E.; Savory, E. Simulation of a downburst-producing thunderstorm using a very high-resolution three-dimensional cloud model. *J. Wind Eng. Ind. Aerodyn.* **2012**, *104–106*, 547–557. [[CrossRef](#)]
42. Oreskovic, C.; Orf, L.G.; Savory, E. A parametric study of downbursts using a full-scale cooling source model. *J. Wind Eng. Ind. Aerodyn.* **2018**, *180*, 168–181. [[CrossRef](#)]
43. Haan, F.L.; Sarkar, P.P.; Gallus, W.A. Design, construction and performance of a large tornado simulator for wind engineering applications. *Eng. Struct.* **2008**, *30*, 1146–1159. [[CrossRef](#)]
44. Church, C.; Snow, J.; Baker, G.L.; Agee, E.M. Characteristics of Tornado-Like Vortices as a Function of Swirl Ratio: A Laboratory Investigation. *J. Atmos. Sci.* **1979**, *36*, 1755–1776. [[CrossRef](#)]
45. Natarajan, D.; Hangan, H. Large eddy simulations of translation and surface roughness effects on tornado-like vortices. *J. Wind Eng. Ind. Aerodyn.* **2012**, *104–106*, 577–584. [[CrossRef](#)]
46. Kuai, L.; Haan, F.L.; Gallus, W.A.; Sarkar, P.P. CFD simulations of the flow field of a laboratory-simulated tornado for parameter sensitivity studies and comparison with field measurements. *Wind Struct. An. Int. J.* **2008**, *11*, 75–96. [[CrossRef](#)]
47. Hamada, A.; Damatty, A.A.E.; Hangan, H.; Shehata, A.Y. Finite element modelling of transmission line structures under tornado wind loading. *Wind Struct. An. Int. J.* **2010**, *13*, 451–469. [[CrossRef](#)]
48. AbuGazia, M.; El Damatty, A.A.; Dai, K.; Lu, W.; Ibrahim, A. Numerical model for analysis of wind turbines under tornadoes. *Eng. Struct.* **2020**, *223*, 111157. [[CrossRef](#)]
49. Diamond, C.J.; Wilkins, E.M. Translation Effects on Simulated Tornadoes. *J. Atmos. Sci.* **1984**, *41*, 2574–2580. [[CrossRef](#)]

50. Liu, Z.; Ishihara, T. Study of the effects of translation and roughness on tornado-like vortices by large-eddy simulations. *J. Wind Eng. Ind. Aerodyn.* **2016**, *151*, 1–24. [\[CrossRef\]](#)
51. Liu, Z.; Ishihara, T. A study of tornado induced mean aerodynamic forces on a gable-roofed building by the large eddy simulations. *J. Wind Eng. Ind. Aerodyn.* **2015**, *146*, 39–50. [\[CrossRef\]](#)
52. Razavi, A.; Sarkar, P.P. Tornado-induced wind loads on a low-rise building: Influence of swirl ratio, translation speed and building parameters. *Eng. Struct.* **2018**, *167*, 1–12. [\[CrossRef\]](#)
53. Leslie, F.W. Surface Roughness Effects on Suction Vortex Formation: A Laboratory Simulation. *J. Atmos. Sci.* **1977**, *34*, 1022–1027. [\[CrossRef\]](#)
54. Wang, J.; Cao, S.; Pang, W.; Cao, J. Experimental Study on Effects of Ground Roughness on Flow Characteristics of Tornado-Like Vortices. *Bound.-Layer. Meteorol.* **2017**, *162*, 319–339. [\[CrossRef\]](#)
55. Karstens, C.D. Observations and Laboratory Simulations of Tornadoes in Complex Topographical Regions—ProQuest. 2012. Available online: <https://www.proquest.com/openview/823fe716e3e721a504fbc2d31de019b5/1?pq-origsite=gscholar&cbl=18750> (accessed on 18 July 2026).
56. Lewellen, D.C. Effects of topography on tornado dynamics: A simulation study. In Proceedings of the 26th Conference on Severe Local Storms, Nashville, TN, USA, 5–8 November 2012.
57. Razavi, A.; Sarkar, P.P. Laboratory Study of Topographic Effects on the Near-surface Tornado Flow Field. *Bound.-Layer. Meteorol.* **2018**, *168*, 189–212. [\[CrossRef\]](#)
58. Case, J.; Sarkar, P.; Sritharan, S. Effect of low-rise building geometry on tornado-induced loads. *J. Wind Eng. Ind. Aerodyn.* **2014**, *133*, 124–134. [\[CrossRef\]](#)
59. Jischke, M.C.; Light, B.D. Laboratory simulation of tornadic wind loads on a rectangular model structure. *J. Wind Eng. Ind. Aerodyn.* **1983**, *13*, 371–382. [\[CrossRef\]](#)
60. Hu, H.; Yang, Z.; Sarkar, P.; Haan, F. Characterization of the wind loads and flow fields around a gable-roof building model in tornado-like winds. *Exp. Fluids* **2011**, *51*, 835–851. [\[CrossRef\]](#)
61. Sabareesh, G.R.; Matsui, M.; Tamura, Y. Dependence of surface pressures on a cubic building in tornado like flow on building location and ground roughness. *J. Wind Eng. Ind. Aerodyn.* **2012**, *103*, 50–59. [\[CrossRef\]](#)
62. Haan, F.L., Jr.; Balaramudu, V.K.; Sarkar, P.P. Tornado-Induced Wind Loads on a Low-Rise Building. *J. Struct. Eng.* **2010**, *136*, 106–116. [\[CrossRef\]](#)
63. Fujita, T.T. *Proposed Characterization of Tornadoes and Hurricanes by Area and Intensity*; University of Chicago: Chicago, IL, USA, 1971.
64. McDonald, J.R.; Mehta, K.C.; Smith, D.A.; Arn Womble, J. The Enhanced Fujita Scale: Development and Implementation. In *Forensic Engineering 2009*; American Society of Civil Engineers: Reston, VA, USA, 2012; pp. 719–728. [\[CrossRef\]](#)
65. Frankignoul, C.; Overland, J.E.; Bamston, A.G.; Dow, K.; Lorenz, E.N.; Meleshko, V.P. The Hurricane Disaster—Potential Scale. *Weatherwise* **1974**, *27*, 169–186. [\[CrossRef\]](#)
66. Zhang, J.; Xie, Q. Failure analysis of transmission tower subjected to strong wind load. *J. Constr. Steel Res.* **2019**, *160*, 271–279. [\[CrossRef\]](#)
67. Muñoz, C.P. Hurricane Resistant Curtain Wall System. Master's Thesis, Polytechnic University of Puerto Rico, San Juan, Puerto Rico, 2011. Available online: <https://prcr.cobimet.org/server/api/core/bitstreams/fd766d52-d786-4180-ba6b-e0d2d8153423/content> (accessed on 18 July 2026).
68. Xiao, H.; Huang, W. Failure mechanism and risk analysis of an elevated house damaged during Hurricane Michael by full-scale modeling of wave-surge loads. *Ocean Eng.* **2024**, *300*, 117387. [\[CrossRef\]](#)
69. Robertson, I.N.; Riggs, H.R.; Yim, S.C.; Young, Y.L. Lessons from Hurricane Katrina Storm Surge on Bridges and Buildings. *J. Waterw. Port Coast. Ocean Eng.* **2007**, *133*, 463–483. [\[CrossRef\]](#)
70. Habte, F.; Asghari Mooneghi, M.; Baheru, T.; Zisis, I.; Gan Chowdhury, A.; Masters, F.; Irwin, P. Wind loading on ridge, hip and perimeter roof tiles: A full-scale experimental study. *J. Wind Eng. Ind. Aerodyn.* **2017**, *166*, 90–105. [\[CrossRef\]](#)
71. Ben Ayed, S.; Aponte-Bermudez, L.D.; Hajj, M.R.; Tieleman, H.W.; Gurley, K.R.; Reinhold, T.A. Analysis of hurricane wind loads on low-rise structures. *Eng. Struct.* **2011**, *33*, 3590–3596. [\[CrossRef\]](#)
72. Kumar, N.; Dayal, V.; Sarkar, P.P. Failure of wood-framed low-rise buildings under tornado wind loads. *Eng. Struct.* **2012**, *39*, 79–88. [\[CrossRef\]](#)
73. Ibrahim, A.M.; El Damatty, A.A.; El Ansary, A.M. Finite element modelling of pre-stressed concrete poles under downbursts and tornadoes. *Eng. Struct.* **2017**, *153*, 370–382. [\[CrossRef\]](#)
74. El Damatty, A.A.; Hamada, A. F2 tornado velocity profiles critical for transmission line structures. *Eng. Struct.* **2016**, *106*, 436–449. [\[CrossRef\]](#)
75. Sarkar, P.P.; Haan, F.L.; Balaramudu, V.; Sengupta, A. Laboratory simulation of tornado and microburst to assess wind loads on buildings. In *Structures Congress 2006*; American Society of Civil Engineers: Reston, VA, USA, 2012; pp. 1–10. [\[CrossRef\]](#)

76. Wang, J.; Cao, S. Characteristics of tornado wind loads and examinations of tornado wind load provisions in ASCE 7–16. *Eng. Struct.* **2021**, *241*, 112451. [\[CrossRef\]](#)
77. Bluestein, H.B.; Golden, J.H.; Bluestein, H.B.; Golden, J.H. A review of tornado observations. *Geophys. Monogr. Ser.* **1993**, *79*, 319–352. [\[CrossRef\]](#)
78. Hangan, H.; Kim, J.D. Swirl ratio effects on tornado vortices in relation to the Fujita scale. *Wind Struct.* **2008**, *11*, 291–302. [\[CrossRef\]](#)
79. Davies-Jones, R.P. The Dependence of Core Radius on Swirl Ratio in a Tornado Simulator. *J. Atmos. Sci.* **1973**, *30*, 1427–1430. [\[CrossRef\]](#)
80. Qin, Y.; Cao, J.; Cao, S.; Ge, Y. Numerical simulation of wind loads and aerodynamic characteristics of streamlined bridge decks under tornado-like vortices. *J. Fluids Struct.* **2022**, *113*, 103623. [\[CrossRef\]](#)
81. ANSYS Inc. *ANSYS Release 11.0 Documentation*; ANSYS Inc.: Canonsburg, PA, USA, 2007.
82. Lee, W.C.; Wurman, J. Diagnosed three-dimensional axisymmetric structure of the Mulhall tornado on 3 May 1999. *J. Atmos. Sci.* **2005**, *62*, 2373–2393. [\[CrossRef\]](#)
83. Razavi, A.; Zhang, W.; Sarkar, P.P. Effects of ground roughness on near-surface flow field of a tornado-like vortex. *Exp. Fluids* **2018**, *59*, 170. [\[CrossRef\]](#)
84. Sabareesh, G.R.; Matsui, M.; Tamura, Y. Ground roughness effects on internal pressure characteristics for buildings exposed to tornado-like flow. *J. Wind Eng. Ind. Aerodyn.* **2013**, *122*, 113–117. [\[CrossRef\]](#)
85. Deng, H.Z.; Xu, H.J.; Duan, C.Y.; Jin, X.H.; Wang, Z.H. Experimental and numerical study on the responses of a transmission tower to skew incident winds. *J. Wind Eng. Ind. Aerodyn.* **2016**, *157*, 171–188. [\[CrossRef\]](#)
86. Amirinia, G.; Jung, S. Along-Wind Response of High-Rise Buildings Subjected to Hurricane Boundary Layer Winds. *J. Struct. Eng.* **2017**, *143*, 04017087. [\[CrossRef\]](#)
87. Stathopoulos, T.; Alrawashdeh, H. Wind loads on buildings: A code of practice perspective. *J. Wind Eng. Ind. Aerodyn.* **2020**, *206*, 104338. [\[CrossRef\]](#)
88. Martins, N.E.; Martín-Pérez, B.; Baskaran, A. Application of statistical models to predict roof edge suctions based on wind speed. *J. Wind Eng. Ind. Aerodyn.* **2016**, *150*, 42–53. [\[CrossRef\]](#)
89. Yoo, Y.; Koliou, M.; Yazdani, N. Assessing elevated home slab retrofitting method for residential coastal buildings under hurricane loads. *J. Build. Eng.* **2024**, *86*, 108994. [\[CrossRef\]](#)
90. Razavi, A.; Sarkar, P.P. Effects of roof geometry on tornado-induced structural actions of a low-rise building. *Eng. Struct.* **2021**, *226*, 111367. [\[CrossRef\]](#)
91. Masoomi, H.; van de Lindt, J.W.; Ameri, M.R.; Do, T.Q.; Webb, B.M. Combined Wind-Wave-Surge Hurricane-Induced Damage Prediction for Buildings. *J. Struct. Eng.* **2019**, *145*, 04018227. [\[CrossRef\]](#)
92. Cope, A.D.; Gurley, K.R.; Gioffre, M.; Reinhold, T.A. Low-rise gable roof wind loads: Characterization and stochastic simulation. *J. Wind Eng. Ind. Aerodyn.* **2005**, *93*, 719–738. [\[CrossRef\]](#)
93. Patruno, L.; Ricci, M.; de Miranda, S.; Ubertini, F. An efficient approach to the determination of Equivalent Static Wind Loads. *J. Fluids Struct.* **2017**, *68*, 1–14. [\[CrossRef\]](#)
94. Aly, A.M.; Bresowar, J. Aerodynamic mitigation of wind-induced uplift forces on low-rise buildings: A comparative study. *J. Build. Eng.* **2016**, *5*, 267–276. [\[CrossRef\]](#)
95. Asghari Mooneghi, M.; Irwin, P.; Gan Chowdhury, A. Large-scale testing on wind uplift of roof pavers. *J. Wind Eng. Ind. Aerodyn.* **2014**, *128*, 22–36. [\[CrossRef\]](#)
96. Chen, B.; Cheng, H.; Kong, H.; Chen, X.; Yang, Q. Interference effects on wind loads of gable-roof buildings with different roof slopes. *J. Wind Eng. Ind. Aerodyn.* **2019**, *189*, 198–217. [\[CrossRef\]](#)
97. Alinejad, H.; Kang, T.H.-K. Engineering Review of ASCE 7-16 Wind-Load Provisions and Wind Effect on Tall Concrete-Frame Buildings. *J. Struct. Eng.* **2020**, *146*, 04020100. [\[CrossRef\]](#)
98. He, W.X.; Hong, H.P. Probabilistic characterization of roof panel uplift capacity under wind loading. *Can. J. Civ. Eng.* **2012**, *39*, 1285–1296. [\[CrossRef\]](#)
99. Abdelhady, A.U.; Spence, S.M.J.; McCormick, J. Risk and fragility assessment of residential wooden buildings subject to hurricane winds. *Struct. Saf.* **2022**, *94*, 102137. [\[CrossRef\]](#)
100. Enajar, A.; El Damatty, A.; Nassef, A. Semi-analytical solution for gable roofs under uplift wind loads. *Eng. Struct.* **2021**, *227*, 111420. [\[CrossRef\]](#)
101. Stathopoulos, T. Wind loads on low-rise buildings: A review of the state of the art. *Eng. Struct.* **1984**, *6*, 119–135. [\[CrossRef\]](#)
102. Krishna, P. Wind loads on low rise buildings—A review. *J. Wind Eng. Ind. Aerodyn.* **1995**, *54–55*, 383–396. [\[CrossRef\]](#)
103. Holmes, J.D.; Sankaran, R.; Kwok, K.C.S.; Syme, M.J. Eigenvector modes of fluctuating pressures on low-rise building models. *J. Wind Eng. Ind. Aerodyn.* **1997**, *69–71*, 697–707. [\[CrossRef\]](#)
104. Stathopoulos, T. Wind loads on low buildings: In the wake of Alan Davenport’s contributions. *J. Wind Eng. Ind. Aerodyn.* **2003**, *91*, 1565–1585. [\[CrossRef\]](#)

105. Kasperski, M. Design wind loads for low-rise buildings: A critical review of wind load specifications for industrial buildings. *J. Wind Eng. Ind. Aerodyn.* **1996**, *61*, 169–179. [\[CrossRef\]](#)
106. Stathopoulos, T.; Suresh Kumar, K.; Mohammadian, A.R. Design wind pressure coefficients for monoslope roofs: A time series approach. *J. Wind Eng. Ind. Aerodyn.* **1996**, *65*, 143–153. [\[CrossRef\]](#)
107. Gavanski, E.; Uematsu, Y. Local wind pressures acting on walls of low-rise buildings and comparisons to the Japanese and US wind loading provisions. *J. Wind Eng. Ind. Aerodyn.* **2014**, *132*, 77–91. [\[CrossRef\]](#)
108. Roueche, D.B.; Prevatt, D.O.; Haan, F.L. Tornado-Induced and Straight-Line Wind Loads on a Low-Rise Building With Consideration of Internal Pressure. *Front. Built Environ.* **2020**, *6*, 18. [\[CrossRef\]](#)
109. Yu, X.F.; Xie, Z.N.; Zhu, J.B.; Gu, M. Interference effects on wind pressure distribution between two high-rise buildings. *J. Wind Eng. Ind. Aerodyn.* **2015**, *142*, 188–197. [\[CrossRef\]](#)
110. Fu, X.; Li, H.N. Uncertainty analysis of the strength capacity and failure path for a transmission tower under a wind load. *J. Wind Eng. Ind. Aerodyn.* **2018**, *173*, 147–155. [\[CrossRef\]](#)
111. Liang, S.; Zou, L.; Wang, D.; Cao, H. Investigation on wind tunnel tests of a full aeroelastic model of electrical transmission tower-line system. *Eng. Struct.* **2015**, *85*, 63–72. [\[CrossRef\]](#)
112. Li, Y.; Li, Z.; Yan, B.; Yan, Z. Wind forces on circular steel tubular lattice structures with inclined leg members. *Eng. Struct.* **2017**, *153*, 254–263. [\[CrossRef\]](#)
113. Fernández Lorenzo, I.; Clavelo Elena, B.; Martín Rodríguez, P.; Elena Parnás, V.B. Dynamic analysis of self-supported tower under hurricane wind conditions. *J. Wind Eng. Ind. Aerodyn.* **2020**, *197*, 104078. [\[CrossRef\]](#)
114. Yang, F.; Dang, H.; Niu, H.; Zhang, H.; Zhu, B. Wind tunnel tests on wind loads acting on an angled steel triangular transmission tower. *J. Wind Eng. Ind. Aerodyn.* **2016**, *156*, 93–103. [\[CrossRef\]](#)
115. Liu, Z.; Zhang, C.; Ishihara, T. Numerical study of the wind loads on a cooling tower by a stationary tornado-like vortex through LES. *J. Fluids Struct.* **2018**, *81*, 656–672. [\[CrossRef\]](#)
116. Uematsu, Y.; Yasunaga, J.; Koo, C. Design wind loads for open-topped storage tanks in various arrangements. *J. Wind Eng. Ind. Aerodyn.* **2015**, *138*, 77–86. [\[CrossRef\]](#)
117. Chen, Z.; Li, H.; Wang, X.; Yu, X.; Xie, Z. Internal and external pressure and its non-Gaussian characteristics of long-span thin-walled domes. *Thin-Walled Struct.* **2019**, *134*, 428–441. [\[CrossRef\]](#)
118. Karaca, Z.; Türkeli, E. Determination and comparison of wind loads for industrial reinforced concrete chimneys. *Struct. Des. Tall Spec. Build.* **2012**, *21*, 133–154. [\[CrossRef\]](#)
119. Hu, W.; Bohra, H.; Azzuni, E.; Guzey, S. The uplift effect of bottom plate of aboveground storage tanks subjected to wind loading. *Thin-Walled Struct.* **2019**, *144*, 106241. [\[CrossRef\]](#)
120. Sayyafi, E.A.; Chowdhury, A.G.; Mirmiran, A. Innovative Hurricane-Resistant UHPC Roof System. *J. Archit. Eng.* **2018**, *24*, 04017032. [\[CrossRef\]](#)
121. Wang, J.; Cao, S.; Pang, W.; Cao, J. Experimental Study on Tornado-Induced Wind Pressures on a Cubic Building with Openings. *J. Struct. Eng.* **2018**, *144*, 04017206. [\[CrossRef\]](#)
122. Hangan, H.; Refan, M.; Jubayer, C.; Romanic, D.; Parvu, D.; LoTufo, J.; Costache, A. Novel techniques in wind engineering. *J. Wind Eng. Ind. Aerodyn.* **2017**, *171*, 12–33. [\[CrossRef\]](#)
123. Solari, G. Thunderstorm Monitoring, Modelling, Response and Loading of Structures. *Wind Eng. JAWE* **2014**, *39*, 344–346. [\[CrossRef\]](#)
124. Solari, G.; Repetto, M.P.; Burlando, M.; De Gaetano, P.; Pizzo, M.; Tizzi, M.; Parodi, M. The wind forecast for safety management of port areas. *J. Wind Eng. Ind. Aerodyn.* **2012**, *104–106*, 266–277. [\[CrossRef\]](#)
125. Repetto, M.P.; Burlando, M.; Solari, G.; De Gaetano, P.; Pizzo, M.; Tizzi, M. A web-based GIS platform for the safe management and risk assessment of complex structural and infrastructural systems exposed to wind. *Adv. Eng. Softw.* **2018**, *117*, 29–45. [\[CrossRef\]](#)
126. Bechmann, A.; Sørensen, N.N.; Berg, J.; Mann, J.; Réthoré, P.E. The Bolund Experiment, Part II: Blind Comparison of Microscale Flow Models. *Bound.-Layer. Meteorol.* **2011**, *141*, 245–271. [\[CrossRef\]](#)
127. Berg, J.; Mann, J.; Bechmann, A.; Courtney, M.S.; Jørgensen, H.E. The Bolund Experiment, Part I: Flow Over a Steep, Three-Dimensional Hill. *Bound.-Layer. Meteorol.* **2011**, *141*, 219–243. [\[CrossRef\]](#)
128. Mann, J.; Angelou, N.; Sjöholm, M.; Mikkelsen, T.; Hansen, K.H.; Cavar, D.; Berg, J. Laser scanning of a recirculation zone on the Bolund escarpment. *J. Phys. Conf. Ser.* **2014**, *555*, 012066. [\[CrossRef\]](#)
129. Gunter, W.S.; Schroeder, J.L. High-resolution full-scale measurements of thunderstorm outflow winds. *J. Wind Eng. Ind. Aerodyn.* **2015**, *138*, 13–26. [\[CrossRef\]](#)
130. Pistotnik, G.; Holzer, A.M.; Kaltenböck, R.; Tschannett, S. An F3 downburst in Austria—A case study with special focus on the importance of real-time site surveys. *Atmos. Res.* **2011**, *100*, 565–579. [\[CrossRef\]](#)

131. Järvi, L.; Punkka, A.-J.; Schultz, D.M.; Petäjä, T.; Hohti, H.; Rinne, J.; Pohja, T.; Kulmala, M.; Pertti, H.; Vesala, T. Micrometeorological observations of a microburst in southern Finland. In *Atmospheric Boundary Layers: Nature, Theory, and Application to Environmental Modelling and Security*; Springer: New York, NY, USA, 2007; pp. 187–203. [\[CrossRef\]](#)
132. Wurman, J. The Multiple-Vortex Structure of a Tornado. *Weather Forecast.* **2002**, *17*, 473–505. [\[CrossRef\]](#)
133. Bluestein, H.B.; French, M.M.; Popstefanija, I.; Bluth, R.T.; Knorr, J.B. A Mobile, Phased-Array Doppler Radar for The Study of Severe Convective Storms: THE MWR-05XP. *Bull. Am. Meteorol. Soc.* **2010**, *91*, 579–600. [\[CrossRef\]](#)
134. Wurman, J.; Gill, S. Finescale Radar Observations of the Dimmitt, Texas (2 June 1995), Tornado. *Mon. Weather Rev.* **2000**, *128*, 2135–2164. [\[CrossRef\]](#)
135. Zhang, T.; Miller, S.A.E. Toward prediction of tornado noise within the turbulent atmosphere using theory, wind tunnel measurements, and field-tests. In *AIAA Scitech 2020 Forum*; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2020; Volume 1, pp. 1–22. [\[CrossRef\]](#)
136. Tiwari, N.D.; Sarkar, P.P. Prediction of dynamic loads and responses of a tall building in tornado wind: Numerical analysis and experimental validation. *Eng. Struct.* **2025**, *326*, 119510. [\[CrossRef\]](#)
137. Asghari Mooneghi, M.; Irwin, P.; Gan Chowdhury, A. Partial turbulence simulation method for predicting peak wind loads on small structures and building appurtenances. *J. Wind Eng. Ind. Aerodyn.* **2016**, *157*, 47–62. [\[CrossRef\]](#)
138. Matsui, M.; Tamura, Y. Influence of incident flow conditions on generation of tornado-like flow. In Proceedings of the 11th American Conference on Wind Engineering, San Juan, PR, USA, 22–26 June 2009.
139. Tang, Z.; Feng, C.; Wu, L.; Zuo, D.; James, D.L. Characteristics of Tornado-Like Vortices Simulated in a Large-Scale Ward-Type Simulator. *Bound.-Layer. Meteorol.* **2018**, *166*, 327–350. [\[CrossRef\]](#)
140. Chowdhury, A.G.; Zisis, I.; Irwin, P.; Bitsuamlak, G.; Pinelli, J.-P.; Hajra, B.; Moravej, M. Large-Scale Experimentation Using the 12-Fan Wall of Wind to Assess and Mitigate Hurricane Wind and Rain Impacts on Buildings and Infrastructure Systems. *J. Struct. Eng.* **2017**, *143*, 04017053. [\[CrossRef\]](#)
141. Morrison, M.J.; Brown, T.M.; Liu, Z. Comparison of Field and Full-Scale Laboratory Peak Pressures at the IBHS Research Center. In *Advances in Hurricane Engineering: Learning from Our Past*; American Society of Civil Engineers: Reston, VA, USA, 2013; pp. 1109–1124. [\[CrossRef\]](#)
142. Refan, M.; Hangan, H.; Wurman, J. Reproducing tornadoes in laboratory using proper scaling. *J. Wind Eng. Ind. Aerodyn.* **2014**, *135*, 136–148. [\[CrossRef\]](#)
143. Savory, E.; Parke, G.A.R.; Zeinoddini, M.; Toy, N.; Disney, P. Modelling of tornado and microburst-induced wind loading and failure of a lattice transmission tower. *Eng. Struct.* **2001**, *23*, 365–375. [\[CrossRef\]](#)
144. Gukendran, R.; Sambathkumar, M.; Sabari, C.; Raj, C.R.R.; Kumar, V.R. Structural analysis of composite wind turbine blade using ANSYS. *Mater. Today Proc.* **2022**, *50*, 1011–1016. [\[CrossRef\]](#)
145. Dassault Systèmes. *Abaqus*, Version 7.84; Simulia: Providence, RI, USA, 2021.
146. Yu, D.; Ye, J.; Yin, C. Dynamics of offshore wind turbine and its seabed foundation under combined wind-wave loading. *Ocean Eng.* **2023**, *286*, 115624. [\[CrossRef\]](#)
147. Computers and Structures, Inc. (CSI). *SAP2000*, Version 25.78; Computers and Structures, Inc. (CSI): Walnut Creek, CA, USA, 2021.
148. Computers and Structures, Inc. (CSI). *ETABS*; Computers and Structures, Inc. (CSI): Walnut Creek, CA, USA, 2021.
149. Ansys Inc. *FLUENT*, Version 19.2; Ansys Inc.: Canonsburg, PA, USA, 2019.
150. Lanzafame, R.; Mauro, S.; Messina, M. Wind turbine CFD modeling using a correlation-based transitional model. *Renew. Energy* **2013**, *52*, 31–39. [\[CrossRef\]](#)
151. National Renewable Energy Laboratory (NREL). *FAST Software*; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2021.
152. OpenCFD Ltd. *OpenFOAM*, Version 7; OpenCFD Ltd.: Bracknell, UK, 2020.
153. Cao, S.; Wang, M.; Cao, J. Numerical study of wind pressure on low-rise buildings induced by tornado-like flows. *J. Wind Eng. Ind. Aerodyn.* **2018**, *183*, 214–222. [\[CrossRef\]](#)
154. Blumhoefer, H.; Sharma, A. Numerical simulation of tornado-like vortices: Swirl ratio optimization. In *AIAA Aviation Forum and ASCEND*; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2025. [\[CrossRef\]](#)
155. Cai, Y.; Li, X.; Zhao, H.; Shi, W.; Wang, Z. Developing a multi-region coupled analysis method for floating offshore wind turbine based on OpenFOAM. *Renew. Energy* **2025**, *238*, 122026. [\[CrossRef\]](#)
156. EN 1991-1-4; Eurocode 1: Actions on structures—Part 1–4: General actions—Wind actions. European Committee for Standardization (CEN): Brussels, Belgium, 2005.
157. National Research Council of Canada. *National Building Code of Canada (NBCC)*; NRC: Ottawa, ON, Canada, 2020.
158. International Code Council. *International Building Code (IBC)*; ICC: Washington, DC, USA, 2021.
159. Standohar-Alfano, C.D.; van de Lindt, J.W.; Ellingwood, B.R. Vertical Load Path Failure Risk Analysis of Residential Wood-Frame Construction in Tornadoes. *J. Struct. Eng.* **2017**, *143*, 04017045. [\[CrossRef\]](#)

160. Salama, A.; Farag, A.A.; Eraky, A.; Samir, R. Optimal configuration of tapered steel gable frames based on total installed costs using the Enhanced Crystal Structure Algorithm. *Structures* **2023**, *53*, 797–805. [[CrossRef](#)]
161. Florida Department of Business and Professional Regulation. *Florida Building Code (FBC)*; Florida Department of Business and Professional Regulation: Tallahassee, FL, USA, 2020.
162. *GB 50009-2012*; Load Code for the Design of Building Structures. China Architecture & Building Press: Beijing, China, 2012.
163. *BS 6399-2*; Code of Practice for Wind Loads. British Standards Institution (BSI): London, UK, 1997.
164. *ASCE 74-2014*; Guidelines for Electrical Transmission Line Structural Loading. American Society of Civil Engineers: Reston, VA, USA, 2014.
165. *AS/NZS 1170.2:2011*; Structural Design Actions—Wind Actions. Standards Australia: Sydney, Australia; Standards New Zealand: Wellington, New Zealand, 2011.
166. Ummah, M.S. Subjective Health Perception and Health-Related Indicators among Community-Dwelling Older Adults. *Sustainability* **2019**, *11*, 1–14. (In Japanese)
167. Baker, C.J.; Sterling, M. Modelling wind fields and debris flight in tornadoes. *J. Wind Eng. Ind. Aerodyn.* **2017**, *168*, 312–321. [[CrossRef](#)]
168. Roueche, D.B.; Prevatt, D.O.; Haan, F.L.; Datin, P.L. An estimate of tornado loads on a wood-frame building using database-assisted design methodology. *J. Wind Eng. Ind. Aerodyn.* **2015**, *138*, 27–35. [[CrossRef](#)]
169. Vickery, P.J.; Wadhera, D.; Powell, M.D.; Chen, Y. A Hurricane Boundary Layer and Wind Field Model for Use in Engineering Applications. *J. Appl. Meteorol. Climatol.* **2009**, *48*, 381–405. [[CrossRef](#)]
170. Sealy, K.S.; Strobl, E. A hurricane loss risk assessment of coastal properties in the caribbean: Evidence from the Bahamas. *Ocean Coast. Manag.* **2017**, *149*, 42–51. [[CrossRef](#)]
171. Jain, A. Hurricane Wind-Generated Debris Impact Damage to the Glazing of a High-Rise Building. In *Forensic Engineering 2015*; American Society of Civil Engineers: Reston, VA, USA, 2015; pp. 361–370. [[CrossRef](#)]
172. García Márquez, F.P.; Peinado Gonzalo, A. A Comprehensive Review of Artificial Intelligence and Wind Energy. *Arch. Comput. Methods Eng.* **2022**, *29*, 2935–2958. [[CrossRef](#)]
173. Dörterler, S.; Arslan, S.; Özdemir, D. Unlocking the potential: A review of artificial intelligence applications in wind energy. *Expert Syst.* **2024**, *41*, e13716. [[CrossRef](#)]
174. Farrar, N.O.; Ali, M.H.; Dasgupta, D. Artificial Intelligence and Machine Learning in Grid Connected Wind Turbine Control Systems: A Comprehensive Review. *Energies* **2023**, *16*, 1530. [[CrossRef](#)]
175. Gao, H.; Hu, G.; Zhang, D.; Jiang, W.; Ren, H.; Chen, W. Prediction of wind fields in mountains at multiple elevations using deep learning models. *Appl. Energy* **2024**, *353*, 122099. [[CrossRef](#)]
176. Loridan, T.; Crompton, R.P.; Dubossarsky, E. A Machine Learning Approach to Modeling Tropical Cyclone Wind Field Uncertainty. *Mon. Weather Rev.* **2017**, *145*, 3203–3221. [[CrossRef](#)]
177. Su, C.; Sahoo, B.; Mao, M.; Xia, M. Machine Learning Techniques for Predicting Typhoon-Induced Storm Surge Using a Hybrid Wind Field. *J. Geophys. Res. Mach. Learn. Comput.* **2025**, *2*, e2024JH000507. [[CrossRef](#)]
178. Wei, M.; Fang, G.; Nikitas, N.; Ge, Y. Machine-learning-based tropical cyclone wind field model incorporating multiple meteorological parameters. *J. Wind Eng. Ind. Aerodyn.* **2024**, *255*, 105936. [[CrossRef](#)]
179. Afshar, A.; Nouri, G.; Ghazvineh, S.; Lavassani, S.H.H. Machine-Learning Applications in Structural Response Prediction: A Review. *Pract. Period. Struct. Des. Constr.* **2024**, *29*, 03124002. [[CrossRef](#)]
180. Tahera; Galagali, S.; Topalakatti, P.M.; Rahul, R.M.; Suma, V.; Chandra, S.S. Wind response of rectangular high-rise buildings: An integrated analytical, experimental, and machine learning study. *Asian J. Civ. Eng.* **2026**, *27*, 1889–1915. [[CrossRef](#)]
181. Gerolimos, N.; Alevizos, V.; Edralin, S.; Xu, C.; Priniotakis, G.; Papakostas, G.A.; Yue, Z. Autonomous Decision-Making Enhancing Natural Disaster Management through Open World Machine Learning: A Systematic Review. *Hum.-Centric Intell. Syst.* **2025**, *5*, 269–284. [[CrossRef](#)]

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