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State-of-the-art review on reducing residential buildings' risk to tornado hazards

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Tornadoes represent one of the most formidable natural hazards in the United States. Despite their frequent occurrence, they have received limited yet growing attention in engineering research and practice. Recent updates to the American Society of Civil Engineers/Structural Engineering Institute (ASCE/SEI 7-22) standards, incorporated into the 2024 International Building Code, mandate that Risk Category III and IV buildings in tornado-prone areas be designed to withstand tornado loads for the first time. Annually, over 1250 tornadoes are reported in the U.S., and post-disaster evaluations consistently reveal that residential buildings, including single-family, multi-family, and manufactured homes, account for two-thirds of the structural damage caused by tornadoes and most tornado-related deaths. However, these homes are not currently covered under the new provisions, leaving them vulnerable. This study reviews the research on mitigating tornado risk to residential buildings from a structural engineering perspective, including coverage on tornado formation, impact analysis and proposed mitigation strategies examined through numerical, experimental, and post-tornado field studies. Finally, the review covers community-level analyses and tornado resilience modeling using fragility methodology that supports risk-informed decision-making. Key findings reveal that current building codes and standards inadequately address tornado-specific loads, particularly for risk category II wood-frame structures. Additionally, this review highlights the need for improved fragility models that account for the unique characteristics of tornado forces, as well as enhanced mitigation strategies such as roof-to-wall connections and debris-resistant designs. These findings underscore the urgency of adopting tornado-resilient provisions in building codes and standards to reduce damage and fatalities in tornado-prone regions.

KEYWORDS

tornado hazards, mitigation strategies, residential buildings, structural engineering, fragility methodology

1 Introduction

Tornadoes are a rapidly rotating column of air capable of producing windspeeds up to 135 m/s (300 mph). Tornado frequency and impacts in the United States have shown significant spatial and temporal variability (Gensini and Brooks, 2018). Despite the United States experiencing the highest number of tornadoes in the world (Guo et al., 2016) and the devastating impacts these events have on the built environment, particularly wood-frame residential buildings, which comprise about 90% of the US building stock (Ellingwood et al., 2004), tornado load provisions for residential buildings (risk category II) are not yet considered in building design and construction codes and standards. This oversight is significant given the average of 77 fatalities and billions of dollars in economic losses incurred annually from tornadoes (Roueche et al., 2024). About two-thirds of tornado-induced damage is attributed to residential buildings (Simmons et al., 2020), making it imperative to mitigate the risk to tornado hazards. With future predictions indicating a growth in tornado exposure, risk, and the potential for disasters (Strader et al., 2017), it is crucial to integrate tornado-specific provisions into building codes and standards to enhance the resilience of residential structures.

Tornadoes have been recorded in all 50 states, but they predominantly occur between the Rocky and Appalachian Mountains, especially in the zones identified as Tornado Alley and Dixie Alley (Kneifel et al., 2022; Standohar-Alfano and Van De Lindt, 2016). Figure 1 shows all the documented tornado tracks in the U. S. between 1950 and 2023 per data collected by the National Oceanic and Atmospheric Administration (NOAA) (SPC, 2024b). As illustrated in Figure 1, the Midwest and southeastern regions incur the highest frequency of tornadoes. According to data from NOAA's Storm Prediction Center (SPC), Texas experiences the most tornadoes of any other U.S., averaging approximately 140 tornadoes annually. Of note, the fatality rate is not directly proportional to the number of tornadoes. For example, Alabama averages around 55 tornadoes annually, ranking fifth in the country (SPC, 2024a), yet it experiences 14 tornado-related fatalities per year, the highest in the U.S. and nearly double that of Missouri, which has the second-highest tornado occurrence rate with eight fatalities annually (Chinchar, 2024). Tornadoes can occur at any time of day, with nighttime tornadoes having a 2.5 times higher fatality rate compared to daytime tornadoes (Ashley et al., 2008). Tornadoes are most common in the late afternoon and during the spring. A study by Sutter and Simmons (2010) concluded that fatality rate is 15% during the spring compared to other times of the year.

Based on the data from SPC, approximately 1,250 tornadoes hit the United States per year. The likelihood of a tornado striking any specific location in the United States each year is relatively low. Elsner et al. (2014) found that the distribution of tornado frequency follows a power-law relationship with a per tornado-day probability of 0.014%. In another study by (Standohar-Alfano and Van De Lindt, 2016), tornado-prone regions were found to have annual probability of 10^{-4} to 10^{-6}. According to ASCE/SEI 7–22 (2022), tornado hazard maps were developed based on annual exceedance probability of 10^{-4} to 10^{-7}. The relatively low probability could be why limited attention has been given to incorporate tornado load provisions for risk category II residential buildings.

Over the past two decades, numerous studies (Amini and Van De Lindt, 2014; Masoomi et al., 2018; Memari et al., 2018; Prevatt et al., 2012b; Standohar-Alfano and Van De Lindt, 2016) have investigated structural and ancillary mitigation strategies for reducing tornado risk to residential buildings. Structural mitigation strategies have primarily focused on enhancing critical load path connections such as roof sheathing, roof-to-wall, and wall-to-foundation connections. For instance, the use of hurricane clips instead of toenails for roof-to-wall connections, and anchor bolts and washers instead of concrete nails for wall-to-foundation connections, have been shown to improve the resilience of these connections and the overall structure to tornadoes (Roueche et al., 2024). Ancillary mitigation strategies, such as tornado shelters, safe rooms, impact-resistant windows, and shutters, have also been effective in saving lives and reducing population dislocation. Life-safety protection can best be offered by a residential shelter. Standohar-Alfano et al. (2015) highlights the effectiveness of tornado shelters and safe rooms in protecting occupants during the May 2013 EF-5 tornado in Oklahoma.

Research on tornado shelters and safe rooms has focused on various aspects, including design, materials, and performance. (Falk et al., 2024; Blahnik et al., 2014). explored the use of commodity wood products and plywood/steel-plate composites in safe room construction, with (Falk and Bridwell, 2018) reporting successful impact and wind pressure testing. Because tornadoes produce windborne debris, the impact resistance of shutters is crucial. Strong impact resistance reduces internal pressure generated by large openings resulting from shutter system failures, which in turn prevents the failure of roof and wall elements. These systems not only protect windows and doors but also safeguard residents and their properties (FEMA, 2023).

This paper reviews residential buildings' risk to tornado hazards from a structural engineering perspective. This study provides insights on impacts of tornadoes on residential buildings, by highlighting and comparing the performance of residential buildings observed from tornado reconnaissance studies, reported fatalities from residential buildings, and performance of shelters and safe rooms during tornadoes. Furthermore, insights are provided on building code coverage and adoption for tornado loads and how mitigation strategies adopted to reduce tornado risk have evolved with improved understanding of tornado occurrences. Finally, this study discusses how building fragility methodology is integrated with community-level analyses and resilience modeling to understand the impacts of tornadoes at neighborhood and community scales. This integration enables the development of targeted mitigation strategies and resilience planning to inform improvements in building safety, rapid recovery, and ensuring long-term sustainability. The review closes with recommendations for future research and policy needs to further reduce tornado risk.

2 Tornado hazards and their impact on residential buildings

Tornadoes typically extend from severe thunderstorms down to the ground, marked by a visible condensation funnel. In the United States, low-pressure systems pull warm, moist air from the Gulf of Mexico and cool, dry air from the Rocky Mountains or the southwestern High Desert. The collision of these contrasting air masses in the central states creates the perfect conditions for severe weather, including the formation of tornadoes (Chinchar, 2024). Tornadoes are characterized by extreme winds, windborne debris, uncertainties, atmospheric pressure change, and sometimes flash flooding. Uncertainties related to tornado include variation in path length intensity, path width intensity, path width variation, number of vortexes, velocity profile and swirl ratio (ASCE/SEI 7, 2022). The intensity of a tornado is determined based on wind speed estimates derived from the observed damage in its aftermath. The current classification of tornado damage is defined using the

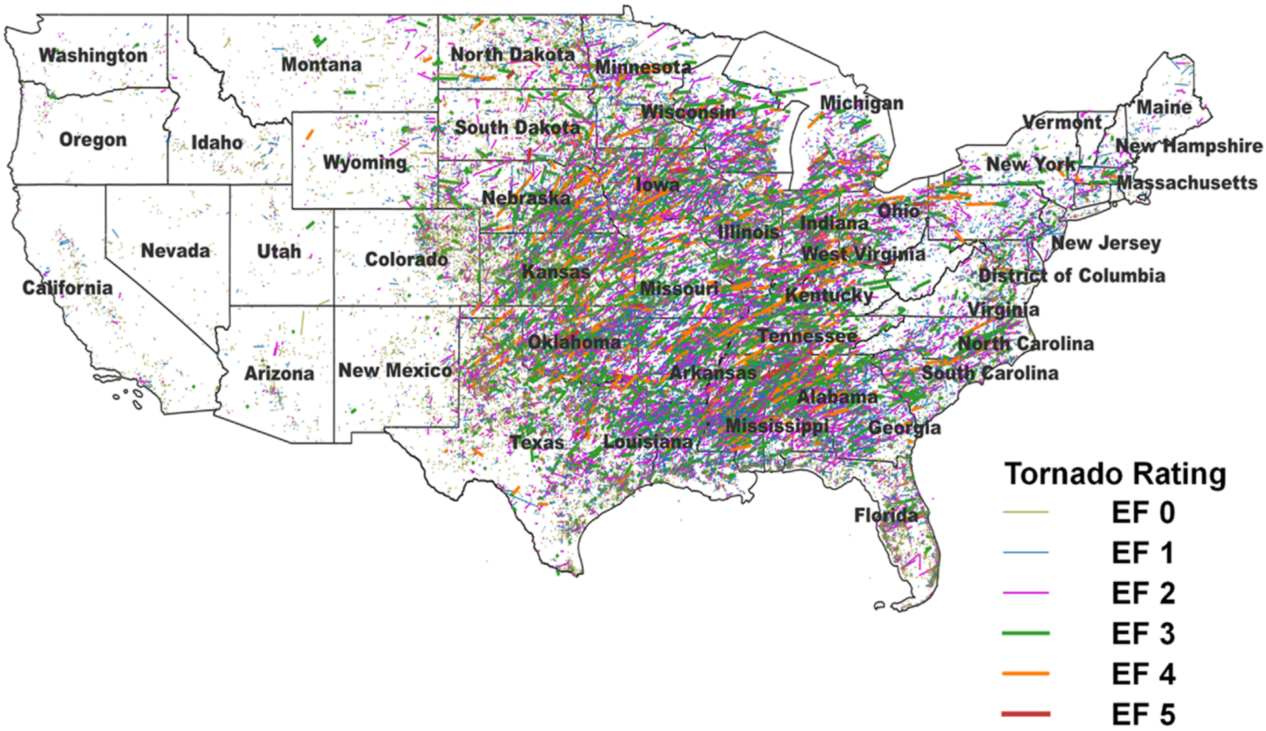

FIGURE 1
U.S. tornado tracks between 1950 and 2023 (data from NOAA's SPC).

Enhanced Fujita (EF) Scale, which was developed and implemented in 2006 by Texas Tech University (McDonald and Mehta, 2006). This scale is an improved version of the original Fujita Scale (F-Scale) created by Fujita (1972). The National Weather Service (NWS) exclusively provides official EF scale ratings, which aim to classify tornadoes based on the maximum wind speed within the damage path. The EF scale ranges from EF-0 (weakest) to EF-5 (strongest). To rate the intensity of tornadoes, NWS personnel use Damage Indicators (DI), which consist of 28 different categories ranging from buildings and structures to trees. For each DI, a Degree of Damage (DOD) is assigned. The NWS personnel can estimate the wind speed causing the damage by comparing it to the expected wind speed values associated with each observed degree of damage. The Degrees of Damage (DOD) for One- and Two-Family Residences are shown in Table 1.

2.1 Formation of tornado loads on low-rise buildings

Understanding the formation of tornado-induced wind loads on buildings is complex. Most wind speed measurements have been obtained using Doppler radars (Wurman and Alexander, 2005). Doppler radar data are widely used to study the formation and large-scale behavior of tornadoes, their resolution is insufficient for examining the turbulence within tornadoes or the wind loads imposed on structures. Additionally, because radars must be positioned far from tornadoes, they can only measure wind speeds at altitudes higher than many structures, particularly low-rise buildings (Tang et al., 2018). According to Roueche et al. (2020), the pressures exerted by tornadoes on a building are primarily composed of three elements as illustrated in Figure 2: the aerodynamic forces on the building's exterior surfaces resulting from the interaction with the airflow, and the internal pressures acting on the building's interior surfaces, and the reduction in atmospheric pressure caused by the conservation of angular momentum within the vortex. Together, these elements create a complex loading condition which differ significantly from the uniform pressures associated with straight-line winds.

Tornado-induced structural actions differ significantly from those caused by straight-line winds in both intensity and distribution. Straight-line winds exert pressure in a single, consistent direction, as illustrated in Figure 2A. In contrast, the rotating wind patterns of a tornado apply pressure from multiple directions, significantly increasing the likelihood of structural failure. Additionally, the low-pressure core of a tornado vortex can cause a rapid change in internal pressure when openings in walls or roofs are present, amplifying the effects of suction forces and internal pressures more dramatically than in straight-line winds (Wang et al., 2020). These combined effects make tornado-induced actions far more destructive and unpredictable. Tornado winds are based on non-stationary wind and should not be modeled based on stationary and straight-line wind (Peng et al., 2016); however, research on modeling non-stationary winds is limited. Several studies including experimental and numerical have simulated tornado-like loading on structures, including low-rise buildings (e.g., Chen et al., 2023; Haan, 2017; Haan et al., 2010; Mishra et al.,

TABLE 1 DOD for one to two-family (FR12) residential home.

DOD	Damage description	Lower bound m/s (mph)	Expected m/s (mph)	Upper bound m/s (mph)
1	Threshold of visible damage	24 (53)	29 (65)	36 (80)
2	loss of roof covering material (<20%), gutters and/or awning; loss of vinyl or metal siding	28 (63)	35 (79)	43 (97)
3	Broken glass in doors and windows	35 (79)	43 (96)	51 (114)
4	Uplift of roof deck and loss of significant roof covering material (>20%); collapse of chimney; garage doors collapse inward or outward; failure of porch or carport	36 (81)	43 (97)	52 (116)
5	Entire house shifts off foundation	46 (103)	54 (121)	63 (141)
6	large section of roof structure removed; most walls remain standing	47 (104)	55 (122)	63 (142)
7	Exterior wall collapsed	51 (113)	59 (132)	68 (153)
8	Most walls collapsed in bottom floor, except small interior rooms	57 (128)	68 (152)	80 (178)
9	All walls collapsed	63 (142)	76 (170)	89 (198)
10	Destruction of engineered and/or wall constructed residence; slab swept clean	74 (165)	89 (200)	98 (220)

2008; Razavi and Sarkar, 2021; Refan et al., 2014; Roueche et al., 2020; Sabareesh et al., 2019; Sabareesh et al., 2013; Sabareesh et al., 2012; Sarkar et al., 2006; Selvam and Millett, 2003; Sengupta et al., 2008; Tang et al., 2018; Wang et al., 2018). A number of these studies were experimental and attempted to establish if and how much tornado-induced wind loads exceed straight-line wind loads when subjected to the same wind speed (Chen et al., 2023; Haan et al., 2010; Mishra et al., 2008; Sabareesh et al., 2012; Sarkar et al., 2006; Wang et al., 2018). Numerical studies conducted with similar objectives have also shared these conclusions (Roueche et al., 2020; Selvam and Millett, 2003; Sengupta et al., 2008).

Furthermore, some studies have examined the impact of factors like geometry, building distance from tornado center, building orientation, roof geometry, swirl ratio, translation speed of the tornado-like vortex, and tornado characteristics, such as path and direction. (Case et al., 2014; Chen et al., 2023; Razavi and Sarkar, 2021; Wang et al., 2018). For example, using an experimental approach, Razavi and Sarkar (2021) studied the effect of three roof geometries: flat, gable, and hip, on loads induced by tornadoes. Their findings identified that ASCE/SEI 7–16 (2016) underestimated the local uplifts and moments, while overestimating shear for all roof types. Correction factors were introduced to improve the accuracy of ASCE/SEI 7–16 in predicting structural actions on low-rise buildings with different roof geometries. Based on experimental analysis, Chen et al. (2023) found that tornado-induced loads on low-rise buildings are significantly influenced by the building's orientation and the tornado's characteristics, such as path, speed, and direction. A major finding from their study is that the highest mean peak negative surface pressures during translation paths occur at the roof corners. These pressures are most influenced by flow separation from the roof edges.

Most of the above studies focus on aerodynamic forces on the building. The effect of atmospheric pressure reduction remains a topic for continued research. Roueche et al. (2020) stated that the reduction of atmospheric pressure depends on how quickly pressure equalizes through leaks or openings in a building, which can be measured by internal pressure. Recent experimental research on tornado-induced internal pressure shows that the contribution of atmospheric pressure reduction relative to aerodynamic pressure depends on the orientation of the largest opening on a wall (Letchford et al., 2015; Sabareesh et al., 2019; Sabareesh et al., 2013; Wang et al., 2018). Internal pressure increases when the largest opening is on the windward wall and decreases when it is on the leeward wall (Sabareesh et al., 2019; Wang et al., 2018).

Based on this understanding and using a combination of existing database and numerical methodology, Roueche et al. (2020) assessed the difference between wind loads induced by tornadoes and those caused by straight-line winds on low-rise buildings with standard openings. The study found that tornado-induced pressures are 13% higher than straight-line wind pressures at equivalent locations. However, at the roof corners and edges, tornado-induced pressures can be up to 100% greater in magnitude.

At this point, much research has focused on the aerodynamic forces exerted by tornado-induced wind loads, consistently showing that these loads can exceed those caused by straight-line winds, particularly at critical areas such as roof corners and edges. However, the role of atmospheric pressure reduction and its interaction

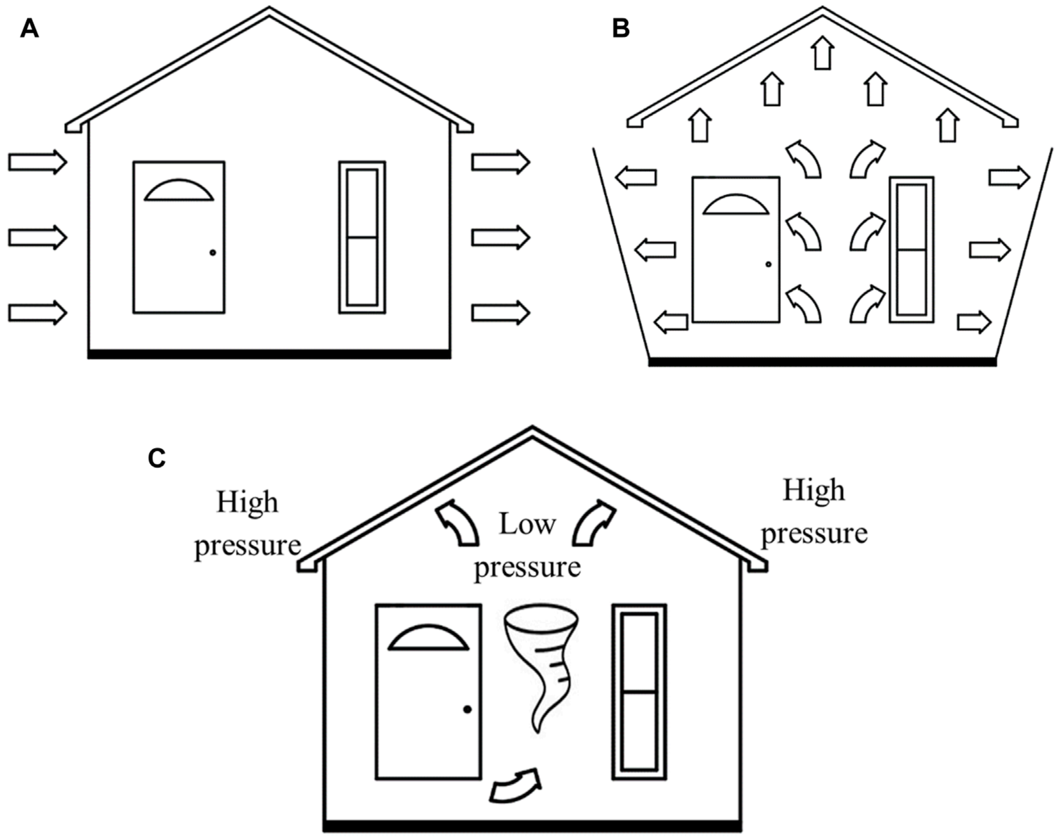

FIGURE 2
Pressure exerted by tornadoes on a building: **(A)** the aerodynamic forces on the building's exterior surfaces; **(B)** internal pressures acting on the building's interior surfaces; **(C)** reduction in atmospheric pressure caused by the conservation of angular momentum within the vortex.

with internal building pressures remains an ongoing area of investigation, with factors like building geometry, orientation, and openings influencing load distribution. As described, the current state of the art, as-practiced, is to amplify straight-line wind loads. Understanding the full nature and extent to which tornado-induced loads differ from straight-line induced wind loads on low-rise residential buildings will be essential for developing effective tornado-specific design provisions for residential building.

2.2 Tornado-induced damage and failure modes

The occurrence of strong tornadoes (EF-2 and above) can have devastating effects on wood-frame residential buildings, as observed from tornado damage reports (Kuligowski et al., 2013; Prevatt et al., 2011). Wood-frame construction is vulnerable to high winds, such as those generated by tornadoes. The basic wind speed for typical buildings in non-hurricane-prone regions is 51.4 m/s (115 mph) according to ASCE/SEI 7 (2022). However, buildings designed to meet this criterion are under-designed to withstand an EF-2 tornado, which can have maximum wind speeds of 60.4 m/s (135 mph) (Roueche et al., 2024). Approximately 20% of tornadoes in the U.S. are classified as EF-2 or higher (Kirkham, 2022). Several studies have documented that all areas within the tornado damage path experience different levels of intensity (Graettinger et al., 2014; Prevatt et al., 2012a; Prevatt et al., 2011; Speheger et al., 2002), as illustrated in Figure 3. As shown in Figure 3, for five notable tornadoes which were rated at EF4 or EF5, approximately 80% of the tornado paths experienced EF-2 or less. Additionally, studies show that approximately 70% of residential buildings in the affected area are damaged by tornado winds rated EF-2 or less, as illustrated in Figure 4 (Burgess et al., 2014; Kuligowski et al., 2013; Marshall et al., 2008). Figure 4 highlights considerable damage across all tornado events in the EF-0 and EF-2 range, which suggests a common vulnerability to low-intensity tornadoes across these regions. Despite the time gaps of up to 15 years between these tornado events, similar damage patterns are observed. This suggests that, irrespective of location, many areas may still face structural vulnerabilities, likely due to inadequate building codes or construction techniques that may not be sufficiently robust for tornado resilience. Additionally, the effectiveness of community awareness and preparedness in these regions might be insufficient. With these statistics in mind, a significant amount of damage can be reduced through enhanced construction of critical connections and improvement in continuity of structural load path for wood frame construction.

Several failure modes, such as sliding, overturning, component and material failure, have been observed after tornadoes (Jordan,

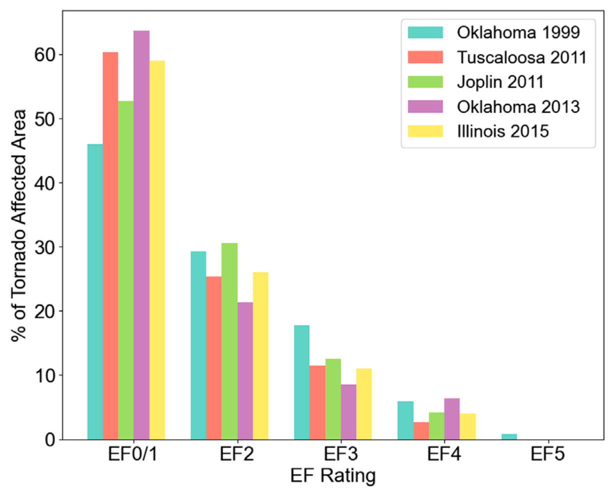

FIGURE 3
Percent of tornado affected areas observed by EF-Scale wind speed rating.

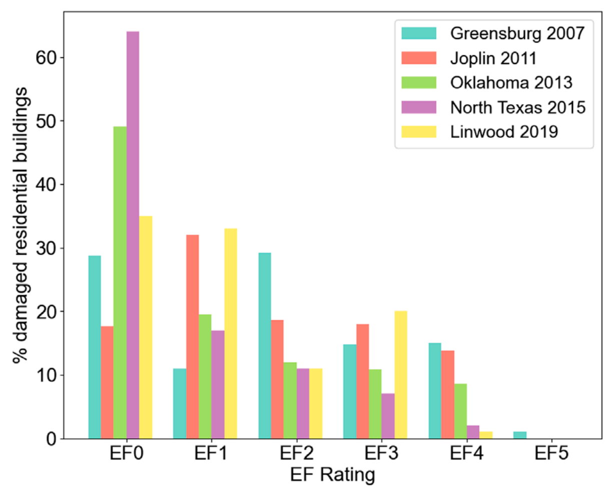

FIGURE 4
Percent of damaged residential building by EF rating for Five Tornado Events.

2007). Component and material failure are more common and include roof cladding failure, roof-to-wall connection failure, wall-to-foundation connection failure, and wall cladding failure (Standohar-Alfano and Van De Lindt, 2016; Sutley et al., 2021). Residential buildings often fail because of disruptions in the continuous load path, leading to failures in the structural system, building envelopes (such as roofs and walls), and the connections between these components. Tornadoes expose buildings to both positive and negative wind pressure and impacts from wind-borne debris, which contribute to these failures. Structural system failures generally occur when the wind forces and moments acting on the structure or its components, like roof sheathing, surpass their capacity. Failure in the building envelope is caused by excessive external pressure or high impact loads from debris. To withstand a tornado, a building must have a continuous load path with robust roofs, walls, floors, foundations, and strong connections between these elements, as well as impact resistance (Honerkamp et al., 2022).

Tornado-induced building damage can be initiated in different ways. Often, the roof of the building is first affected due to strong uplift forces induced by the tornadic wind (Standohar-Alfano and Van De Lindt, 2016). In other scenarios, breaching of the building envelope by windborne debris and combination of tornadic wind results in the failure of roof structure, subsequently leading to the collapse of wall structure (Graettinger et al., 2014; Kuligowski et al., 2013; Prevatt et al., 2011; Roueche et al., 2019b; Yan et al., 2019). A study by Roueche and Prevatt (2013) showed that there is a strong correlation between roof failure and wall collapse, where 86% of the time, roof structure failure was accompanied by multiple wall collapses highlighting the importance of the roof diaphragm in supporting the wall structure. Studies by Marshall (2002), Graettinger et al. (2014) and Wood et al. (2020) noted that damage to residential buildings often begins at the garage doors, particularly those oriented in the windward direction. The failure of light-gauge metal garage doors, especially in garages that protrude from the house, cause the garage to become pressurized. This leads to the roof over the garage being blown off, and subsequently, the collapse of both the garage and the exterior walls.

Roof-to-wall connection failure is also commonly observed after tornadoes (Kuligowski et al., 2013; Marshall, 2002; Pilkington et al., 2021; Prevatt et al., 2011; Roueche et al., 2024; Sutley et al., 2021). Roof-to-wall connections secure the roof structure to the wall and are important for providing uplift and lateral resistance. In typical code-based light-frame construction, two or three toenails are used to secure the wall top plate to the roof truss. Toenailed connections do not have high capacity for uplift or lateral loads and thus tend to perform poorly under tornadic winds. NIST observed homes that performed better during the 2011 Joplin tornado had robust hurricane connectors for the roof-to-wall connection given that they provide approximately three times the capacity of a toenailed connection (Marshall, 2002). However, in recent studies by Rouche et al. (2024) and Pilkington et al. (2021), researchers observed that in some homes with hurricane clips, the clips were only attached to the upper of the double top plates, and the wall sheathing only overlapped the lower of the double top plates. This resulted in a failure plane between the upper and lower plates occurring before reaching the capacity of the hurricane strap.

Aside from roof structure and roof-to-wall connection failures, weak wall-to-foundation connections have been observed in post-tornado studies as well (Graettinger et al., 2014; Kuligowski et al., 2013; Marshall, 2002; Marshall et al., 2008; Prevatt et al., 2011; Roueche et al., 2019b). The wall bottom plate is typically connected to a concrete slab or masonry foundation using anchor bolts. Concrete cut nails have also been observed (Marshall (2002); Roueche et al. (2019b), although those homes were found to have been constructed before 1995 when the Council of American Building Officials (CABO) for one and two-family dwelling building code for residential structures began requiring that anchor bolts should be used for the wall-to-foundation connection (FEMA, 1999). Even when anchor bolts performed well during tornadoes, wall studs were observed to pull away from the bottom plate (Pilkington et al., 2021; Prevatt et al., 2011). Additionally, it was discovered that homes were often built on unreinforced, and sometimes ungrouted, concrete masonry block stem walls, offering minimal to no resistance against wind uplift forces resulting in failure of the wall-to-foundation connection (Roueche et al., 2019a; 2019b). The capacities of the connections within the structural load path of a structure must be equivalent and meet the tornadic wind capacity of the structure to prevent failure (Roueche et al., 2019a). A weak link in the load path is critical and must be avoided. The foundation was found to be the weakest link in some case studies observed by Prevatt et al. (2012a).

Some studies have also reported the performance of residential shelters and safe rooms during tornado (Gardener et al., 2000; Graettinger et al., 2014; Liang et al., 2014; Standohar-Alfano et al., 2015), while other post-tornado studies (Marshall et al., 2008; Prevatt et al., 2012a; Sutley et al., 2021; Yan et al., 2019) did not report whether residential shelter or safe rooms were available in the surveyed area. Above-ground and below-ground shelters were observed to perform well in the 2013 Oklahoma tornado. In some cases, below-ground shelters were found to be covered by debris and flooded by rain following the storm passage and above-ground shelters had cosmetic damage due to windborne debris (Graettinger et al., 2014). Kuligowski et al. (2013) observed that the presence of residential shelters was limited during the 2011 Joplin tornado, as the city of Joplin does not require the construction of shelters and safe rooms. In addition, Kuligowski and colleagues observed that only about 17% of homes had basements, which can serve as in-home shelter when a safe room is not available.

Tornadoes account for more annual fatalities than earthquakes and hurricanes combined (Kneifel et al., 2022). The fact that most fatalities are often associated with residential buildings is particularly concerning. In the Oklahoma tornado of 1999, the Joplin tornado of 2011, and the Southeastern tornado outbreak of 2019, about 75%, 50%, and 68% of the fatalities, respectively, occurred in residential buildings (Gardener et al., 2000; Kuligowski et al., 2013; Roueche et al., 2019b). This highlights the urgent need for improved residential building standards and better preparedness measures to protect occupants during such catastrophic events. One study observed that the areas with the most severe damage had either obsolete building codes or lacked building codes entirely (Sutley et al., 2021). Some other studies noted that a statewide building code is adopted but not enforced for one-two single family dwellings (Kuligowski et al., 2013; Prevatt et al., 2011; Sutley et al., 2021). This means that some homes might not even meet the minimum requirements by IRC which in turn will escalate the damage caused by tornadoes. The age of buildings could also affect the degree of damage caused by a tornado. Most post-tornado studies implied that recent and older residential buildings suffered similar damages when exposed to similar tornado wind (Graettinger et al., 2014; Kuligowski et al., 2013), while Prevatt et al. (2011) observed the deterioration of structural system such as rotting wood framing and corroded fasteners as a function of age of the building. These findings further imply that buildings over 30 years may be vulnerable to any intensity of tornado.

Over the past two decades, numerous significant tornadoes have impacted the U. S Table 2 catalogs twelve tornado events noting their historical significance and describing observed building damage. Tornadoes frequently cause widespread damage. By examining the destruction they leave behind, we can infer the mechanisms by which tornadoes create such devastation (Honerkamp et al., 2022).

3 Coverage of tornado loads and resistance in building codes and standards

This section outlines the general characteristics of tornado loads and resistance specified and/or provided by building codes and standards and associated construction practices for residential buildings in the United States. Where building codes are adopted in the U.S., light-frame wood construction (LFWC) is built according to the specifications of the International Residential Code (IRC) and the International Building Code (IBC). Building codes set legally enforceable minimum requirements for the design and construction of buildings and are adopted at local, county, and sometimes state levels. The IRC, developed by the International Code Council (ICC), provides minimum requirements specifically for the construction of one- and two-family dwellings and townhouses not exceeding three stories above grade.

The IRC aims to safeguard public health and safety through model code regulations suitable for all communities, large and small. It references the latest edition ASCE/SEI 7 for determining wind loads in building design. To address environmental loads, such as wind, the IRC employs a prescriptive approach, eliminating the need for custom designs by architects or engineers. However, these prescriptive criteria apply only to regions where the design wind speed is 140 mph (161 km/h) or less. Areas with higher wind speeds should adhere to the Wood Frame Construction Manual (WFCM), ICC Standard for Residential Construction in High Wind Regions (ICC-600), ASCE/SEI 7 and IBC. One key principle in the IRC is the continuous load path, which ensures that gravity, uplift and lateral loads are transferred from the roof through the structure and down into the foundation, enabling the building to resist high straight-line winds. Tornado loads are distinguished from straight-line wind loads through higher uplift (suction) loads and loads created through internal pressure changes. As a result, buildings in tornado-prone areas may require enhanced connections in their load path to resist tornadic winds.

The IRC is adopted and enforced by local jurisdictions at their discretion and is used across all contiguous states in the U.S., as well as the District of Columbia, Guam, Puerto Rico, and the U.S. Virgin Islands. However, Wisconsin and Arkansas are the only states that have not adopted the IRC (ICC, 2024). Currently, there are no requirements in the IRC for residential buildings to be designed specifically for tornadoes, though homebuilders can choose to use enhanced construction techniques for better tornado performance (Scott et al., 2024). Upon IRC adoption, some jurisdictions modify the code to align with local practices and laws. While most states adopt the IRC, its enforcement varies; municipalities within these states may choose to adopt different model building codes. Localities may also adopt amendments that increase or decrease the level of structural resistance prescribed in the code.

3.1 International Residential Code (IRC) coverage of structural load paths

While the IRC does not explicitly address load path requirements for tornado-prone regions, it establishes the foundation for a continuous load path, which is essential for withstanding the high uplift and lateral loads associated with tornadoes. A continuous load path ensures that a building can resist gravity, uplift and lateral loads by creating a series of designed connections that transfer these loads from the roof down to the foundation. According to the IRC, "A continuous load path shall be provided to transmit the applicable uplift forces in Section R802.11 from the roof assembly to the foundation."

The 2024 IRC includes prescriptive requirements for framing, bracing, and fastening wood-framed one- and two-family dwellings and townhouses. Sections R802.10 and R802.11 outline the specifics for wood truss design and roof tie uplift resistance. As previously stated, these provisions are applicable only in regions where wind speeds do not exceed 62.5 m/s (140 mph), covering many tornado-prone regions. However, while the IRC's wind-resistant design overlaps with some tornado-prone regions, it is important to note that wind-resistant design is not equivalent to tornado-resistant design. Tornadoes can produce wind speeds far exceeding 140 mph, and the IRC provisions are not designed to handle the extreme uplift forces, debris impact, and rapid pressure changes associated with tornadoes.

In areas where the basic wind speed is 51.4 m/s (115 mph) or less, rafters or trusses must be attached to the top plate following the specifications in Table R602 (1). This table mandates that the connection of rafters or roof trusses be toenail-fastened using three 16d [88.9 × 3.44 mm (3.5 × 0.135 in.)] nails. However, this practice, commonly observed in tornado-prone areas, has been shown to perform poorly even under the lower wind speeds of EF0 to EF1 tornadoes (Kuligowski et al., 2013; Prevatt et al., 2012a). Toenailed connections are weak in tension and are unable to resist uplift and lateral load from tornadic winds (Marshall, 2002).

It is also important to recognize that these prescriptive requirements only apply to new constructions. Many existing homes that have sustained damage in tornadoes, as illustrated in Table 2, were built prior to the adoption of current IRC requirements and different parts the country do not necessarily meet the requirement of previous IRC editions. As such, older buildings may lack the continuous load path, adequate roof-to-wall connections, and anchorage that are necessary for tornado resilience. This discrepancy between older, non-compliant buildings and modern construction highlights the need to improve the resilience of both new and existing buildings.

While the IRC provides a robust framework for creating a continuous load path in residential buildings, which is essential for withstanding up to an EF-2 tornado wind speed, failures are still observed in buildings constructed using these prescribed details as seen in recent post-tornado investigations (Roueche et al., 2024). Hence, more research and improvements are necessary to further enhance the load paths in residential construction, making homes more resilient to tornadoes.

3.2 Fortified standard

The FORTIFIED standard, developed by the Insurance Institute for Business & Home Safety (IBHS), goes beyond the IRC by offering enhanced construction methods designed to protect homes against extreme wind events, including hurricanes and tornadoes. While IBHS suggests the FORTIFIED standard applies to HUD manufactured homes, it has not yet been implemented in such structures and may be limited in its effectiveness without a permanent foundation.

The FORTIFIED Home program includes three levels: FORTIFIED Roof, FORTIFIED Silver, and FORTIFIED Gold. Table 3 compares the key differences between the FORTIFIED standard and IRC (2024), with specific attention to requirements such as roof sheathing attachment, roof-to-wall connection, and wall-to-foundation connection. While the FORTIFIED Roof designation strengthens roof performance during high winds, hurricanes, and EF-2 tornadoes, FORTIFIED Silver builds upon this by improving the strength of windows, doors, and attached structures. FORTIFIED Gold extends beyond the lower levels by ensuring the home has a continuous load path, enhancing resistance to wind speeds up to 58.1 m/s (130 mph). Homes built to FORTIFIED Gold standard benefit from stronger roof-to-wall connections and wall-to-foundation anchorage, which provides superior protection during tornadoes compared to the IRC. Retrofitting existing homes to achieve FORTIFIED Gold, however, is often cost-prohibitive, so it's more commonly recommended for new construction. According to Henzi (2019), just over 56% of homes designated as FORTIFIED meet the Roof level, while 41% achieve the Gold level, and less than 2% meet the Silver designation.

Over 80% of the approximately 50,000 FORTIFIED homes nationwide are located in Alabama (Stich, 2023), a state that faces both frequent hurricanes and tornadoes. While most southeastern states such as Alabama, Mississippi, North Carolina, Florida and Louisiana benefit from high FORTIFIED adoption as illustrated in Figure 5, tornado Alley states such as Kansas, Oklahoma, and Missouri have significantly lower FORTIFIED adoption, despite being within high wind-speed zones as indicated by FEMA safe room design contours. This disparity suggests that many tornado-prone areas may continue to experience preventable damage in future tornadoes, especially since many homes in these regions lack the structural reinforcements provided by the FORTIFIED standard.

Although incentives like insurance discounts and tax credits are offered in some states depending on insurance provider, FORTIFIED adoption remains limited. Ghosh et al. (2023) found that achieving a FORTIFIED designation in Oklahoma costs between 1% and 2.6% of a home's sale price, a cost that aligns with estimates from Gould (2020) yet is lower than the 3%–7% range provided by the FORTIFIED program itself (IBHS, 2020).

The enhanced connections and material requirements in FORTIFIED Gold homes provide significantly greater resilience to tornadoes compared to homes built to IRC standards. Homes built to FORTIFIED standards, particularly Gold-level homes, are better equipped to resist the high wind speeds and associated forces seen in EF-2 or stronger tornadoes, making them an attractive option for enhancing community resilience in tornado-prone areas.

TABLE 2 Selected tornadoes of historical significance across the U. S.

Event date	State(s)	EF rating	Historical significance	Description of observed failure	Source(s)
3 May 1999	OK	5[1]	23 out of 45 fatalities occurred in site-built homes	Damage was observed to residential buildings with concrete slab foundations, where bottom wall plates used 50 mm (2 in.) long tapered cut nails penetrating approximately 12.7 mm (0.5 in.) into the concrete slab (Marshall, 2002). Roof structures pulled-apart from the top plate; toenailed connections between the rafter and the top plate were insufficient to withstand uplift forces generated from tornadic wind (Gardener et al., 2000)	Marshall (2002), Gardener et al. (2000)
4 May 2007	KS	5	First EF-5 rating since the previous record (3 May 1999, OK tornado). The 2007 KS tornado destroyed 95% of built structures in GreensburgKS.	Reconnaissance observations noted 53 homes slid off their foundation blocks, and that many homes were more than twice as likely to lose their entire roof compared to just a portion of it due to weak roof-to-wall connections	Marshall et al. (2008)
27 April 2011	AL	4	One of the largest and costliest tornadoes in U.S. of the time	Failures observed to residential buildings included weak toe-nailed truss-to-wall connections, inadequate foundation attachments, hinge failures at gable end trusses, and insufficient wall sheathing, often causing homes to lift off their foundations (Prevatt et al., 2012a). Other issues included debris impacts collapsing interior walls, lack of debris protection for glazing, and poorly secured anchor bolts in masonry foundations (Prevatt et al., 2011)	Prevatt et al. (2011), Prevatt et al. (2012a)
22 May 2011	MO	5	Recorded as the deadliest single tornado in U.S. history. Approximately 59% of fatalities occurred in residential buildings	Residential building failures were primarily due to inadequate connections rather than component failures (Prevatt et al., 2012b). Windborne debris contributed significantly to the damage of residential buildings. Buildings experienced winds above design speeds, causing roof-to-wall connection failures, and walls being swept off slab-on-grade foundations. Multi-family homes with hurricane connectors performed better, but most lacked strong mechanical connections between roofs, walls, and foundations (Kuligowski et al., 2013)	Prevatt et al. (2011), Prevatt et al. (2012b), Kuligowski et al. (2013)
13 May 2013	OK	5	Third major tornado to strike Moore, OK in 15 years and one of the strongest to hit a densely populated area	Damage to residential buildings often began at garage door openings and connections, leading to roof failures and subsequent wall collapse. Homes shifted off their foundations because anchor bolts could not resist uplift and sliding, due to the absence of washers and nuts	Graettinger et al. (2014)
9 April 2015	IL	4	Due to the devastating nature of the tornado, residential buildings could not be properly assessed	Residential buildings suffered severe damage during the event, with most structures along the tornado path being destroyed. Due to the extent of the damage, it was impossible to assess the quality of the roof-to-wall or wall-to-foundation connections	Prevatt et al. (2015)
3 March 2019	FL, GA, AL	4	Deadliest tornado recorded since May 2013, about 34 tornadoes were confirmed across southeastern United States	Insufficient foundation attachment due to inadequate anchorage to resist uplift, lack of structural sheathing (use of non-structural sheathing), and breaches in the building envelope were observed. New constructions showed evidence of damage at wind speeds of 115 mph (Roueche et al., 2019a)	Roueche et al. (2019a)

(Continued on the following page)

TABLE 2 (*Continued*) Selected tornadoes of historical significance across the U. S.

Event date	State(s)	EF rating	Historical significance	Description of observed failure	Source(s)
22 May 2019	MO	3	The tornado traveled through the downtown portion of the city, damaging numerous homes and businesses	Yan et al. (2019) and Honerkamp et al. (2022) reported that wind-borne debris damaged walls, windows, doors of residential buildings. Honerkamp et al. (2022) found that single-story buildings outperformed two-story buildings during the tornado due to stronger connections between the first story and the foundation	Honerkamp et al. (2022) and Yan et al. (2019)
28 May 2019	KS	4	The Linwood, KS tornado struck one of Kansas's least vulnerable areas, highlighting that many counties still lack building codes despite significant building impacts	Failures observed in residential buildings included the loss of shingles, garage door failure, significant damage to doors and windows, walls shifting off foundations, and roof truss damage. Researchers also observed that a significant portion of the surveyed homes were built before the year 2000, and therefore before the roof tie down requirement was introduced in the 2015 IRC.	Sutley et al. (2021)
3 March 2020	TN	4	It was a nocturnal tornado, which contributed to the increase in fatality and injury	Wood et al. (2020) found significant deficiencies in the structural load path to the foundation in modern single-family homes, with unreinforced masonry block walls offering little resistance to wind uplift. Garage door failures and weak gable roofs, wall-to-floor connections, and sill plate anchorage were also noted. Most truss and roof failures began at the gable ends (Henderson et al., 2021)	Wood et al. (2020) and Henderson et al. (2021)
10 Dec 2021	AR, KY, TN, MO	4	Recorded as the longest tornado track in Kentucky history, it was deemed as the worst disaster in the state's history by the Governor	Roof-to-wall failures occurred in homes where only three 16d toenails were used, and wall-to-foundation failures stemmed from inadequate sill or bottom plate connections. Homes with hurricane straps performed better, despite roof cover loss and windborne debris damage (Pilkington et al., 2021)	Pilkington et al. (2021)
22 March 2022	LA	3	The Arabi, LA tornado mainly affected single-family homes, damaging approximately 200 homes	Roueche et al. (2024) found that despite using hurricane-resistant techniques like clips, anchor bolts, and ring-shank nails, structural failures still occurred in both pre- and post-IRC homes. Overdriven nails and small nail heads caused fastener pull-through in roof sheathing, and roof failures included rafter fractures and top plate separations	Roueche et al. (2024)

3.3 Overview of ASCE 7 chapter 32

Recently, the ASCE/SEI 7 (2022) standards incorporated provisions for tornado loads, which were subsequently adopted into the 2024 version of the International Building Code. This is a historic milestone, as it is the first-time buildings in tornado-prone areas have specific guidance and requirements (where adopted) to withstand tornado loads. However, the ASCE/SEI 7–22 standards for tornado loads apply exclusively to risk category III and IV buildings, leaving risk category II residential buildings without specific protection or guidance. The tornado load provisions are captured in Chapter 32 of ASCE/SEI 7–22 (2022). According to Chapter 32 provisions, not all structures in tornado-prone regions need to be designed for tornado loads. If the design tornado speed is below 60 mph (26.8 m/s), tornado loads typically do not govern over wind loads. Additionally, if the tornado speed is less than 60 percent of the basic wind speed, tornado loads will not control. To determine whether tornado loads are required, a flowchart in Figure 32.1.2 (ASCE/SEI 7 (2022)) outlines the process to be followed. Subsequently, Figure 32.1-3 (ASCE/SEI 7 (2022)) details the steps needed for determining tornado loads. Tornado-induced load, p_T in psf for MWFRS according to Chapter 32 is given by Equation 1:

$$p_T = 0.00256\, K_{zTor} K_{dT} K_{zT} K_e V_T{}^2 \left[K_{vT}\left(G_T C_p\right) - \left(GC_{piT}\right)\right] \quad (1)$$

where K_{zT} = topographic factor; K_{dT} = tornado directionality factor; K_{zTor} = tornado velocity pressure exposure coefficient; K_e = ground elevation factor; K_{vT} = tornado pressure coefficient adjustment factor; V_T = tornado wind speed; G_T = tornado gust effect factor; C_p = external pressure coefficient; GC_{piT} = tornado internal pressure coefficient.

These provisions represent a significant advancement in building code requirements, aiming to enhance the safety and resilience of structures in tornado-prone regions. While the current ASCE/SEI 7–22 standards do not extend tornado load provisions to risk category II residential buildings, there is a growing recognition of the need to include these buildings (Scott et al., 2024). Given that a significant

[1]The tornado was rated using F-scale.

TABLE 3 Comparison between IRC 2024 and FORTIFIED standard requirements for wood-frame construction.

Component/Category	IRC (2024)	FORTIFIED standard
Design consideration	Designed for wind speeds up to 62.5 m/s (140 mph). It covers many tornado-prone areas, but design is not tornado-resistant	FORTIFIED Gold resists wind up to 58.1 m/s (130 mph). Offers better protection for buildings to resist up to EF-2 tornadoes
Roof sheathing framing	Truss or Rafter should be spaced at 405 mm (16 in.) o.c, with a maximum of 24 in. o.c. permitted. Minimum nominal sheathing panel thickness of 9.5 mm (3/8 in.) and minimum structural panel span rating of 24/16	Truss or Rafter should be spaced at a maximum of 405 mm (16 in.) o.c. Minimum nominal sheathing panel thickness of 11.9 mm (15/32 in.) and minimum structural panel span rating of 24/16
Roof sheathing attachment	8d [3.33 × 63.5 mm (0.131 × 2.5 in.] common nails at 150 mm (6 in.) o.c. at edges, 150 mm (6 in.) o.c. in the field	8d [3.33 × 63.5 mm (0.131 × 2.5 in.)] ring shank nails at 150 mm (6 in.) o.c. at edges, 150 mm (6 in.) o.c. in the field
Roof uplift resistance	Metal connectors rated for at least 890 N (200 lbf) uplift resistance	Metal connectors rated at least 2.2 kN (500 lbf) uplift resistance
Roof-to-wall connection	Three 16d [88.9 × 3.44 mm (3.5 × 0.135 in.)] nails	Metal connectors rated for a minimum uplift resistance of 2.2 kN (500 lbf). In addition, wall sheathing must overlap both top plate and additional connection must be used to transfer load from the top plate to the wall stud
Exterior wall sheathing framing	Typically, 405 mm (16 in.) o.c. stud spacing is used with a maximum of 584 mm (24 in.) spacing permitted	The maximum stud spacing should be 405 mm (16 in.) o.c
Exterior wall sheathing attachment	Minimum thickness of 11.1 mm (7/16in.) and be nailed with 8d common nails [3.33 × 63.5 mm (0.131 × 2.5 in.]	Minimum thickness of 11.1 mm (7/16in.) and nailed with 8d ring shank nails [3.33 × 63.5 mm (0.131 × 2.5 in.)]
Wall-to-foundation connection	Requires 12.7 mm (1/2 in.) diameter anchor bolts, 178 mm (7 in.) embedded into concrete	Requires 15.9 mm (5/8 in.) diameter anchor bolts embedded 200 mm (8 in.) into concrete. Hold-downs connecting exterior walls at corners and interior shear walls at ends to foundation shall be installed
Doors and windows	No specific requirements for high wind resistance	Wind rated doors and windows required for FORTIFIED Silver and Gold
Gable-end bracing	It requires that roof framing members, such as rafters or trusses, be properly anchored to the wall top plates. Also, it requires straps or ties installed to secure the gable end walls to the structure below	In addition to IRC requirements, additional framing members, diagonal braces, and structural panels are required to provide extra rigidity and resistance to lateral forces

proportion of tornado damage affects residential structures, enhancing their design to withstand tornado loads could greatly reduce property damage and save lives. The extension of these provisions to risk category II buildings would provide comprehensive protection across a broader range of structures, ensuring a higher level of safety and resilience in tornado-prone areas.

3.4 Tornado-specific provisions for international standards

Outside the U.S., tornado-specific provisions are rare, as tornadoes predominantly occur in the U.S. However, other countries that experience tornadoes, such as Canada, Japan, Australia, New Zealand, and parts of Europe (e.g., the United Kingdom, Germany, and Poland), address tornado-induced hazards through the wind provisions in their respective building codes.

For instance, the prescriptive design provisions in Part 9 of the National Building Code of Canada (NBCC) (Canadian Commission on Building and Fire Codes, 2020) includes measures to mitigate wind risks in wood-frame buildings, such as improved fastener schedules for roof sheathing, roof-to-wall connections capable of withstanding 3 kN uplift, and braced wall panels for resisting lateral loads. However, reports by Sandink et al. (2018) and Stevenson et al. (2020) highlight that many of these measures are structurally insufficient to resist tornado loads. For example, NBCC specifies roof sheathing requirements that allow OSB or plywood panels up to 10 mm (0.4 in.) thick, fastened with 51 mm (2 in.) common or spiral nails or 45 mm (1.77 in.) ring shank nails. Fastener spacing is 150 mm (6 in.) along panel edges and 300 mm (12 in.) along intermediate supports. Post-disaster reports and related literature indicate that Canadian homes with these specifications perform poorly under tornadic winds (Gavanski et al., 2014; Kopp and Morrison,

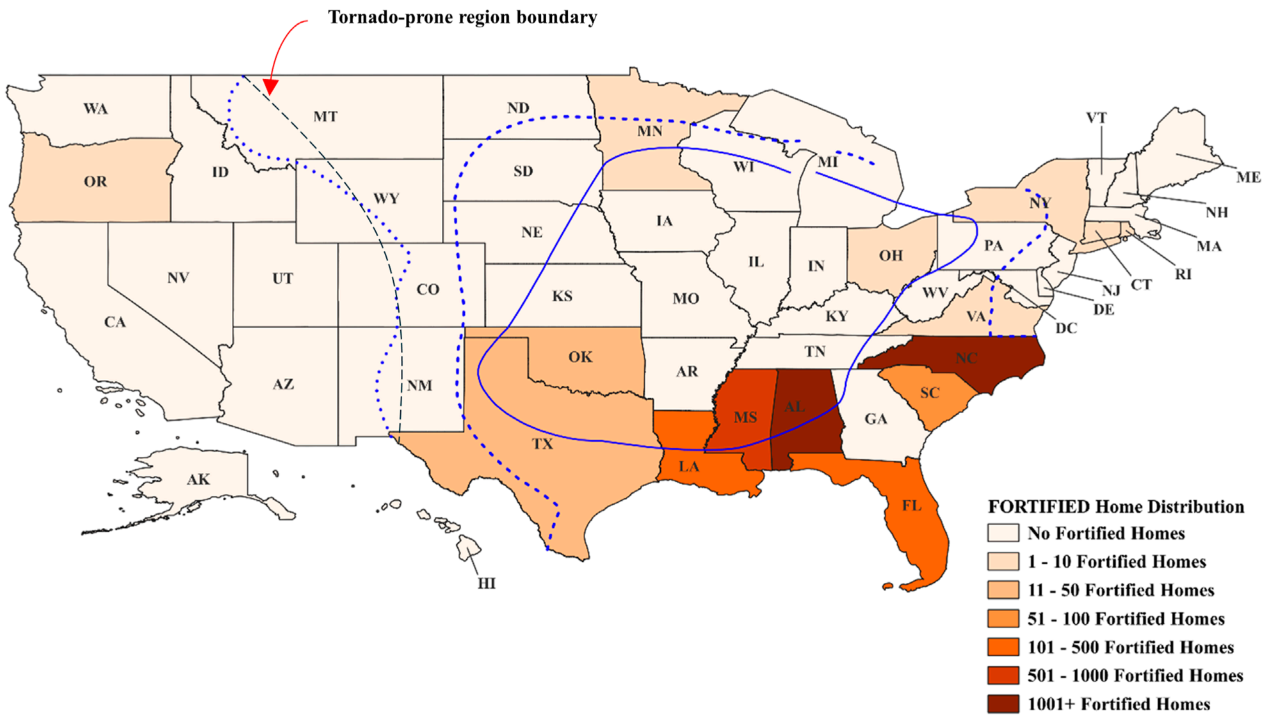

FIGURE 5
Fortified home distribution and FEMA's safe room design wind speed contours for tornadoes (data adapted from IBHS (2023)).

2018; Morrison et al., 2014; Stevenson et al., 2020; 2019; 2018) Recommendations by Sandink et al. (2018) to improve continuous load paths in buildings have been proposed but are yet to be incorporated into the NBCC.

In contrast to Canada, other countries such as Australia, New Zealand, and parts of Europe also rely on general wind provisions but lack tornado-specific standards. The Australian and New Zealand Standard (AS/NZ 1170.2) (Standards Australia/Standards New Zealand, 2021) provides guidelines for determining wind loads on structures but does not include specific provisions for tornado loads. Eurocode EN 1991-1-4: General Actions–Wind Actions offers similar guidance for wind load determination on buildings (European Committee for Standardization, 2005), but tornado-specific considerations are absent. Likewise, the Building Standard Law of Japan focuses on typhoons and winter storms, leaving gust events like tornadoes outside its scope (Government of Japan, 2020). This global gap in tornado-specific provisions underscores the importance of adopting stricter design standards to improve building resilience in tornado-prone regions worldwide.

3.5 Challenges in implementing tornado-specific provisions for residential buildings

Currently, no tornado-specific provisions exist for retrofitting existing residential buildings in standard codes. This contrasts with seismic resilience frameworks such as ASCE 31 and ASCE 41, which provide guidelines for evaluating and retrofitting buildings to improve earthquake resistance. Similarly, in hurricane-prone regions, the FORTIFIED standard provides wind retrofit guidelines for older buildings. However, the FORTIFIED standard is more cost-effective when applied to new construction compared to retrofitting older buildings (IBHS, 2020), which may lack continuous load path required for tornado resilience. The higher cost of retrofitting older homes remains a significant deterrent to implementing tornado-specific provisions.

Additionally, many homeowners in tornado-prone areas believe their homes are already built to code and capable of withstanding tornado events (Scott et al., 2024). This perception often leads to a lack of willingness to invest in resilience improvements, particularly when tornado-specific retrofits are perceived as expensive and unnecessary. Another challenge lies in the socioeconomic disparity between homeowners. Lower-income households often face disproportionate risks due to substandard construction and a lack of financial resources to invest in retrofits (Scott et al., 2024). Without subsidies, incentives, or cost-sharing programs, these households remain highly vulnerable to tornado hazards.

4 Mitigation strategies

Research has revealed vulnerabilities in the structural load paths of wood-frame residential buildings. Several studies, including those by Insurance Institute for Business & Home Safety (IBHS, 2020), van de Lindt et al. (2013), Roueche et al. (2024), and Prevatt et al.

(2011) have focused on improving the performance of wood-frame residential buildings to withstand high wind events including tornadoes. These studies suggest that by enhancing the structural load path with increased lateral and uplift resistance, wood-frame residential buildings can potentially provide occupant safety with significantly reduced damage for up to an EF-2 tornado and maximum wind speeds of 60.4 m/s (135 mph). Based on observations from the 2011 Tuscaloosa tornado, van de Lindt et al. (2013) proposed a dual-objective-based design philosophy for residential buildings aimed at reducing damage and saving lives by addressing different tornado intensity levels. The study found that building performance can be improved at various wind speeds through specific measures: At EF0 and EF1 wind speeds, enhancements can be made at the component level, focusing on connections. At EF2 and EF3 wind speeds, design improvements should target the system level, such as shear walls, roof diaphragm and load paths. For EF4 and EF5 wind speeds, life safety can be ensured using alternative methods, such as incorporating safe rooms.

4.1 Structural mitigation strategies

To ensure load path continuity from the roof to the foundation of a building, connections such as sheathing-to rafter, roof-to-wall, exterior wall sheathing, and wall-to-foundation must be securely connected using mechanical connectors capable of resisting high winds. In addition, proper materials and construction techniques must also be followed judiciously. Having established the need for continuous load paths, it is important to now focus on how specific building components should be constructed to meet these requirements. A critical first step is to strengthen the roof sheathing, which is a common point of failure in high-wind events.

Failure of roof sheathing can be mitigated by using a thicker material and a tighter fastener schedule, as recommended by Prevatt et al. (2013), van de Lindt et al. (2013), and FEMA (2023). Oriented Strand Board (OSB) or plywood with a minimum thickness of 11.1 mm (7/16 inch) and a minimum span rating of 24/16 should be used as roof sheathing. This sheathing should be nailed with 8d ring shank nails [3.33 × 63.5 mm (0.131 × 2.5 in.)] or 10d nails [3.76 × 76.2 mm (0.148 × 3in.)] at 100 mm (4 in.) on center (o.c.) at the edges and 150 mm (6 in.) o.c. in the field, as specified by Ramseyer et al. (2016). However, the Insurance Institute for Business & Home Safety (IBHS, 2020) recommends a minimum roof sheathing thickness of 11.9 mm (15/32 in.). The use of appropriate roof coverings is also crucial for ensuring the durability of the roofing system. FEMA (2023) advises using Class F and H rated asphalt shingles, which should be installed following the manufacturer's instructions.

In addition to securing the roof sheathing, the connections between the roof and walls play an essential role in ensuring the overall structural integrity of the building. Rafters or trusses should be framed at 406 mm (16 in.) o.c. and connected to the top plate using metal connectors, such as hurricane clips, capable of resisting at least 2.2 kN (500 lbf) in tension and compression, as advised by Ramseyer et al. (2017), Ramseyer et al. (2016), Ramseyer et al. (2014) and IBHS (2020). Research by Roueche et al. (2024), Pilkington et al. (2021), and Henderson et al. (2021) has identified a discontinuity in the load path between the upper and lower wall top plates and the wall studs. These studies have noted separations between the upper and lower top plates. These studies recommend that wall sheathing should overlap both the upper and lower wall top plates to transfer loads from the wall top plates to the wall studs. Additionally, FEMA (2023) suggests using metal straps nailed to both the side and face of the stud, as well as to the top of the top plate.

Attention must also be paid to the strength and continuity of the wall sheathing, which plays a crucial role in resisting lateral forces. Loss of exterior wall sheathing can be prevented by using the continuous sheathing wood sheathing panel (CS-WSP) method and a tighter fastener schedule, as recommended by Ramseyer et al. (2016), van de Lindt et al. (2013), and Prevatt et al. (2011). Wall sheathing should have a minimum thickness of 11.1 mm (7/16 inch) and be nailed with 8d ring shank nails [3.33 × 63.5 mm (0.131 × 2.5 in.) or 10d nails [3.76 × 76.2 mm (0.148 × 3 in.)] at 100 mm (4in.) on center (o.c.) along the edges and 150 mm (6 in.) o.c. in the field. The maximum stud spacing should be 406 mm (16 in.), as specified by Ramseyer et al. (2016) and IBHS (2020).

Exterior wall coverings, such as vinyl siding and brick veneer, should be high wind-rated and installed according to the manufacturer's specifications. FEMA (2023) provides guidelines for installing brick veneer and vinyl siding in high-wind regions.

Ramseyer et al. (2016), Henderson et al. (2021), and Roueche et al. (2024) have identified shortcomings in the continuous load path between the wall bottom plate and the foundation. To address this issue, wall sheathing should overlap the bottom or sill plate to facilitate the transfer of tensile forces from the walls to the foundation, as indicated by these studies. Furthermore, Henderson et al. (2021) suggests that using straps or ties placed at intervals between the walls and the floor can help delay connection failure.

Proper wall-to-foundation connections are key to maintaining load path continuity. In slab-on-grade foundations, where the bottom or sill plate is directly attached to the concrete foundation with anchor bolts, continuous sheathing (with wall studs and the sill plate nailed to the sheathing) can prevent wall uplift and overturning under lateral wind loads with holddowns installed at wall ends. This construction practice helps to mitigate the prying effects that could cause steel anchor bolts to yield, pull out, or break. According to Ramseyer et al. (2016), Ramseyer et al. (2014), this failure mechanism of the bolts is nearly impossible under such conditions, which is why this construction practice is recommended.

For masonry foundation walls, it is important to fill the concrete masonry units (CMU) with grout, as studies (Henderson et al., 2021; Pilkington et al., 2021; Wood et al., 2024) have observed that ungrouted CMUs reduce the hold-down capacity of the foundation. Fully grouted CMUs attached to the sill plate with J-bolts ensure adequate tensile and shear resistance, as emphasized by Henderson et al. (2021). In addition to J-bolts, Henderson et al. (2021) recommends using dowels to connect the CMU wall and concrete footing, as shown in Figure 6 of the referenced study. Alternatively, it is recommended to use threaded rods that extend from the sill plate to the concrete footing. These methods ensure a positive connection between the sill plate and the foundation, providing a continuous load path to resist uplift forces.

One commonly overlooked yet highly vulnerable part of the building during tornadoes is the gable end wall. To reinforce these areas, several strategies are recommended to prevent failure during high wind events. Failure of gable end walls has been consistently

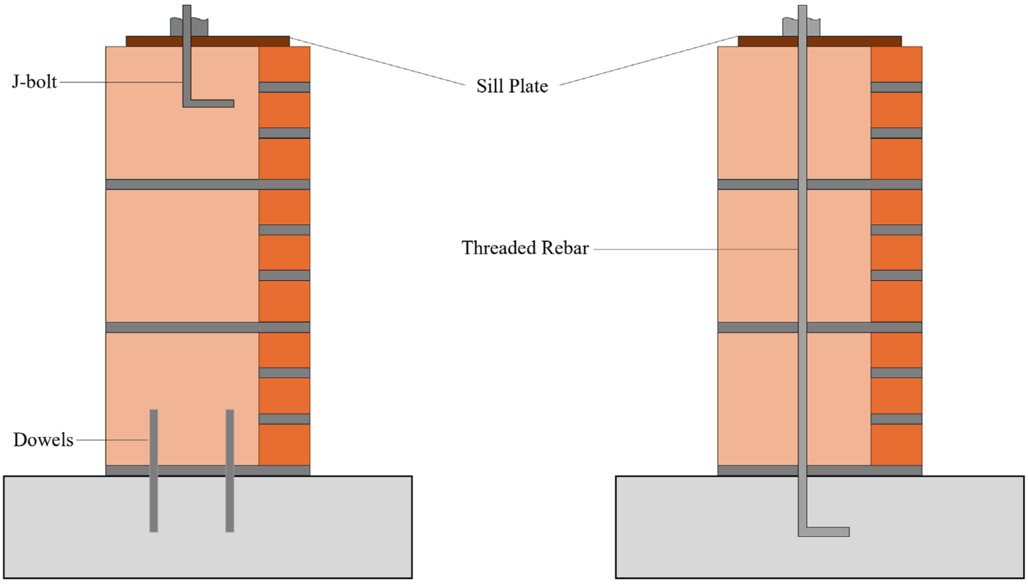

FIGURE 6
Recommended CMU wall and concrete footing connection (adapted from Henderson et al., 2021).

reported in several post-tornado assessment studies. To address this issue, studies by Henderson et al. (2021), IBHS (2020), and guidelines from FEMA (2023) recommend several construction practices to enhance the resilience of gable end walls. One key recommendation is the use of diagonal truss members instead of the traditional vertical members used to connect the top and bottom chords of the truss. Diagonal truss members significantly increase the wall's resistance to penetration and add extra out-of-plane stiffness, which helps the structure better withstand high winds and flying debris. Furthermore, the use of metal straps at the ends of gables is advised. These straps help secure the gable end walls more effectively, reducing the risk of failure under extreme wind conditions. Additionally, Henderson et al. (2021) suggest the use of double plywood sheathing to further decrease the likelihood of out-of-plane windborne debris penetration. This added layer of protection helps prevent debris from breaching the gable end walls, thereby maintaining the integrity of the building envelope during a tornado.

Table 4 summarizes the structural mitigation strategies necessary for a building to achieve continuous load path. It outlines the best or enhanced practices for each strategy and explains their respective mechanisms for reducing wind damage. Implementing these measures enhances the structural integrity and resilience of buildings, especially in high-wind regions, by ensuring a robust connection along the structural load path. This, in turn, helps in reducing the risk of failure during severe weather events and improves overall building safety.

4.2 Ancillary mitigation strategies

4.2.1 Residential shelters

Prior to the publication of ASCE/SEI 7–22 Chapter 32 for tornado loads, FEMA 320 (Taking Shelter from the Storm: Building a Safe Room for Your Home, 2021), FEMA P-361 (Design and Construction Guidance for Community Safe Rooms, 2021), and ICC 500 (Standard for the Design and Construction of Storm Shelters, ICC/NSSA 2020) were the only provisions providing design specifications for tornado loads. Wood-frame residential buildings are incapable of providing life-safety protection at high wind speeds, such as those from EF-4 and EF-5 tornadoes (Van De Lindt et al., 2013). Although the occurrence of tornadoes above EF-4 is minimal and the damage gradients are small, devastating damage and fatalities have resulted from tornadoes, which highlights the critical role of residential shelters in protecting occupants.

The term *residential shelter* is used here as an umbrella term encompassing all forms of protective spaces where individuals seek refuge during a tornado. These include safe rooms, storm shelters, hardened areas, the best available refuge areas (BARA), and a safe spot. Each of these shelter types offers varying levels of safety, depending on design standards and construction. The terms "safe room" and "storm shelter" are often confused, but they are not synonymous. While both safe rooms and storm shelters are designed to offer refuge during extreme weather events, they differ in their levels of protection. For instance, safe rooms, designed to comply with FEMA 320 (FEMA, 2021b) and FEMA P-361 (FEMA, 2021a) standards, are built to withstand the extreme forces of EF-4 and EF-5 tornadoes, providing the highest level of protection. In contrast, storm shelters, built to ICC 500 standards, offer robust protection but do not meet the same rigorous performance criteria as safe rooms. Other types of residential shelters, such as hardened areas of refuge, are typically improvised spaces that do not adhere to FEMA or ICC standards. Finally, the BARA and a safe spot are similar. Although BARA might be a hardened wall like a basement, a safe spot is typically non-hardened interior of a home such as closet or bathroom. Table 5 provides a description of different spaces people use to shelter, the codes adopted to design them, associated

TABLE 4 Summary of structural mitigation strategies, enhanced practices, and their mechanisms for reducing wind damage.

Structural mitigation strategies	Enhanced/Best practice	Mechanism for reducing wind damage
Roof Sheathing nailing	OSB or Plywood as roof sheathing with nailed with 8d ring shank nails [3.33 × 63.5 mm (0.131 × 2.5 in.)] or 10d nails [3.76 × 76.2 mm (0.148 × 3in.)] at 100 mm (4 in.) on center (o.c.) at the edges and 150 mm (6 in.) o.c. in the field	This practice increases resistance to uplift forces by securing roof sheathing with stronger fasteners and reduced spacing
Roof Framing	Truss or Rafter should be spaced at 16″o.c with minimum nominal sheathing panel thickness of 15/32″and minimum structural panel span rating of 24/16	This practice increases the overall structural integrity of the roof, reduces susceptibility to uplift and suction forces, and minimizes the likelihood of progressive failures during tornado events
Roof Connector	Roof framing connections should be designed for both tension and compression of at least 2.2 kN (500 lbf) and may consist of nail connectors, and connections to brace wall top plates or ceiling joists	This practice ensures effective load transfer and structural integrity, reducing the risk of roof detachment during tornado events
Top or bottom plate to stud	Metal straps should be used to connect the double top plate to the wall stud to provide additional uplift resistance	This practice enhances uplift resistance by securing wall-to-roof connection, reducing the risk of separation during tornado events
Wall Sheathing	Wall sheathing should have a minimum thickness of 7/16”shall be nailed with 8d ring shank (0.131 × 2.5 in)] or 10d (0.148 × 3 in.) nails at (4 in.) on center along the edges and (6 in.) on center in the field, with max stud spacing of 16”. Use CS-WSP method to continuously sheath walls. Intermittent braces are not allowed for exterior walls	This method ensures continuous load transfer and improves lateral resistance which reduces the vulnerability to wind-induced wall failures
Rafter-to-wall connection	Three 16d box (3.5”× 0.135”) along with hurricane straps capable of withstanding at least 500 Ibs in tension and compression	This practice ensures secure load transfer which reduces the risk of roof uplift and separation during tornado events
Gable end connection	Tie gable end walls to structure. Steel connection plates or straps work well. Make sure the improved connections are included at the top and bottom of the gable end wall. Use structural sheathing panel	This practice ensures improved load transfer at the top and bottom of gable end wall which minimizes its risk of failure during tornado events
Wall-to-foundation anchorage	Anchor floor system and exterior walls to foundation using 5/8-in.-diameter anchor bolts with 8 in. embedment into concrete and a 3-in. x 3-in. x 1/4-in.-thick plate washer at 24 in. O.C. maximum and 6 in. from end of bottom plate. In addition to this, dowels or threaded rods that extend from the sill plate to the concrete footing are recommended	This setup prevents wind-induced uplift forces from separating the walls from the foundation and resist lateral sliding forces caused by tornadic pressure. Additionally, this practice ensures a positive connection between the sill plate and the foundation which provides a continuous load path to resist uplift forces

wind speeds, and whether the space offers life-safety protection from tornadoes.

Although the design and construction of safe rooms or storm shelters play a vital role in enhancing tornado resilience, ensuring their accessibility is equally critical. There are two forms of safe rooms or storm shelters: above-ground and below-ground. Several post-tornado studies have reported the presence and performance of both types during field reconnaissance. Above-ground and below-ground shelters can be located inside or outside the building. Above-ground safe rooms are easily accessible to children, elderly people, and people with disabilities. They should not serve as an exterior wall for a building (Standohar-Alfano et al., 2015). However, if they are used as an exterior wall, it is recommended that they not be on the southern or western sides, as these are more vulnerable to tornadic winds (Standohar-Alfano et al., 2015). Below-ground shelters are not the same as basements. Below ground shelters are typically prefabricated and surrounded by soil on all sides, although they might be difficult to access for occupants with disabilities or limited mobility (FEMA, 2012).

Despite the well-documented benefits of tornado-safe rooms and shelters, their presence in residential areas remains limited, leaving many homes vulnerable during extreme weather events. Field observations from major tornadoes, including the 2011 EF-4 tornadoes in Joplin, Missouri, and Tuscaloosa, Alabama, as well as the 2013 EF-5 tornado in Moore, Oklahoma, reveal important insights into shelter performance and accessibility.

In all three events, the majority of residential homes lacked safe rooms and storm shelters, forcing many occupants to rely om non-hardened spaces such as bathrooms and safe spots within their homes (FEMA, 2012). These spaces, however, were inadequate

TABLE 5 Classification of residential shelters.

Residential shelter	Description	Design wind speed (mph)	Provides life safety protection from tornado	References
Safe Room	A safe room is a fortified structure that can be located inside a building or be an entirely separate building. It is specially designed to meet FEMA P-361 criteria, meet or exceed ICC 500 requirements, and provide near-absolute life safety protection for its occupants during extreme wind events up to the design wind speed	250	Yes	FEMA (2021a)
Storm Shelter	A storm shelter is a reinforced structure designed in accordance with ICC 500 (2020), approved and tested by NSSA to provide life safety for its occupants during extreme wind events up to the design wind speed. Storm shelters do not meet all FEMA 320 and FEMA P-361 design criteria	250	Yes	ICC 500
Hardened Area	A hardened area is a room in a building designed to resist higher loads from wind or wind-borne debris. Hardened areas are not built in accordance with FEMA P-361 nor tested by NSSA.	Varies	Maybe	FEMA (2012)
Best Available Refuge Area (BARA)	BARA is an area of a building determined by an engineer or architect as the least vulnerable to the life threating effects of tornadoes or hurricanes	Varies	Maybe	FEMA P-431, (2009)
Safe Spot	A safe spot is a non-hardened interior area of a home typically closet or bathroom	Varies	Not likely	Graettinger et al. (2014)

against the extreme winds, contributing significantly to the high fatality rates, with approximately 60% of fatalities in Joplin resulting from insufficient sheltering (Kuligowski et al., 2013). Although a few hardened rooms were observed in Tuscaloosa, these spaces were not designed to FEMA or ICC standards and exhibited vulnerabilities such as wooden doors and improper latching mechanisms, which failed to withstand wind-borne debris impacts (FEMA, 2012).

When properly designed to FEMA or ICC standards, however, residential shelters demonstrated exceptional performance across these events. In Joplin, above-ground shelters meeting FEMA design criteria sustained only cosmetic damage, effectively protecting occupants from high winds and wind-borne debris. Similarly, in Moore, the presence of residential shelters in approximately 16% of homes played a key role in reducing fatalities compared to Joplin and Tuscaloosa (Graettinger et al., 2014). Both above-ground and below-ground shelters provided life-safety protection, though below-ground shelters faced challenges such as accessibility, debris blockage, and water leakage. Only one below-ground shelter in Moore was compromised by wind-debris penetration due to substandard construction and poor siting (Graettinger et al., 2014; Standohar-Alfano et al., 2015).

Traditionally, residential shelters are constructed using materials like steel, concrete, and masonry, which offer strong resistance to wind forces. However, recent studies (Falk et al., 2024; Falk and Bridwell, 2018) have shown that wood products, long regarded as less durable, can be successfully engineered to meet ICC 500 standards for residential tornado safe rooms.

While shelter design and construction are crucial for tornado resilience, accessibility is just as important. In communities with manufactured homes or multi-family residences, signage plays a vital role in guiding residents to shelter locations quickly. Clear, visible signs help reduce the time it takes to reach a shelter, which is critical when a tornado warning has been issued (ICC 500, 2023). FEMA (2012) advises that residents should be able to reach a shelter facility within a maximum travel time of 5 min or a maximum distance of 0.5 miles after a shelter notice is issued. A sign at the entrance of the safe room should display design information, including the safe room's occupant capacity, storm type, design wind speed, and the safe room manufacturer or builder (FEMA, 2012). In a study about safe room performance during 2013 Moore tornado, Standohar-Alfano et al. (2015) reported that many residents were aware of the location of residential shelters in their vicinity and took refuge there during the tornado, and this contributed to the reduction in fatalities reported during the aftermath of the event.

4.2.2 Protection of openings and garage doors

Tornadoes pose significant threats to buildings, particularly through damage to doors, glazed windows, and garage doors from wind-borne debris impact. The failure of these components often leads to increased internal pressure, which can result in catastrophic roof damage and water intrusion from wind-driven rain, damaging building contents. Studies by Kovar et al. (2018) and Jaffe et al. (2019) have demonstrated that door, window glazing, and garage door failures can lead to severe structural damage during tornadoes.

High wind-rated garage doors have shown the capability to withstand the forces of tornadoes rated EF-2 and above (Jaffe et al., 2019; Ramseyer et al., 2016; Van De Lindt et al., 2013). For example, Jaffe et al. (2019) experimental testing on various garage door products found that failure pressures ranged between 0.42 and 1.75 kPa, corresponding to estimated failure wind speeds of [36–72 m/s (80–160 mph)]. Additionally, the study also suggested that stronger garage doors are unlikely to be the initial point of failure during extreme wind events, as often reported by Prevatt et al. (2011) and Graettinger et al. (2014). These findings underscore the importance of using high wind-rated garage doors in tornado-prone areas.

Impact-resistant windows and doors are also crucial for buildings in high wind zones. To ensure their effectiveness, these components must satisfy static pressure testing and missile impact testing according to ASTM E1886 (2019) and ASTM E1996 (2023) standards. Experimental and numerical studies carried out by researchers, including Minor (1994), Shah (2009), Beason (1974), NAHB Research Center (2002), Norville (1998), Zhang et al. (2020), and Yardani et al. (2006), have conducted debris impact tests on glazed openings at varying speeds. Their findings indicate that laminated glass or polycarbonate systems, or a mixture of both materials, can withstand wind-borne debris impacts. Although the laminated glass or polycarbonate may fracture upon impact, perforation by the test missile is impermissible according to ICC 500 standards, preventing wind and water intrusion.

In cases where impact-resistant glazing is not used, the installation of storm shutters is recommended. Storm shutters provide additional protection for glazed openings against wind-borne debris from tornadoes, as highlighted by studies from NAHB Research Center (2002) and Borges et al. (2009).

The integration of impact-resistant glazing and doors, as well as high wind-rated garage doors, is essential for mitigating wind borne debris impact in tornado-prone areas. These measures help to maintain the structural integrity of buildings, prevent catastrophic roof damage, and minimize water intrusion, thereby protecting both the building and its contents.

4.3 Community-level tornado resilience analyses

Community-level analyses are essential for understanding and quantifying the impacts of tornadoes, especially in residential neighborhoods, and can be very beneficial for risk-informed decision-making. These analyses often involve the use of resilience modeling methodologies to assess vulnerabilities, forecast potential building and infrastructure damage using fragility functions, simulate recovery and test mitigation strategies. One such tool, developed by the Center of Excellence for Risk-Based Community Resilience Planning, is the Interdisciplinary Networked Community Resilience Modeling Environment (IN-CORE). IN-CORE enables researchers and communities to predict community-level building and infrastructure damage and forecast household housing recovery after a tornado. The methodology behind this tool can be found in van de Lindt et al. (2023), and its key components include risk assessment, hazard simulation, disaster impact and recovery, policy development, and public awareness and education.

Incorporating tornado-resistant design into risk category II buildings is a significant step toward enhancing community resilience since two-thirds of tornado-induced damage affects wood-frame residential buildings. High-intensity tornadoes, such as EF-3 and above, typically cause devastating damage to the entire neighborhood, leading to significant disruptions in daily activities. Consequently, households are often displaced, and recovery can take months (Hamideh and Sen, 2022; Sutley and Hamideh, 2020; Wang et al., 2024a; 2024b; Weber and Lichtenstein, 2015). For instance, Wang et al. (2024b) reported that it takes on average, 1.5 years for residential buildings in Mayfield, Tennessee, to be fully repaired after the 2021 Mayfield EF-4 tornado. Thousands of families were displaced following the 2011 Joplin and 2021 Mayfield EF-4 tornadoes (Kanti Paul and Stimers, 2014; Wang et al., 2024a).

Various studies have observed the effects of tornadoes on buildings and infrastructure, as well as population dislocation after a tornado (Wang et al., 2022b; Wang et al., 2022a; Wang et al., 2024a; Wang et al., 2024b; Wang et al., 2021). Researchers have compared the effects of tornado-resistant building designs on building damage and population dislocation to those of minimum building standard designs design (Wang et al., 2022b; Wang et al., 2024a; Wang et al., 2021). The outcomes of these studies have shown that community-level resilience modeling can inform community resilience planning, enhance informed decision-making, and promote effective policies to guide communities toward faster recovery after a disaster. These findings further underscore the importance of incorporating tornado load provisions for residential buildings and encouraging resilience-based design in building codes and standards.

4.3.1 Importance of tornado fragility functions for resilience analysis

The fragility methodology, developed by Ellingwood et al. (2004), has been widely adopted in numerous community resilience

TABLE 6 Summary of tornado fragility studies for residential buildings.

				Inclusion of building component resistance										
Fragility methodology	Structural resistance determination	Number of building archetypes considered	Fragility curve type	Roof covering	Doors	Windows	Roof sheathing	Roof-to-wall connection	Wall-to-foundation connection	Wall sheathing	Type of Tornado Pressure	Wind load statistics	Tornado Wind Pressure Calculation Approach	References
Analytical	Experimental test from previous studies	5	Component-level and building-level	Yes	Yes	Yes	Yes	Yes	No	No	Uplift and lateral	ASCE 7–10 and ASCE 7–16	Tornado amplification factor from Amini and van de Lindt (2014)	Masoomi et al. (2018)
Analytical and Empirical	LRFD-based strength equations	1	Component-level and building-level	No	No	No	Yes	Yes	Yes	Yes	Uplift	ASCE 7–16 and ASCE 7–22	ASCE 7–22 Chapter 32	Roueche et al. (2024)
Analytical	Finite element analysis	3	Component-level and building-level	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Uplift and lateral	ASCE 7–16	Tornado amplification factor from ASCE 7–16	Maloney et al. (2018)
Empirical	Not applicable	Not applicable	Building-level	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Uplift and lateral	Not applicable	Not applicable	Roueche et al. (2017)
Analytical	Experimental test from previous studies	5	Component-level	No	No	No	Yes	Yes	No	No	Uplift	ASCE 7–10	Tornado amplification factor from Haan et al. (2010)	Amini and van de Lindt (2014)
Analytical	Experimental test from previous studies	5	Component-level	No	No	No	Yes	Yes	No	No	Uplift	ASCE 7–10	Tornado amplification factor from Haan et al. (2010)	Standohar-Alfano and van de Lindt (2016)
Analytical	Experimental test from previous studies	5	Component-level	No	No	No	Yes	No	No	No	Uplift	ASCE 7–02	None	Lee and Rosowsky (2005)
Analytical	Experimental test from previous studies	Not applicable	Component-level	Yes	Yes	No	Yes	No	No	No	Lateral	ASCE 7–02 and ASCE 7–10	Tornado amplification factor from Haan et al. (2010)	Dao et al. (2014)

(Continued on the following page)

TABLE 6 (*Continued*) Summary of tornado fragility studies for residential buildings.

Fragility methodology	Structural resistance determination	Number of building archetypes considered	Fragility curve type	Inclusion of building component resistance							Type of Tornado Pressure	Wind load statistics	Tornado Wind Pressure Calculation Approach	References
				Roof covering	Doors	Windows	Roof sheathing	Roof-to-wall connection	Wall-to-foundation connection	Wall sheathing				
Analytical	Experimental test current study	1	Component-level	No	No	No	Yes	Yes	No	No	Uplift	ASCE 7–10 and Datin and Prevatt (2009)	Tornado amplification factor from Haan et al. (2010)	van de Lindt et al. (2013)
Analytical	Design capacity equation	1	Component-level	No	No	No	Yes	Yes	No	No	Uplift	ASCE 7–10	Tornado amplification factor from Haan et al. (2010)	Amini and van de Lindt (2014)

studies. Fragility functions describe the relationship between the probability of exceeding a particular limit or damage state of a structure given a hazard intensity, in this case, tornado wind speed. Fragility functions are expressed as $P\,(DS \geq ds|D = x)$, where DS is the specific damage state and D is the hazard intensity. Building system fragility functions are typically modeled using a lognormal cumulative distribution function (CDF) (Amini and Van De Lindt, 2014; Ellingwood et al., 2004; Lee and Rosowsky, 2005; Masoomi et al., 2018; Roueche et al., 2017). The lognormal CDF is given by Equation 2:

$$F(x) = \varphi\left[\frac{In\,(x) - \mu}{\sigma}\right] \tag{2}$$

Where Φ (.) = standard normal CDF; μ = logarithmic median capacity of wind speed; σ = logarithmic standard deviation capacity of wind speed.

Several studies, summarized in Table 6, have utilized fragility functions to model the performance, analyze the risk of structural components, and assess system-level risk to residential buildings under tornado conditions. The most common approach to developing fragility curves is analytical, as shown in Table 6, with only one study employing an empirical approach to evaluate tornado fragility functions for residential buildings.

The structural resistances modeled in these studies often stem from laboratory experimental tests, such as those conducted by Reed et al. (1997), Ellingwood et al. (2004), Lee and Rosowsky (2005), van de Lindt et al. (2013) and Unnikrishnan and Barbato (2016). The three main vertical load path connections typically modeled are the roof sheathing, roof-to-wall, and wall-to-foundation connections. However, some studies, such as those by Maloney et al. (2018) and Masoomi et al. (2018), also considered roof coverings, windows, and doors in their analyses.

It is important to note that most studies focused solely on the effects of tornado uplift pressure and overlooked the contributions of lateral pressure. Additionally, all studies used the tornado load amplification factor recommended by Haan et al. (2010) to correct the ASCE/SEI 7–10 and 16 wind load calculation for tornado load demand, except for Roueche et al. (2024), which applied the tornado load equation from ASCE/SEI 7–22 Chapter 32. To further emphasize the importance of tornado-specific fragility modeling, Figure 7 compares fragility curves for tornado and straight-line wind events for a one-story wood-frame residential building, adapted from Masoomi et al. (2018). The curves demonstrate the higher probability of structural damage under tornado wind loads at lower wind speeds, reflecting the localized intensity and unique loading patterns of tornadoes compared to straight-line winds. This highlights the necessity for tornado-specific fragility functions to accurately assess building performance and inform resilience strategies. Readers are encouraged to refer to Masoomi et al. (2018) for a detailed description of the structure typology and fragility methodology used in generating these curves.

5 Summary of key findings with recommendations

This study presented a comprehensive review of tornado hazard risks to residential buildings from a structural engineering

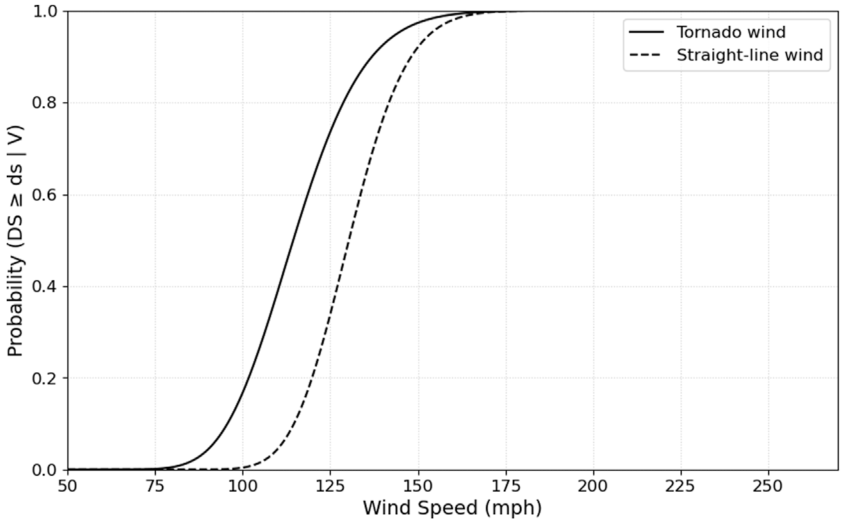

FIGURE 7
Fragility curve for tornado vs. straight-line wind for one story wood-frame residential building (adapted from Masoomi et al., 2018).

perspective. It highlighted the significant impact of tornadoes on residential structures and critically examined the current mitigation strategies outlined in existing building codes, post-tornado observation reports, and journal publications. The review revealed a continued gap in tornado provisions for residential buildings that until resolved will continue to lead to preventable damage, disruption, and loss of life. Additionally, this review explored how the application of community resilience modeling has been used to simulate building damage from tornadoes and evaluate enhancements to improve building resilience and reduce population dislocation. Highlights from the review include:

Highlights that until resolved will lead to continued vulnerability:

- Numerical and laboratory simulations show tornado-induced loads often exceed straight-line wind loads, influenced by roof geometry, building orientation, and tornado characteristics. Further research on interaction between internal pressures and atmospheric pressure drop is key to developing tornado load provisions for residential buildings.
- ASCE/SEI 7–22 does not include tornado load provisions for risk category II residential buildings, which leaves a significant portion of the housing stock vulnerable.
- On average, approximately 80% of damage paths in high intensity tornadoes are EF-2 or less, indicating that adoption of FORTIFIED standard or similar mitigation strategies used in hurricane prone regions will minimize damage to residential buildings during tornadoes.
- At least 50% of tornado-related deaths occurred in residential buildings which calls for the adoption of safe rooms in tornado prone regions, which include those in the middle of the country and hurricane-prone regions.
- According to post-disaster reconnaissance, due to inconsistent statewide building code adoption in some states, residential buildings are not constructed with consistent building codes.

Highlights that demonstrate the potential for enhancing tornado-resistant design of residential buildings:

- Buildings designed to meet the FORTIFIED Gold level can withstand wind speeds of up to 130 mph, nearly matching the maximum wind speed for an EF-2 tornado. Adopting the FORTIFIED standard can significantly mitigate property damage and save lives during severe weather events.
- Adoption rate of current IRC across the U.S is quite low, only about 33% of contiguous states have adopted the 2021 IRC edition.
- On average, approximately 70% of damaged residential buildings experienced documented during post-tornado reconnaissance studies were recorded as an EF-2 or less tornado intensity, indicating the need for stronger and more resilient structural component and connections.
- Globally, tornado-specific provisions are largely absent, with most countries addressing tornado hazards through general wind provisions in their building codes.
- Community-level resilience analysis can inform community resilience planning, enhance informed decision-making, and promote effective policies to guide communities toward faster recovery after a disaster.

5.1 Recommendations for the research community

- Future post-tornado studies should include detailed documentation of tornado gradient paths to improve the understanding of damage patterns, improve our understanding of tornadoes as a hazard, and inform better construction practices.
- Tornado pressure calculations should include lateral wind pressures in addition to uplift pressures when developing

fragility functions. This ensures a more comprehensive approach to building resilience against tornadoes.
- Laboratory simulations using small cubic models may not accurately replicate realistic tornadic wind pressures for residential buildings. There is a need to develop larger tornadic wind simulators that can accommodate more accurate building prototypes.
- Further empirical research is needed to validate fragility functions for various construction types under tornado loading conditions, providing more accurate risk assessments.
- A benefit-cost analysis of incorporating the tornado load provisions of ASCE/SEI 7–22 into risk category II buildings should be conducted to assess the economic viability of these updates.
- With new technologies emerging, research on advanced construction techniques such structural adhesives and improved metal connectors for robust connections in the structural load path is highly encouraged to enhance building resilience.
- More research is needed on effective retrofitting strategies and associated cost-benefit for existing buildings to meet enhanced tornado-resistant standards, especially in vulnerable communities.

5.2 Recommendations for policymakers

- Strengthen the adoption and enforcement of building codes across all tornado-prone regions to ensure consistent and resilient building designs. Additionally, ensure that older buildings are retrofitted to meet current building standards.
- Regularly update building codes to incorporate the latest research findings on tornado resilience, ensuring that all new construction is built to promote the health, safety, and welfare of the public.
- Provide financial incentives, such as tax breaks, insurance premium reductions, or grants, for homeowners and developers who incorporate tornado-resistant features into their residential construction projects.
- Implement policies that incentivize the presence of safe rooms in single- and multi-family homes and require them in mobile home parks located in tornado prone regions.
- Launch public education campaigns to inform the public about the effects of tornadoes on residential buildings and the importance of tornado-resistant construction and other mitigation strategies.
- Encourage the development of community-level preparedness plans that include tornado response and recovery strategies, ensuring a coordinated effort to protect residents.

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