Tornado Effects on Buildings

Are Target Performance Objectives Consistent with Recent Damage Observations?

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Severe tornados struck the central and southern United States late on December 10, 2021. The heavy damage and the associated loss of life, which received extensive coverage by U.S. media outlets and piqued the general public's interest, raised questions regarding the relative risks to structures from various natural hazards, including wind, tornadoes, earthquakes, floods, and fires. The damage from these tornados appeared to the casual observer disproportionate to the structural damage from other hazards such as hurricanes and earthquakes. Moreover, the tornado outbreak coincided with the release of ASCE 7-22, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, which includes a new Chapter 32 related to tornado loads and raised the profile of performance under tornado loads in the minds of practicing structural engineers. This article focuses on how risks associated with different hazards are considered by structural engineers in current design standards and whether the devastation observed in December 2021 is somehow inconsistent with these approaches.

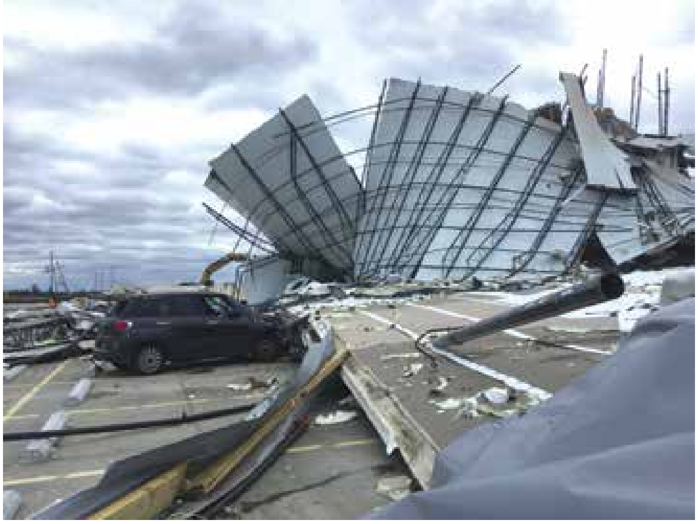

Figure 1. Structural damage to an Amazon facility in southern Illinois.

Risks Across Hazards in ASCE 7

Load combinations in ASCE 7 were calibrated initially to provide a level of reliability implied by the existing building stock in service several decades ago. The reliabilities of structures in resisting dead and live loads are the benchmarks for reliability for all other non-seismic loads. Leaving aside code adoption and enforcement, this suggests that, despite improvements to codes and standards over time, the structural failure risk (as represented by the occurrence of first yield in members) embodied in buildings constructed 30 to 40 years ago should not substantially vary from those designed according to current standards.

Observations of damage, tabulations of property losses, and numbers of injuries and fatalities caused by structural failures in earthquakes, hurricanes, and tornadoes do not merely reflect the current status of modern building codes and standards. Instead, they represent a complex mixture of factors, including code/standard evolution, regional and local building code adoption, variations in local code enforcement practices, willingness to increase construction costs, and perhaps the influence of climate change (and the associated increases in the frequency of extreme weather events).

The wind speed and seismic acceleration maps were updated in ASCE 7-10 to reflect a more consistent risk target considering structural failure across hazards. The former uniform-hazard ground snow load maps were replaced with risk-targeted maps in ASCE 7-22.

The target reliabilities for structures of various risk categories are (helpfully) stated directly in Section 1.3 of ASCE 7-22. Notably, the bases for seismic and non-seismic loads are somewhat different. Target reliabilities for the latter are for the failure of any member, whereas seismic reliabilities are based on the risk-targeted maximum considered earthquake (MCE_R). According to the standard, as described in Section 21.2.1 of ASCE 7-22, seismic design is expected to achieve a 1% probability of collapse within a 50-year period (or approximately a 2×10^{-4} annual collapse risk). On the other hand, the annual probability of member failure due to a non-seismic load in a Risk Category III building that does not lead to widespread damage progression is stated as being 1.25×10^{-5}.

The tornado wind speed maps added to the 2022 standard, combined with the accompanying modifications to analysis methods for tornado loads, are intended to achieve similar levels of reliability for new structures compared to the wind load provisions. There were media reports of a compromise within the ASCE 7 standard committee that limited the application of the tornado provisions to only Risk Category III and IV structures due to concerns about added construction costs in the building industry. In a private communication to the authors, a member of the ASCE 7 committee stated that these media reports included misquotations of ASCE 7 committee members and that the decision to limit the tornado provisions to Risk Category III and IV structures was included after a study showed that only these structures would be controlled by EF-0 to EF-2 tornadoes. The commentary to ASCE 7 states, "Risk Category II includes the vast majority of structures, including most residential, commercial, and industrial buildings." Therefore, only a small minority of structures will be subject to the new tornado provisions. Nevertheless, Designers and Owners can elect to use the new provisions for any structure. ASCE 7 represents *minimum* standards that can be exceeded.

December 2021 Tornado Outbreak

The tornados that struck the central and southern United States on December 10, 2021, inflicted heavy damage. Famous examples from southern Illinois and western Kentucky are shown in *Figure 1* and *Figure 2*. In Mayfield, Kentucky, a candle factory was heavily damaged while many employees were reportedly working inside.

The observed damage in Mayfield was classified as EF-4. According to the Enhanced Fujita Scale, a damage-based intensity scale, the wind speeds associated with EF-4 damage are estimated to be in the range of 166 to 200 mph.

The new tornado wind speed maps in Chapter 32 of ASCE 7-22 indicate that the occurrence of an EF-4 tornado at a building site in Mayfield, KY, corresponds approximately to an event with a 100,000-year return period (*Figure 3, page 10*). The occurrence of wind speeds that severe coming from non-tornadic events correspond to events with 1,000,000 year return periods, which is well outside the range of return periods one should expect to reasonably predict.

The ASCE 7-22 Tornado maps show that the tornado wind speeds at Mayfield for 40,000-square-foot Risk Categories III and IV structures (i.e., 1,700 and 3,000 year return periods) are 82 and 101 mph, respectively, which are substantially lower than the corresponding non-tornadic wind speeds of 113 and 118 mph. These lower tornado wind speeds reflect that ASCE 7-22 considers EF-0 to EF-2 tornados and not EF-3 to EF-4 tornados such as those that occurred during the December 2021 outbreak. Whether the new tornado provisions will impact construction in a place like Mayfield depends on aspects of the tornado wind load calculations other than the wind speed itself.

Computation of Main Wind Force Resisting System (MWFRS) uplift pressures on the windward roof edge of a Risk Category III, flat-roofed building in Mayfield that is 20 feet high, 100 feet wide, and 400 feet long shows that the tornado provisions in Chapter 32 of ASCE 7-22 give lower design pressures than the non-tornado wind provisions in Chapters 26 and 27. The details of the calculation are provided in the *Table (page 10)*. The augmentations of the exposure factor, internal pressure coefficient, and external pressure coefficients that account for special wind loading effects in tornados are not enough to make up for the significant differences in wind speed. Before the modifications to Chapter 32, the 82 mph tornado wind speed would produce only 53% of the pressure of the non-tornado wind speed of 113 mph, as the pressures are a function of the velocity squared. Therefore, for Risk Category III structures and below, the new tornado provisions either do not apply or would not provide more robust MWFRS designs than the conventional wind load provisions. This same analysis for a Risk Category IV structure shows that the tornado roof uplift pressures are 24% larger than those for non-tornado winds. Very few buildings fall into this category. The calculation of Components and Cladding (C&C) loads for roofs could exceed those for non-tornado winds due to variations in the tornado pressure coefficient adjustment factor that depend on roof zone and roof slope.

Mismatch between Tornados and Other Hazards

There is an apparent mismatch between tornado casualties and losses and those caused by other hazards. The damage and casualties from the December 2021 tornadoes were certainly newsworthy and appeared to the casual observer to be disproportionate relative to the impacts from other hazards. In fact, more people were killed between 1950 and 2011 by tornadoes than by earthquakes and hurricanes combined, and the Insurance Institute for Business & Home Safety (IBHS) reported that the insured losses from events involving tornadoes occurring between 1997 and 2016 were slightly larger than those for hurricanes and tropical storms. This range includes the especially active hurricane years of 2004, 2005, 2008, and 2012. One would intuitively guess that requiring structural engineers to deliberately consider tornado loads would reduce the disproportionate losses to life and property from tornadoes over the years as existing building stock is replaced. However, this may not be the case since the tornado provisions apply narrowly and may not produce MWFRS loads that control over non-tornado wind loads.

Figure 2. Candle factory in Mayfield, Kentucky, from October 2019 (top) and December 2021 (bottom). Courtesy of Google Earth and Maxar Technologies.

The authors are skeptical that the seeming mismatches between tornado impacts and impacts from other hazards are not a product of random chance. Earthquakes tend to cause many fatalities across a wide geographical region in a single event, but they do not happen very often. Similarly, a small number of hurricanes make landfall each year. On the other hand, tornadoes occur in large numbers, even if the majority of them are on the weak end of the spectrum. If an M8.0 earthquake were to occur on the San Andreas fault in Northern California, it is conceivable that accumulated earthquake damage and deaths could leapfrog tornadoes in an instant.

Given that the tornado damage that makes national headlines is often caused by events that we now would classify as quite rare (i.e., 10,000 to 500,000 year return periods) and that the contiguous United States has not yet experienced another seismic event comparable to the 1906 San Francisco earthquake, it is difficult to draw reliable conclusions regarding the apparent disproportionality of tornado impacts.

Impacts of Climate Change

Our estimation of structural risks due to weather-related hazards represents backward-looking snapshots. The spatial distributions and return periods of severe events will evolve over time with an evolving climate.

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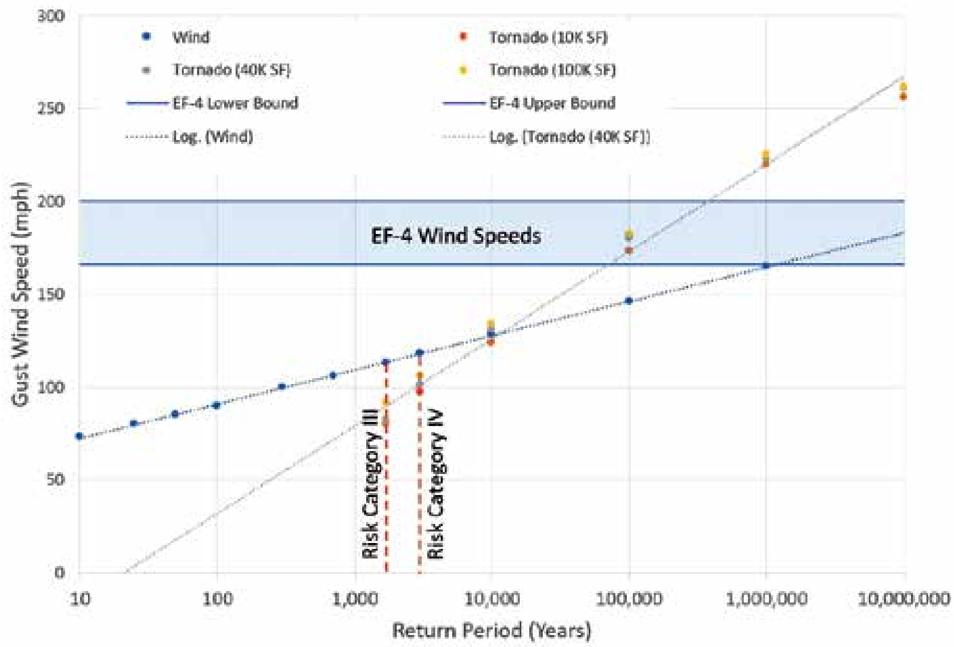

Figure 3. ASCE 7-22 Wind Speed Return Periods for Mayfield, Kentucky.

Table comparing MWFRS roof uplift pressures for a Risk Category III Structure in Western Kentucky.

	Non-Tornado	Tornado
Risk Category III Wind Speed	$V = 113$ mph	$V_T = 82$ mph
Exposure Factor h = 20 feet, Exposure Category C	$K_h = 0.9$ ASCE 7-22 Table 26.10-1	$K_{hTor} = 1.0$ ASCE 7-22 Table 32.10-1
Topographic Factor	$K_{zt} = 1.0$ ASCE 7-22 Section 26.8	N/A
Ground Elevation Factor considering elevation of 480 feet above sea level	$K_e = 0.981$ ASCE 7-22 Table 26.9-1	$K_e = 0.981$ ASCE 7-22 Section 32.9
Velocity Pressure (Also, internal pressure q_i for roofs)	$q_h = 0.00256\ K_h\ K_{zt}\ K_e\ V^2$ $q_h = 28.86$ PSF ASCE 7-22 Equation 26.10-1	$q_h = 0.00256\ K_{hTor}\ K_e\ V_T^2$ $q_h = 16.88$ PSF ASCE 7-22 Equation 32.10-1
Directionality Factor	$K_d = 0.85$ ASCE 7-22 Section 26.6-1	$K_{dT} = 0.80$ ASCE 7-22 Table 32.6-1
Gust Effect Factor	$G = 0.85$ ASCE 7-22 Section 26.11	$G_T = 0.85$ ASCE 7-22 Section 32.11
MWFRS External Pressure Coefficient for windward portion of flat roof	$C_p = -0.9$ ASCE 7-22 Figure 27.3-1 For h/L = 0.05	$K_{vT}\ C_p = (1.1)\ (-0.9) = -0.99$ ASCE 7-22 Table 32.14-1 for MWFRS roofs
Internal Pressure Coefficient	$GC_{pi} = 0.18$ ASCE 7-22 Table 26.13-1 for enclosed building. Positive value chosen since uplift pressure on roof is being considered	$GC_{piT} = 0.55$ ASCE 7-22 Section 32.12.2 and Table 32.13-1 for partially enclosed building. Positive value chosen since uplift pressure on roof is being considered
Roof Pressure	$P = q_h\ K_d\ G\ C_p - q_i\ K_d\ (GC_{pi})$ P = -23.2 PSF ASCE 7-22 Equation 27.3-1	$P = q_h\ K_{dT}\ G_T\ K_{vT}\ C_p - q_i\ (GC_{piT})$ P = -20.7 PSF ASCE 7-22 Equation 27.3-1

For example, recent research has shown that while the total number of tornadoes has not increased over the past few decades, their locations have. Tornados are occurring less frequently in the southern and central Great Plains and more frequently in the Southeast, Midwest, and Northeast of the U.S. Warmer oceans supply more energy to tropical cyclones, and storm severities associated with these weather systems are expected to increase.

Based on the latest research, we should expect regular, upward adjustments of design wind speeds for non-tornados and shifting contours on the tornado wind speed maps in ASCE 7 to keep up with climate trends and achieve the underlying risk targets in our designs.

Conclusions

News coverage of recent tornados suggests that these events cause disproportionate structural and life-safety impacts compared to other hazards such as earthquakes or non-tornadic wind events. If the damage is disproportionate, we must answer questions about whether structural engineers are treating all hazards consistently. However, the new tornado wind speed maps indicate that the recent instances of severe tornado damage that have caught our interest were exceptionally rare, with return periods far exceeding what structural engineers typically consider in design. Moreover, the lack of casualty and property loss data for earthquakes limits our ability to say whether these impacts were indeed disproportionate to what would be produced by a similarly rare seismic event in a heavily populated area. Since we cannot definitively conclude that the December 2021 tornado impacts were disproportionate to other hazards or with current expectations of performance, we must ask whether the destruction was acceptable and whether design targets should be adjusted across the board so that scenes like those we saw in southern Illinois and western Kentucky last year are prevented in the future.▪

References are included in the PDF version of the online article at **STRUCTUREmag.org**.

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