Comparative Reliability Analysis of Tornado Pressure

A case study of Matador tornado

Anamika Malla
a.malla@ttu.edu
National *Wind* Institute
Texas Tech University

Introduction

Tornados are violently rotating column of air that touches the ground and can cause widespread damage and pose significant threats to human safety, with 70% of the world's total tornadoes occurring in the United States. On average, 1,200 tornadoes result in 60 to 65 deaths and 1,500 injuries every year [1]. The tornado on June 21 in Matador, Texas claimed 4 lives, injured 15 people, and caused substantial damage [2]. Beyond the devastating human toll, the calamity poses substantial risks to the structural integrity of buildings and hence, tornado loads criteria are now mandated as the baseline design load for traditional building design in tornado-prone regions with the release of ASCE 7-22 [3]. As the light-weight low-rise building is the most common residential building in U.S, studies that expose their vulnerability will aid in disaster and community resilience but are wanted. This study examined the reliability of tornado design load of low-rise building using Monte Carlo simulation to calculate the probability of exceedance of tornado loads as described by ASCE 7 22 against Matador values.

Methodology

2.1 Tornado Modeling

ASCE 7 22, Chapter 32 describes the method to calculate tornado loads: the equation for tornado velocity is $q_{zt} = 0.613 K_{zTor} K_e V_T^2\ (m/s)$, where V_T is tornado speed, K_e is ground elevation factor, and K_{Tor} is tornado velocity pressure exposure coefficient. Accordingly, the tornado pressures p_T for a low-rise building can be determined by:

$$p_T = q\, G_T K_{dT} K_{vT} C_p - q_i (GC_{piT}) (N/m^2)$$

Where, G_T = Tornado gust-effect factor from Section 32.11, K_{dT} = Tornado directionality factor from Table 32.6.1, K_{vT} = Tornado pressure coefficient adjustment factor from Section 32.14, C_p = External pressure coefficient from Section 27.3.1 and (GC_{piT}) = Tornado internal pressure coefficient from Section 32.13.

2.2 Monte Carlo Simulation:

The study employed Monte Carlo to determine the probability of failure of a typical one-story building in Texas, US. The probability of failure for a limit state function $g(X)$ is defined as:

$$p_f = P(g(X) \leq 0) = \iiint_{g(X) \leq 0} f_X(X) dX = (R - S \leq 0)$$

Defining $g(X) = R - S,$ where R is resistance or design strength variables, and S is the loads or load combinations applied on the structure.

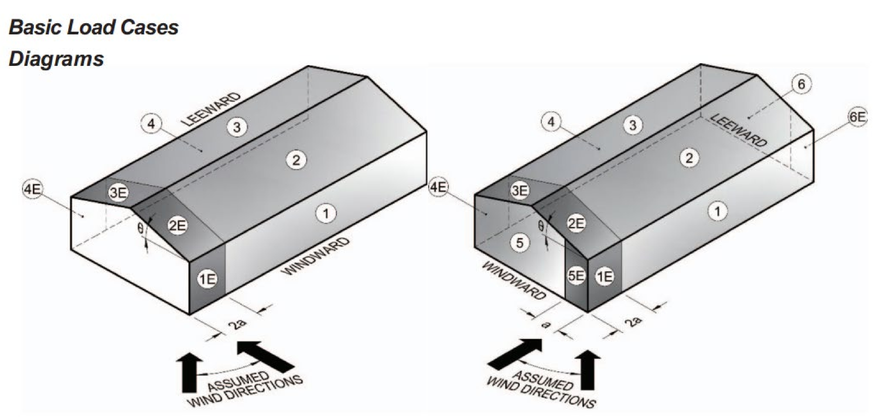

Figure 1: Allowable Case I (left) and Allowable Case II (right) as per ASCE 7-22 standard[3].

Figure 1 shows the load combinations for allowable design strength as per ASCE 7 22 : Load Case I - D+ 0.6 (W or W_T) and Load case II -0.6D + 0.6 (W or W_T), where W_T is the tornado pressure p_T and D is the Dead load of the structure.

2.3 Risk Assessment

The **Enhanced Fujita Scale (EF Scale)**, implemented on February 1, 2007, serves as a classification system to assign a rating to tornadoes based on estimated wind speeds and associated damage. During damage assessments, the observed destruction is compared to predefined Damage Indicators (DIs) and Degrees of Damage (DoD), aiding in the estimation of the likely range of wind speeds generated by the tornado. The scale ranges from EF0 to EF5, with each rating corresponding to a specific range of 3-second gust wind speeds: EF0 (65-85 mph), EF1 (86-110 mph), EF2 (111-135 mph), EF3 (136-165 mph), EF4 (166-200 mph), and EF5 (over 200 mph).

2.4 Selection of structure:

The Matador tornado developed in the southern Texas Panhandle and moved south-southeastward reaching Matador around 8pm on June 21, 2023 [2]. The tornado was classified as an EF-3, with consultation from Dr. Kishor Mehta and Dr. Delong Zuo from the Texas Tech University National Wind Institute. Figure 2 displays the low-rise flat roof building that was destroyed in the tornado located at the intersection of Bailey Avenue and Pipkin Street in Matador, Texas. The building resembles a typical one-story light-weight low-rise building in Texas, US.

Figure 2 : Track Map of Tornado - Matador, Texas (June 21, 2023)[2](bottom left), Building destroyed in Matador tornado(bottom right)(Bruce Haynie)[2], Google street view of building before Matador tornado (top).

Results

Table 1 summarizes the failure cases for various building components for allowable cases, Case I and Case II. In Case I, Building Components 1, 1E, 4, and 4E exhibit increasing P_f values from EF0 to EF5. Components 5 and 5E, however, display a consistent P_f of 0, indicating a low vulnerability. In Case II, all building components, except for 5E, demonstrate a P_f of 1 across all EF categories, suggesting a higher risk under this load scenario. These findings highlight the lack of sensitivity of the mean P_f to the chosen load case. The building surfaces have the same behavior for both allowable load cases.

	Building component	Mean Probability of failure (P_f) EF0	EF1	EF2	EF3	EF4	EF5
Allowable Case I	1	0.9983	1	1	1	1	1
	1E	1	1	1	1	1	1
Allowable Case II	1	1	1	1	1	1	1
	1E	1	1	1	1	1	1
Allowable Case I	4	0.9972	1	1	1	1	1
	4E	0.9983	1	1	1	1	1
Allowable Case II	4	1	1	1	1	1	1
	4E	1	1	1	1	1	1
Allowable Case I	5	0	0	0	0	0	0
	5E	0	0	0	0	0	0
Allowable Case II	5	0	0	0	0	0	0
	5E	1	1	1	1	1	1

A distinct limitation is the high probability of failure observed even at low tornado scales. Figure 3 plots the probability of failure of the model against Matador values. Leeward walls and Leeward roof have shown 0% probability of failure for all the cases, whereas the windward walls and windward roof have 100% probability of failure for Load Case II. The side walls shows 0% probability of failure for both cases however, the wall was damaged in the Matador tornado.

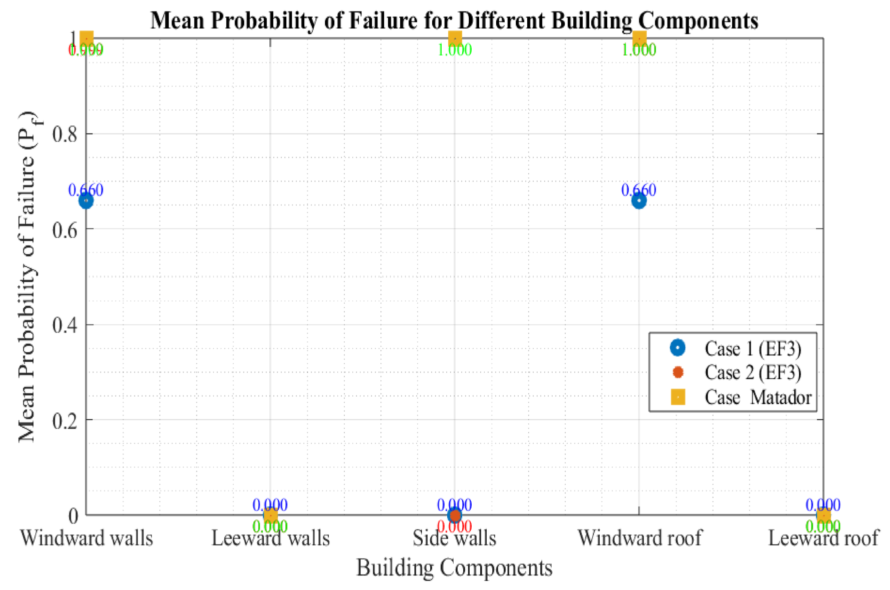

Figure 3 : Comparison of mean probability for Model and Matador values.

Conclusion

In conclusion, the comprehensive risk assessments evaluates the probability of failure (P_f) for different load cases and building components provide valuable insights into the structural vulnerabilities and resilience of the examined structures. The results indicate varying levels of vulnerability across different Enhanced Fujita (EF) scale categories, with windward walls and windward roof components exhibiting higher probabilities of failure, especially in EF3 to EF5 scenarios. The disparities between the calculated probabilities of failure for both load cases and the observed values from the Matador tornado are also shown. The notably high probability of failure for the windward roof in Matador, contrasting with the actual lack of damage, underscores the importance of refining and validating models to better capture real-world behavior. The study's insights contribute to advancing the understanding of structural resilience under tornado pressures, informing future design enhancements and risk mitigation strategies for improved overall safety and reliability.

References

1. Administration, N.O.a.A., A PREPAREDNESS GUIDE, U.S.D.O. COMMERCE, Editor., National weather Service: Online. p. 20.
2. Service, N.W. Matador Tornado. 2023; Available from: https://www.weather.gov/lub/events-2023-20230621-Matador
3. Engineers, A.S.o.C. Minimum design loads and associated criteria for buildings and other structures, ASCE/SEI 7-22. 2022. American Society of Civil Engineers.