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RISK-BASED LIFECYCLE BENEFIT-COST ANALYSIS FOR TORNADO HAZARD MITIGATION FOR WOOD-FRAME RESIDENTIAL BUILDINGS

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Abstract. *The increasing frequency and intensity of tornadoes, exacerbated by climate change, underscore the urgent need for resilient and economically sustainable infrastructure. This research evaluates the benefit-to-cost tradeoffs of designing risk category II wood-frame residential buildings to withstand tornado loads which currently lack coverage under the recent update to the ASCE/SEI 7-22 standard. The current standard newly incorporated design requirements for Risk Category III and IV buildings in tornado-prone areas, yet residential structures, which account for two-thirds of tornado-induced structural damage and most related fatalities, remain excluded.*

This study integrates probabilistic tornado hazard models with building fragility functions to evaluate the performance of minimum-standard and tornado-resistant residential buildings for up to EF-2 tornado-resilient designs. The resulting damage estimates are incorporated into a life-cycle cost model to calculate the expected economic losses due to tornado hazards over a building's lifespan. A subsequent benefit-cost analysis compares these losses with the benefits of implementing tornado-resistant design features. A Monte Carlo Simulation (MCS) is employed to quantify uncertainties in life-cycle cost and benefit-to-cost ratio (BCR) estimations. By generating stochastic samples for initial construction costs, additional cost due to tornado-resistant construction, and building damage ratios. The MCS produces robust statistical distributions of economic outcomes over varying analysis periods. The analysis focuses on one-story single-family wood-frame residential buildings located in tornado-prone regions as specified in the ASCE/SEI 7-22 tornado maps.

The study presents location-specific BCRs and net present costs due to tornado events over time for a one-story single-family home. The findings from this study provide valuable insights into the tradeoffs between upfront investments in resilience and long-term economic benefits.

1 INTRODUCTION

Tornadoes remain among the most severe natural hazards in the United States, causing more annual fatalities than earthquakes and hurricanes combined and resulting in higher insured losses than hurricanes and tropical storms combined [1]. In the first quarter of 2025 alone, over 500 tornadoes were recorded, with approximately 90% classified as EF-2 or lower [2]. This underscores the persistent threat posed by tornadoes and highlights the urgency of implementing effective mitigation strategies. Despite this reality, current residential building codes do not incorporate tornado-resistant requirements, leaving these structures vulnerable to significant damage and contributing substantially to disaster-related fatalities and financial losses. Notably, housing reconstruction and relocation constitute roughly half of the total disaster losses [3], further emphasizing the critical need for enhancing residential structural resilience.

Recent advancements have been made through the incorporation of tornado load provisions into the ASCE/SEI 7-22 standards, adopted into the 2024 International Building Code. This marks a landmark achievement mandating tornado-resistant design in tornado-prone regions for the first time. However, these provisions currently apply only to risk category III and IV buildings, omitting risk category II residential structures, which constitute the vast majority of residential buildings. Over 90% of residential construction in the U.S. consists of wood-frame structures [4], most of which remain vulnerable due to their exclusion from mandatory tornado-resistant provisions. Consequently, as rapid urbanization in tornado-prone regions continues, the potential exposure and subsequent risk are substantially increased [5], underscoring the urgency for adopting risk-informed hazard mitigation strategies. Thus, it is critically important that new residential construction in tornado-prone regions incorporate enhanced construction techniques and effective mitigation strategies.

Understanding the economic rationale behind adopting tornado mitigation measures is crucial to facilitating public acceptance and improving community resilience. As of early 2025, approximately 35% of jurisdictions vulnerable to natural hazards have adopted up-to-date hazard-resistant building codes [6], which signifies growing recognition but also highlights that a substantial gap remains. Benefit-Cost Analysis (BCA) emerges as a valuable tool for evaluating financial viability, yet its application specifically to tornado-resistant designs in residential wood-frame buildings remains limited in existing literature. Filling this gap through risk-based lifecycle cost analyses can inform homeowners, stakeholders, and policymakers of the long-term benefits and economic feasibility associated with adopting enhanced structural resilience measures.

This study employs a Performance-Based Engineering (PBE) framework integrated within a lifecycle cost analysis to evaluate the economic and structural feasibility of incorporating tornado-resistant design strategies into residential buildings, specifically addressing designs capable of withstanding tornadoes rated up to EF-2. By leveraging probabilistic tornado hazard modeling, system and building-level fragility analyses, and comprehensive benefit-cost assessments, this research illustrates the logic behind mitigation requirements, highlighting how investments in structural enhancements can lead to substantial resilience dividends. These insights can ultimately support informed decision-making and advocate for broader adoption of tornado-resistant building practices, substantially mitigating future human and economic losses.

2 BENEFIT-COST ANALYSIS FOR TORNADO HAZARD STUDIES

The low probability of a tornado striking a specific building may discourage the consideration of long-term benefits versus the initial investment in tornado-resistant construction by codes and standards committees. Several studies have shown that tornado mitigation strategies for residential buildings are economically viable through BCA. For example, enhanced building codes implemented in Moore, Oklahoma, demonstrated a Benefit-Cost Ratio (BCR) of approximately 3 to 1 for the entire state [7]. A further study by Simmons and College [8] reported an even higher BCR of 6 to 1 by including deductibles, code improvements, and losses from homes built to the wind-resistant designs.

A broader analysis by Simmons et al. [9] covering 20 states found positive BCRs in eight states, with three states showing paybacks within 20 years, which highlight the broader applicability and benefit of adopting wind-enhanced building codes. Additionally, Ghosh et al. [10] assessed the costs and benefits of achieving FORTIFIED home designations in Oklahoma, noting that the incremental costs ranged from about 1.1 to 2.25% of home's sale price. The reported costs are consistent with the 1 to 3% range identified by Gould [11] but fall below the 3% to 7% range indicated by the FORTIFIED program director [12]. These variations in reported initial investment are crucial for the BCA as they provide essential context for understanding the upfront financial requirements associated with adopting tornado-resistant design practices. Although these incremental costs might appear relatively minor compared to the total value of a home, they represent significant considerations when evaluating the practicality and broader implementation of tornado mitigation strategies in residential construction due to socioeconomic disparity between homeowners [13]. Although these studies affirm the potential economic benefits of enhanced construction standards, they have not extensively applied probabilistic approaches to address uncertainties inherent in tornado hazard modeling and structural performance.

This gap highlights the necessity for comprehensive, risk-based lifecycle benefit-cost analyses that can more accurately inform homeowners, stakeholders, and policymakers about the economic viability of investing in tornado-resistant residential construction.

3 METHODOLOGY

This study integrates probabilistic tornado hazard models with building fragility functions to evaluate the performance of minimum-standard and tornado-resistant residential buildings for up to EF-2 tornado-resistant designs. This study exclusively evaluates EF-2 or lower as a practical design limit for ensuring adequate performance of light-frame wood buildings under tornado conditions [14-15]. The framework for the risk-based BCA is illustrated in Figure 1 and the flow chart for the Monte Carlo simulation employed to quantify uncertainty in the lifecycle cost and benefit-cost ratio estimation is shown in Figure 2.

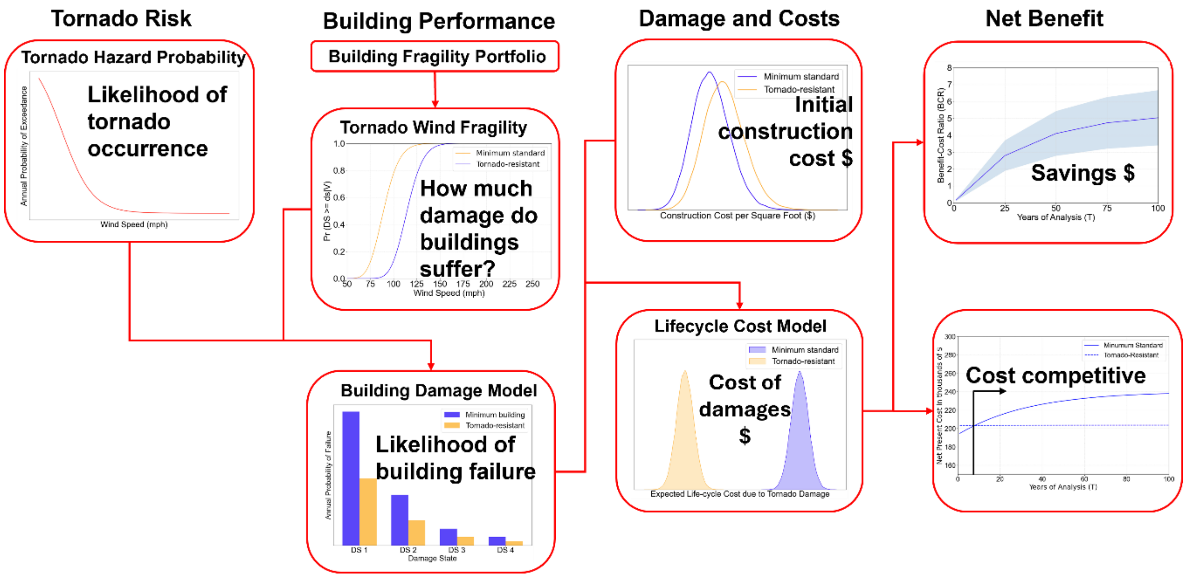


Figure 1: Lifecycle benefit-cost generalized framework for tornado-resistant design of residential buildings

First, the annual probability of failure of a building given by Equation 1 is estimated by convolving the tornado hazard probability, $H(x)$ curve with the building fragility curve, $F\,(x)$ for both minimum and tornado-resistant buildings.

$$P_{Af} = \int_{0}^{\infty} F(x)\, H(x)\, dx \tag{1}$$

The tornado hazard probability curve is fitted using Gumbel (type I) distribution expressed as Equation 2:

$$H(x) = P(> x) = 1 - \exp\left(-\left(exp - \left(\frac{x - U}{a}\right)\right)\right) \tag{2}$$

where U and a are the mode and scale parameters of the Type I distribution.

Fragility functions serve as a key tool in capturing the inherent uncertainties in structural and non-structural performance following a tornado event. Fragility functions provide the probability that a component reaches or exceeds a defined damage state at a given hazard intensity. Building component failure is assumed to occur when the applied tornado wind load, W exceeds the sum of the component's dead load, D and resistance, R, expressed as Equation 3:

$$W > D + R \tag{3}$$

Damage probabilities are quantified through fragility functions of the form (Equation 4):

$$P\,(DS \geq ds | D = x) \tag{4}$$

where DS is the specific damage state and D is the hazard intensity.

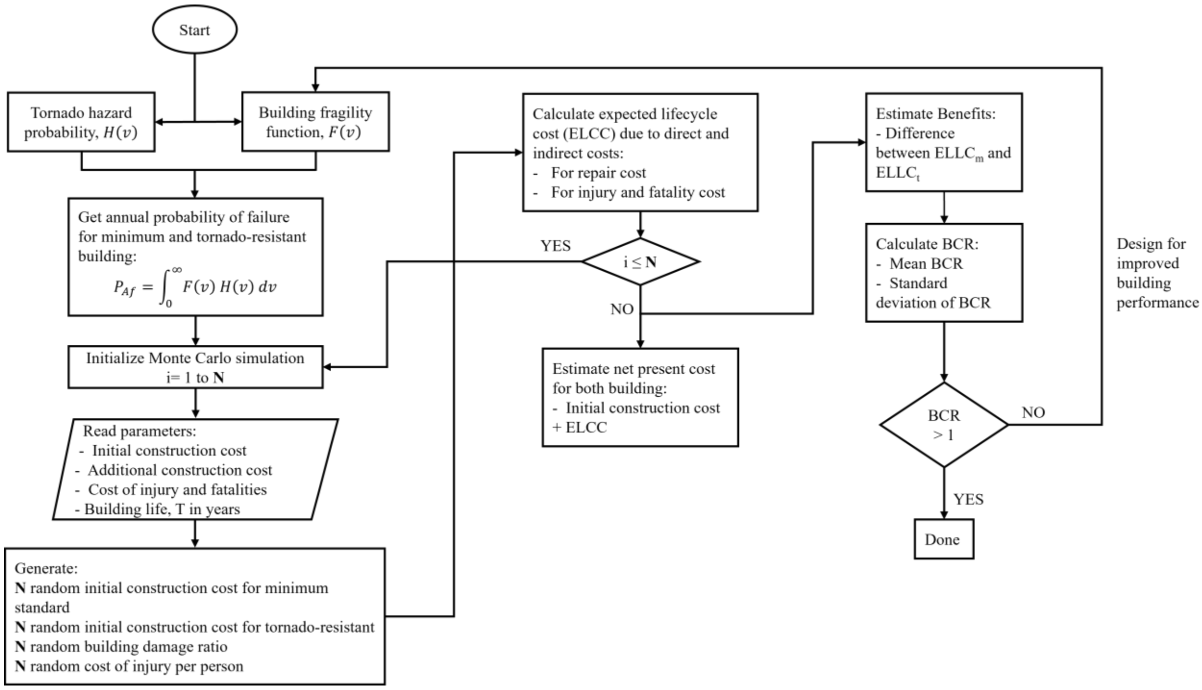


Figure 2: Flowchart showing methodology of the developed framework

These component-level functions are combined to derive building-level fragility, typically represented by a lognormal cumulative distribution function expressed as Equation 5 [16]:

$$F(x) = \varphi \left[\frac{In\,(x) - \mu}{\sigma}\right] \tag{5}$$

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

It is important to note that the tornado-resistant improvements considered in this study focus specifically on roof structures as the roof is frequently the first point of failure in tornado events [17-20]. The evaluated tornado-resistant measures include increased sheathing thickness, closer nailing patterns, and the use of hurricane straps at roof-to-wall connections [21]. Improvements to other structural elements such as walls and foundations are not considered here, based on the tornado building fragility functions available in the literature and the assumption that maintaining roof integrity significantly reduces overall building damage.

Tornado occurrences can be modeled as a Poisson process, assuming events are random, occur independently, and follow a constant annual rate [22]. Based on this assumption, the expected lifecycle cost, $ELCC$ of a building due to tornado hazards over a defined service period T is estimated in present value terms. This follows the formulation outlined by Ellingwood and Wen [23] and Padgett et al. [24], which integrates hazard occurrence, damage state probabilities, and consequence costs given as Equation 6:

$$ELCC = \frac{1}{d * T}(1 - e^{-d*T}) \sum_{j=1}^{N_{ds}} \left\{-C_j \left[\ln\left(1 - p_{(f,t)_j}\right) - \ln\left(1 - p_{(f,t)_{j+1}}\right)\right]\right\} \tag{6}$$

where d is the discount rate, N_{ds} is the number of damage states, C_j is the cost in present dollars of losses associated with damage state j including cost of repair, injuries and fatalities, and $p_{(f,t)_j}$ represents the cumulative probability of failure for damage state j over years T expressed as Equation 7:

$$p_{(f,t)_j} = 1 - \left(1 - p_{f,1}\right)^T \tag{7}$$

The $ELCC$ reflects both direct repair costs and indirect losses, including injuries and fatalities, across all defined damage states. To capture the stochastic nature of this analysis, a Monte Carlo Simulation (MCS) is implemented with 10,000 iterations (see Figure 3 for MCS flowchart). Within this simulation, key input parameters such as initial construction costs, additional cost for tornado-resistant measures, building damage ratios, and casualty-related losses are treated as random variables. The *damage ratio* is defined as the proportion of the building's replacement value lost due to damage from a tornado, varying across different damage states. In the simulation, damage ratios are used to estimate the expected repair costs based on the severity of damage for both minimum code and tornado-resistant design cases. These variables are drawn from appropriate probability distributions to simulate a range of potential outcomes for both minimum code and tornado-resistant design cases.

The economic benefit, B_t of adopting tornado-resistant measures is quantified as the difference in expected lifecycle cost between minimum, $ELCC_m$ and tornado-resistant, $ELCC_t$ design. To evaluate cost-effectiveness, the Benefit-Cost Ratio (BCR) is then calculated by dividing the projected B_t by the additional upfront cost of tornado-resilient construction, $Cost_T$ determined by Equation 8:

$$BCR = \frac{B_t}{Cost_T} \tag{8}$$

4 CASE STUDY

To illustrate the core concepts of the framework introduced above, a representative one-story, single-family wood-frame residential building with an area of 125 m^2 (1350 ft^2) and a gable roof is selected as the case study. It is important to note that most residential wood-frame buildings in the U. S. are not formally engineered; rather, they follow the prescriptive guidelines set forth in the International Residential Code (IRC) where buildings codes are adopted. The archetype used in this study, originally developed by Amini and van de Lindt [25], reflects a typical home found in tornado-prone regions and has been widely adopted in previous research for evaluating wind-related fragility [21], [26]. In modeling building performance, four damage states are considered, ranging from minor damage (Damage State 1) to complete destruction (Damage State 4), following the classification developed by Masoomi et al. [21].Detailed resistance and performance data for this archetype were sourced from Masoomi et al. [21], who developed fragility functions for tornado scenarios. In this study, buildings categorized as minimum standard are constructed in accordance with the 2018 IRC, while the tornado-resistant standard follows the enhanced roof system configuration outlined in Masoomi et al. [21].

Figure 3 presents the schematics of the selected building archetype and its corresponding fragility curves under both minimum and tornado-resistant design standards. In Figure 3, the solid lines represent the fragilities of the tornado-resistant building while the dashed lines represent the minimum standard version. At the 50th percentile, a difference of approximately 25 to 40 mph in wind speed is observed between the two designs, highlighting a substantial improvement in performance for the tornado-resistant structure across varying levels of tornado intensity.

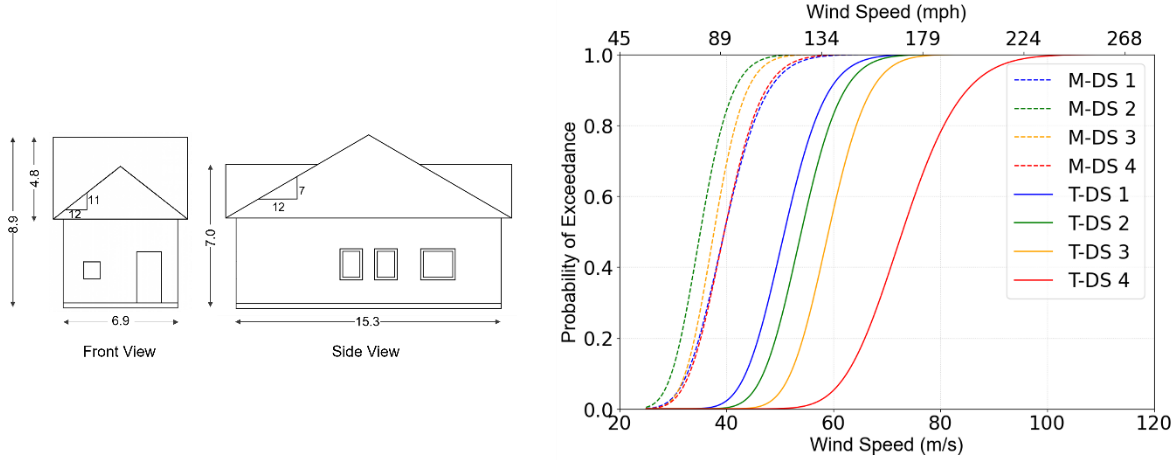


Figure 3: Building schematic with associated fragility curves (M=minimum standards; T=tornado resistant; DS=damage state; units in meters) (Adapted from Massomi et al. [21]

To account for regional variability in tornado exposure, this study considers two study locations: Oklahoma City, Oklahoma, which represents a high tornado hazard environment, and Springfield, Illinois, which represents a moderate tornado hazard level. Tornado hazard probabilities for each location were developed based on the ASCE/SEI 7-22 tornado maps for Risk Category III buildings with an effective area of 185 m^2 (2,000 ft^2). The hazard curves were then fitted using Gumbel extreme value distributions as given by Equation 2. For Oklahoma City, the fitted parameters were U = -68.92 and a = 20.73; the parameters for Springfield were U = -91.9 and a = 20.28. The fitted hazard curves are shown in Figure 5.

Uncertainty in initial construction cost is a critical input to the lifecycle analysis. In this study, baseline construction costs for minimum standard homes were obtained from *Today's Homeowner* [27], which provides national average cost estimates. These values are modeled as a lognormal distribution with a coefficient of variation (COV) of 0.2 to reflect local and regional variability.

The incremental cost associated with adopting tornado-resistant construction is less well documented. While some hurricane mitigation studies suggest a 1 - 10% range [28-32], the FORTIFIED Gold designation has reported a range between 3 and 7% [12]. To account for this variability, this study models the additional cost as a random variable with a mean of 5% and the same COV as the initial cost. Figure 6 shows the distribution of simulated initial construction costs for both locations.

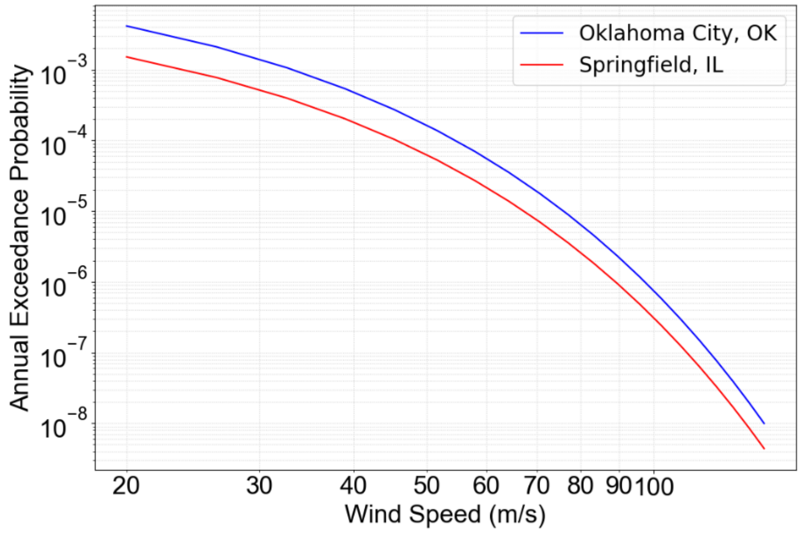
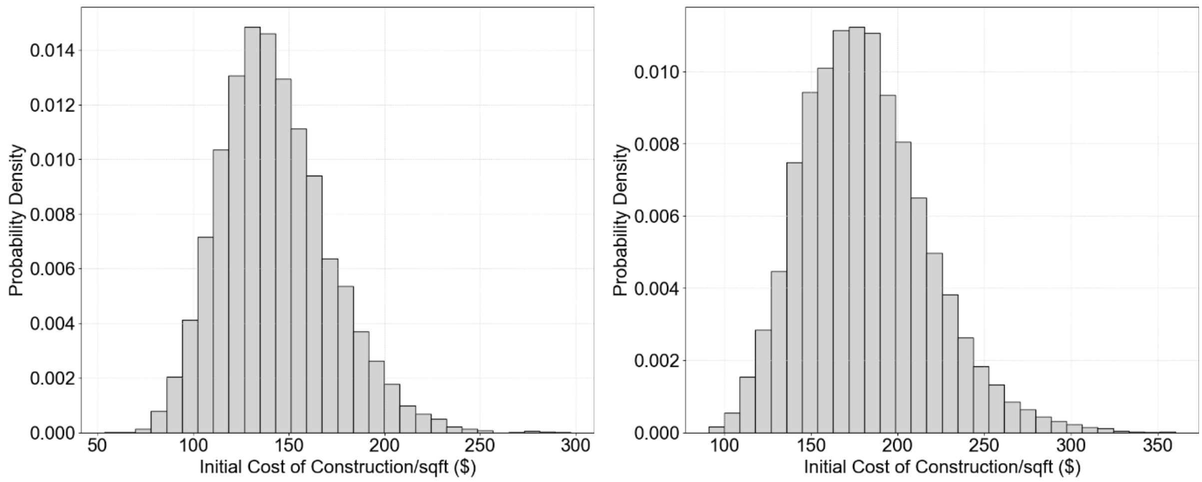


Figure 3: Tornado hazard probability for study locations

Table 1 summarizes the key parameters used for each design standard, including damage ratios, injury rates, and fatality rates per damage state. The damage ratio values are synthesized from several prior studies [31-33], while injury costs are modeled between $7,000 and $14,000 per person, and the cost of a fatality is set at $4 million per person, consistent with estimates from Ellingwood and Wen [23] and Li [28].



a) b)

Figure 4: Simulated initial construction cost for: a) Oklahoma City, OK; b) Springfield, IL

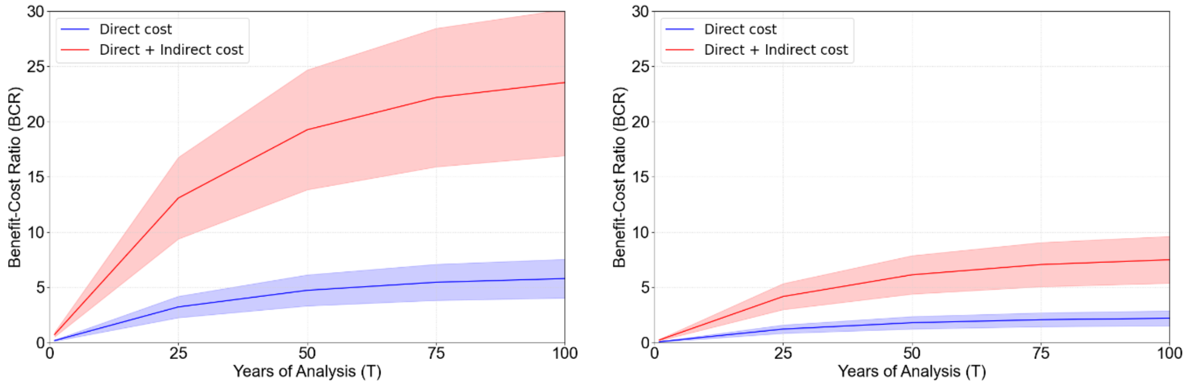
To discount future costs to present value, a 3% discount rate is applied. This rate is recommended by the U.S. Office of Management and Budget for economic evaluation of federal programs [34] and is commonly used in resilience-focused infrastructure studies.

Table 1: Parameters for cost components

Damage state	Damage ratio	Injury rate	Fatality rate
1	0.01 – 0.1	0	0
2	0.1 – 0.3	0.1	0.01
3	0.3 – 0.6	0.2	0.02
4	0.5 – 1.0	0.6	0.04

5 RESULTS

Following the steps outlined in the previous sections, the expected lifecycle cost due to tornado damage was estimated, and the Benefit-Cost Ratio (BCR) and Net Present Cost (NPC) values were determined. Figures 5 illustrate the BCR for tornado-resistant construction in Oklahoma (Figure 5a) and Springfield (Figure 5b) under the EF-2 or less intensity threshold. In these figures, the blue lines represent the BCR calculated using direct costs only, while the red lines show the BCR when both direct and indirect costs (including injuries and fatalities) are incorporated. The shaded areas around the lines represent the variability in the calculations over time. Both figures demonstrate that the BCR increases as the analysis period progresses.



a) b)

Figure 5: BCR over building life: a) Oklahoma City, OK; b) Springfield, IL

For a 50-year building life, the BCR values considering only direct costs range from approximately 3.0 to 6.0 and increase to around 13.0 to 24.0 when indirect costs are included for Oklahoma City, OK. This indicates that tornado-resistant construction in Oklahoma becomes increasingly cost-effective as the building ages, with indirect costs associated with potential injuries and fatalities playing a crucial role in enhancing the overall benefit. Similarly, for Springfield, IL, the BCR trends show a gradual increase over time. While the direct cost

BCR is lower than that of Oklahoma, which is expected given the relatively lower tornado hazard in Springfield, the inclusion of indirect costs leads to a significant increase in the BCR. This makes tornado-resistant measures more attractive over time. The gap between the direct and indirect cost BCRs also widens in Springfield, suggesting that although the upfront costs are somewhat lower, the long-term benefits, including the avoided costs of injuries and fatalities, remain substantial.

The magnitude of the NPC is determined by the expected lifecycle cost due to tornado damage and the initial construction cost for both minimum standard and tornado-resistant buildings. Figure 6 shows the NPC for minimum standard (M) and tornado-resistant (T) designs in Oklahoma City, OK, and Springfield, IL. The solid lines represent the NPC for minimum standard buildings, while the dashed lines show the NPC for tornado-resistant buildings. Figure 6 plots the net costs, which include both the initial construction cost and the expected future losses due to tornado damage.

For Oklahoma City, the NPC for the tornado-resistant design (T) begins with a higher initial cost than the minimum standard design (M) but increases at a slower rate over time. This reflects the high initial investment required for tornado-resistant measures, which is offset by reduced damage and losses over time. Within a year, the tornado-resistant design becomes cost-competitive, which can be observed when the solid lines cross over the dashed line. In contrast, for Springfield, IL, a similar pattern is observed, although the rate of increase in NPC for tornado-resistant buildings is more gradual. The initial difference between minimum standard and tornado-resistant designs is greater in Springfield compared to Oklahoma, likely due to the lower tornado risk. However, the tornado-resistant design still offers long-term benefits, with the NPC for the tornado-resistant design eventually surpassing that of the minimum standard design after approximately six years.

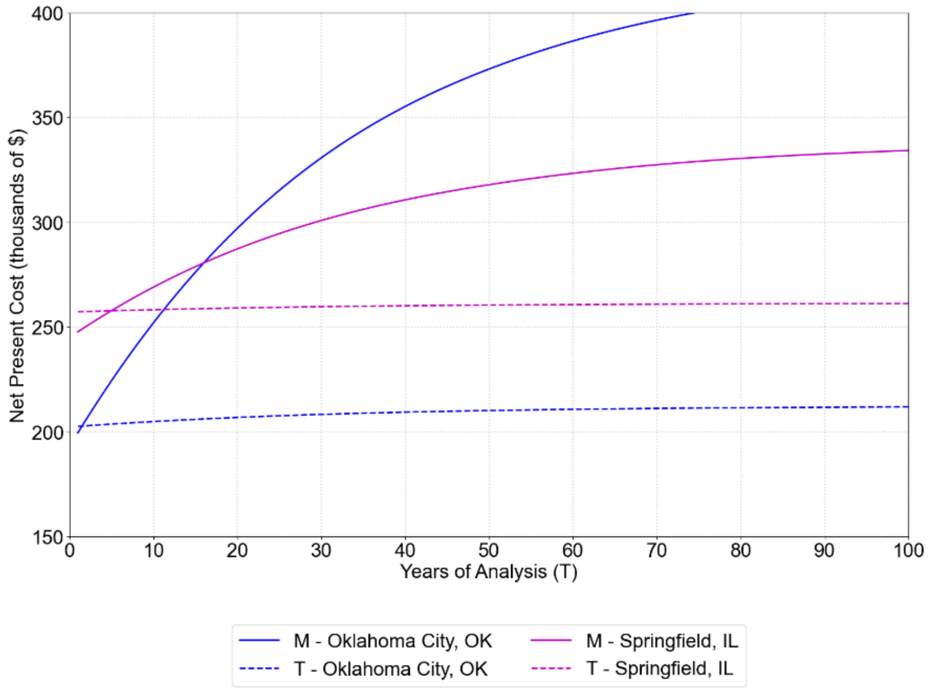


Figure 6: Estimated cost due to initial construction and estimated loss due to an EF-2 tornado or less

6 CONCLUSIONS AND FUTURE WORK

This study underscores the critical need for conducting a risk-based lifecycle benefit-cost analysis to evaluate the economic viability of tornado-resistant construction in residential buildings. By integrating probabilistic tornado hazard models with fragility functions and lifecycle cost analysis, this approach provides a comprehensive assessment of the long-term economic benefits and risks associated with tornado mitigation strategies. The findings reveal that tornado-resistant design measures, such as enhanced roofing systems, not only reduce repair costs but also significantly improve safety by decreasing fatalities and injuries. The economic analysis suggests that investing in tornado-resistant construction can reduce on average $18 in damages for every dollar spent on mitigation, emphasizing the importance of both immediate and long-term financial considerations in high-risk tornado areas.

A key finding from the benefit-cost analysis is that tornado-resistant construction becomes cost-competitive with minimum standard building practices within 1 to 10 years, depending on the location's tornado risk. High-hazard areas, such as Oklahoma City, see faster returns on investment, while more moderate-risk areas, like Springfield, experience a longer time frame for cost parity to be reached. This illustrates the substantial long-term value of investing in tornado-resistant designs, especially considering the increasing frequency and severity of tornado events and the catastrophic costs they impose on communities.

Furthermore, tornado-resistant construction not only provides immediate economic benefits by reducing damage costs but also has the potential to enhance property values. Homes with higher resilience features are more attractive to buyers, particularly in high-wind-prone areas. Studies indicate that such homes can see a nearly 7% increase in resale value [35], further justifying the initial investment.

Building upon the findings of this study, next steps involve incorporating additional building archetypes and geospatial mapping of the Benefit-Cost Ratio (BCR) across the United States, considering regional variations in tornado risk. This analysis will expand the current study by integrating data from additional tornado-prone regions, offering a more comprehensive view of the economic feasibility of tornado-resistant designs. This could inform future construction practices and potentially lead to the development of regional guidelines that address specific risks based on local hazard profiles. Additionally, future research will incorporate a wider range of indirect costs, such as the economic impact of debris removal and relocation caused by tornadoes. By expanding the scope of the analysis and incorporating more indirect costs, the results will provide a more robust understanding of the economic viability and resilience benefits of tornado-resistant construction, potentially influencing policy, building codes, and community resilience planning.

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