EVALUATING THE BENEFIT-TO-COST TRADE-OFFS OF EXTENDING TORNADO LOAD PROVISIONS TO RESIDENTIAL BUILDINGS

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INTRODUCTION

Tornadoes are one of the most formidable natural hazards in the United States, accounting for more annual fatalities than earthquakes and hurricanes combined, and more insured losses than hurricanes and tropical storms combined. Yet tornadoes are not considered in the residential building codes which are frequently damaged and destroyed by tornadoes.

Figure 1: Observed Damage after 2020 Nashville Tornado (National Weather Service, 2024)

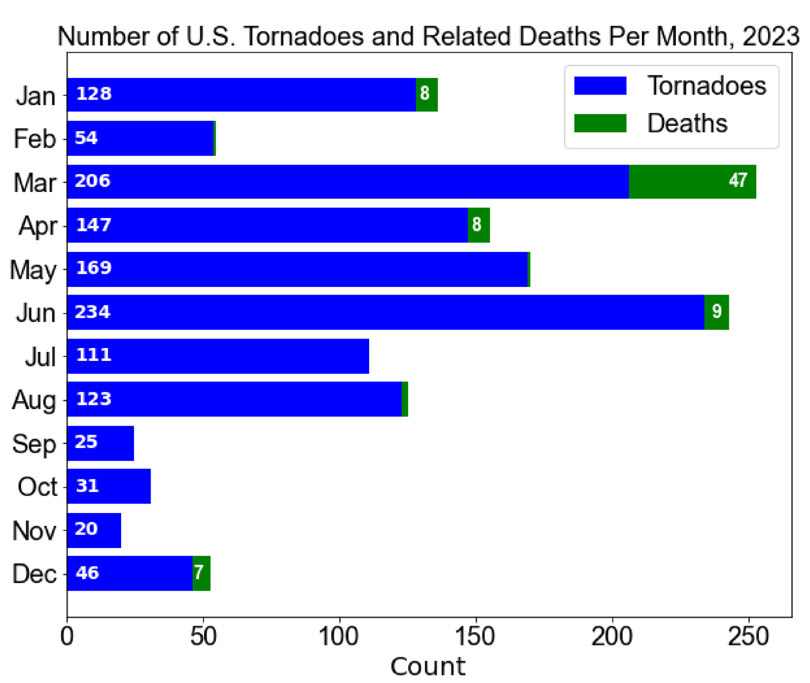


Figure 2: No. of US Tornadoes and Deaths Per Month, 2023 (Insurance Information Institute, 2023)

- Over 1,200 tornadoes are reported annually.
- Tornadoes can occur at any time of the day and year, most common in later afternoon and in the spring.
- Each year dozens of people are killed by tornadoes, including 83 reported tornado-caused deaths in 2023 alone.

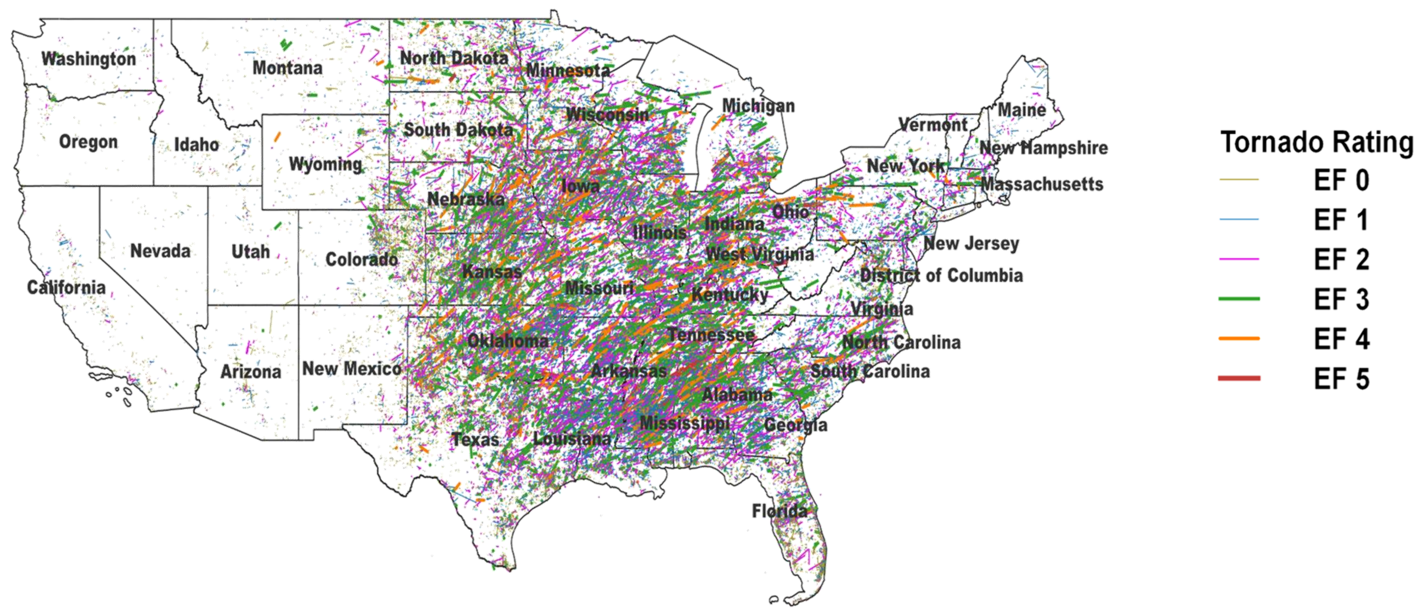


Figure 3: U.S. Tornado Tracks between 1950 and 2022 (Data from Storm Prediction Center)

BUILDING CODE COVERAGE

- Until 2022, only nuclear facilities, storm shelters and safe rooms were required by building codes and standards to be designed to withstand tornado loads.
- In 2022, provisions for tornado loads were adopted into the ASCE/SEI 7-22 standard, which was then adopted into the 2024 version of the International Building Code.
- The ASCE/SEI 7-22 provisions are applicable for Risk Category III and IV buildings which do not include residential buildings.

CHALLENGES

- 95% of recorded tornadoes are EF 2 or below
- Tornado paths are very localized compared to other hazard's impacted areas
- Residential buildings consist of two-thirds of tornado-induced damage

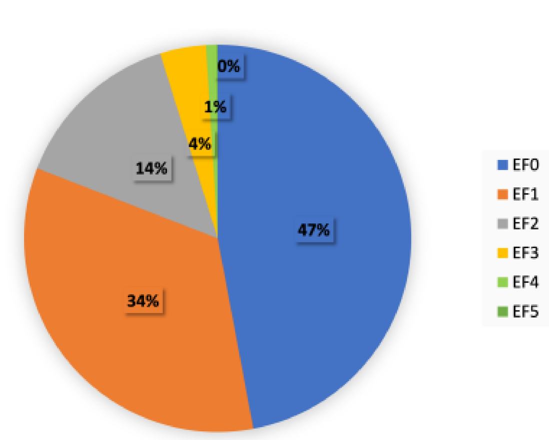
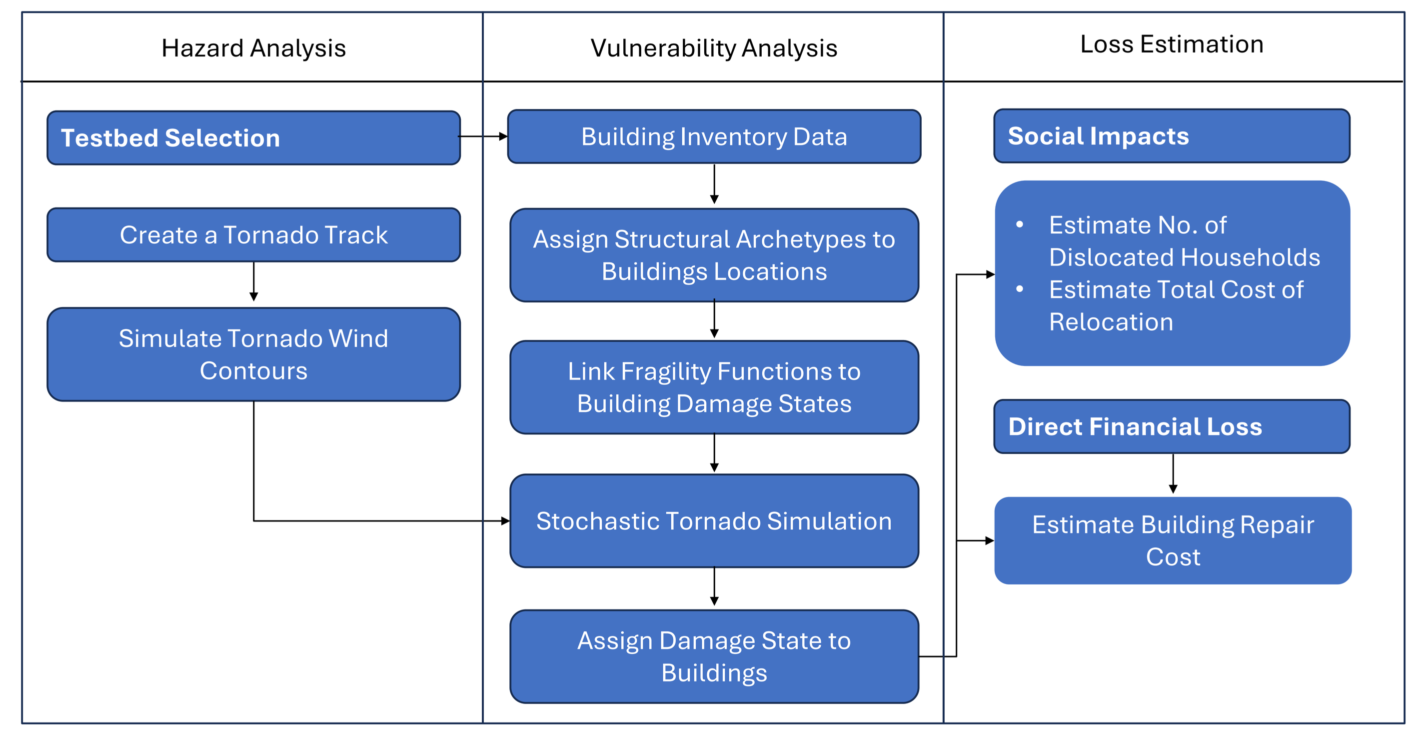


Figure 4: Tornado Occurrence by EF Rating (Kirkham, 2022)

OBJECTIVES

Evaluate benefit-cost trade-offs of incorporating tornado loads into the structural design of Risk Category II residential buildings considering life cycle impacts under specified tornado scenarios.

TORNADO IMPACT FRAMEWORK



BUILDING ARCHETYPES

Five structures are selected to represent typical U.S. residential construction. Three of structures were originally developed by Nofal and van de Lindt (2020) (shown here). The other two archetypes considered in this research are a single-wide and double-wide manufactured home.

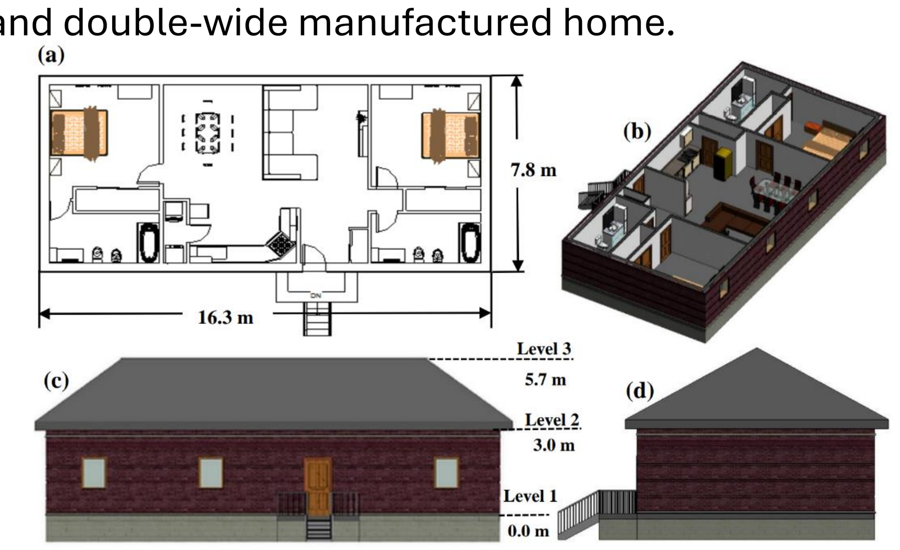


Figure 5: One-story Single-Family Home (Nofal and van de Lindt (2020) a) Plan view; b)3-D view; c) Front view; d)Side view

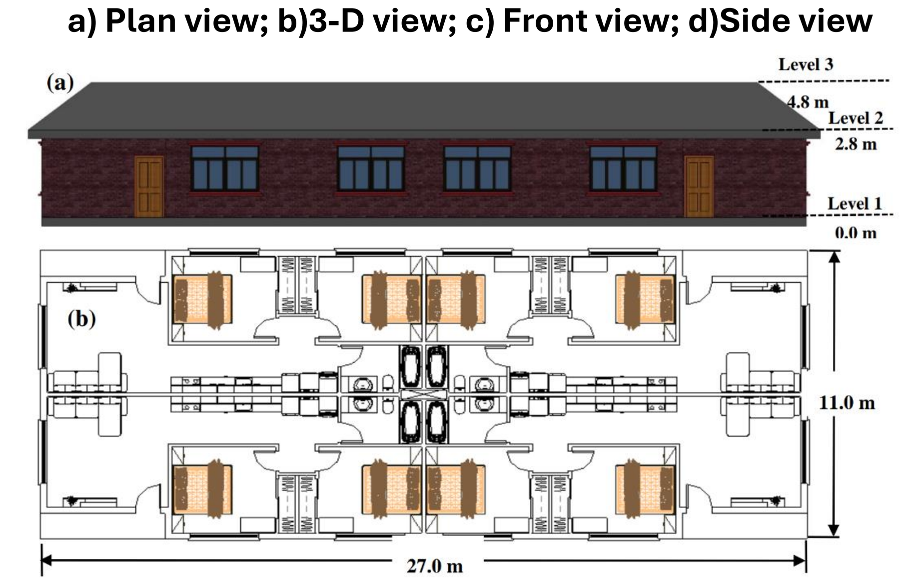
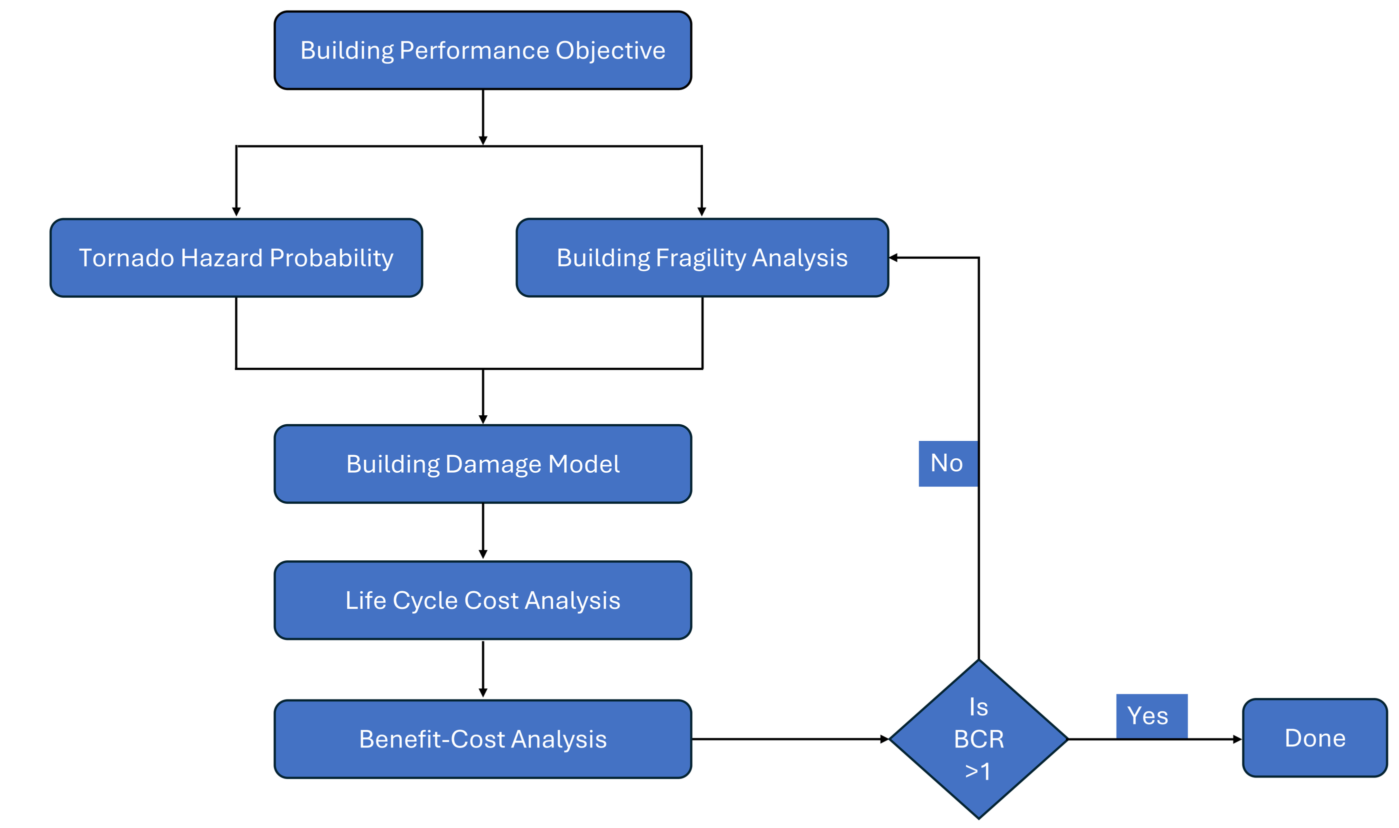


Figure 6: One-story Multi-Family Home (Nofal and van de Lindt (2020) a) Front view; b) Plan view

Figure 7: Two-story Single-Family Home (Nofal and van de Lindt (2020) a) 1st-story plan view; b)2nd-story plan view; c) 1st-story 3-D view; d) 2nd-story 3-D view ;e) Building 3-D view

BENEFIT-COST ANALYSIS FRAMEWORK



LIFE CYCLE BENEFIT-COST ANALYSIS

Quantifying the expected life-cycle cost of hazards would require assessing the likelihood of exceeding different damage states. The annual probability of exceeding each damage state can be evaluated by convolving the associated fragility with tornado hazard curve $H(v)$ as shown below (Standohar-Alfano and van de Lindt, 2015):

$$p_{Af} = \int_0^{\infty} \Pr(DS > ds | D = x) \left[\frac{dH(v)}{dv}\right] dv$$

The expected life cycle cost due to tornado in present value can be expressed as (Padgett et al., 2010; Noshadravan et al., 2017):

$$ELCC_T = \frac{1}{d*T}\left(1 - e^{-d*T}\right) \sum_{j=1}^{N_{ds}} \{C_j[In(1 - p_{Tfj}) - In(1 - p_{Tfj+1})\}$$

$C_j = cost\ associated\ with\ damage\ represented\ as\ a\ percent\ of\ loss\ relative\ to\ the\ initial\ value\ of\ the\ building;\ N_{ds} = Number\ of\ damage\ state;$
$d = real\ discount\ rate;\ T = year\ of\ analysis\ period$
$p_{Tfj}\ is\ the\ T - year\ probability\ of\ exceeding\ a\ damge\ state, estimated\ as$:
$p_{Tfj} = 1 - (1 - p_{Af})^T$

The benefit of a particular performance objective is evaluated as the difference between the expected present value of the losses with minimum standard, $ELCC_{Min.Standard}$ and the present value of the losses with tornado-resistant, $ELCC_{Tornado-resistant}$ as shown below:

$$Benefit, B_T = ELCC_{Min.Standard} - ELCC_{Tornado-resistant}$$

The benefit-cost ratio (BCR) for a particular performance objective is assessed as the ratio between the net present value of the investment in tornado-resistant and the initial cost of the tornado-resistant building, C_T:

$$BCR_T = \frac{B_T}{C_T}$$

FUTURE WORK

- Assign Building Archetypes and Fragility Functions along Tornado Tracks
- Estimate Building Damage States
- Estimate Household Dislocation
- Estimate Building Repair Cost
- Evaluate Benefit-Cost Ratio at Building-, Community-, and National-levels

ACKNOWLEDGEMENT

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