THESIS

LIFE-CYCLE COST AND CARBON-FOOTPRINT ANALYSIS FOR BUILDINGS AND COMMUNITIES SUBJECTED TO TORNADOES

Submitted by

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ABSTRACT

LIFE-CYCLE AND CARBON-FOOTPRINT ANALYSIS FOR BUILDINGS AND COMMUNITIES SUBJECTED TO TORNADOES

Tornadoes pose a significant threat to life and buildings, especially residential buildings, causing an average of $8 billion per year in damage and numerous casualties. The dominant form of single-family residential buildings in the United States is light-frame wood construction. In this study, light-frame buildings threatened by tornadoes are analyzed from a life cycle perspective intended to identify post-tornado repair strategies that are resilient, economic and sustainable. The life cycle framework takes into account the randomness in tornado occurrences for an individual building, and both randomness in tornado occurrence and tornado footprint for a residential community. Capacities for the building structure and envelope are modeled by fragility functions, which were developed for three building archetypes that are assumed to be representative of housing practices in the U.S. Along with the repairs due to hazard, the methodology also incorporates the regular repair and maintenance that occur during the life of the building. This research provides a framework for integrating minimum cost and carbon footprint objectives into a single decision-making process, a topic that appears to be lacking in the literature. It shows how a balance between resilience, sustainability and cost might be achieved in an individual building and how those ideas might help in decision-making and policy formation for homeowners, home builders and community planners at a community level.

DEDICATION

to

dedication,

universe,

and

whisper of the heart

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1. INTRODUCTION

The key to growth is the introduction of higher dimensions of consciousness into our awareness.

- Lao Tzu

1.1. Residential Buildings and Tornado Hazard

The housing market in the U.S. was valued at $33.3 trillion in 2018 (Gerrity, 2019). The average construction cost for single family homes in the U.S. has risen from $124,276 in 1998 to $237,760 in 2017 (Statista, 2019). At the individual level, roughly 65% of the housing units in the U.S. are owner occupied (CRS, 2019). While the number of renter occupied homes in the U.S. has increased from 33 million housing units in 2004(Q1) to 43 in 2020(Q1) (FRED, 2019a), the number of owner occupied housing units has increased from over 73 million in 2004(Q1) to over 81 million in 2020(Q1) (FRED, 2019b). More than 90% of the U.S. housing market is comprised of light-framed wood building construction. Residential communities are a major part of building sector in the U.S. Housing construction also provides widespread employment as investment in residential investment accounts for 15% of GDP in 2018 (CRS, 2019).

Light-framed wood residential buildings are susceptible to damage from extreme winds. The impact of extreme weather phenomena, including hurricanes and tornadoes, on such structures and the social and economic wellbeing of a community can be severe (Kuligowski et al., 2014). Tornadoes, in particular, are relatively rare, localized events, but can have significant impacts on communities that receive a direct hit. Although tornadoes have a low probability of striking a specific residential neighborhood (Standohar-Alfano and van de Lindt, 2014), tornadoes have caused an average of nearly $8 billion per year in economic losses between 1993 and 2012 (Heberton, 2014), making them one of the most significant natural hazards in terms of economic and social impact. Furthermore, losses due to severe natural hazards, including tornadoes, are trending upward more rapidly than growth in national GDP (Hallegatte, 2017). With population growth and economic development, there is an increase in hazard impact. Recent tornado disasters – the Joplin, MO tornado of May, 22, 2011 (an Enhanced Fujita (EF) scale Category 5 event), which caused 161 deaths, injured over 1,100 and caused insured losses of approximately $US 3 billion, and the Moore, OK, EF5 tornado of May 20, 2013, which caused 24 deaths, 212 injuries and damages of approximately $US 2 billion – are examples of the enormous socioeconomic as well as environmental impacts of tornadoes. These and other tornado events have resulted in hundreds of fatalities, thousands of injuries and billions of dollars in direct and indirect economic losses. For the 22-year period from 1995-2016, there were 2,201 casualty-producing tornadoes that affected 479,779 housing units resulting in 25,959 casualties. (Fricker, 2020). Increases in urbanization and economic development during the past two decades are likely to lead to even greater risks and socio-economic losses in the future (Bouwer, 2019).

The impact of Hurricane Andrew in 1992 has brought about improvements in the development of wind provision in building codes and standards, mainly in coastal areas susceptible to hurricanes. However, tornadoes have received less attention. Reducing the impacts of tornadoes on residential building construction requires improved standards and construction practices to achieve sustainable and resilient communities in tornado-prone areas. Studies have been conducted to evaluate the impact of tornados on residential dwellings in terms of annual failure probability (Standohar-Alfano and van de Lindt, 2014) and deriving empirical fragility functions (Roueche et al., 2017). Other studies assessed losses at a community scale (van de Lindt and Dao, 2020; Romanic et al., 2016; Strader et al., 2016; Pilkington et al., 2020). While these previous studies have advanced tornado damage assessment, they have stopped short of integrating sustainability and resilience objectives for optimal decision-making towards reducing tornado-induced damage and losses. The life-cycle analysis concept introduced in section 1.3 is an attractive tool that can be used for such integration.

1.2. Resilience and Sustainability

Community resilience is the ability to prepare for anticipated hazards, adapt to changing conditions, and withstand and recover rapidly from disruptions (Ellingwood et al 2016). Resilience as a concept has been on the national agenda for more than a decade, with the realization that performance of individual buildings and other infrastructure, considered individually, is not sufficient to ensure the well-being of communities as a whole (Kuligowski et al., 2014). The challenge in adapting the built environment to the natural environment, and vice-versa, has become an important concept for policy making (Keessen et al., 2013). Measures taken to increase resilience of residential building communities by reducing the impacts from tornadoes have an effect on their life-cycle cost and carbon footprint and should be sustainable, if at all possible.

The World Commission on Environment and Development (WCED) defined sustainable development in the Brundtland Report in 1987 as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). For our research, this definition is applied as: “For single family residence or residential community, construction, repair and maintenance have to be done and planned such that the cost needs of the future generation for regular repair and maintenance or repair due to hazard is lessened and carbon-footprint is minimized”.

Not all measures to enhance resilience are sustainable in the usual sense of the term (Hall and Ashley, 2008). The development of sustainable construction practices takes on some urgency because of global climate change. Human activities have increased the natural concentration of carbon dioxide (CO_2) in the Earth's atmosphere from 338 ppm to 411 ppm since 1980 (Lindsey, 2020), amplifying the earth's natural greenhouse effect. Among civil infrastructure sectors including building construction, commercial and industrial facilities, transportation, and electric power, the contribution of CO_2 from residential buildings in 2018 was approximately 20% (DOE, 2020); contribution includes construction as well as utilization. The DOE has projected that residential homes will be responsible for 56 billion metric tons of CO_2 - equivalent (CO_2e) GHG emissions during the period from 1985 to 2035 (DOE, 2010). Current building codes, which are aimed at protecting building occupants from extreme events, such as windstorms, earthquakes and fires at reasonable cost rarely address issues related to resilience and sustainability (Vaughan and Turner, 2013), let alone community resilience.

Fig. 1.1 depicts the relationship between the key concepts that we have introduced. The decisions which takes into account carbon-footprint, cost and resilience together help deliver sustainable development.

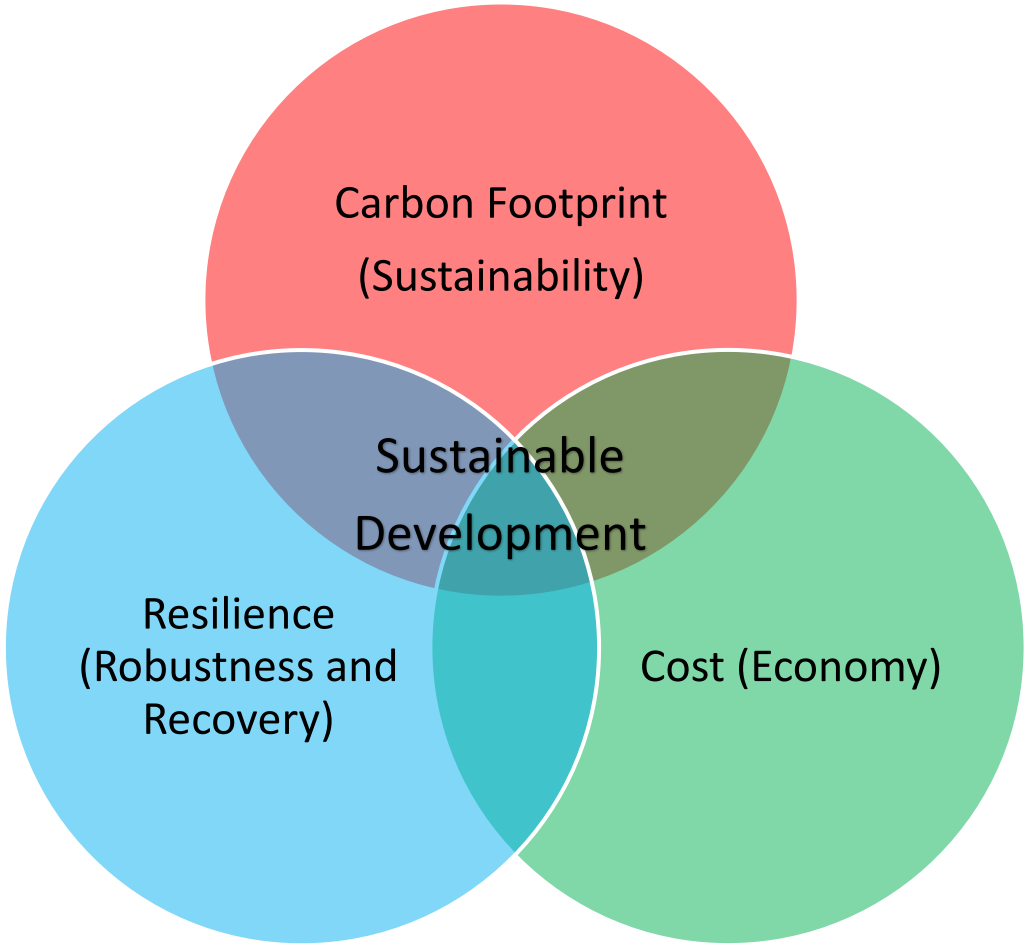


Figure 1.1 Relationship between resilience, cost, carbon-footprint and sustainability

1.3. Life-Cycle Analysis and Decision-Making

Life-cycle analysis is a quantitative tool that can be used to assess cost and carbon-footprint of all building products/components used during the lifecycle of the building. Life-cycle costs include costs incurred during initial construction, routine repair and maintenance costs, and costs incurred to repair damage due to severe natural hazards during the life of the building.

For most homeowners, their residence is their single largest investment. For this reason, most building developers (and homeowners) are concerned more with keeping initial costs of residential construction as low as possible, consistent with approved residential building practices, rather than with minimizing life-cycle costs. This focus on initial cost may have an adverse impact on the resilience to hazard and carbon footprint of a building during a typical residential building service life that could be as much as 105 years (Aktas and Bilec, 2012), during which it may be exposed to extreme winds and require repair on multiple occasions. A life-cycle perspective may offer advantages to developers and homeowners that make resilient and sustainable residential building design and construction practices more attractive from a financial and social stance. For example, Noshadravan et al. adopted a life-cycle perspective to investigate the cost-effectiveness of a typical wood-framed residential building when the resistance to earthquake and hurricane hazards is taken into account. They found that the decision-making process for homeowners, homebuilders and policy makers for evaluating the value of alternative choices during the life-cycle is driven by different goals and metrics, and thus is multi-objective in nature. Their study, however, did not specifically address the sustainability of these alternative choices. Maloney et al. (2018) linked performance of individual building components to the performance of the building system as a whole and identified improvements to existing construction practices that would enhance community resilience performance targets. Wang et al. (2018) provided a framework for identifying minimum building performance criteria by de-aggregating community resilience goals to individual buildings.

This research builds on these previous studies to present a life-cycle analysis (LCA) methodology for examining the benefits of different residential building practices using tradeoffs between cost and carbon footprint of owner-occupied single-family dwellings of light-frame wood construction in regions susceptible to tornado hazards. The benefits of these practices on both individual buildings and portfolios of buildings constructed at different periods is analyzed. Cost and carbon footprint functions are formulated which enable the initial construction cost, repair and maintenance costs, and damage cost due to the random occurrence of tornadoes to be amortized over the life-cycle of the building. Building design/retrofit policies for the objectives of cost (expressed in dollars) and carbon footprint (expressed in kg of CO2e) are evaluated using a multi-objective approach to reveal any tradeoffs that may occur between resilient and sustainable practices for typical residential construction. It is found that when the life-cycle of a typical residence is considered, optimal decisions involving home construction or home repair following a tornado to enhance resilience and minimize carbon footprint by upgrading to latest code-compliant design, differ significantly from decisions made on an initial cost basis. The flexibility of the framework established herein permits its use for different hazards at different geographical locations as well as for comparing different construction technologies for minimizing life-cycle cost.

In this study, we perform a scenario, or conditional, risk assessment of tornado damage to residential buildings rather than a fully coupled risk assessment in which the fragility and mean annual frequency of the tornado hazard are convolved. There are two reasons for this. First, the mean annual frequency of a tornado striking a residence typically is very small (less than10^{-3}/yr); thus, the expected cost or carbon footprint resulting from building damage would also be very small. Second and more important, a conditional scenario analysis is far more useful to public decision-makers who are not risk-informed because they can easily relate the likely damage to their communities under a particular scenario to damage from similar tornados striking other communities. They can understand the consequences of an EF4 tornado from experience clearly, even though they may not understand an event with a mean annual frequency of 10^{-5} or less.

1.4. Study Objectives and Scope

The study presented herein provides a foundational framework for developing and integrating the ideas of resilience and sustainability into single-family light-framed wood building construction as well as communities of such buildings. A methodology for life-cycle analysis of individual buildings were developed and expanded to the residential community level. Fragilities for tornado hazard were developed for residential constructions that are assumed to represent most of the housing in the U.S. An analysis of single-family dwellings and building inventories reveals that certain repair strategies, if adopted during the service life of the building, are economic and more environmentally sound than others. This cluster of solutions near the optimal does not change when scaling up to the community level. Analysis shows that simplifying the hazard models to get tentative solutions will drastically underestimate the impacts.

Life-cycle analysis done herein does not include energy usage during the service life of the building. Analyses of energy use during the life-cycle of a building are available elsewhere (Junnla and Horvarth, 2003; Cabeza et al 2014; Hajare and Elwakil, 2020) and are outside the scope of this study. Non-residential sectors of the community, education, business, health, utilities, etc., are not considered herein because a healthy and vibrant residential building market is one of the foundations of community welfare.

1.5. Organization of Thesis

This thesis addresses significant issues related to decision-making when considering both the resilience and sustainability during a service life of building, and is organized around the essential ingredients of that decision-making process.

Chapter 2 describes the building archetypes and different construction practices and materials considered in this study. Three different archetypes are modeled that are representative of construction practices in the Central U.S. Two different materials are introduced to represent different construction practices – standard which is representative of practices before Hurricane Andrew, and enhanced which is representative of practices after Hurricane Andrew. This point of delineation was selected because a number of changes were made to wind-resistant design of residential buildings in large areas of the U.S. in the years immediately following Hurricane Andrew.

Chapter 3 introduces the life-cycle method used in the research for individual buildings and residential community. The life-cycle perspective is taken when looking at both the cost and carbon-footprint of a building and a community.

Chapter 4 describes in detail how the fragilities, which describe the uncertainties in capacities of building components and systems, are integrated into the methodology in Chapter 3 are developed.

Chapter 5 describes in detail the modeling of a residential sector of a community which represents two different construction practices as described in Chapter 2. A simplified model of a tornado that will strike the community is presented.

Chapter 6 presents the results of the life-cycle analysis for individual buildings and for the community. This chapter utilizes the methodology and models developed in the previous chapters to arrive at repair strategies that are optimal for the individual buildings and for the community as a whole.

Chapter 7 provides a summary of the important conclusion drawn from the research, limitations of the research and future expansion of the research methodology.

2. BUILDING ARCHETYPES DESCRIPTION

It is possible for the unconscious or an archetype to take complete possession of a man and to determine his fate down to the smallest detail.

\- *Carl Jung*

Three building archetypes that represent general housing construction practices in the U.S. are introduced in this chapter. These archetypes were also considered by Maloney et al. (2018) in a comprehensive finite element-based study to identify deficient building components and to improve construction practices to meet resiliency goals. The archetypes are described in detail in the following section.

2.1. Building Archetypes

The three archetypes of light-framed wood residential buildings identified for life-cycle analysis for tornado hazard are summarized in Table 2.1. None of the archetypes are considered to have basements. Fragility analyses are performed for the building components (standard and enhanced components) based on the construction practice (roof types, nailing patterns, truss spacings, etc.) summarized in Table 2.2.

Table 2.1 Summary of different archetypes used in the study

Archetypes	Dimensions	Number of Stories	Mean Roof Height	Roof Type
A1	12.2 m x 9.14 m (40ftx30ft)	One	4.42 m (14.5 ft)	Hip
A2	12.2 m x 9.14 m (40 ft x30 ft)	One	4.47 m (24.5 ft)	Gable
A3	24.39 m x 18.29 m (80 ft x 60 ft)	Two	4.42 m (14.5 ft)	Hip

2.1.1. Archetype A1

The first archetype, designated as A1 (Figure 2.1a), is a single-story building with basic dimensions: 12.2 m L x 9.14 m W x 4.42 m H (40ft x 30ft x 14.5ft). A1 features hip roof system. The building layout and basic details/dimensions are taken from CUREE Publication No. W-29 (Reitherman and Cobeen, 2003). The construction details for Archetype A1 are provided in CUREE Publication No. W-29. The original building A1 was developed as part of a seismic study, and was considered herein because the building model had been tested and could be independently verified by finite element analysis (Maloney et al 2018). Deviations from the original building details were made by Maloney et al. (2018) and were adopted in this study as well. As one example, details regarding the windows and doors were not mentioned in the CUREE publication; so generic construction details was used. As another example, the 1x6 sheathing boards used to sheath the roof, specified in Reitherman and Cobeen (2003), were changed to plywood sheathing representing typical modern construction in most parts of the U.S.

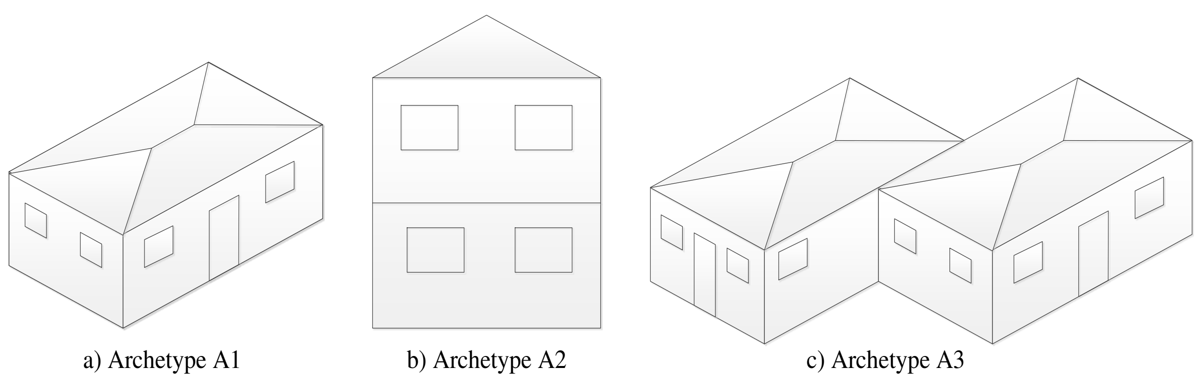


Figure 2.1 Single and two-story archetypes (after Maloney et al. 2018)

2.1.2. Archetype A2

The second archetype, denoted A2 (Figure 2.1b), has the same 12.2 m L x 9.14 m W (40 ft x 30 ft) footprint as A1 but is a two-story residence with 223 m^2 (2,400 ft^2) living area with a gable roof. The same construction techniques and materials used for A1 are also assumed to be used for A2. The second floor plan is similar to the first floor plan. The basement for A2 is not included in the present analysis.

2.1.3. Archetype A3

The third archetype, denoted A3 (Figure 2.1c), is a large 223 m^2 (2,400 ft^2) single-story building with a hip roof system and without a basement. The floor plan is staggered (Figure 2.1c). The floor plan for each staggered unit for A3 is the same as that of A1. Archetypes A1, A2, and A3 have been analyzed by finite element analysis, as reported in Maloney et al. (2018).

2.2. Roof Types

To represent two of the most common types of roofs in construction practices in the U.S. A2 features a gable roof while A1 and A3 feature hip roof systems. Both types of roofs were considered to have a rise of (1.37 m) 4.5 ft with no overhang at the edges. Roof shingles are assumed to be 0.3048 m x 0.914 m (1 ft x 3 ft) in dimension with either class of asphalt shingles mentioned in Table 2.2. The resistance statistics of individual roof shingles are taken from Maloney et al. (2018) based on data from Romero (2012). Roof panels are plywood sheets of dimension 1.22 m x 2.44 m (4 ft x 8 ft). The rafter member size is 0.058 m x 1524 m (2 in x 6 in). The trusses are connected by SPF ridge board of size 0.0254 m x 0.2032 m (1 in x 8 in) at the peak of the roof.

2.2.1. Hip Roof

Hip roof is a roof sloped upward from all sides of the structure to form a ridge like structure. A1 and A3 have hip roof system. The slope of the hip roof used in our archetypes is 3V:12H. The sloped trusses in the hip roof are spaced at 0.61 m (2 ft) on center.

2.2.2. Gable Roof

Also known as pitched or peaked roof, gable roofs are the most common roof in the US. The gable roof of A2 has a slope same as that of hip roof and the spacing and member sizes of the roof trusses are the same as in the hip roof system.

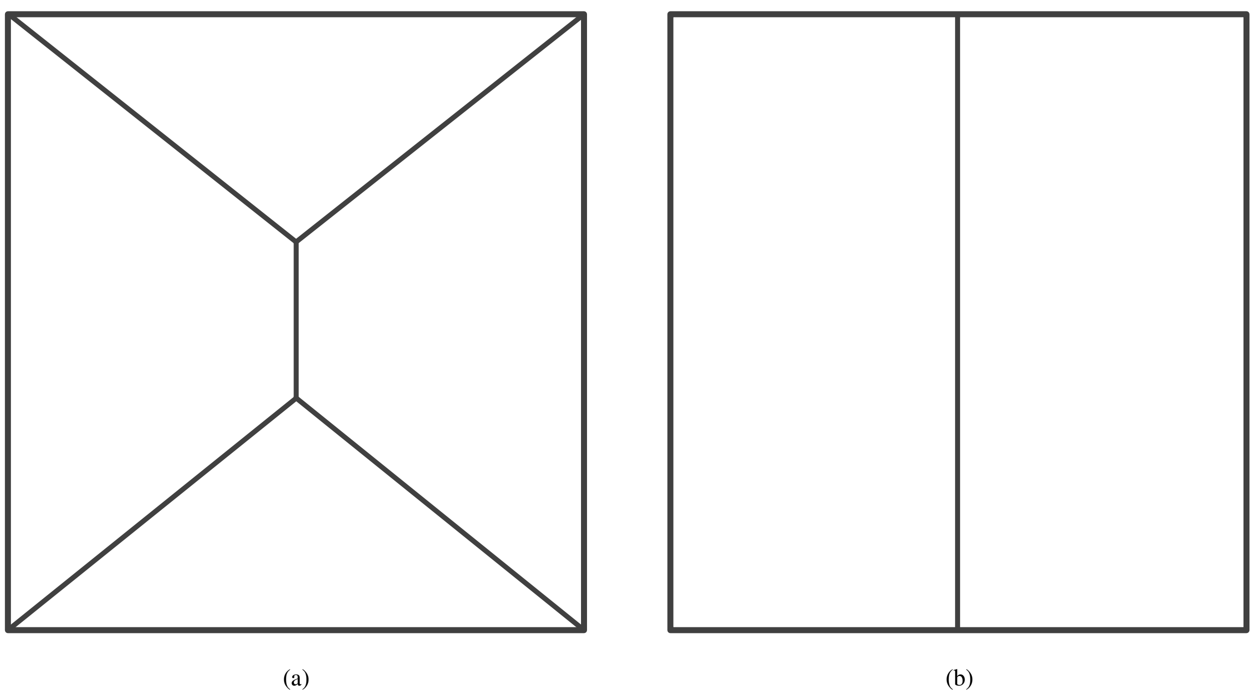


Figure 2.2 Top view of roof systems (a) hip roof and (b) gable roof

2.3. Construction Quality

Using detailed 3D finite element simulations, Maloney et al. (2018) analyzed each of the archetypes described in the above sections for four levels of construction quality: basic, enhanced (focus on life safety), improved (focus on reparability), and resistant (focus on continued function).

This study considers only two levels of construction quality: standard and enhanced. Standard construction is analogous to construction quality which was prevalent before Hurricane Andrew and referred synonymously as “Pre-Andrew Construction” while enhanced, referred also as “Post-Andrew Construction” is analogous to resistant quality and incorporates life safety, reparability and continued function all in one. All the archetypes are assumed to have the same construction quality which helps us make objective comparisons.

Table 2.2 Standard and enhanced building components and installation configurations

Components	Standard Condition	Enhanced Condition	Nominal Strength Increase (Maloney et al., 2018)
Roof Shingles	Class D asphalt shingles	Class H asphalt shingles	74 psf - 181 psf
Roof Panels	6x12 Spa/8d nails/SPF rafters	6x6 spacing/W-L rafters/ 10D nails	63 psf – 222 psf
Windows and Doors	DP 25	DP55	40 psf – 80 psf
Wall Panels	1/2" gypsum wall board on the interior and 1” thick stucco on the exterior	No change	No change
Rafter-Sill Connection	3-16d box toe nail	H2.5 clip	750 lb – 3446 lb
Foundation Connection	½” bolts, 6’ o.c.	5/8” bolts, 2’ o.c.	Factor of 3 increase

*12” = 1ft; 1ft = 0.3048m; 1lb =4.448 Newton; 1psf = 47.88 KN/m^2

Housing construction has evolved over time. The construction practices are rooted in the technologies available at the time of construction. The evolution of structural materials and methods in the construction of homes in the US from 1900 to 2000 is presented in NAHB (2001). The provisions for different loads are also updated every few years. The evolution of wind loads provisions is concisely summarized in (Barben and Solnosky, 2017). Hurricane Andrew occurred in August of 1992 with maximum peak 3-s gust wind speeds in excess of 78 m/s (175 mph). The forces due to wind loads were well above those from the design 50-year return period wind speed in many locations, and hence significant changes to design loads in wind provisions were necessary (Crandell, 1998), as described below.

2.3.1. Standard Construction

The building components defined as standard construction in Table 2.1 is assumed to be representative of the most common construction practices across residential housing units before Hurricane Andrew. The standard construction is typical of Pre-Andrew construction with class D shingles, 3-16d box toenails for roof to wall connection, 0.127 m (½ in) bolts spaced 1.83 m (6 ft) center to center for wall to foundation connection, and other components as already mentioned in Table 2.2. The standard quality of glasses used for windows and doors is assumed to have allowable pressure rating of 1915 N/m^2 (40 psf), represented as DP25. DP stands for Design Pressure. It is the pressure rating that identifies the load induced by wind that the product is rated to withstand in tis end-use application.

This standard construction is a housing unit that has not been retrofitted or enhanced to be more resilient to mitigate or withstand risks.

2.3.2. Enhanced Construction

Estimated property damage due to Hurricane Andrew was $30 million dollars with 80,000 people seeking refuge after the storm (Quinn et al., 1994). After Hurricane Andrew, significant changes were made to construction practices and building codes. Setting standards for more resilient construction would protect homeowners and insurers from similar storms. As mentioned in chapter 1, the effect of tornadoes on both economy and people is significant. Hence, the lessons from hurricanes can be applied to tornado to protect homeowners and insurers.

Class D asphalt shingles were updated to Class H asphalt shingles for "Post-Andrew Construction". Glass for windows and doors are updated from DP25 to DP50. The increase in design wind speed for buildings changed the construction practice; 3-16d box toenails were replaced by hurricane clips.

All three building archetypes are considered with different components, representing standard and enhanced building components as, summarized in Table 2.2. As noted previously, our focus in this study is on structural and nonstructural building components and systems. The wall panels and their nailing patterns are identical for standard and enhanced construction. With two alternatives for each building components in Table 2.2, 32 combinations of building products are possible when considering a building that has a mix of any of standard and enhanced components as shown in Table 2.2. For individual building analysis these different 32 combinations of building products were considered and optimal cost and carbon-footprint during the useful life of the building (see Section 6.1) was found. For community analysis, two different building construction zones within the community were considered where each zone are built either with fully standard or fully enhanced construction (see Section 6.2).

3. LIFE-CYCLE METHODOLOGY

Methodology is intuition reconstructed in tranquility.

- *Paul Lazarsfeld*

Life-cycle assessment is a systematic approach that can be used to analyze environmental impacts (or cost) of a product over its lifetime (Junnila and Horvarth, 2003); from its manufacture to its destruction. Herein, life-cycle analysis is used to assess costs and emissions due to construction, maintenance and rehabilitation/repair of the structural system and envelope of typical residential wood frame buildings during its service life.

The life cycle of a building can be represented by Figure 3.1 below. The total life-cycle cost and carbon-footprint depend on the decisions taken at the times of initial construction, routine maintenance, and repair or reconstruction following tornado-induced damage. All costs and carbon-footprints are discounted to present worth. The cost is discounted with a factor d_c and the carbon-footprint is discounted with a factor d_m, as described in detail in the following sections. Cost and carbon-footprint attributed to tornado-induced damage, discounted to present value, depend on time of occurrence and intensity of the event. In the LCA of residential buildings presented herein, the focus is on direct damage costs; indirect economic losses, morbidity and mortality are not considered because of the difficulties in assigning costs to these factors. Nor are costs incurred prior to construction (project development costs) or following the end of the service life (salvage or demolition) considered. Contents (e.g. furniture, appliances, etc.) damage can be an important component of total loss, depending on the general economic status of the homeowner. While this component is important for losses in insurance underwriting, it requires additional information that is not available to us and which would have extended the study far beyond our intended scope and is not considered in the current framework.

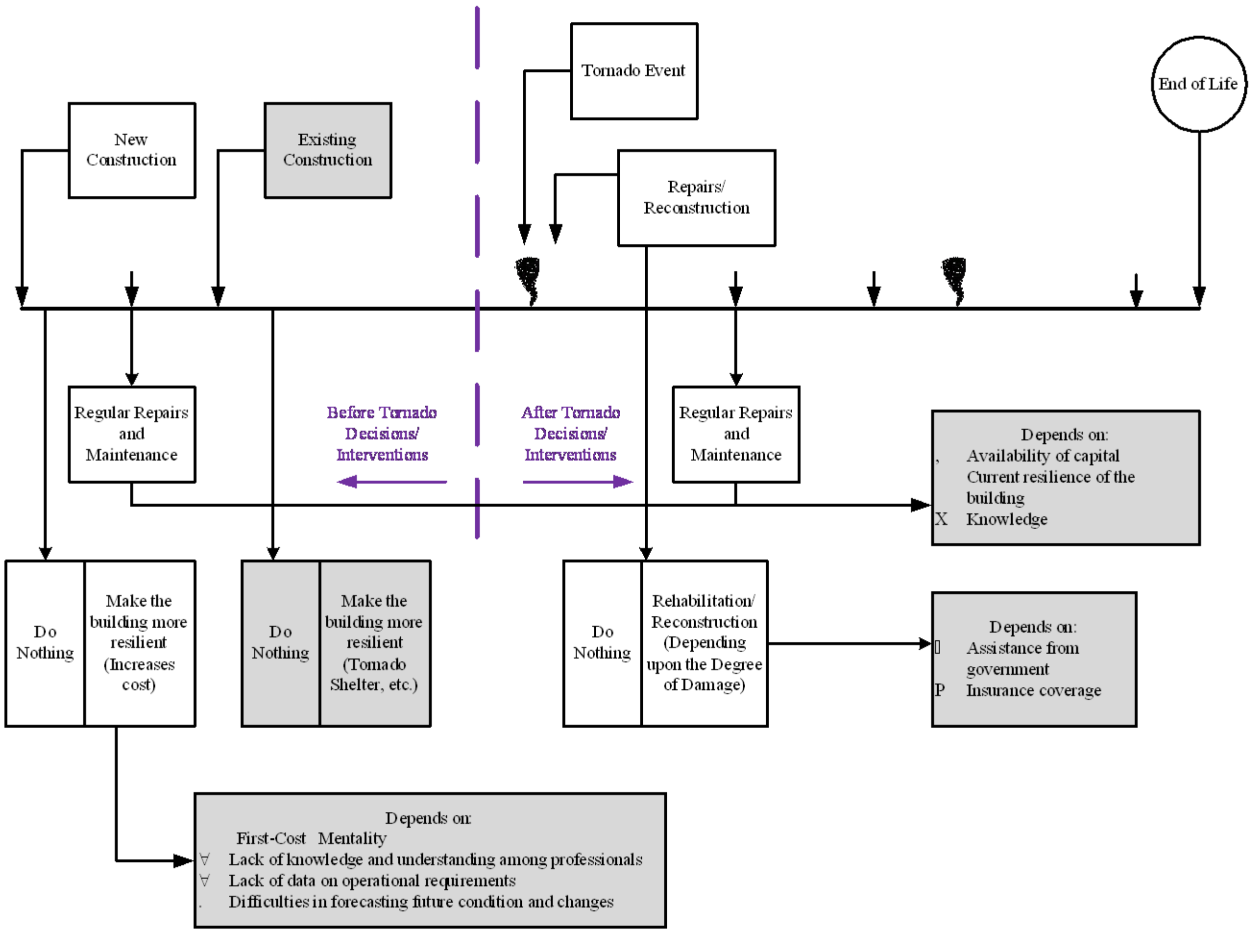


Figure 3.1 Representation of building life-cycle

3.1. Assessment of Life-cycle Cost

Total Life-Cycle Cost. The present value (PV) life-cycle cost of a building exposed to a scenario tornado with 3-sec gust wind speed, $\boldsymbol{v}$, includes initial cost, periodic repair/maintenance cost, and costs of repairing damage following the occurrence of a tornado, respectively:

$$PV_{cost}(v) = C_0(X) + \sum_{i=1}^{n}\sum_{j=1}^{k}\frac{C_{j,rm}(X1)}{(1+d_c)^{i\Delta t}} + \sum_{j=1}^{k}\frac{C_{j,T}(v,X_2)}{(1+d_c)^{T_{tor}}}P_j(v) \qquad \text{Equation 3.1}$$

in which $\boldsymbol{C_0}(\boldsymbol{X})$ = initial cost, $\boldsymbol{X}$ represents a vector of design variable vectors defined in Table 2.2, and the remaining terms are defined below. The expected life-cycle cost can be broken down into maintenance cost and expected damage repair cost, as itemized below:

Regular Repair/Maintenance Cost. Routine maintenance is assumed to occur at approximately regular intervals and the associated costs are:

$$\sum_{i=1}^{n}\sum_{j=1}^{k}\frac{C_{j,rm}(X_1)}{(1+d_c)^{i\Delta t}} \qquad \textit{Equation 3.2}$$

in which,

$\boldsymbol{n}$ = the number of routine maintenance actions carried out during the life-cycle of the building assumed to occur at regular intervals, for e.g. roof shingles and windows/doors are assumed to be replaced every 20 years, etc.

k = the total number of building components, i.e. design variables, considered for regular repair during its lifecycle (see Table 2.2),

$\boldsymbol{C_{j,rm}}(\boldsymbol{X_1})$ = repair cost for the j^{th} repair/maintenance of component j at regular intervals of time t,

$\boldsymbol{X_1}$ = subset of the design variable vector,

$\boldsymbol{d_c}$ = discount rate for expected cost, and

$\boldsymbol{\Delta t}$ = interval of repair or replacement (assumed to be constant for the given design variables).

Expected Damage Repair Cost. Given the occurrence of a tornado, the expected cost of repairing the damage or replacing building components is:

$$\sum_{j=1}^{k} \frac{C_{j,T}(v,X_2)}{(1+d_c)^{T_{tor}}} P_j\,(v) \qquad \text{Equation 3.3}$$

in which,

k = the total number of building components, i.e. design variables, considered for repair after a tornado scenario,

$C_{j,T}(v, X_2)$ = tornado repair cost of the j^{th} building component,

X_2 = subset of the design variable vector *X*,

$P_j(v)$ = fragility of j^{th} building component, described subsequently in Chapter 4,

T_{tor} = random time during the life of the building at which the tornado occurs.

3.2. Assessment of life-cycle carbon-footprint

The life-cycle carbon footprint is analyzed in a similar fashion as the life-cycle cost summarized in Equation 3.1:

$$PV_{carbon}(v) = M_0(X) + \sum_{i=1}^{n} \sum_{j=1}^{k} \frac{M_{j,rm}(X1)}{(1+d_m)^{i\Delta t}} + \sum_{j=1}^{k} \frac{M_{j,T}(v,X2)}{(1+d_m)^{T_{tor}}} P_j\,(v) \qquad \text{Equation 3.4}$$

in which M_0, $M_{j,rm}$ and $M_{j,T}$ are the carbon emissions (expressed in *kg*) due to initial construction, regular repair and maintenance, and hazard repair, respectively. The carbon footprint due to regular repair and maintenance, which are incurred at n regular intervals, Δt, is discounted at the rate, d_m. The carbon footprint due to repair of tornado damage depends on v, the wind speed during the tornado event, and T_{tor}, the random time of occurrence during the service life of the building and is also discounted to present value, where the discount rate $\boldsymbol{d_m}$. The damage to component $\boldsymbol{j}$ is described by the fragility, $\boldsymbol{P_j}$, as explained in Chapter 4. The carbon emissions are also discounted to present value because the carbon dioxide emitted today will have a long-lasting impact (Tol 2019). However, the discount rate, $\boldsymbol{d_m}$, might differ from that used for cost because the future impacts of climate change beyond around 2050 are highly uncertain, and the assumption of a higher discount rate has the effect of shifting the burden of mitigating risk unduly to future generations (Lee and Ellingwood 2015).

3.3. Framework for Assessing Life-Cycle Cost and Carbon Footprint for an Individual Building

We present the framework for the life-cycle analysis for a single-family residence from purely a building structure and envelope perspective. The expected service life of a single-family residential building is taken as 100 years (Aktas and Bilic, 2014). Routine maintenance is taken to occur at uniform intervals of 20 years, and involves replacement of roof shingles, exterior doors and windows only. The other components in Table 2.2 are unlikely to be replaced at regular intervals unless they are heavily damaged by a tornado which is taken into account in this analysis. Tornado scenarios are defined by their 3-s gust wind speeds, derived from the Enhanced Fujita scale, discussed in more detail in Section 5. Tornado occurrence is a random event, with measurable probability associated with zero, one, or two tornado occurrences[1] during the life-cycle of the building. Here, we examine scenarios in which one or two tornados occur during the life-cycle of the building. In the one-tornado scenario, the occurrence of the tornado is assumed to be uniformly distributed within the service life of the residence; 50 realizations of that tornado

[1] With typical mean annual frequencies on the order of 10^{-3} or less of a tornado striking a typical residence, the probability of three or more tornado strikes in 100 years is approximately 1.6×10^{-4}.

scenario in order to compute the expected PV, as described subsequently. For the two-tornado scenario, the second tornado is assumed to be uniformly distributed between the occurrence of the first tornado and 100 years. The 20-year routine maintenance schedule is reinitialized at the time of the most recent tornado event, as shown in Figure 3.2. The discount rate for expected cost is assumed to be 3%, consistent with the rate of return on long-term financial instruments. The discount rate on carbon footprint is 1%, since the future impacts of climate change beyond around 2050 are highly uncertain, and the assumption of a higher discount rate would shift the burden of mitigating risk unduly to future generations, as noted previously.

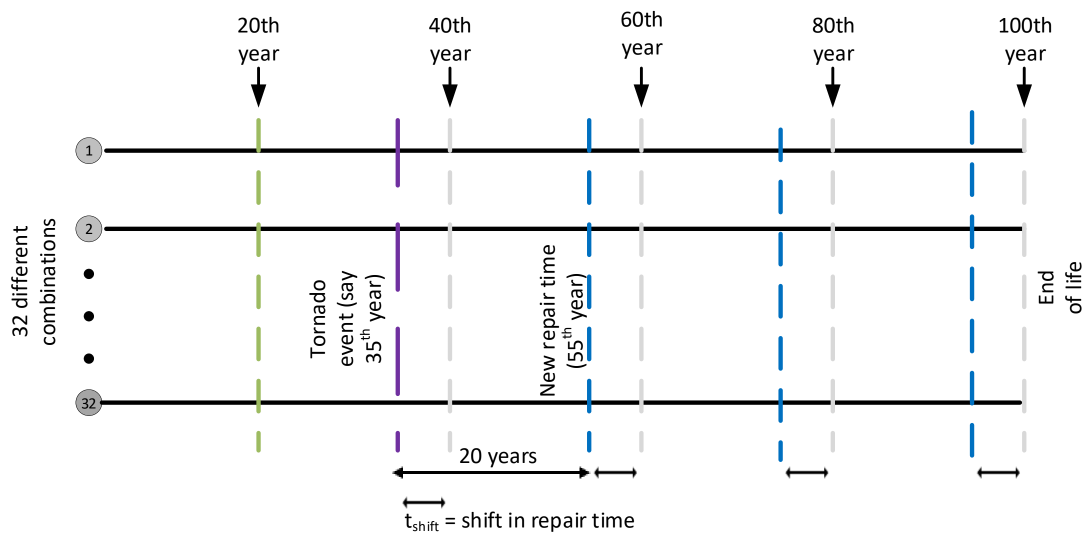


Figure 3.2 Representation of tornado event effects on routine maintenance

A typical home might be constructed with a mix of standard and enhanced components. However, in the LCA that follows, any building product replaced during the service life, either as a result of routine maintenance or repair following a tornado, is replaced with a building product of the same quality. In other words, if the residence is constructed with standard roof shingles and enhanced doors and windows, any replacement during the service life is also with standard roof shingles and enhanced doors and windows. The same applies to all the components for repair or reconstruction after a tornado event; i.e. the damaged components are repaired/reconstruction with the same quality of materials they were previously. With two alternatives for each building product in Table 2.2 except the wall panels, we have 32 combinations of building products to consider as shown in Table 3.1.

Table 3.1 Different combination of variables (building components)

	Roof cover	Windows and Doors	Roof panels	Roof structure	Wall structure		Roof cover	Windows and Doors	Roof panels	Roof structure	Wall structure
1	standard	standard	standard	standard	standard	17	standard	standard	standard	standard	enhanced
2	enhanced	standard	standard	standard	standard	18	enhanced	standard	standard	standard	enhanced
3	standard	enhanced	standard	standard	standard	19	standard	enhanced	standard	standard	enhanced
4	enhanced	enhanced	standard	standard	standard	20	enhanced	enhanced	standard	standard	enhanced
5	standard	standard	enhanced	standard	standard	21	standard	standard	enhanced	standard	enhanced
6	enhanced	standard	enhanced	standard	standard	22	enhanced	standard	enhanced	standard	enhanced
7	standard	enhanced	enhanced	standard	standard	23	standard	enhanced	enhanced	standard	enhanced
8	enhanced	enhanced	enhanced	standard	standard	24	enhanced	enhanced	enhanced	standard	enhanced
9	standard	standard	standard	enhanced	standard	25	standard	standard	standard	enhanced	enhanced
10	enhanced	standard	standard	enhanced	standard	26	enhanced	standard	standard	enhanced	enhanced
11	standard	enhanced	standard	enhanced	standard	27	standard	enhanced	standard	enhanced	enhanced
12	enhanced	enhanced	standard	enhanced	standard	28	enhanced	enhanced	standard	enhanced	enhanced
13	standard	standard	enhanced	enhanced	standard	29	standard	standard	enhanced	enhanced	enhanced
14	enhanced	standard	enhanced	enhanced	standard	30	enhanced	standard	enhanced	enhanced	enhanced
15	standard	enhanced	enhanced	enhanced	standard	31	standard	enhanced	enhanced	enhanced	enhanced
16	enhanced	enhanced	enhanced	enhanced	standard	32	enhanced	enhanced	enhanced	enhanced	enhanced

3.4. Framework for Assessing Life-Cycle Cost and Carbon-Footprint for a Community

In this section, we present a framework for assessing the life-cycle cost and carbon-footprint of a community (neighborhood) of residential buildings. This residential sector being a collection of individual buildings, we can apply the formulation of life-cycle cost and carbon-footprint developed for a single building as Equation 3.5.

$$PV_{cost}(v) = \sum_{h=1}^{N}\left(C_0(X) + \sum_{i=1}^{n}\sum_{j=1}^{k}\frac{C_{j,rm}(X1)}{(1+d_c)^{i\Delta t}} + \sum_{j=1}^{k}\frac{C_{j,T}(v,X_2)}{(1+d_c)^{T_{tor}}}P_j\,(v)\right) \qquad \textit{Equation 3.5}$$

in which,

PV_{cost} = the total present value cost of the community exposed to a scenario tornado.

N = the total number of buildings in the community

All the other definitions are as defined in Equation 3.1. Since the strike probability for an individual building is uncertain, as described in Section 5, the last part of Equation 3.5, which represents the repaired damage due to a tornado, applies only to those buildings that lie in the tornado path. Similarly, Equation 3.4 for the carbon-footprint can also be used in a similar manner to represent the total life-cycle carbon-footprint of the community.

4. TORNADO FRAGILITY ANALYSIS

nothing which we are to perceive in this world equals the power of your intense fragility.

\- *e. e. cummings*

4.1. Performance Limit States

The probabilities of damage to structural and nonstructural components and systems of a light-frame wood building exposed to tornado effects in Equations 3.1 and 3.4 are determined by their fragilities, defined as the conditional probability of damage as a function of the 3-sec gust wind speed, v. To determine these damage state probabilities, each limit state is defined in the general form:

$$g(X, v) = R - (W(v) - D) \quad \textit{Equation 4.1}$$

in which R = component or system resistance, D = dead load, and $W(v)$ = wind load as defined in *ASCE Standard 7-16* (ASCE, 2016):

$$W(v) = q_h(v)\left(GC_p - GC_{pi}\right) \quad \textit{Equation 4.2}$$

in which $q_h(v)$ = velocity pressure evaluated at mean roof height, h, above ground and GC_p and GC_{pi} = aerodynamic coefficients for the exterior and interior surfaces of the building (ASCE, 2016). Tornado wind effects usually cause uplift or suction on building surfaces; thus, W generally acts in a direction opposite to D. The vast majority of residential buildings are less than 18.3 m (60 ft) in height; thus, the provisions in ASCE 7-16 for low-rise buildings, in which the velocity pressure is measured at mean roof height, h, can be used. This velocity pressure is:

$$q_h = 0.613 K_Z K_{Zt} K_d V^2 \text{ (N/m}^2\text{); (}V \text{ in m/s)} \quad \textit{Equation 4.3}$$

$$q_h = 0.00256 K_Z K_{Zt} K_d V^2 \text{ (lb/ft}^2\text{); (}V \text{ in mph)}$$

in which K_Z = exposure factor and K_{Zt} = topography factor, both evaluated at height, h; K_d = wind directionality factor, and V = the 3-sec gust speed, referenced to an elevation of 9.144 m (30 ft). In tornado damage assessment, it is common to assume that K_Z, K_{Zt} and K_d are equal to 1.0 because the building is located in open-country exposure (Exposure C in ASCE 7-16) and the boundary layer profile, surface roughness and directionality effects are different than for straight winds (Maloney et al., 2018).

The component or system fragility, $P(v)$, is:

$$P(v) = P[R < W(v) - D|V = v] \qquad \textit{Equation 4.4}$$

Fragilities of structural components and systems and expected damage are developed as a function of tornado wind speed using the limit states defined subsequently. For single-family one and two-story dwellings, the aerodynamic coefficients, GC_p, in Equation 4.2 can be determined from the provisions for components and cladding (C&C) in Section 30.3 of *ASCE 7-16* to assess damage to roof shingles, roof panels (plywood sheathing), doors and windows, and wall panels (see Table 4.1). Failures of connections of rafters to upper sill plate and wall to foundation, which result in major structural damage to the residence, are assessed using GC_p for main wind force-resisting systems (MWFRS) in Chapter 28.3 of *ASCE 7-16*. In calculating tornado wind pressures on MWFRS and C&C, the methods described in commentary section C26.14 to *ASCE Standard 7-16* were followed because tornado wind loading is different from loading due to straight-line winds, as noted above. Method 1 in C26.14 is used to modify the coefficients appearing in Equation 4.2.

Statistical parameters and distributions types for the variables that can be applied for all types of archetypes are taken from Maloney et al. (2018) based on methods from Lee and

Rosowsky (2005), which are modified based on Ellingwood and Tekie (1999). These parameters and their statistics are summarized in Table 4.1. A comprehensive general description of fragility development is illustrated in Figure 4.1.

Table 4.1 Summary of wind load parameters for all archetypes

Parameters	Category	Nominal	Mean	SD	COV	Dist.
K_z (Exposure C)	33ft high	1	0.85	0.13	0.14	Normal
G_{Cpi}	Enclosed	(+-) 0.18	0.15	0.05	0.33	Normal
	Partially Enclosed	(+-) 0.55	0.46	0.15	0.33	
G	Rigid Structure	0.85	0.82	0.08	0.10	Normal
Kc Roof	MWFRS – Roof	1.8 - 3.2				Uniform
	C&C - Roof	1.4 – 2.4				
Kc Walls	MWFRS - WW & LW	1.5				Uniform
	C&C - WW & LW	1.3				
	MWFRS – SW	1				
	C&C - SW	1				

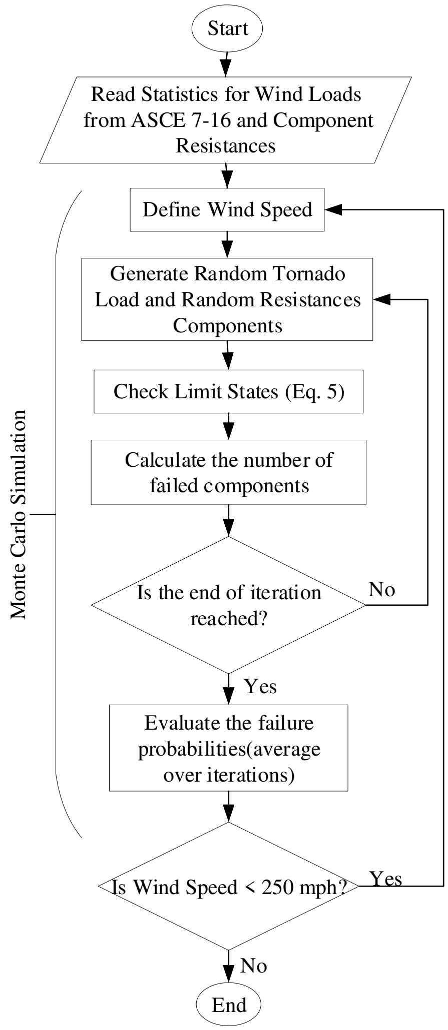


Figure 4.1 Developing fragility curves

4.2. Tornado damage cost and carbon footprint assessment

Several previous investigators (e.g., Masoomi and van de Lindt, 2017; Maloney et al., 2018) have used the qualitative descriptions of damage states for residential buildings in the HAZUS hurricane module (MH 2.1, 2018), modified to account for the difference in damage caused by hurricanes and tornados having the same wind speed and summarized in Table 4.2.

Table 4.2 Damage states for residential construction class

Damage State	Qualitative Damage Description	Roof Cover Failure	Window Door Failure	Roof Deck	Missile Impacts on Walls	Roof Structure Failure	Wall Structure Failure
0	<u>No Damage or Very Minor Damage</u> Little or no visible damage from the outside. No broken windows, or failed roof deck. Minimal loss of roof cover, with no or very limited water penetration.	≤ 2%	No	No	No	No	No
1	<u>Minor Damage</u> Maximum of one broken window, door or garage door. Moderate roof cover loss that can be covered to prevent additional water entering the building. Marks or dents on walls requiring painting or patching for repair.	>2% and ≤15%	One window, door, or garage door failure	No	<5 impacts	No	No
2	<u>Moderate Damage</u> Major roof cover damage, moderate window breakage. Minor roof sheathing failure, Some resulting damage to interior of building from water.	>15% and ≤50%	> one and ≤ the larger of 0% &3	1 to 3 panels	Typically 5 to 10 impacts	No	No
3	<u>Severe Damage</u> Major window damage or roof sheathing loss. Major roof cover loos. Extensive damage to interior from water.	>50%	> the larger of 20% & 3 and ≤50%	>3 and ≤25%	Typically 10 to 20 impacts	No	No
4	<u>Destruction</u> Complete roof failure and/or, failure of wall frame. Loss of more than 50% of roof sheathing.	Typically >50%	>50%	>25%	Typically >20 impacts	Yes	Yes

However, the HAZUS damage state definitions cover a range of component damages and the exact damage costs or CO2 footprints cannot be determined from the damage states definitions in Table 4.2. For example, the HAZUS severe damage state (Damage State 3) includes damage to roof shingles exceeding 50%, damage to roof panels ranging from 3 panels to 25% of the total number, and loss of between 20% and 50% of windows. Such definitions make cost and carbon footprint analysis on the basis of damage state problematic. Calculating cost based on damage state can be misleading. Consider two cases: the building with minor damage to roof shingles and severe damage to roof panels, and the building with severe damage to both roof shingles and roof panels. Both are categorized as being in damage state 3. Damage state 3 itself will have variation in cost and carbon-footprint. Taking a component-based approach enables the exact damage to a building at a given tornado scenario to be determined. Moreover, the damage state definitions are not internally consistent. For example, in the first case above, the damage to roof panels is more than the damage to roof shingles. This does not seem consistent with how the failure patterns in the damaged buildings are observed; roof shingles fail before roof panels.

Accordingly, the fragilities developed in the sequel are based on damage to the components listed in Table 2.2 rather than damage states in Table 4.2, from which the costs and carbon footprints can be determined in a straightforward fashion.

4.3. Fragility of Roof Shingles

In this section, the damage assessment for roof shingles is illustrated in detail; damage to roof panels, doors and windows, and wall panels are assessed similarly in subsequent sections. A comprehensive general description of fragility development is illustrated in Figure 4.1.

Figure 4.2 (adapted from *ASCE Standard 7-16*, Figures 30.3-2B and 30.3-2E) shows the different zones on which wind pressures act on the building envelope of gable and hip-roof systems. The external pressure coefficients, GC_p, for low-rise buildings are area-dependent as well as zone-dependent as identified in Figure 4.2. The size of the roof zones depends primarily on the roof height (ASCE-Standard 7-16). The most severe wind pressures on the roof occurs in the region where there is hydrodynamics air flow separation at the ridge, eave and corners. For the gable roof, zones (2n, 2r, 3e) and zones (1, 2e) have the same external pressure coefficients. Similarly, for the hip roof, zones (2e, 3) have the same external pressure coefficients. Although not included in calculating roof shingles fragilities, internal pressures on interior surfaces of the building develops due to breach of doors and windows by wind pressure, debris and hail. Roof shingles are not subjected to internal pressure because the internal pressure is resisted by the roof panels before it has any effect on the shingles. Hence, the suction pressure on the roof shingles is:

$$W(v) = q_h GC_p \qquad \textit{Equation 4.5}$$

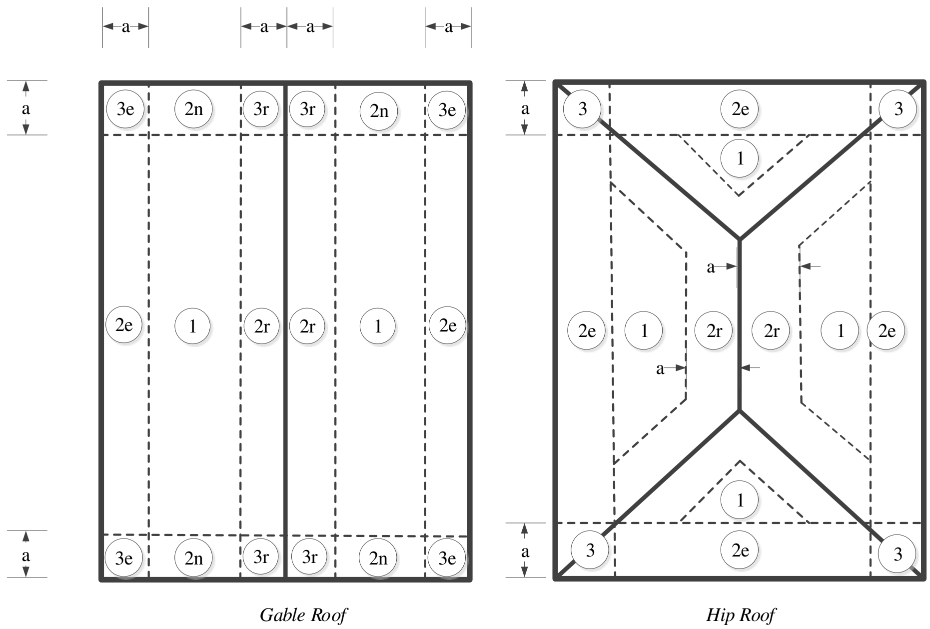


Figure 4.2 Different wind pressure zones acting on (a) gable roof and (b) hip roof; after: ASCE 7-16 (2016)

The pressure coefficients in the zones identified above for the roof of Archetype A1 are ordered, in intensity, as: $GC_{p,2\&3} > GC_{p,2r} > GC_{p,1}$. Thus, it is expected that the shingles in zones 2e and 3 will fail before shingles in zone 2r; and shingles in zone 2r will fail before shingles in zone 1.

We use this information to determine the extent of damage to the roofs of the building archetypes identified above. Archetypes A1 and A3 have similar hip roof structures. Suppose that the number of shingles in zones 1, 2r and (2e, 3) is N_1, N_2 and N_3, respectively. Similarly, for

Archetype A2, the number of shingles in zones (1, 2e), (2n, 2r, 3e) and 3r is N_1, N_2 and N_3, respectively. Then, the failure probability of the shingles, P_F, is:

$$P_F = (N_1 + N_2 + N_3)/N_T \qquad \textit{Equation 4.6}$$

where,

N_1 = total number of shingles in zone 1,

N_2 = total number of shingles in zone 2r in A1 and A3, and zones 2n, 2r and 3e in A2,

N_3 = total number of shingles in zones 2e and 3 in A1 and A3, and zone 3r in A2

This approach is slightly different from the method used by Lee and Rosowsky (2005), where they calculate the weighted average of external pressure coefficients rather than the number of shingles. The combined total failure probability for both types of shingles is shown in Figure 4.3.

The pressure distributions for archetype A3 are not covered in *ASCE Standard 7-16*, but would be somewhat different from those on A1. The author is unaware of any wind tunnel studies that should shed light on these pressure distributions. Thus, the pressures acting on the roof of A3 are assumed to be identical to those on A1. Figure 4.3 shows example of the fragilities produced for different zones for roof shingles in a hip-roof system (A1). It is important to point out that the fragilities in Figure 4.2(a) describe damage probability for the entire roof, as described by zones 1, 2r, and (2e, 3) where the later zones (i.e. 2e, 3) are grouped together since they have the same external pressure coefficients.

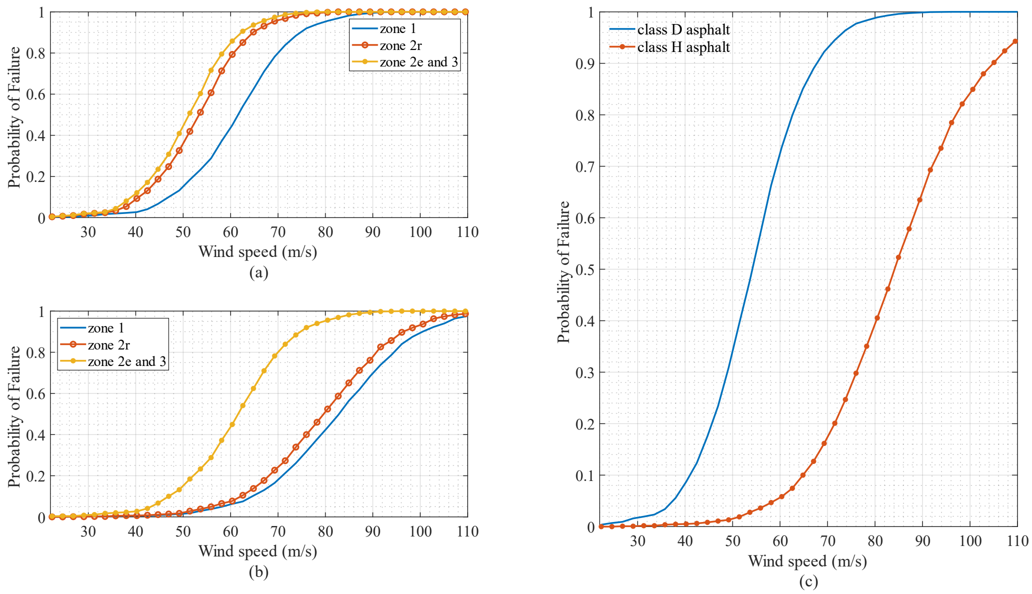


Figure 4.3 Different zones fragilities for roof shingles in a hip-roof system (A1) for (a) class D asphalt, (b) class H asphalt, and (c) combined fragilities of class D and class H asphalt

4.4. Fragility of Roof Panels

A procedure similar to that used for the roof shingles was used to calculate damage to individual roof panels and the roof sheathing as a whole. In contrast to the shingles, which are only subjected to external wind pressures, the roof panels are subjected to both external pressures and internal pressures developed within the building during a tornado scenario. Thus, the wind pressure on the individual panels is given by Equation 4.5. The failure probability of panels for the two nailing patterns identified in Table 2.2 is computed using Equation 4.6. Figure 4.4 shows the roof panel fragilities for both construction qualities for A1.

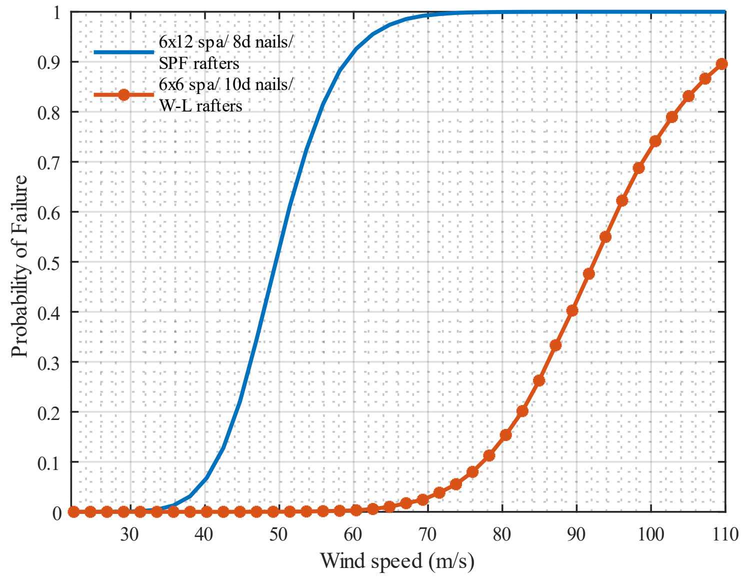


Figure 4.4 Roof panels fragilities for A1

4.5. Fragility of Windows and Doors

Two types of glass panels with different rated design pressures are considered 80 psf and 40 psf - as indicated Table 2.2. The different pressure regions in a typical building wall are illustrated in Figure 4.5. Since zone 5 has a width of 0.914 m (3 ft) for the archetype considered in this study, it will be assumed that all windows and doors in all three archetypes are located in zone 4. Figure 4.6 shows the fragilities for windows and doors combined for A1.

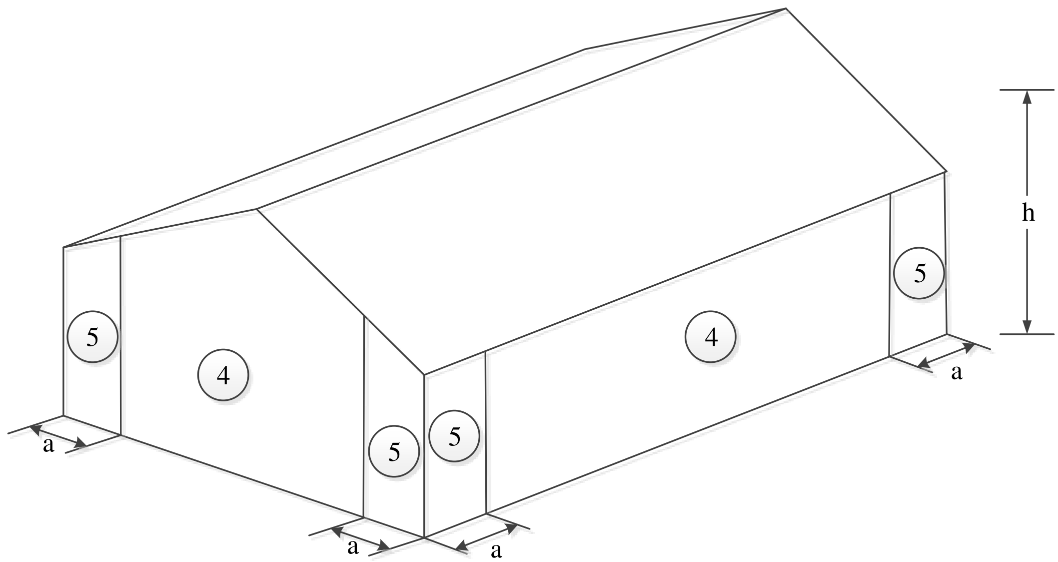


Figure 4.5 C&C pressure areas (ASCE 7-16)

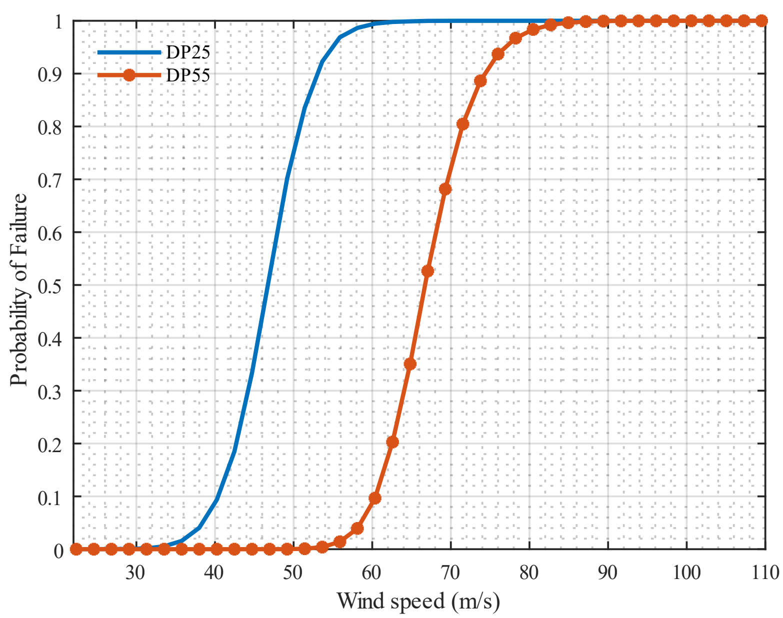


Figure 4.6 Windows and doors fragilities for A1

4.6. Fragility of Wall Panels

The performance of wall panels can be described by two fragilities – for zone 4 and zone 5 (see Figure 4.5). Pressures are higher on the region where there is flow-separation at the corners of the walls; the wind pressure on walls is higher on the corners (zone 5) than the interiors (zone 4). The pressures around the walls for A3 are assumed to be the same as for A1, for reasons discussed earlier. Figure 4.7 illustrates the fragility for A1.

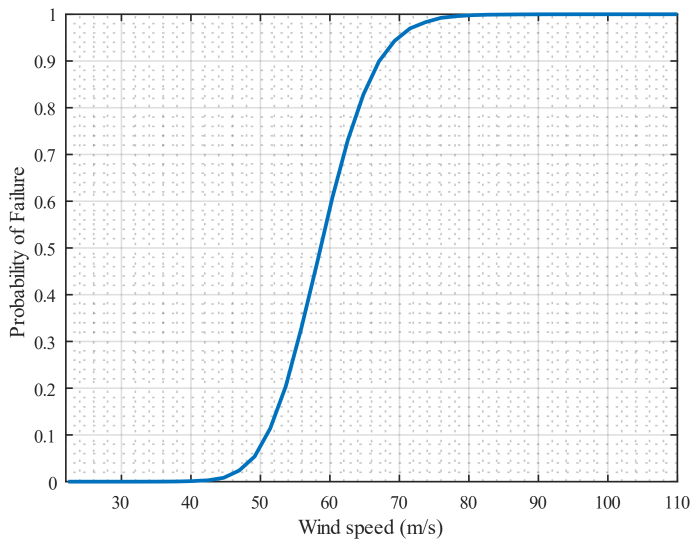


Figure 4.7 Wall panels fragilities for A1

4.7. Fragility of Roof-to-Wall Connection

Failure of the connection between the rafter and upper sill occurs when the uplift force (reaction) from the large suction pressures acting on the tributary area of each roof truss exceeds the resistance of the connectors. Pressures acting on the eave region (zone), interior (zone) and ridge region (zone) all contribute to this reaction. The uplift forces are transferred to the wall from the roof to wall connection. When the roof is severely damaged or removed, the walls lose stability and the building is likely to become a total loss. Figure 4.8 shows the fragilities for two roof-to-wall connection types.

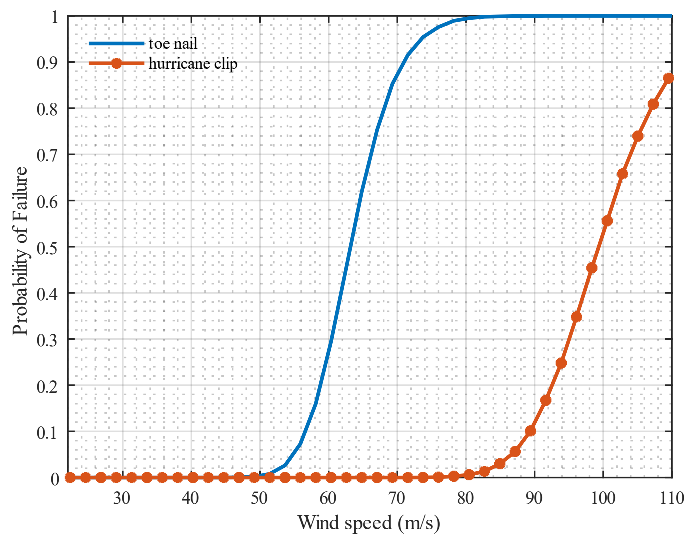


Figure 4.8 Roof-to-wall connection fragilities for A1

4.8. Fragility of Wall-to-Foundation Connection

The wall-to-foundation connection strength is determined from tests performed by (Standohar-Alfano and van de Lindt, 2017), in which the test frame was built with lateral restraints so that the wall would remain in-plane when loaded. Wall type A in (Standohar-Alfano and van de Lindt, 2017) is similar to the wall used in our archetype and its capacity is defined by an interaction curve between shear force, S, in KN/m (lb/ft) and uplift, R, in KN/m (lb/ft). The most critical load case occurs when the structural action (moment, tension or shear) due to the dead load acts in a direction opposite to the wind load (Ellingwood and Li 2009). Thus, as long as the wind load effect is less than the dead load effect, the wall-to-foundation connection does not experience uplift forces and its performance is based on wall racking, i.e. shear, the experimental values of which are found in Figure 5 of Standohar-Alfano and van de Lindt (2017). Beyond this point, however, uplift governs failure with resistance determined by Equation 4.7. The distribution for the resistance was assumed by Standohar-Alfano and van de Lindt (2017) to be normal. Figure 4.9 shows the fragility curves for two foundation connection types.

$R = -8.61 * S + 1.46$; with COV of 0.704 *Equation 4.7*

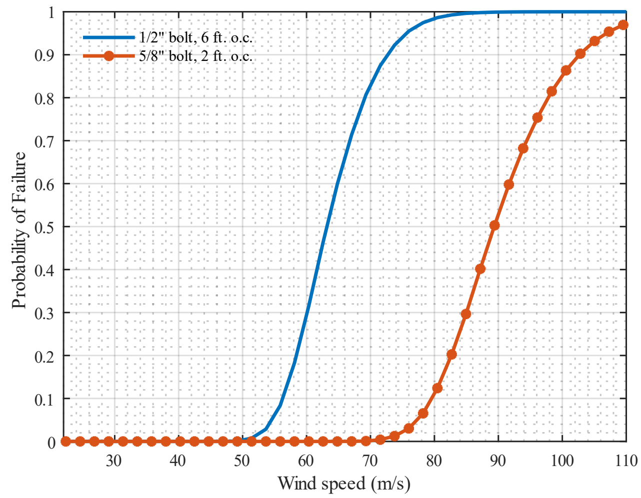


Figure 4.9 Wall-to-foundation connection fragilities for A1

Similar fragility curves are also developed for A2 and A3. Figure 4.10-4.12 show fragilities for the aforementioned components for A1, A2 and A3. Failure probabilities for different components for particular wind speeds is presented in Tables 4.3-4.5. The differences in fragilities are due to the differences in aerodynamic coefficients for the hipped-roof and gable-roofed building Archetypes A and C, as well as the second story on Archetype B.

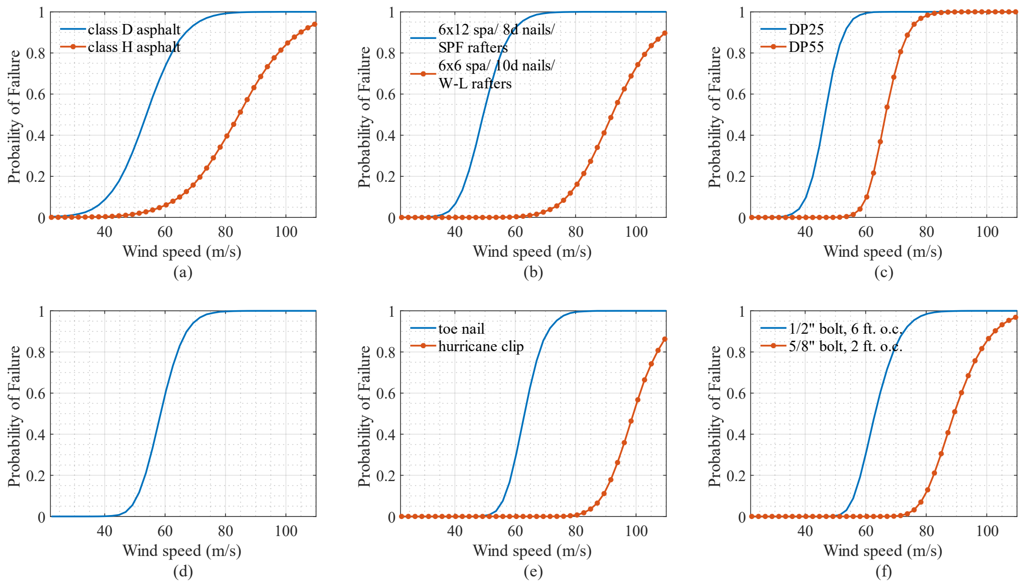


Figure 4.10 Fragility of different components of the Archetype A1 for a) roof shingles, b) roof panels, c) windows, d) wall panels, e) roof-to-wall connection, and f) wall-foundation connection

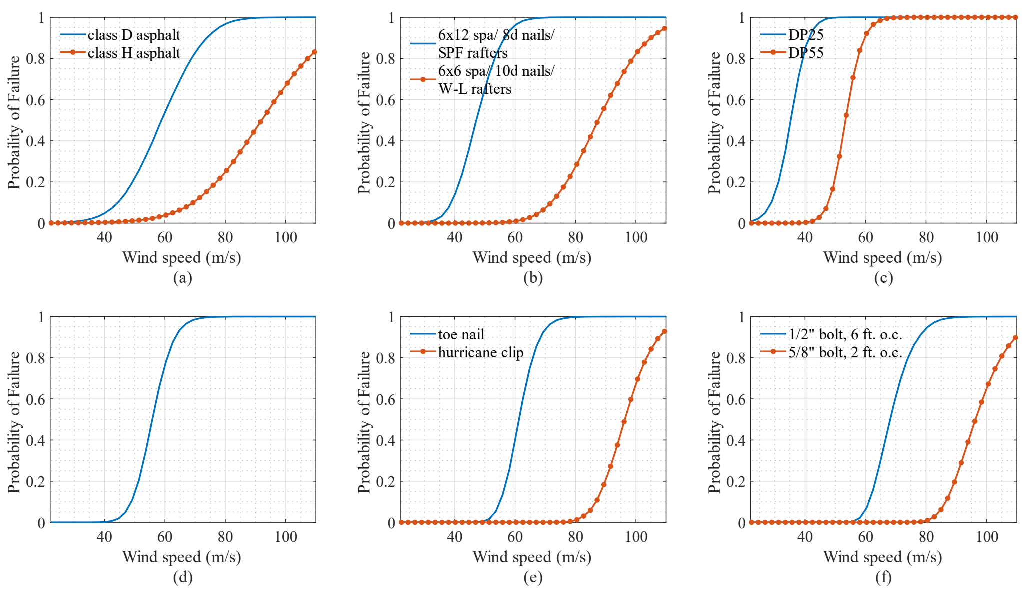


Figure 4.11 Fragility of different components of the Archetype A2 for a) roof shingles, b) roof panels, c) windows, d) wall panels, e) roof-to-wall connection, and f) wall-foundation connection

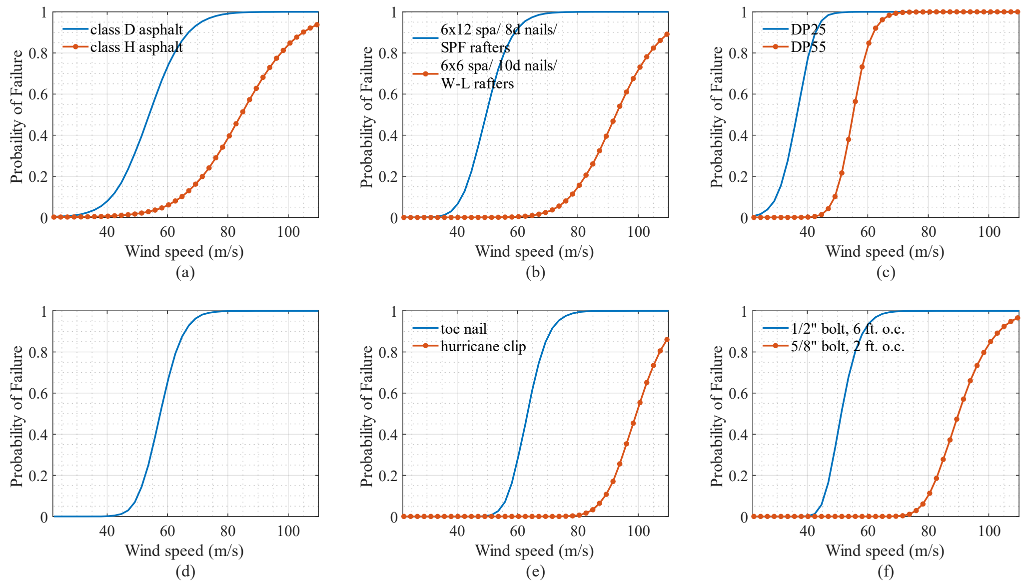


Figure 4.12 Fragility of different components of Archetype A3 for a) roof shingles, b) roof panels, c) windows, d) wall panels, e) roof-to-wall connection, and f) wall-foundation connection

Table 4.3 Expected damage percentage for archetype 1 for different wind speeds

Wind Speed #	Wind Speed m/s (mph)	Roof Cover		Windows and Doors		Roof Panels		Exterior Wall Panels		Roof Structure		Wall Structure	
		Stand.	Enha.	Stand.	Enha.	Stand.	Enha.	Stand.	Enha.	Stand.	Enha.	Stand.	Enha.
1	22.32 (50)	0.30	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	33.53 (75)	2.13	0.24	0.54	0.00	0.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	44.70 (100)	16.50	0.90	33.85	0.01	22.51	0.01	0.81	0.81	0.00	0.00	0.00	0.00
4	49.17 (110)	30.76	1.59	70.29	0.05	48.28	0.02	5.51	5.51	0.16	0.00	0.09	0.00
5	53.64 (120)	48.37	2.82	92.03	0.42	72.54	0.06	20.80	20.80	2.68	0.00	3.14	0.00
6	58.12 (130)	66.51	4.63	98.47	3.88	88.14	0.21	46.61	46.61	16.63	0.00	18.79	0.00
7	62.59 (140)	80.69	7.84	99.76	20.59	95.51	0.52	72.43	72.43	46.53	0.00	46.03	0.00
8	67.06 (150)	89.99	12.69	99.94	52.78	98.50	1.49	89.04	89.04	75.63	0.00	71.40	0.01
9	71.53 (160)	95.29	19.31	99.98	80.38	99.58	3.66	96.50	96.50	91.59	0.01	87.53	0.42
10	80.47 (180)	99.16	39.54	99.99	98.31	99.97	16.19	99.76	99.76	99.46	0.67	98.59	12.78
11	89.41 (200)	99.88	62.65	100.00	99.90	100.00	40.86	99.98	99.98	99.95	10.70	99.87	50.30
12	111.76 (250)	100.00	95.32	100.00	100.00	100.00	91.88	100.00	100.00	100.00	90.16	100.00	97.87

Table 4.4 Expected damage percentage for archetype 2 for different wind speeds

Wind Speed #	Wind Speed m/s (mph)	Roof Cover		Windows and Doors		Roof Panels		Exterior Wall Panels		Roof Structure		Wall Structure	
		Stand.	Enha.	Stand.	Enha.	Stand.	Enha.	Stand.	Enha.	Stand.	Enha.	Stand.	Enha.
1	22.32 (50)	0.26	0.11	0.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	33.53 (75)	1.58	0.27	34.54	0.01	1.45	0.00	0.02	0.02	0.00	0.00	0.00	0.00
3	44.70 (100)	10.55	0.74	97.76	3.13	35.80	0.01	1.62	1.62	0.01	0.00	0.00	0.00
4	49.17 (110)	19.70	1.14	99.80	17.06	61.16	0.06	11.14	11.14	0.26	0.00	0.00	0.00
5	53.64 (120)	32.49	1.92	99.97	51.65	81.37	0.16	34.75	34.75	4.81	0.00	0.07	0.00
6	58.12 (130)	47.27	3.23	100.00	83.98	93.31	0.49	65.58	65.58	26.07	0.00	2.16	0.00
7	62.59 (140)	62.45	5.12	100.00	96.62	98.18	1.46	87.54	87.54	59.24	0.00	15.76	0.00
8	67.06 (150)	75.63	8.24	100.00	99.38	99.60	3.76	96.71	96.71	84.95	0.00	43.34	0.00
9	71.53 (160)	85.84	12.78	100.00	99.87	99.93	8.47	99.25	99.25	96.07	0.01	68.63	0.00
10	80.47 (180)	96.85	26.27	100.00	100.00	99.99	27.43	99.95	99.95	99.80	1.41	94.67	0.99
11	89.41 (200)	99.64	44.68	100.00	100.00	100.00	54.37	100.00	100.00	99.97	17.64	99.54	19.07
12	111.76 (250)	99.99	85.99	100.00	100.00	100.00	95.94	100.00	100.00	100.00	95.31	100.00	92.65

Table 4.5 Expected damage percentage for archetype3 for different wind speeds

Wind Speed #	Wind Speed m/s (mph)	Roof Cover		Windows and Doors		Roof Panels		Exterior Wall Panels		Roof Structure		Wall Structure	
		Stand.	Enha.	Stand.	Enha.	Stand.	Enha.	Stand.	Enha.	Stand.	Enha.	Stand.	Enha.
1	22.32 (50)	0.32	0.08	0.62	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	33.53 (75)	2.08	0.29	27.91	0.01	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	44.70 (100)	16.50	0.89	95.49	1.64	21.69	0.00	1.01	1.01	0.00	0.00	5.94	0.00
4	49.17 (110)	30.34	1.58	99.20	10.87	47.40	0.01	6.88	6.88	0.12	0.00	33.39	0.00
5	53.64 (120)	48.38	2.77	99.92	38.24	72.49	0.02	24.82	24.82	2.52	0.00	68.70	0.00
6	58.12 (130)	66.03	4.79	100.00	72.68	88.00	0.16	53.94	53.94	16.21	0.00	88.78	0.00
7	62.59 (140)	80.55	7.86	100.00	91.95	95.45	0.50	79.44	79.44	45.41	0.00	96.90	0.00
8	67.06 (150)	89.90	12.74	100.00	98.20	98.54	1.39	93.01	93.01	75.06	0.00	99.29	0.03
9	71.53 (160)	95.37	19.72	100.00	99.53	99.56	3.58	98.12	98.12	91.47	0.00	99.86	0.38
10	80.47 (180)	99.22	39.59	100.00	99.96	99.98	16.11	99.88	99.88	99.29	0.74	99.99	11.59
11	89.41 (200)	99.90	62.68	100.00	99.99	100.00	40.68	99.98	99.98	99.93	11.13	100.00	48.07
12	111.76 (250)	100.00	95.37	100.00	100.00	100.00	91.70	100.00	100.00	100.00	90.53	100.00	97.73

5. MODELED COMMUNITY AND TORNADO HAZARD

You never change things by fighting the existing reality. To change something, build a new model that makes the existing model obsolete.

- *R. Buckminster Fuller*

5.1. Residential Community Modeling

Figure 5.1 illustrates a portion of the residential community considered. This residential community is 1.3 km x 0.8 km (0.8 miles x 0.5 miles) in area and includes 965 residential buildings and approximately 2,500 inhabitants. Since the costs are location-dependent, we assume that the residential community is located in Norman, OK.The open-source collaborative project, OpenStreetMap (OSM), was used as a tool to define its geodata. Consistent with the objectives and scope of the study, only a portion of the residential community is modeled, where our information on tornado fragilities as well as cost and carbon-footprint data on our archetypical buildings are sufficient. Even a community of this size is a complex system with buildings – residential and commercial – as well as civil infrastructure systems consisting of transportation and lifeline networks (electric power, natural gas, water/wastewater systems).

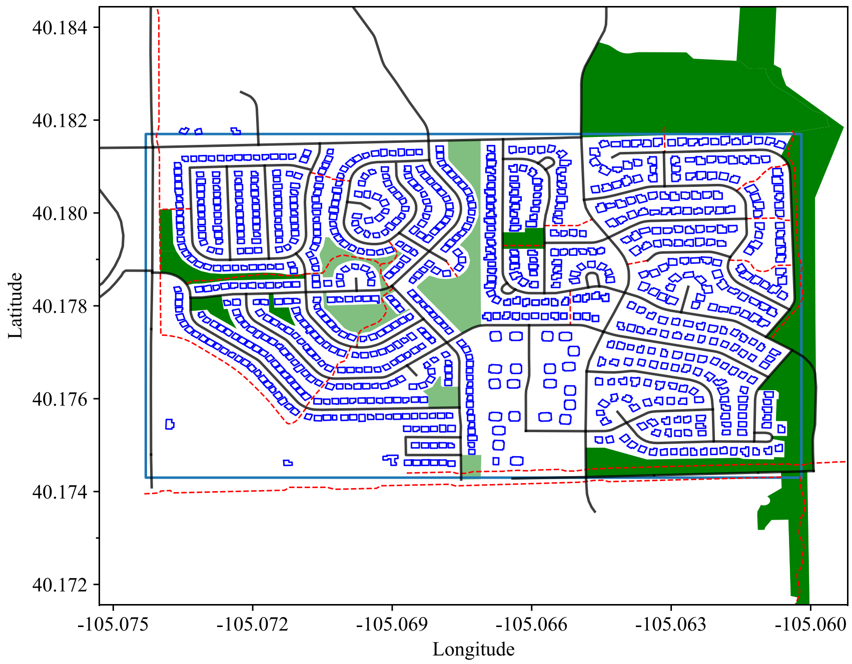


Figure 5.1 Residential community considered in the study

We assume that this community has developed after World War II, with construction over that period reflecting evolving building practices. Barben and Solnosky (2017) looked at the historical trends of building code evolution evaluating impacts, influence, and conservatism. There was a decrease in net design wind pressures from those in ASA-1945 to ANSI-1972, with a gradual increase since 1972. Sparks, Schiff and Reinhold (1994) studied the insurance losses due to wind damage to envelopes of houses following Hurricane Hugo, in 1989, and Hurricane Andrew, in 1992. They concluded that to reduce the vulnerability of future housing to extreme wind events, the envelopes should be designed for the same probability of failure as the main structural system. The large impact of Hurricane Andrew has influenced the development of wind provisions in building codes and standards from the mid-1990s to the present time.

Cities and towns tend to develop on their periphery due to population and economic growth (Batty and Longley 1994). Even though there are many structures of city development, a circular grid like structure, where the city expands from the city center with the residential areas on the outskirts of the area, is assumed for simplicity. A community the size of the one considered may have developed in stages under all the above-mentioned building codes and provisions. For simplicity, however, the current research will consider two construction practices: Pre-Andrew construction (zone 1) and Post-Andrew construction (zone 2). Standard materials as described in Table 2.2 are assumed to be used for construction of all buildings within zone 1 while enhanced materials are considered for zone 2. Figure 5.2 represents the separation of the community into the two afore-mentioned zones.

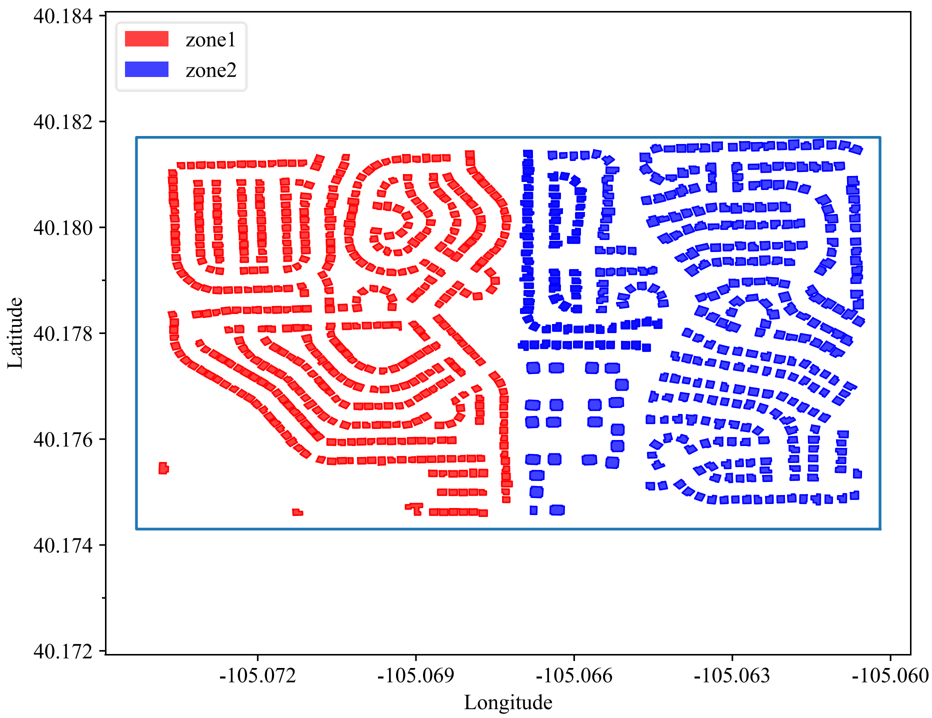


Figure 5.2 Zones in community representing two different construction practices (Pre-Andrew and Post-Andrew)

5.2. Tornado Modeling

The Enhanced Fujita (EF) scale rates the intensity of tornadoes based on the damage they cause. The EF scale, used in USA for the first time in 2007, replaced the older Fujita scale that had been introduced in 1971. Tornadoes are categorized into six categories ranging from EF0 to EF5, as shown in Table 5.1. The Enhanced Fujita scale uses 3-second gust wind speeds estimated at the point of damage based on judgement of 3-12 levels of damage to 28 indicators as mentioned in McDonald and Mehta (2006); one of which with 10 levels of damage is shown in Table 5.2. The design wind speeds for synoptic winds for Risk Category II buildings in ASCE 7-16 (which include residential construction) in much of the Central U.S. that is prone to tornadoes ranges from 46.5 m/s to 51 m/s (104 mph to 114 mph), suggesting that tornadoes of EF2 and less are unlikely to cause much damage to well-constructed homes, while tornadoes of intensity EF3 and above pose a serious threat to residential construction and building occupants. One of the damage indicators is "one- or two-family residences" which is the only relevant indicator for our study. EF0 indicates minor or no damage while EF5 indicates total destruction of building. The degree of damages to the residential structure is summarized in Table 5.2.

Table 5.1 Enhanced Fujita scale for tornado damage (McDonald and Mehta, 2006)

EF Number	3 Second Gust m/s (mph)	Mean value m/s (mph)	Used in this research m/s (mph)
EF0	29-38 (65-85)	34 (75)	34 (75)
EF1	39-49 (86-110)	44 (98)	45 (100)
EF2	50-60 (111-135)	55 (123)	54 (120)
EF3	61-74 (136-165)	67 (150)	67 (150)
EF4	75-89 (166-200)	82 (183)	80 (180)
EF5	>89 (>200)	110 (225)	101 (225)

**these mean wind speeds are considered for simplicity by the author for this study only*

Table 5.2 Damage indicators for one- and two- family residences

DOD*	Damage description	Expected wind speed m/s (mph)	Lower Bound wind speed m/s (mph)	Upper Bound wind speed m/s (mph)
1	Threshold of visible damage	29 (65)	24 (53)	36 (80)
2	Loss of roof covering material (<20%), gutters and/or awning; loss of vinyl or metal siding	35 (79)	28 (63)	43 (97)
3	Broken glass in doors and windows	43 (96)	35 (79)	51 (114)
4	Uplift of roof deck and loss of significant roof covering material (>20%); collapse of chimney; garage doors collapse inward; failure of porch or carport	43 (97)	36 (81)	52 (116)
5	Entire house shifts off foundation	54 (121)	46 (103)	63 (141)
6	Large sections of roof structure removed; most walls remain standing	55 (122)	47 (104)	64 (142)
7	Exterior walls collapsed	59 (132)	50 (113)	68 (153)
8	Most walls collapsed, except small interior rooms	68 (152)	57 (127)	80 (178)
9	All walls collapsed	76 (170)	64 (142)	89 (198)
10	Destruction of engineered and/or well-constructed residence; slab swept clean	89 (200)	74 (165)	98 (220)

*DOD is degree of damage

While a tornado is categorized by the maximum intensity in its path, there are variations in intensities along both the width and length. The intensity of tornado increases following its touchdown point in its movement forward, and after certain point the intensity starts decreasing and dissipates at the end point. The tornado intensity is highest at the center and decreases perpendicularly outward from the tornado centerline (Reinhold and Ellingwood, 1982). In other words, an EF3 tornado includes four sub-EF intensities ranging from EF3 to EF0 over its footprint, and similarly for EF4 and EF5 tornadoes.

We utilize the gradient method proposed by Standohar-Alfano and van de Lindt (2014) to simulate a tornado path. A tornado footprint between touchdown and end points can take on virtually any shape. As a simplification, we assume in this study that the footprint consists of a set of nested rectangles, as illustrated in Figure 5.3 for an EF5 tornado. The tornado center is assumed to lie randomly in the predefined boundary of our community and travel through the community during its life in a straight line. The tornado path direction was also considered to be random variable with uniform distribution (measured from north) between 0 and $\pi/2$. The statistics for tornado width and length, as well as the deterministic values for variation of intensity along width and length of tornado paths needed for using the gradient method, are presented in Masoomi and van de Lindt (2017) and are shown in Table 5.3. Table 5.4 shows percentage of width and length corresponding to each sub-EF (ef) scale in the tornado path.

Table 5.3 Distribution parameters for tornado path length and width

	Marginal Weibull Parameters				
	Length, km (mile)		Width, km (mile)		Correlation Coefficient
EF Scale	Scale Parameter (A)	Shape Parameter (B)	Scale Parameter (A)	Shape Parameter (B)	
EF0	1.155 (0.718)	0.675	0.041 (0.025)	1.043	0.225
EF1	4.299 (2.671)	0.727	0.093 (0.058)	0.943	0.250
EF2	10.484 (6514)	0.796	0.188 (0.117)	0.912	0.253
EF3	25.533 (15.865)	1.031	0.420 (0.261)	1.004	0.180
EF4	43.448 (26.997)	1.117	0.703 (0.437)	1.150	0.307
EF5	61.274 (38.074)	1.291	0.921 (0.572)	1.423	0.367

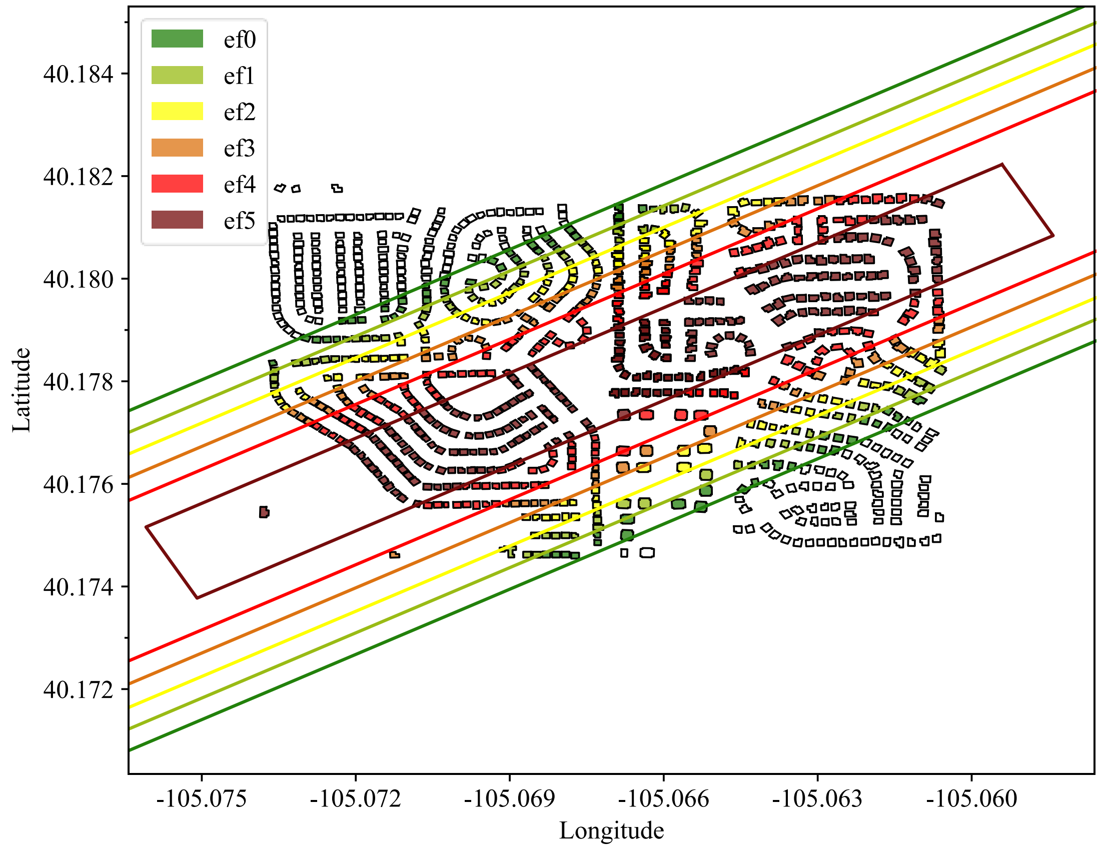


Figure 5.3 EF5 tornado profile passing through the community, rectangles showing the ef5, ef4 and so on zones within the EF5 tornado

Table 5.3 The percentage of width and length corresponding to each sub-EF scale (Data from Standohar-Alfano and van de Lindt, 2014)

EF Category	Width Percentage	Length Percentage
	EF5 Tornado Path	
EF5	14.9	27.3
EF4	185.	19.9
EF3	24.2	13.6
EF2	18.9	13.8
EF1	10.3	12.7
EF0	13.2	12.7

Total	100	100
EF4 Tornado Path		
EF4	21.2	27.3
EF3	21	18.7
EF2	27.8	19.0
EF1	15.8	17.5
EF0	14.2	17.5
Total	100	100
EF3 Tornado Path		
EF3	32.1	33.8
EF2	31.8	20.2
EF1	24.4	26.2
EF0	11.7	19.8
Total	100	100
EF2 Tornado Path		
EF2	36.7	47.5
EF1	35.2	31.4
EF0	28.1	21.1
Total	100	100
EF1 Tornado Path		
EF1	42.6	62.5
EF0	57.4	37.5
Total	100	100

6. LIFE-CYCLE COST AND CARBON-FOOTPRINT ANALYSIS

Science cannot solve the ultimate mystery of nature. And that is because, in the last analysis, we ourselves are a part of the mystery that we are trying to solve.

- *Max Planck*

Multi-objective optimization is a method used in decision-making when more than one objective function must be optimized simultaneously (Chang, 2015). In this study we have two objectives: to minimize cost and carbon footprint associated with the building during its service life. These two objectives may be competing, in the sense that minimizing carbon footprint typically requires an additional investment beyond a minimum cost solution. Minimization of multi-objective functions may involve different optimization techniques like genetic algorithms, simulated annealing, etc., depending upon the complexity of the problem (Xiujuan et al., 2002). The problem considered herein does not involve a high-dimension decision parameter space, which allows us to use a simple sort and rank method to reach a conclusion. The cost and environmental impact of different building construction choices depends on the dimensions, materials and techniques used. The following describes, in detail, the methods used for estimating cost and carbon footprint. The scope of this study includes those phases of residential building construction that comprise manufacturing, transport and construction/installation of each material (EN 15978:2011).

Most cost data used in this study are taken from RS Means Residential Cost Data (2018), which provides prices for various aspects of house construction including material, labor, and installation costs. The price sheets in the RS Means are characterized by a material quantity, labor hours, and cost per square foot broken down by material and installation prices. Some of the items not found in RS Means are taken from websites of Home Depot, GAF Materials Corp. and Lowes, and telephone interviews with representatives from these companies to obtain the average price for standard quality of each item. The total initial cost of the building is calculated by summing the individual component costs.

Most of the data for carbon emissions for archetypes and specific construction materials used for the LCA were extracted from the Athena Impact Estimator (Athena, 2015), a computer software program developed by the Athena Sustainable Materials Institute. This tool utilizes data intended to represent an industry average. For some items not in the Athena database, other sources like environmental product declaration (EPD) were consulted, or the kg CO2e - equivalent of assemblies was calculated by the authors. The total initial kg CO2e for the building was calculated by summing all the individual components kg CO2e.

The initial cost for housing construction with different combinations of components as mentioned in Table 3.1 is presented in Table 6.1. Costs for individual components can be found in RS Means Residential Cost Data (2018).

Table 6.1 Initial construction cost for houses with different combinations of components

House type	Carbon-footprint (in kg)	Cost (Dollars)
1 (standard)	35984	103810
2	36017	105232
3	36807	105210
4	36840	106632
5	36019	108301
6	36053	109723
7	36843	109701
8	36876	111123
9	35996	104157
10	36029	105579
11	36819	105557
12	36852	106979
13	36031	108648
14	36064	110070
15	36854	110048

16	36887	111470
17	36004	104390
18	36037	105812
19	36827	105790
20	36860	107212
21	36039	108881
22	36072	110303
23	36863	110281
24	36896	111703
25	36016	104737
26	36049	106159
27	36839	106137
28	36872	107559
29	36051	109228
30	36084	110650
31	36874	110628
32 (enhanced)	36880	111676

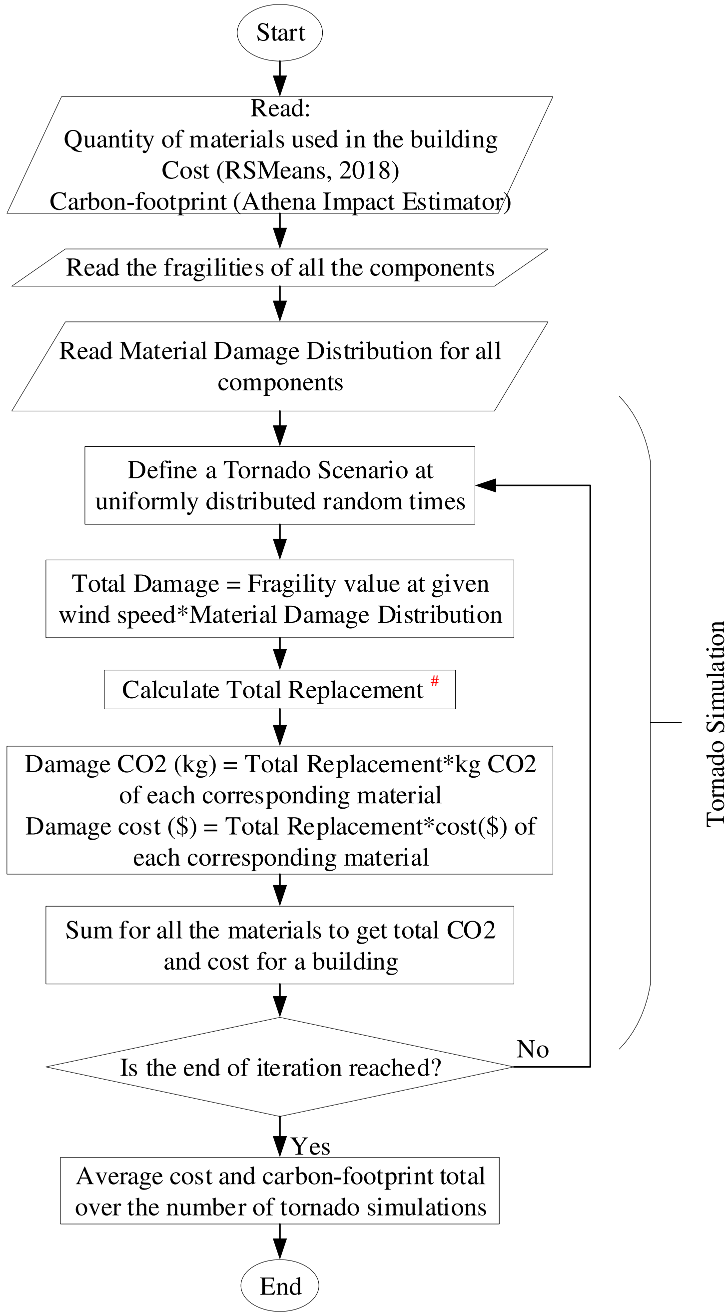
The Life-Cycle Analysis process is summarized in Figure 6.1. The damage of each building component, evaluated under scenario tornado winds, is listed as a percentage of the whole of that particular component in Table 6.2. This percentage acts as a basic multiplier for the projected percent failure for each component. The damage percentage includes damage to the individual component and the damage caused by failure of other components. An allowance was added for damage to interior finishes, based on the extent of damage to the building envelope as follows[2]:

- 100% damage to roof shingles may result in 20% damage to flooring, 100% damage to roof insulation and vapor barrier, and 20% damage to the moisture resistant gypsum board (interior walls) due to ingress of rain.

[2] Prof. Kathrina Simonen and Ms. Aiwen Xie, University of Washington, Seattle.

- 100% damage to the roof structure may result in 50% damage to flooring due to ingress of rain.
- 100% damage to roof-to-wall connection may result in 80% damage to gypsum board as well as gypsum board-studs connection.
- 100% damage to exterior wall panels may result in 50% damage to exterior walls and 10% damage to flooring.
- 100% damage to windows and doors may result in 20% damage to flooring due to ingress of rain.
- 100% damage to wall-to-foundation connection may result in 100% damage to interior walls, roof, windows and exterior walls.

Without available quantitative studies of building non-structural and contents damage at the level of detail used in the analysis, these estimates are based largely on engineering judgement. While they are believed to be reasonable based on previous post-disaster investigations (Kuligowski et al., 2014) and enable the method to be tested, additional research into the sensitivity of costs due to input parameter assumptions/variability is essential. Such assumptions are approximate but avoid the need for actual testing. All damages are summed to obtain the total damage, with a maximum of 100%.



We assume when damage% of some material is over a certain number, it should be replaced totally, because they can't be recycled even though they are not 100% damaged.

Figure 6.1 Life-cycle cost and carbon-footprint analysis for a tornado scenario

As an illustration of how damage and carbon footprint are determined for one of the components, we consider roof shingles. Suppose that the 3-s gust wind speed is 130 mph. Using Equations 4.1 – 4.5, we find that 67% of the roof shingles must be replaced for standard-quality construction and 5% for enhanced quality construction. Table 6.2 illustrates how the total replacement is found for roof shingles. Row 1 lists the fragilities for standard building components. Row 2 lists the material damage distribution. Row 3 shows the relation of roof shingles damage due to damage to other components. As can be seen from Table 6.2, damage to windows, doors and wall panels do not contribute to the damage of the roof shingles while roof panels, roof-to-wall connection and wall-to-foundation do. This is obtained by multiplying the fragilities by the material damage distribution. The total failure is either 100% or the sum of all failure percentages, whichever is less. For the roof shingles if the total failure is more than 50%, it is taken as 100% due to insurance replacement standards and the need to ensure that the replacement roof is watertight. Similar types of logical assumptions based on engineering judgement are reached for all the components.

Table 6.2 Fragilities, materials damage distribution for roof shingles and total replacement

	Material Name	Roof Shingles Failure	Windows & Door Failure	Roof Panel Failure	Exterior Wall Panel Failure	Roof Structure Failure	Wall Structure Failure	Total Failure	Total Replacement
1	58 m/s (130 mph) fragilities	67%	92%	88%	47%	17%	18%		
2	Material damage distribution for shingles	100%	0%	100%	0%	100%	100%		
3	Class D shingles	67%	0%	88%	0.%	18%	18%	100%	100%

If 67% of the shingles are damaged, 100% are replaced, but if 5% of roof shingles are damaged, a like percentage are replaced. The cost for replacing 100% of the standard shingles is \$4,977 and 736kg CO2e, while the cost for replacing 5% of the enhanced shingles is \$305 and 37 kg CO2e. Repeating this calculation for all six components, we find the total damage cost and CO2e footprint attributed to a particular tornado scenario.

6.1. Illustration of life-cycle analysis of single-family residential building

Tornado events for analyzing the impact of one and two tornado events on a single residential building during its service life of 100 years are defined by the median wind speeds of EF3 and EF4 intensities of the building. The damage cost and carbon footprint (kg) are determined by carrying out 50 Monte Carlo simulation since tornado occurrences and component capacities are random. The points in the figures below represent average cost and carbon-footprint for the particular alternatives in Table 3.1. Figure 6.2 shows the results of the LCA for a single event of the EF3 and EF4 median wind speeds. Similarly, Figure 6.3 shows the results when the individual residence is exposed to two tornado events. A comparison of these figures reveals little difference in the present value of the total life-cycle cost and carbon-footprint of the building, other than a slight upward-right shift in the plot indicating increase in both the cost and carbon-footprint.

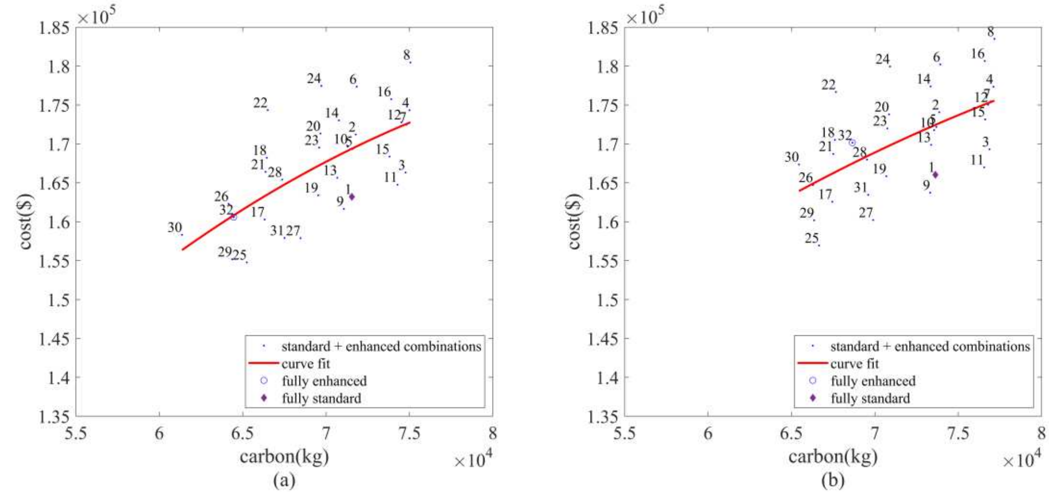


Figure 6.2 Carbon vs cost for a single tornado event during service-life of building A1 for a) 67.10 m/s (150 mph) corresponding to median wind speed for EF3; and b) 80.46 m/s (180 mph) corresponding to median wind speed for EF4

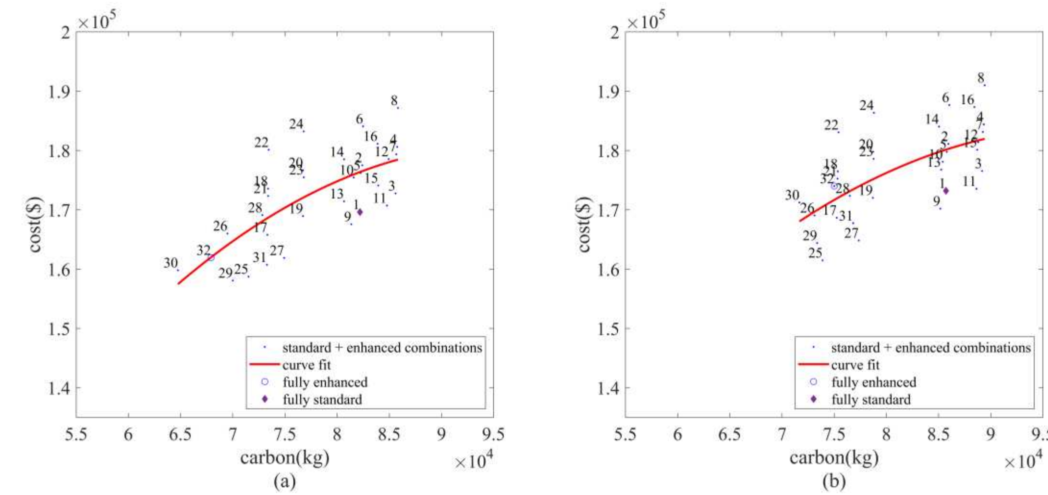


Figure 6.3 Carbon vs cost for two tornado events during service-life of building A1 for a) 67.10 m/s (150 mph) corresponding to median wind speed for EF3; and b) 810.46 m/s (180 mph) corresponding to median wind speed for EF4

For a median EF3 wind speed i.e. 67 m/s (150 mph), the building with the lowest carbon footprint in both cases, single and two tornado event(s), is building type 30, while the building with the lowest cost is building 25 for a single event and building 29 for two events, the difference between them is due to the use of standard and enhanced roof panels, respectively. All three building types are constructed, maintained and repaired with a mix of standard and enhanced components (see Table 2.2). Building 30 consists of enhanced roof shingles, while buildings 29 and 25 both have standard roof shingles. Even though the tornado damage is higher for standard shingles, the fact that there is a considerable difference in cost ($4,977 for standard and $6,399 for enhanced), and that regular repair and maintenance is performed at least 3 times during the life-cycle of the building, makes the standard roof cover more cost-effective. However, because of the small difference in carbon-footprint (737 kg for standard and 770 kg for enhanced) the regular repair and maintenance does not have as much effect on the carbon-footprint as the repairs due to tornado event for the roof shingles.

Building 8 is the least optimal in terms of both carbon-footprint and cost because it has standard roof-wall and wall-foundation connections, which causes increased damage during a tornado event. The fact that this building has enhanced roof cover and windows has little benefit when an EF4 tornado is likely to cause major structural damage. For an EF2 intensity median wind speed, 54 m/s (120 mph), the results obtained are similar but for EF1 intensity tornado median wind speed of 45 m/s (100 mph) or less, the results is different as shown in Figure 6.4. A residence with fully standard construction details is optimal in this case because the damage due to low wind speed is not significant.

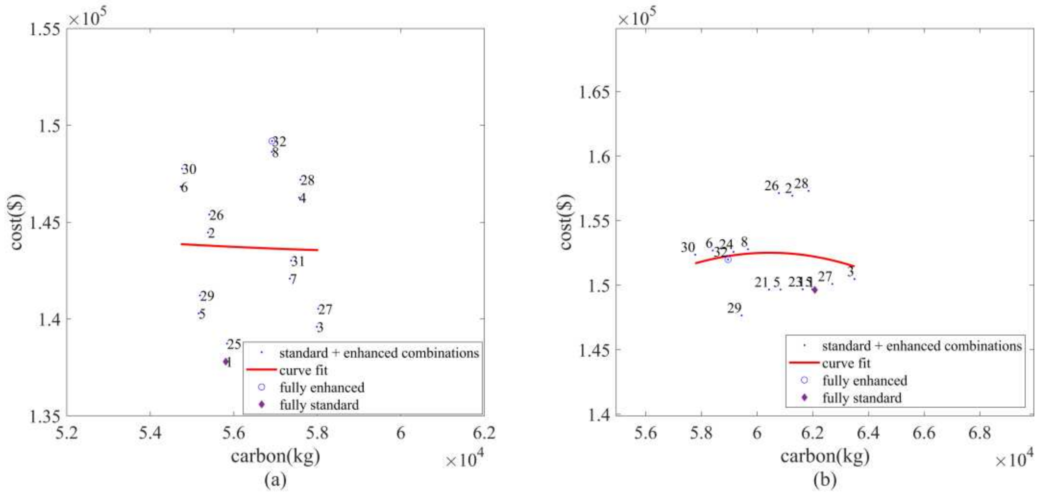


Figure 6.4 Carbon vs cost for a single tornado event during service-life of building A1 for a) 454.70 m/s (100 mph) corresponding to median wind speed for EF1; and b) 543.64 m/s (120 mph) corresponding to median wind speed for EF2

Figures 6.2 and 6.3 show that there is a cluster of building types where the houses with enhanced wall-foundation connections are more optimal than those with standard connections. The gap in the clusters seem to decrease with the increase in wind speed as seen in the distinction between the 54 m/s (120 mph), 67 m/s (150 mph) and 80 m/s (180 mph) wind speed graphs as in the figures below. This is true for both one and two tornado scenarios. Though the most optimal option, as analyzed for A1, remains the same, i.e. building 25, there is regrouping and reorder in other suboptimal options when we analyze A2 and A3 under single tornado event of EF3 and EF4 as shown in Figure 6.5 and Figure 6.6, respectively.

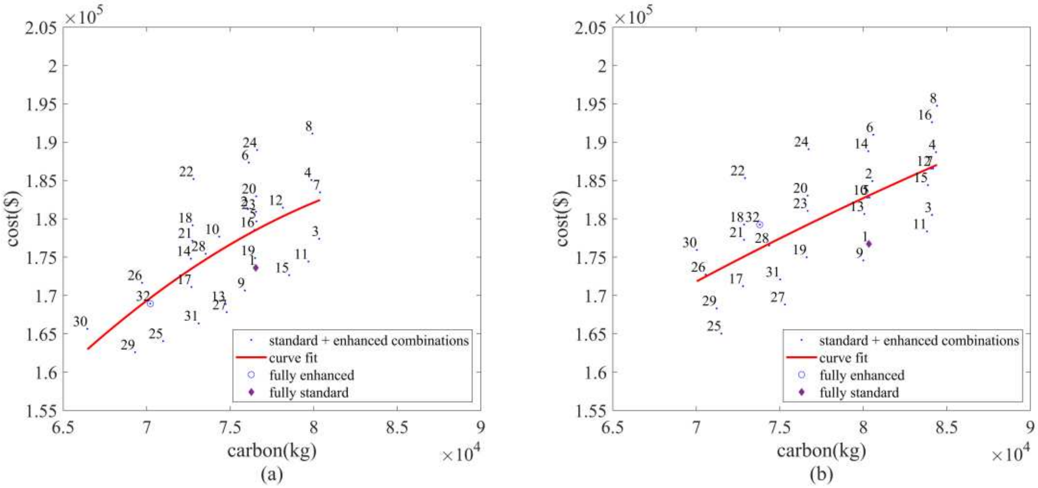


Figure 6.5 Carbon vs cost for a single tornado event during service-life of building A2 for a) 67.10 m/s (150 mph) corresponding to median wind speed for EF3; and b) 80.46 m/s (180 mph) corresponding to median wind speed for EF4

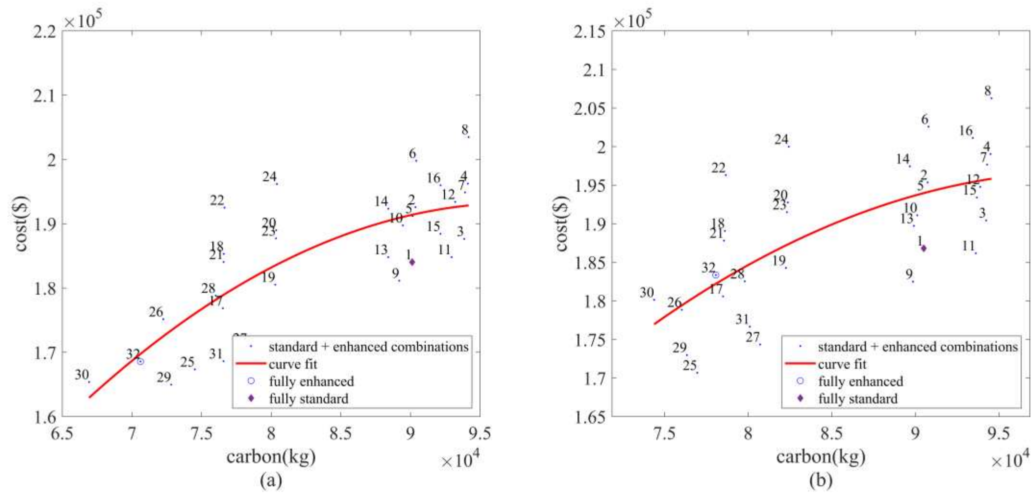


Figure 6.6 Carbon vs cost for a single tornado event during service-life of building A3 for a) 67.10 m/s (150 mph) corresponding to median wind speed for EF3; and b) 80.46 m/s (180 mph) corresponding to median wind speed for EF4

Similar to the results obtained for A1, analysis for two tornado events show no apparent difference other than up-right shift in the carbon vs cost data. This shows that considering only one tornado scenario event is sufficient for life-cycle analysis for wood-framed residential buildings.

6.2. Illustration of life-cycle analysis of a residential community

Scaling up from an individual building to a community level is important in decision-making and policy formulation for building a resilient and sustainable community as resilience and sustainability has come to the fore-front of community decision-making. When a community consisting of such individual buildings is considered with a tornado passing through the community, the difference in the optimal repair decisions is not that clear. The regular repair and maintenance strategies as well as strategies for repairs following a hazard is considered same as for the individual building (see Section 3.3). The results are similar to those of the individual building in terms of how optimal and suboptimal solutions are grouped together. Comparing Figure 6.2(b) and Figure 6.7 shows that the optimal and near optimal decision strategies are clustered together as well as the sub-optimal as well as near sub-optimal strategies are clustered together. The community would sustain the least cost and carbon-footprint if alternative 30 were to be adopted for all the buildings in the community, as shown in Figure 6.7. This type of analysis is important when planning a new community. If an individual homeowner wants to build a new house in a residential area, he/she will want to optimize the cost and carbon-footprint based on the results of the individual building. For example, for archetype A1 individual building analysis showed that using alternative 25 is the most optimal in terms of cost and carbon-footprint. In contrast, if the home-owner abides by the results extracted from a community analysis, he/she must select alternative 30, which will cost him more in terms of cost (though in terms of carbon-footprint, alternative 30 is slightly better).

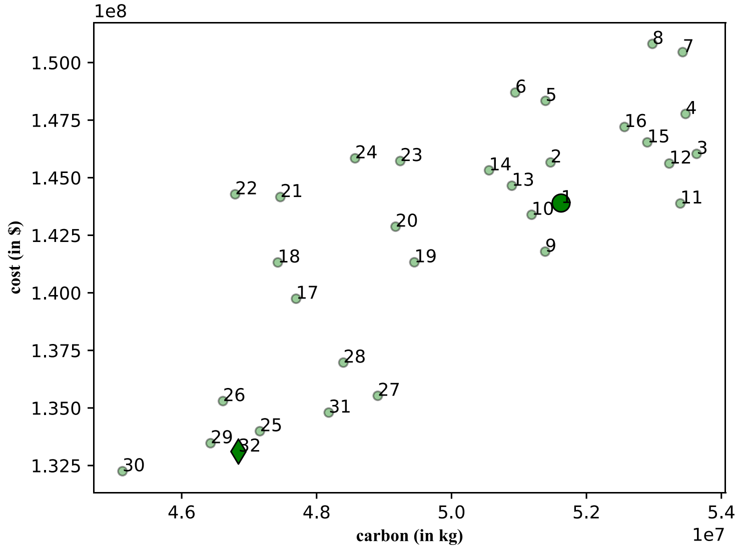


Figure 6.7 Carbon vs cost for a single tornado event for a community during a 100-year period 80.46 m/s (180 mph) corresponding to median wind speed for EF4

The decision to repair in the aftermath of tornado event depends on numerous factors – home-owner's insurance coverage, economic condition, and age, incentives offered by the community, local building code requirements, etc. For example, consider a Pre-Andrew house with standard roof shingles, where fewer than 20% of the shingles have been damaged. In this situation, the insurance may not pay for the replacement of all the roof shingles but just the 20% replacement. Nor is the homeowner required by building codes to replace all shingles in the event of such slight damage. The homeowner might decide to replace the damaged shingles with standard shingles. However, if the financial status of the homeowner is good, then he/she might consider replacing the standard shingles with enhanced shingles.

New damage levels are introduced (Table 6.3) to simplify the decision-making. Combining Tables 5.1 and 5.2, we construct six levels of damage to a residential structure. Some of the DOD mentioned in Table 5.2 are similar and could be condensed for simplifying the decision-making process. For example, the difference in wind speeds for DOD 3 and 4 is minimal

(96 mph vs 97 mph), which results in similar type of damage sustained by the structure. Therefore, combining both DODs to represent the same "Damage Level" – Damage Level 1 will suffice. Similar exercise is carried out for all the DODs and they are all concisely defined as shown in Table 6.3. The wind speed is taken as average of the mean wind speed of the number of DOD associated with the damage levels and is somewhat similar to that of mean wind speed taken for EF scales and tornado modeling in Section 5.2. For example, the mean wind speed for DOD 3 is 42.9 m/s (96 mph) and DOD 4 is 43.4 m/s (97 mph) which gives an average of 43.14 m/s (96.5 mph) which is near to the mean wind speed for EF1 44.7 m/s (100 mph). The EF scales use 3-second gusts estimated at the onset of damage based on judgement of 3-12 levels of damage to 28 indicators. One of the damage indicators is "one- or two-family residences" which is the only relevant indicator for our study. So, the wind speeds might be under-estimated or over-estimated when we only consider one of the damage indicators. For simplicity, the average wind speeds considered in Table 5.1 is used for the study.

Table 6.3 New damage levels

Damage Levels	Degree of Damage	Associated mean wind speed (mph)
0	DOD 1-2	72
1	DOD 3-4	96.5
2	DOD 5-7	121.5
3	DOD 8	142
4	DOD 9	170
5	DOD 10	200

Based on engineering judgement, the probabilities stated in Table 6.4 is assigned to repair strategies for individual homeowners. Decisions on repair strategies are based on the following assumptions:

a. Repairs are made with building materials and products that are equal to or better in quality than what is being replaced. Hence, the enhanced buildings (zone 2) always follow the repair strategy where enhanced materials are chosen to replace enhanced materials however, standard materials may be replaced with either standard or enhanced materials, depending on the preference of the homeowner.
b. Some communities require that improvements be calculated cumulatively over several years. All improvement and repair projects undertaken over a period of five years, 10 years or the life of the structure when added up exceeds 50 percent, the building must be brought into compliance as if it were new construction (FEM, 2010). All new buildings must comply with current building regulations. Thus, when damage to a Pre-Andrew building exceeds 50% in repair cost [assumed to be complete damage to the building in this study] (damage level 5), the new construction adheres to the new building codes and adopts the Post-Andrew construction quality (i.e. enhanced construction quality).
c. IBC (2000) had a provision such that if the repair cost of the building does not exceed 50% of the building's value, the undamaged components were left alone and upgrades were made only to the affected portion of the building. IBC (2015) was more lenient towards such upgrades and required that the building components be restored to pre-damaged construction assuming that the building was considered safe and sanitary before the damage. The decision to upgrade to enhanced or remain at standard construction comes into play now. These decisions depend on the home-owners and their psychology after the

hazard, their risk aversion, their economic resources, etc. These decision alternatives, where permitted by local regulations, are modeled by the probabilities in Table 6.4. For example, for a Pre-Andrew dwelling suffering damage level 2, the probabilities of staying with standard or upgrading to enhanced are 0.6 and 0.4, respectively; for damage levels 3 – 5, the local building regulations will require enhanced. Similarly, the probability that the damaged components will be replaced by enhanced components when the damage level is 1 is assumed to be 0.8 and 0.6.

d. When there is no quantitative damage and the damage is in the threshold of visible damage (damage level 0), the building owner does not have any substantial structural damage and there is no need to upgrade existing building components by enhanced materials.

Table 6.4 Probability of decisions

Zones	Repair Strategies Probabilities		
	Damage Level	Standard	Enhanced
Pre-Andrew Community	0	1	0
	1	0.8	0.2
	2	0.6	0.4
	3	0	1
	4	0	1
	5	0	1
Post-Andrew Community	All (1-6)	0	1

The scenario EF4 tornado is defined in Section 5.1.2. and 50 simulations as before for the occurrences of tornado during the service life of the building and, to be able to take into consideration the randomness in variables like length, width, azimuth, touchdown point, etc., 100 simulations of the tornado profile that hits the community is carried out. The replacement values for each building that lie inside sub-EF zones of tornado path are determined as per Table 6.2, similar to what was done for a single building.

The first analysis is done by considering a tornado modeled as described in Section 5.2 with fixed length and width, and the center of the tornado lying randomly in the pre-determined boundary of the community. The second analysis includes uncertainty in in tornado length and width, along with the randomness in the location of its center. In all cases, the tornado path direction is random, described by a uniform distribution between 0 and $\pi/2$. With these assumptions and the repair/reconstruction probabilities mentioned in Table 6.4 is applied, the results are as shown in Figures 6.8 and 6.9. Figure 6.8 shows that the distribution when the tornado path is deterministic is similar to normal distribution but randomness in the tornado path makes the resulting distribution more deviated from normal. The expected average CO2e lies in the range of 14 to 22 million kg for when deterministic tornado is considered while it seems to vary anywhere from 22 to 55 million kg when the tornado footprint is assumed to be random as described in Section 5.2. The 95% upper confidence level is 21 million kg for deterministic tornado but is 60 million kg for random tornado. This indicates that the carbon footprint will be underestimated by a factor of 3 if deterministic tornado is taken as a basis for analysis. Similarly, from Figure 6.9 the cost will be also be underestimated by a factor of 3.

This indicates that the simplification in tornado modeling will only result in underestimation of the tornado damage and have a great impact when it comes to mitigation, preparedness, response and recovery process for the hazard management.

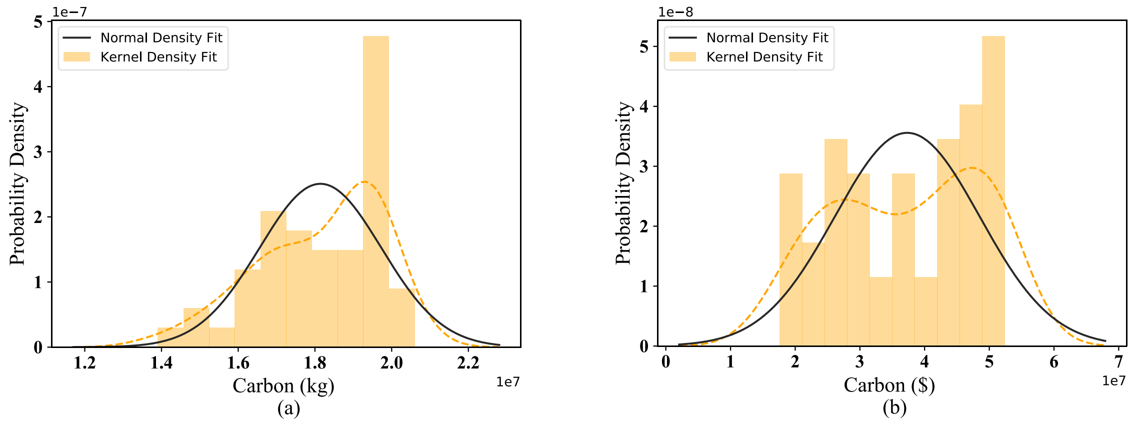


Figure 6.8 Histogram and probability density community CO2e, (a) deterministic tornado footprint (b) random tornado footprint

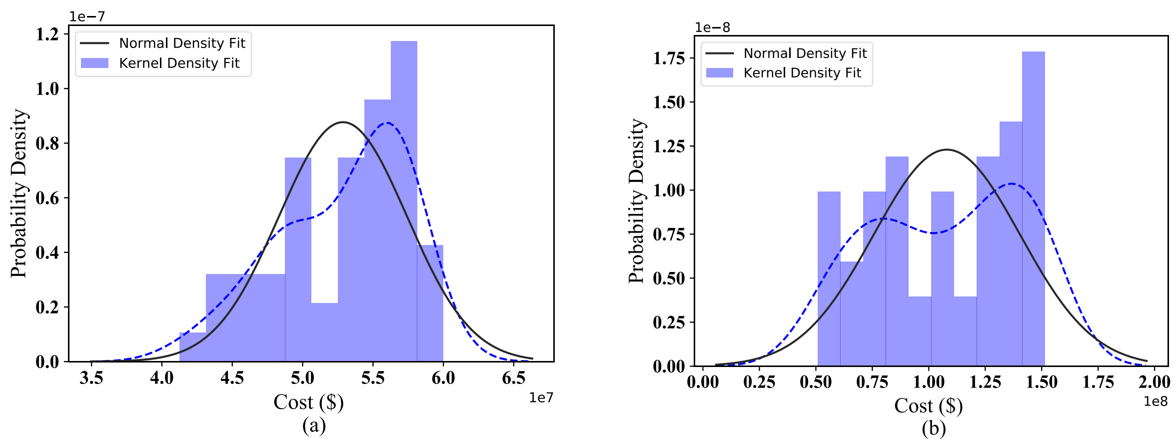


Figure 6.9 Histogram and probability density for community cost, (a) deterministic tornado footprint (b) random tornado footprint

7. CONCLUSIONS

When I examined myself and my methods of thought, I came to the conclusion that the gift of fantasy has meant more to me than my talent of absorbing positive knowledge.

-Albert Einstein

In this study, both economic and environmental LCA are utilized for an integrated analysis of resilience and sustainability of light-frame wood construction in tornado-prone regions. Three buildings, which are representative of light-frame wood residential buildings in the U.S., were considered in this analysis. The tradeoffs between resilience and sustainability over a 100-year service life were examined through a detailed analysis of cost and carbon footprint functions, respectively. These functions accounted for initial construction cost, repair and maintenance costs, and damage cost due to the random occurrence of tornadoes. Tornadoes were modeled as scenario events, with time of occurrence, footprint size and building component fragilities as random in nature. A tornado passed through the model residential community once in a 100-year period to analyze the life-cycle perspective form the community level. The following conclusions can be made based on the analysis results.

- When construction decisions are made on a life-cycle basis, decisions involving home construction or home repair following a tornado to enhance resilience and minimize carbon footprint may differ significantly from decisions made on an initial cost basis.
- The scenario event analysis helped in finding optimal decisions which are easily understood by homeowners or homebuilders who might not be risk-informed.
- As the results show that enhanced constructions are more optimal than standard construction, provisions similar to building constructions in hurricane zones can be adapted to areas where tornado hazard is prominent.

- Except for tornado intensity EF1, a building with all enhanced components is closer to optimality (in terms of both cost and carbon footprint) than a building with all standard components, suggesting that additional initial and periodic investments to enhance building resilience and sustainability pays off in the long term. The decisions as to which solutions are adopted will depend on economic status and risk-aversion of the homeowner or homebuilders and the requirements set by building codes and standards.
- The study shows that considering only one tornado scenario event and one archetype, given that the archetypes are not too dissimilar in construction materials and practices, is sufficient for life-cycle analysis for wood-framed residential buildings. This is because the probability of two or more tornadoes striking the same building (or small neighborhood) in 100 years is very small.
- The solutions for optimizing cost and carbon footprint do not create the tradeoff that often is seen in multi-objective optimization. Rather, there is a positive correlation between life-cycle carbon footprint and life-cycle cost, indicating that minimum cost solutions may also be near-optimal in terms of carbon footprint, and conversely.
- Unlike for a single building, where the maximum wind speed of an EF scale tornado is assumed to hit the building, tornado damage to the buildings in the community is determined to a considerable extent by the sub-EF zones that the buildings are in. This reflects the randomness in tornado footprint and this will exhibit a higher range of damage.
- Tornado hazard modeling should be done by including all the randomness in the model to estimate as the impacts on individual buildings and on residential communities. Disregarding stochasticity of the model and over simplifying can lead to underestimation of the effects of hazard by a large factor.

The findings in this study emphasize the importance of life-cycle thinking when deciding on alternative building constructions with both resilience and sustainability in mind.

Recommendations for Further Research:

- Energy use during the service life of the building was not taken into account in this study. Energy use also has a large footprint in terms of both cost and carbon. Oftentimes, large appliances are part of the purchase price of the home and to minimize the life-cycle cost and carbon footprint, additional investment has to be considered at construction time to pay off over the service life of the building. Development of life-cycle analysis taking into consideration the household appliances and energy usage might add another dimension to the decision-making process.
- The imperceptible difference between some of the near optimal choices might change when more impact categories are introduced or more variables (furniture, appliances, mechanical fixtures, etc.) are added. Increasing the size of the variable by increasing the choices in different building components will increase the decision-making space and provide more optimal decision-making strategies for the construction of new buildings or repair of existing buildings. This might have a much bigger impact at the community level as scaling-up is considered. As such, further studies to evaluate the effect of the aforementioned variables on the total life-cycle cost and carbon footprint for both buildings and community are recommended.
- Scenario events are considered in this study because these types of analysis is far more useful to homeowners as well as public decision and policy makers who are not risk-informed. A life-cycle analysis with probabilistic model of different intensity tornado

occurrences which might help determine how the decision process alter compared to scenario event would be a useful research practice.

- Simplification of hazard modeling might lead to under-estimation or over-estimation of the effect of the hazard when a larger framework is built. To take away the under-estimation from this research without further analysis will be fallacious.
- Development of a framework to integrate different networks of the community might provide more concrete decision-making strategies for increasing the sustainability and resilience of the building.

The established framework is sufficiently general that it could be used to establish minimum life-cycle cost alternatives for other building technologies besides light-frame wood residential construction. So, it would be interesting to how other types of buildings fare when we apply the methodology developed in this paper.

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