Prioritizing Residential High-Performance Resilient Building Technologies for Immediate and Future Climate Induced Natural Disaster Risks

Oluwateniola E. Ladipo

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Georg Reichard, Chair
Andrew P. McCoy
Annie R. Pearce
Paul L. Knox

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ABSTRACT

Climate change is exacerbating natural disasters, and extreme weather events increase with intensity and frequency. This requires an in-depth evaluation of locations across the various U.S. climates where natural hazards, vulnerabilities, and potentially damaging impacts will vary. At the local building level within the built environment, private residences are crucial shelter systems to protect against natural disasters, and are a central component in the greater effort of creating comprehensive disaster resilient environments. In light of recent disasters such as Superstorm Sandy, there is an increased awareness that residential buildings and communities need to become more resilient for the changing climates they are located in, or will face devastating consequences. There is a great potential for specific high-performance building technologies to play a vital role in achieving disaster resilience on a local scale. The application of these technologies can not only provide immediate protection and reduced risk for buildings and its occupants, but can additionally alleviate disaster recovery stressors to critical infrastructure and livelihoods by absorbing, adapting, and rapidly recovering from extreme weather events, all while simultaneously promoting sustainable building development. However, few have evaluated the link between residential high-performance building technologies and natural disaster resilience in regards to identifying and prioritizing viable technologies to assist decision-makers with effective implementation. This research developed a framework for a process that prioritizes residential building technologies that encompass both high-performance and resilience qualities that can be implemented for a variety of housing contexts to mitigate risks associated with climate induced natural hazards. Decision-makers can utilize this process to evaluate a residential building for natural disaster risks, and communicate strategies to improve building performance and resilience in response to such risks.

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GENERAL AUDIENCE ABSTRACT

With the growing concern of climate change, and the increased frequency and severity of extreme weather events, homes need to be made to better withstand the potential impacts of natural disasters. This research developed a decision-making process that can be used to assess natural disaster risks to residential buildings, and also identify the best technology options to reduce these risks while also increasing building performance. Risk is explored and evaluated for residential buildings in terms of how critical the physical damages can be as a result of natural hazard impacts, and also in regards to what can increase a home's vulnerability to the impacts of natural hazards. Risk mitigation options include qualities that increase a home's disaster resilience (e.g. better ability to withstand and recover from natural disasters) and building performance (e.g. enhanced durability, energy efficiency, health and comfort) to various natural hazards. The process developed in this research prioritizes risks and technologies specific to various household locations, occupancy types, and standards and qualities of construction.

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1 Introduction

Over the past 100 years, research has shown that the surface temperature on Earth has risen by more than 1.4°F (0.8˚C) with much of that increase having taken place over the last 35 years. This increase will lead to various changes that will be experienced in the environment including heavier rainstorms, exacerbated droughts, a reduction in snowpack, a rise in sea-levels, more frequent heat waves, shorter and milder cold periods, and 60 to 90 additional days per year with a heat index reaching above 100°F in the United States (NRC 2012). Climate change is our reality, and it has become increasingly important to become more aware of the many implications it will have on our lives, our environments, and our infrastructures. In building construction, the consequences of climate change are already taking a toll on builders, owners, and occupants in various ways. The U.S. energy sector, in particular the aging electric grid (DOE 2013), is being pushed to its limits in the wake of severe weather-related power outages that have occurred and that are projected to increase in frequency (EIA 2013). Additionally, the majority of the grid exists above ground and is thus exposed directly to harsh weather conditions leaving it vulnerable to increased deterioration. These events and circumstances contribute to billions of dollars in annual economy fluctuation and inflation as a result of costs incurred for repairs and maintenance, where recently in 2012 the year of "Superstorm" Hurricane Sandy, costs to repair damages were estimated to be $52 billion (DOE 2013).

In addition to the vulnerabilities that the built environment faces, people are also becoming more vulnerable to the adverse consequences of severe weather-related exposure and climate change. Mortality rates could potentially increase in varying levels of socioeconomic communities that are susceptible to extreme temperatures. This is especially true in areas with older homes and lower standards of living, as access to air conditioning systems becomes more of a necessity to reduce the risk of death in the event of extreme heat (Anderson and Bell 2009; Chestnut et al. 1998; Curriero et al. 2002). Similarly, in the event of power failures, poor construction and building enclosure performance lack the resilience and adequate protection for occupants susceptible to adverse and extreme weather conditions. There is no doubt that in the wake of climate change, disasters can and will strike taking a toll on the built environment and many lives. Disaster resilience, as an integrated approach across the various construction standards and practices addressing the different performance mandates, ranging from structural, to thermal, moisture, visual, and environmental performance will be necessary to overcome the changes we will inevitably face.

Resilience as defined by the Department of Homeland Security (DHS) is "the ability to prepare for and adapt to changing conditions, and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents" (DHS 2014). There is a great potential for specific high-performance building technologies (e.g. technologies with energy efficient and enhanced performance features) to play a vital role in creating and increasing resilience through the application of such technologies on a local scale. Such technology applications can be used to alleviate disaster recovery stressors to critical infrastructure and livelihoods, and ultimately, reduce the risk of detrimental natural disaster impacts. High-performing communities that are strong and adaptable with resources readily available, and the ability to apply and reorganize them to ensure functionality during and/or after a disturbance, could contribute to risk mitigation and disaster resilience on a local, building level. Homes that are not only built to be high-performing as a single entity, but also designed to interact as a community and work as an interconnected system, could be an invaluable approach and asset in disaster response and risk management practices.

High-performance technologies such as those implemented by the PassivHaus standard, which provide significant heat loss reduction and incorporates passive heating and cooling strategies to maintain thermal comfort and reduce energy consumption, can be of large benefit when constructing resilient homes and communities. To illustrate this, in the event of a power failure experienced during a severe cold front, a PassivHaus enclosure's superior thermal resistance in comparison to conventional building code enclosures can provide long-lasting shelter against dangerous rapid temperature drops, which could otherwise force occupants from their homes. Other similar passive design strategies can harness benefits from solar gain, shading devices, natural lighting, thermal mass, and natural heating/cooling from the exterior and underground to maintain livable interior conditions in the event of a natural disaster. Utilizing co-generation systems incorporated into a community to produce and store combined heat and power for neighbors, offsetting the power demand and disaster threat levels as a buffer could allow for self-sufficiency in the event of utility failure and/or disconnect. For example, in the above-mentioned scenario of a community wide power failure during extreme cold weather, buildings with high-performing thermal enclosures could maintain safe living conditions without or with only intermittent use of mechanical heating for a longer period of time than those constructed to a lesser standard. This in turn could reduce the power demand for a community generating energy used for priority based distribution on a local level by supplying power to buildings with occupants at greater risk first, while simultaneously working to alleviate power recovery stressors and expenditure on a larger regional/state level. Potable water supply is another critical resource that can be disrupted during the event of natural disasters such as a drought or weather-related power outages where pump stations are required to maintain water pressure and demand. Communities with disaster preparedness plans and systems in place such as alternative water distribution sources and/or pipe interconnections to adjacent utilities, which allows for shared water supply between neighboring communities can provide safe and immediate sources of water supply in the event of water supply disruptions (AWWA and CDM 2011).

Considering localized, regional climate conditions and future projections of climate change is an important factor to also consider in resilient, high-performance building construction, especially when prioritizing hazards and considering adaptations to existing strategies. Generalized regional historical climate data has been proven to no longer be sufficient in providing reliable projections (Cullen and Lea 2001; de Wilde and Coley 2012; McLeod et al. 2011) and high-performance design data where typical temperatures, building and population densities, and topography may have changed. Reports and studies that discuss and investigate the need to incorporate micro level and 'future proof' climate change data into building designs and simulations (Belcher et al. 2005; Jentsch et al. 2008; McLeod et al. 2013; Mourshed 2011; Tantasavasdi et al. 2011), as well as a personal experience, have revealed some insight into the importance of this issue. While living in a PassivHaus apartment building in the summer of 2013 located in Vienna, Austria, record temperature levels were reached surpassing 40˚C (104˚F) during the summer months. Even with passive design technologies in place in the building including a highly thermally resistant enclosure and strategic shading, interior comfort conditions were difficult to tolerate for a prolonged amount of time. Although this can be highly subjective, it was brought to light that other building residents during that summer also found the interior comfort levels difficult to withstand. Many of which are even native to similar climates and accustomed to spaces conditioned without the use of mechanical cooling systems. It should be noted that cooling systems are not common for residential buildings in Austria's alpine influenced climate, and thus other residential buildings were equally uncomfortable. The key point is that it became clear that such temperature levels are currently not anticipated in design codes and thus even high-performance building technologies may not yet be equipped to deal with these changes. This is one example of how rapidly localized climate data and predications are becoming all the more important to comfort, as well as adopting the reality of climate change. This also brings to attention the changes that may now become necessary to maintain occupant comfort with air conditioning systems or alternative technologies in areas that have not typically utilized those in the past. Research in this area could influence policy decisions, building codes, and building standards, even more so for high-performance standards where lower heating and cooling load requirements become more sensitive to system sizing and will need to be reconsidered and appropriately altered. High-performance building standards are dissimilar and have varying requirements and focuses that may require the integration of additional technologies and strategies in order to become more suitable for more climates and the associated natural hazards, which may not be apparent or explicitly addressed in their current certification processes.

The benefits of disaster resilient high-performance buildings and communities can be diverse, with strategies such as creating "survival cell" homes and communities through the use of enhanced enclosure systems, and implementing local cogeneration utilities while collapsed infrastructure systems can be brought back online, reducing the strain on disaster response efforts and expenditures. Additionally, any system-integrated effort towards disaster resilience would also continue efforts towards energy efficiency and supreme building performance standards. At the local, building level, private residences can be viewed as crucial system to protect and enhance towards the greater effort of creating a comprehensive disaster resilient built environment. High-performance building technologies as well as disaster resilience strategies are popular in the residential construction industry, where either approach is often a requirement for many builders and owners. There are viable high-performance building technologies that can simultaneously provide disaster resilience, however, what is not well known are the desired results to be expected in regards to their influence on building performance and disaster resilience, and if they appropriate for a specific building, especially when considering interactions between multiple climate hazards, and differing vulnerabilities, communities, and building technologies. This has been especially exacerbated as Earth's climate continues to change, where unexpected and intensified weather conditions can arise requiring closer attention to local climate conditions. This in turn leads to the following question posed by this research: how can we identify and prioritize high-performance building technologies that can provide residential buildings with higher resilience towards local level climate induced natural disaster risks currently experienced and anticipated throughout the diverse U.S. climate regions?

2 Background

2.1 CLIMATE INDUCED DISASTERS AND BUILDING IMPACTS

Different climates around the world can induce various types of naturally occurring hazards, commonly referred to as extreme weather events. When these events cause catastrophic damage and loss of life, they become classified as natural disasters. According to the Centre for Research on the Epidemiology of Disasters (CRED), there are two types of generic categories for what a disaster can be: natural or technological. CRED further divides natural disasters into five sub-categories covering 12 types of disasters, which are defined and summarized in Table 1.

Table 1 Natural Disaster Classifications (CRED 2014)

Disaster Subgroup	***Definition***	***Disaster Type***	***Disaster Sub-Type***
Geophysical	Events originating from solid earth	Earthquake, Volcano, Mass Movement (dry)	Ground Shaking, Tsunami Volcanic Eruption Rockfall, Avalanche, Landslide, Subsidence
Meteorological	Events caused by short-lived/small to meso-scale atmospheric processes (in the spectrum from minutes to days)	Storm	Tropical Storm, Extra-Tropical Cyclone (winter storm), Local/Convective Storm
Hydrological	Events caused by deviations in the normal water cycle and/or overflow of bodies of water caused by wind set-up	Flood, Mass Movement (wet)	General River Flood, Flash Flood, Storm Surge/Coastal Flood Rockfall, Landslide, Avalanche, Subsidence
Climatological	Events caused by long-lived/meso- to macro-scale processes (in the spectrum from intra-seasonal to multi-decadal climate variability)	Extreme Temperature, Drought, Wildfire	Heat Wave, Cold Wave, Extreme Winter Conditions Drought Forest Fire, Land Fires (grass, scrub, bush, etc.)
Biological	Events caused by the exposure of living organisms to germs and toxic substances	Epidemic, Insect Infestation, Animal Stampede	Infectious Diseases (Viral, Bacterial, Parasitic, Fungal, Prion)

The devastation that can occur to the built environment as a result natural disasters has become all too familiar as an unfortunate and uncontrollable product of our Earth's nature. In recent years, the frequency and intensity of climate related (meteorological and climatological) natural disasters over time such as hurricanes, droughts, and extreme temperatures has risen, and consequently so has the detrimental impacts of the aftermath associated with these events. From 2002 to 2011, a reported 107,000 people were killed and 268 million people were victims of natural disasters worldwide, excluding biological disasters (Guha-Sapir et al. 2013). The same report states that the U.S. is among the top five countries in the world that are most frequently impacted by natural disasters, where in 2012 it experienced 79 natural disasters and suffered the most damages of any country in the world. Damages suffered were a reported 65.7% of global damages experienced, which was estimated to cost $157 billion, well above average levels experienced in prior years (Guha-Sapir et al. 2013). Much of the damages and costs that were incurred as a result of natural disasters in 2012 can be attributed to Hurricane Sandy, the most expensive natural disaster of 2012, followed by droughts and heat waves that were experienced predominantly in the mid-west and south-west regions that same year (Guha-Sapir et al. 2013). Post-natural disaster, during the aftermath and rebuilding efforts, victims can still be exposed to various residential and occupational hazardous conditions, debris, and materials leading to serious health issues (FEMA 2008), which could potentially increase the amount of fatalities and injuries. This can be especially exacerbated for individuals with damaged housing located in severely impacted areas.

There is no doubt that the devastation experienced in the past and recent history as a result of natural disasters has brought about a stronger awareness and motivation to change the way structures are built, as well as how to prepare for and react to severe weather events. The following subsections (2.1.1 to 2.1.5) detail some of the most recent and devastating climate induced natural disasters that the U.S. has experienced and their impact to the built environment as a result. In some cases, many have grounds to argue these events are also a result of a changing climate, where events such as these are likely to increase in frequency and severity in the near future.

2.1.1 Hurricanes and "Superstorms"

Perhaps one of the most well-known and devastating natural disasters and national tragedies to ever strike the U.S. was Hurricane Katrina, which occurred in August of 2005. The hurricane slammed into the Gulf Coast devastating the area with far-reaching catastrophic impacts still being felt today. As the costliest hurricane in history, the scope of human suffering as a result of Katrina is greater than any hurricane to have struck the U.S. in several generations (Knabb et al. 2011). Katrina caused widespread flooding, strong winds, and spawned over 40 tornadoes in its wake, all leading to a reported death toll reaching a staggering 1,833 fatalities (Knabb et al. 2011). The majority of the buildings and communities that were located along the coast were vastly decimated. Thousands of other homes, businesses, property, and transportation pathways and structures located in the hurricanes reach were either completely destroyed or severely damaged. Approximately three million people were left without electricity to their homes for several weeks (Knabb et al. 2011). Over one million housing units located in the Gulf Coast were damaged, with many of the victims left permanently displaced from their homes in the devastated area (Plyer 2013). The devastation caused by Katrina totaled an estimated $41.1 billion in insured damages, making it the largest single loss event in the history of the global insurance industry (Hartwig and Wilkinson 2010). In total, the damages as a result of Katrina was approximately $150 billion (Plyer 2013). Two additional severe hurricanes, Rita and Wilma, followed after Katrina later that year in 2005 contributing to extensive damage, deaths, and costs.

In 2008 another catastrophic hurricane struck parts of the Gulf Coast again causing the most significant damage in parts of Texas and Louisiana. This was Hurricane Ike, today known as one of the costliest and devastating hurricanes to strike the U.S. among the likes of Katrina. Winds reached tremendous speeds, rainfall caused massive flooding and water level rise, and 29 tornadoes spawned as a result of Ike adding to its severity (FEMA 2008). When Ike's intensity had diminished over Texas, flooding spread into parts of Missouri, Illinois, and Indiana (FEMA 2008). Ike resulted in 103 deaths throughout Hispaniola, Cuba, and the U.S. Gulf Coast, with additional deaths and damage also reported in parts of the Ohio Valley and the southeastern part of Canada (Berg 2010). The U.S. Department of Energy (DOE) estimated that 2.6 million people in Texas and Louisiana lost power as a result of Ike, worsened by the destruction of several oil refineries, reserves, and major pipelines (FEMA 2008). Many communities suffered from the destruction caused by Ike with numerous homes, businesses, and facilities destroyed and severely damaged in Ike's wake. 8,000 houses were lost as a result of Ike, with estimated costs to damaged houses totaling $3.4 billion (FEMA 2008). Figure 1 portrays an example of the devastation caused to an area heavily populated with houses along a coastline in Texas hit by Ike. Overall, the estimated damages of Ike totaled approximately $24.9 billion (FEMA 2008).

The most recent hurricane to hit the U.S. was Superstorm Sandy, once again causing historic widespread devastation, this time mostly impacting the northern and eastern parts of the country. Sandy impacted almost the entire east coast, with the most significant damage striking New York, New Jersey, and Connecticut. The National Hurricane Center released a tropical cyclone report detailing the major impacts of the storm in the U.S. with staggering facts and figures explaining why Sandy is said to be the second most devastating hurricane behind Katrina. The report estimated a total of 147 deaths as a result of Sandy, with 72 having taken place in the U.S. (Blake et al. 2013). 650,000 houses were destroyed or damaged, and 8.5 million people were left without power for weeks, some even for months due to the storm (Blake et al. 2013). 50 deaths resulted from a loss of power during cold weather as people fell victim to hypothermia or carbon monoxide poising from the use of generators and poorly operated cooking devices (Blake et al. 2013). Sandy also brought unusual weather that is not often associated with tropical storms. Snowstorms and blizzards struck states following Sandy, leaving several states blanketed with snow and cold weather conditions. All in all, the estimated cost of damages as a result of Sandy was reported to exceed $50 billion.

Figure 1 USGS image of before and after Hurricane Ike impact on Bolivar Peninsula, TX. The yellow arrows marks the house that survived the impact of the hurricane (USGS 2008)

2.1.2 Extreme Heat and Droughts

Over the past decade, record highs have outpaced record lows in the U.S. by a ratio of 2:1, with this trend expected to increase dramatically in the coming decades as recent years have shown (Meehl et al. 2009). The record highs experienced can take shape in the form of a heat wave lasting a number of days, often referred to as an extreme heat event (EHE). The Centers for Disease Control and Prevention (CDC) defines an EHE as summer temperatures that are substantially hotter and humid than the norm for a particular location and time of year (CDC 2013). In 2012, record-breaking EHEs occurred beginning in March and continuing on into the summer. The impacts of the heat waves were experienced in many states throughout the U.S. with varying levels of intensity and damages suffered.

In March 2012, between the 13th and 19th of the month, a considerable amount of time before the summer months, an unprecedented heat wave led to the occurrence of summer-like temperatures, which shattered temperature records in more than 1,054 locations within the U.S. (Voiland 2012). Figure 2 depicts the temperatures experienced throughout the U.S. during this time period. Areas with warmer than average temperatures are shown in red, while areas that experienced temperatures nearer to normal averages are shown in a lighter shade closer to white. The areas with blue shades are where temperatures were cooler than the average base period used, which was taken from 2000-2011. Examples of the extreme heat levels during March 2012 can exemplified with places such as Michigan, where the overnight low temperatures were much warmer than the typical high temperatures experienced during that time of year (Freedman 2012). Similarly in Minneapolis, Minnesota, record highs hit 79˚F, and lows that are typically at 25˚F in March were much warmer at record levels of up to 63˚F (Freedman 2012). In Chicago, April typically averages only one day reaching the 80˚F mark, but during the March 2012 heat wave, temperatures surpassed 80˚F consistently (NOAA 2014; Voiland 2012).

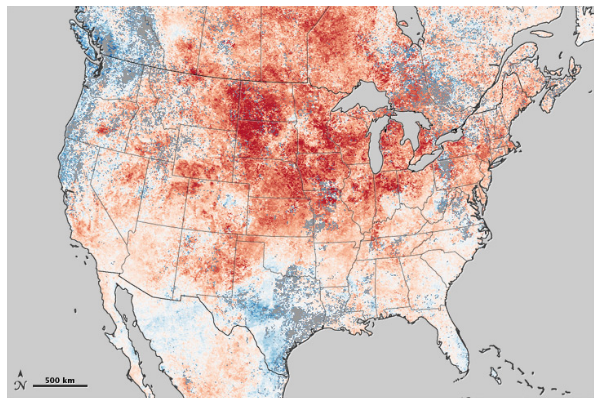


Figure 2 NASA Earth Observatory image acquired March 8-15, 2012 of the observed heat waves in North America

The heat did not stop there in 2012, as record temperatures were experienced again in June through to July surpassing 100˚F as yet another heat wave struck, breaking or tying over 8,000 warm temperature records (Freedman 2012). This time around, the extreme temperatures also instigated a surge of severe winds and thunderstorms known as derechos in its wake causing massive devastation. Wind gusts were up to 80 miles per hour, and the storms resulted in power outages that affected approximately 3.8 million people lasting multiple days (CDC 2013).

Severe droughts were a part of the aftermath associated with the 2012 heat waves. 50.92% of the U.S. reported facing various stages of drought, with 31.11% of the U.S. experiencing conditions of severe drought or worse, and 29 states eligible for drought disaster assistance (NDMC 2012). The droughts exacerbated by the heat waves parched and charred vast areas of land throughout the West and Southwest, and hindered agricultural production in the Midwest (NDMC 2012). Multiple water supply and quality issues as well as wildfires were also reported in states such as Colorado (NDMC 2012).

Heat waves can be relentless to the environment, infrastructures, building systems, and also to building occupants, often offering little to no relief from high temperatures occurring in the daytime and spanning well into nighttime. Extreme heat is the leading cause of weather-related deaths in the U.S. surpassing hurricanes, tornadoes, lightning, floods and earthquakes combined (Luber and McGeehin 2008). From 1999-2009, an average of 658 heat related-deaths per year took place in the U.S. (CDC 2013; Kochanek et al. 2011) A total of 32 heat-related deaths were reported as a result of the EHE that took place during the summer of 2012, with the majority of the heat exposure to the victims having occurred within their homes (CDC 2013). 22 of the victims died at home with a lack of air conditioning, and five died at home who had functioning air conditioning, although it was not turned on, and in some cases the type of housing was also reported as a contributor to the deaths by medical examiners (CDC 2013). With the large portion of the existing building stock of homes built at or below state building code levels, the enclosure performance they offer fails to provide long lasting habitable conditions for occupants if the were power to go out during extreme heat when compared to enclosures built to better performance standards (Leigh et al. 2014).

Other damages and devastation caused by EHEs, including the 2012 events, have included exacerbated droughts, instigation of severe storms, power outages affecting millions of people, and negative impacts to critical resource production and supply. The U.S. power sector relies heavily on the steady supply of cool freshwater to function and supply energy to customers. In 2005 power plants in the U.S. withdrew over 40% of freshwater within the U.S. to operate as needed (Spanger-Siegfried 2012). In the event of extreme heat, such as the events that took place in 2012, it can lead to a scarcity in water supply or incoming water that is too hot causing power plants to cut back on production, and in some cases completely shut down (Spanger-Siegfried 2012). Power and resource disruptions such as this can be extremely detrimental to the safety of individuals within buildings who could not only be cut off from safe water supply, but could additionally be left exposed to dangerous unrelenting heat in dwellings disconnected from cooling systems without fail-safes in place for protection.

2.1.3 Wildfires

Droughts can also lead to the onset of wildfires, another natural disaster caused by hot, dry conditions that can lead to the enormous destruction of its surroundings. A wildfire, as defined by the Natural Disasters Association (NDA), is an uncontrolled fire fueled by natural vegetation. A combination of high temperatures and drought conditions, followed by a period of vegetation growth to fuel the fire triggered by a natural event such as lightening, can form a wildfire (NDA 2014). Although wildfires are considered natural disasters, they are actually more of a quasi-natural disaster, as they can often be started from human activity as well as exacerbated natural circumstances present in the atmosphere. Wildfires occur an average of 1,500 to 2,500 times per year, burning and average of 8,000 to 10,000 acres of land in the U.S. (DOF 2014). These fires lead to numerous deaths and injuries of people and animals, and destroy buildings and the environment in their paths. Areas in the tropics and the western pacific are most vulnerable to wildfires, with the highest risk zones having Mediterranean or continental climates due to rainfall patterns occurring mostly in the winter leaving vegetation very dry in the summer (NDA 2014). These conditions are perfect for wildfires to form and prosper due to the abundant dry fuel provided by parched vegetation. As wildfires typically occur in the rural wilderness, where they also contribute to a cleaning and ecological restoration effect allowing its vegetation to rejuvenate (Center for Biological Diversity 2016), they can burn for a vast amount of time and spread across great distances.

Wildfires reach and impacts can be tremendous, as past events have shown. In 2004 Alaska had an unprecedented wildfire season in its very dry summer. The highest number of lightning strikes for the state was recorded during that summer leading to the largest acreage of land to be burned in Alaskan history, a staggering 6.6 million acres (AMQA 2014). In the summer of 2008, California also experienced one of its worst fire seasons in history instigated by a statewide drought and lightning strikes produced by a series of severe thunderstorms. The 2008 "Fire Siege" burned over 1.2 million acres of land that summer in California, destroying over 350 structures causing hundreds of millions of dollars in damage, disrupted power supply, communication and transportation, and also effected the air quality for weeks (Albright et al. 2008). The 2012 heat waves and droughts previously discussed in section 2.1.2 fueled wildfires out in the western states. The devastating Waldo Canyon Fire in Colorado Springs, Colorado was among the wildfires that spawned from the 2012 EHEs in June. It is now known as the worst fire in Colorado history after burning 18,247 acres in 18 days, destroying 347 homes, and killing two people (City of Colorado Springs 2013). Numerous counties and municipalities neighboring Colorado Springs were affected, while simultaneously, other large fires instigated by the drought and heat conditions also began and spread in other states including Utah, Wyoming, Montana, New Mexico, and Arizona (Voiland 2012).

If heat and drought conditions continue to escalate as they have been doing so, it is reasonable to assume that wildfires could continue to ignite more frequently and increase in duration. A not so settling prospect for the environment, and the buildings and people situated in the locations with increasing vulnerability to these conditions and events.

2.1.4 Cold Waves and Winter Storms

Although climate change and global warming are typically focused more towards the increased frequency and intensity of warming events, extreme cold weather events have also been identified as associate impacts. Extreme regional snowstorms in the U.S. have been increasing in frequency, where the number of occurrences since 1960 have doubled those that took place 60 years prior (Kunkel et al. 2013). Cold weather and heavy spells of snow and ice have caused their share of devastation and disruption to the U.S. in the past and also very recently. At the end of 2013 and the beginning of 2014, the U.S. was hit with unusually low temperatures nationwide due to an intensified polar vortex shift from Canada (Masters 2014). The polar vortex created record-breaking cold waves that crippled many states, and even left areas most typically accustomed to a warmer climate and temperatures unprepared for such conditions. Artic chills hit states in the Midwest, Northeast, Mid-Atlantic, and Southeast regions, going as far south as Central Florida (Masters 2014). In total, over 200 million people were impacted by the cold waves with a total estimated cost of up to $5 billion in damages (The Guardian 2014).

Figure 3 A New Jersey building's roof collapsed due to heavy snow load in 2014 (Photo source: NJ.com)

Four years earlier, the event commonly referred to as "Snowmageddon" brought winter weather extremes and devastation in the form of severe blizzards, ice, and wind. Preceded by months of record snowfall levels and subnormal temperatures, the Northeast was hit by the Snowmageddon winter storm in February of 2010 bringing record-breaking snowfall levels across the Mid-Atlantic states (Horvitz and Magnus 2010). This lead to declarations of states of emergency, a halt to transportation systems, and roads that were rendered impassable due to snowfall accumulation (Horvitz and Magnus 2010). Power lines were pulled down by heavy snow, fallen trees, and strong winds leaving hundreds of thousands of people without power (McFadden 2010). Several roofs collapsed in the D.C. area due to the weight of the snow that had settled on top of buildings (WTOP 2010), and as people were left barricaded and trapped inside their homes, two people died and dozens were injured as a result of carbon monoxide poising from trying to keep warm using generators and other heating devices (Kane 2010).

The year before in 2009, ice, in lieu of snow, was the winter weather culprit leading to mass disruption and devastation. Kentucky and Arkansas experienced days of freezing rain leading to heavy ice accumulation across the states taking out many power lines. 1.3 million people were left without power, dozens of roofs collapsed, and 42 people died as a result of traffic accidents, hypothermia, and carbon monoxide poising (Dolce and Erdman 2014).

2.1.5 Future Climate Hazards

When it comes to the subject of climate change, views and opinions regarding its various future implications can be conflicting and controversial, especially when it is discussed as being a cause of extreme weather events. While the U.S. has definitely experienced record-breaking extreme weather recently such as Superstorm Sandy and a summer of strong heat waves, it is important to acknowledge that a single event is not evidence of climate change alone (Del Genio 2011). On the contrary, studies of the occurrence of such events over a long period of time creates more evidence and a stronger case and grounds to support the need to raise awareness and prepare for the impending weather devastation to come. The future frequency of extreme weather events, as well as the intensity of their impacts, have been widely studied and debated. But with unequivocal evidence of climate change and a warming globe, it is very likely that extreme weather conditions such as droughts, extreme heat, tropical storms, and blizzards will continue to increase in occurrences and intensity (IPCC 2007; Voiland 2013). As a result of this, the possibility for natural hazards and disasters to devastate the built environment, leaving people vulnerable to the impacts, will also rise, even much more so with an existing housing stock lacking the appropriate adaptations and resilience needed. Climate change projections for locations across the U.S. could potentially alter the weather patterns and natural disaster hazards certain regions may need to now expect and become accustomed to. Building systems, communities, and resource infrastructures may not be equipped to endure such change. This is why it is important to understand the impacts climate change will have in a wide array of situations. Additionally, becoming aware of the interconnections and dependencies between different systems that will be affected are just as important. When it comes to the built environment, there are an abundance of interconnected systems and linkages that can be impacted by extreme weather events. Climate data used as an aid to model and construct the built environment will also be influenced by these changes. Climate data has changed and is still doing so, and it is vital that systems, builders, and designers consider this in the planning, construction, and occupancy phases of a building's lifetime.

Weather-Related Impacts

As previously stated, extreme weather events are expected to increase in frequency and intensity throughout the 21st century. This is due to the small global mean change in temperature that the Earth has experienced (1˚F to 2˚F) creating a more sensitive atmosphere with increasingly larger problems in regards to weather events. As a result of this, the lowest layer of the Earth's atmosphere known as the troposphere has become notably warmer, and so has the oceans (Voiland 2013). This has created extra heat and humidity in the atmosphere (NOAA 2009), which many scientists believe is a factor that is strengthening storms due to the nourishment they receive from this added heat energy available (Voiland 2013). By 2100, projections have consistently indicated that the average intensity of tropical cyclones will likely increase by 2%-11% globally (Knutson et al. 2010), and it is probable that there will be more recurrent environments favorable to severe thunderstorms (Brooks 2013).

Within the U.S., temperatures will continue to rise, with the south, southwest, and northeastern regions likely to be the most prone to the expected increases (Duffy and Tebaldi 2012). The NOAA Climate Extremes Index (CEI) in Figure 4 graphs the extreme temperatures that have been experienced across the U.S. since 1910 (NOAA 2014). The percentages on the axes represent the portion of the country that was subject to extreme temperatures in a particular year, e.g. 100% would mean the entire country was subject to extreme temperatures. Anything above 20% exceeds the average for the amount of extreme temperatures experienced. As it can be seen in the graph, extreme highs have been outpacing extreme lows, with more of the country being subject to such conditions than in the past. By the end of this century, it is projected that a once-every-20 year heat wave is expected to occur every other year (Climate Communication 2012). This temperature increase will inevitably lead to the likelihood of more frequent and severe heat waves along with the exacerbation of drought conditions. Wildfire seasons are expected to last longer in many regions throughout the U.S. (Liu et al. 2012), with larger areas of land and vegetation available for fuel and vulnerable to the impacts of the extremely dry and hot atmosphere. Additional changes expected in relation to weather events include stronger winds, increased rainfall intensity, and rising sea levels leaving coastal communities at greater risk of flooding.

Some climate change impacts on weather activity can be more difficult to interpret and model than others (Schrope 2009), which can produce various levels of uncertainty in terms of what to expect and believe from the available data. Climatologists and meteorologists who work diligently to provide important models and projections of climate and weather activity have acknowledged this (Thorpe 2005). The scientific community can reasonably understand this uncertainty as a standard part of any scientific process of investigation, but for the layperson, it can lead to detrimental misrepresentation and ill-informed opinions to spread. Uncertainties and skepticism in prediction models should not dismiss the fact that climate change and its impacts are real. Nevertheless, more analysis and comprehensive evaluations of climate change impacts on weather patterns and extreme weather events is an essential necessity, especially when the stakes are so high in regards to the consequences. The more research and data we can compile in this area, the better prepared and equipped society will be in order to appropriately adapt to changes in the environment and reduce uncertainties.

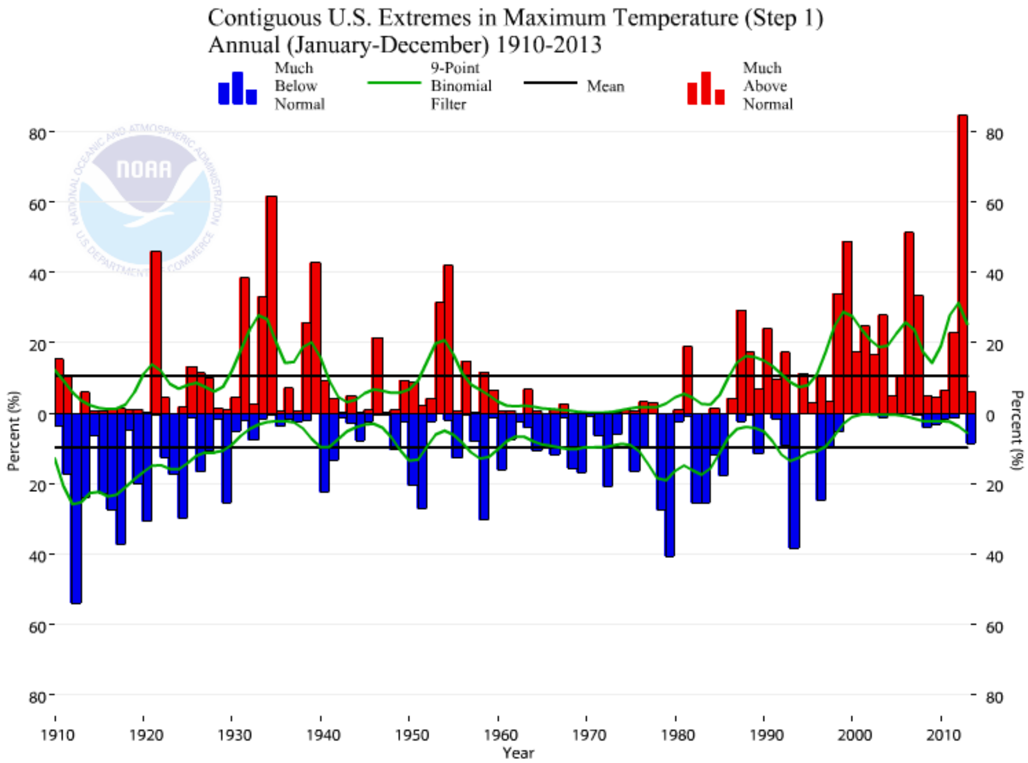


Figure 4 NOAA U.S. Climate Extremes Index (CEI) – Annual Extremes in Maximum Temperature Graph in Contiguous U.S.

Building Systems, Energy, and Occupant Impacts

Climate change and the adaptations it will impart on weather and natural hazards will also have a significant impact on the built environment, which includes building systems, infrastructure, and building occupants. Energy supply and demand will most likely be negatively impacted by climate change. With rising temperatures and projected increases in heat wave frequency, the demand for cooling will rise as building occupants seek to escape from intense heat. This rise in cooling demand as well as the rise in temperature levels and drought conditions will add significant strain on energy suppliers. "Energy-water collisions", the dangerous implications associated with the strong link that exists between energy and water to produce power in the wake of a changing climate, are expected to increase in frequency and become worse (UCS 2010). The availability of water for fossil fuel, nuclear energy, and also renewable energy producers, such as solar thermal and hydroelectric power, will become more scarce and/or unusable for the cooling needs associated with energy production (IPCC 2007; Larsen et al. 2011; Spanger-Siegfried 2012; UCS 2010). The use of natural ventilation as a supplementary or alternative source to mechanical cooling systems will decrease, where simply opening the window for cooling relief will no longer be an effective option (Larsen et al. 2011; Roberts 2008).

The interiors of buildings and homes will also become much hotter especially during the summer months, and potentially even in the months prior to that. This will require either the adaptation of occupants to new thermal comfort levels, or the adaptation of conventional building enclosure construction and mechanical systems to reduce excessive heat gains. In either scenario, appropriate risk mitigation strategies will need to be developed and incorporated into buildings and occupancy guidelines for sufficient protection, efficiency, and longevity. Regions throughout the U.S. will experience varied changes in regards to climate change and systems requiring adaptation and resilience strategies weighted specifically for the most critical hazards and vulnerabilities. For example, some areas will experience the risk of extreme heat more so than for hurricanes and flooding, in addition to other potential hazards and vulnerabilities that will need to identified and efficiently prioritized for effective risk mitigation decision-making. Thus, it is apparent that further research and impact studies are needed to evaluate the localized impacts climate change will have on various aspects of the built environment in numerous locations on a downscaled level (de Wilde and Coley 2012; Larsen et al. 2011).

Climate Data and Model Impacts

Various forms of climate and meteorological data have historically been utilized in building designs and simulations to ensure buildings perform and operate optimally for a given location. Data such as Typical Meteorological Year (TMY) is commonly used in the U.S. to represent typical weather patterns for a location based on data compiled from previous years. Global Climate Models (GCM) are also commonly developed and implemented to make climate change projections used in projects and adaptation planning (Schrope 2009). However, as climate change knowledge and awareness has grown, so has the need for more detailed and accurate "future-proof" meteorological and climatological data for use in building construction, simulations, and adaptation planning in order to go beyond compliance and achieve resilience (Cullen and Lea 2001; Roberts 2008). The Earth's atmosphere is changing, thus so must the climate data we use in creating and adapting the built environment. Changes on a local level where ambient temperatures have risen and extreme weather events are projected to increase, has strengthened the need to shift from a historic, generic, global climate data focus to more specific, detailed localized data (de Wilde and Coley 2012). TMY data is no longer a sufficient source to use in regards to representing future climate change trends and weather extremes in building design and operation. GCMs similarly are not the most efficient source of data for regional/local level climate change impact assessments, where finer details are needed in lieu of the coarser data provided by a typical GCM.

"Downscaling" GCMs is an approach used to bridge the gap between global and local climate change projections and impact assessments by generating more locally relevant projections of weather patterns (Cooney 2012). These downscaled GCMs are commonly referred to as Regional Climate Models (RCM). RCMs can simulate extreme weather events that may occur at the local or regional level that are too difficult for GCMs to generate (Cooney 2012). Extreme weather events often appear less powerful than what would actually occur when using a GCM over an RCM (Cooney 2012). This is why downscaling is often considered the better option to improve accuracy in climate and weather projections for specific locations, a value-added approach of sorts. To prepare for the future, climatologists need to further develop downscaled climate projections, which must then be translated into specific impact models, and subsequently presented and disseminated effectively to society to be used by decision makers in diverse industries (Girvetz et al. 2013).

Downscaling climate model data and using future projections has already been implemented in various sectors by individuals such as public health officials, agricultural managers, and water resource mangers in order to develop climate change adaptation plans (Cooney 2012; Girvetz et al. 2013). The building construction industry is no different, where efforts are being made to use and enhance downscaled climate models in order to compile data towards adapting the built environment to climate change. In a study investigating the use of regional and future projections of climate data in the design of PassivHaus buildings in the UK, high-resolution climate data was used (McLeod et al. 2011). Findings from the study suggested that if a coarser proxy climate data set were used in lieu of the higher resolution data, it would lead to underestimation of annual heat demands, a conclusion that reinforces the findings of other similar studies. In another study investigating the impacts of climate change on heating and cooling requirements in buildings located in Dhaka, Bangladesh, downscaled climate data was used to identify and evaluate the likely impacts (Mourshed 2011). It was concluded that future increases in temperatures would add stress to Bangladesh's infrastructure, and also lead to overheating in buildings year-round, not just in the summer and monsoon seasons typically anticipated for the country.

2.2 Disaster Resilience and Buildings

When looking ahead to the future, it is clear that the built environment is going to face more challenging circumstances and exposure to severe climates and weather events. This vulnerability can lead to natural disasters, which as history has shown, can cause a great amount of disruption and devastation to many systems and structures that people rely on for survival and daily functions. The overall goal is clear, resilience to multiple events that can lead to disasters is a national imperative that needs to be given more attention and taken further in order to ensure society is prepared for the worst. Climate change and *Disaster Resilience* are becoming increasingly linked as a way to manage the associated risks, with recognition that further complementary research and development at multiple scales is still in need (World Bank 2013). Resilience can protect and preserve the built environment and lives from devastation, and the benefits of resilience can positively influence environmental, economic, and societal goals in the process by reducing detrimental impacts if implemented strategically. Resilience is a term and approach that has gained some prominence recently with many different definitions, interpretations, and metrics used by a variety of disciplines. With so many different explanations of resilience available it is important to first have an understanding of what resilience means, how it can be applied, and how it can be measured. Then more specifically for this context, know how resilience can and has been implemented in the building construction industry as a way to combat natural disasters and climate change consequences.

2.2.1 Resilience Definitions

Many definitions and interpretations of resilience exist across multiple disciplines making it a difficult concept to quantify, evaluate, and gain clarity for what it means and how it applies to different industries (Hassler and Kohler 2014). For example, the Department of Homeland Security (DHS) defines resilience as:

> *"The ability to prepare for and adapt to changing conditions, and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents"* (DHS 2014).

While in another definition, the Intergovernmental Panel on Climate Change (IPCC) defines resilience as:

> *"The ability of a system and its component parts to anticipate, absorb, accommodate or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration or improvement of its essential basic structures and functions."* (IPCC 2012)

In a review of several definitions of resilience used by multiple organizations and industries (Patterson et al. 2013), three key principles and verbs were derived from all the definitions included to represent resilience. These principles are to reduce risk, decrease recovery time, and foster adaption, while the three key verbs are absorb, adapt, and recover (Patterson et al. 2013).

Various frameworks attempting to measure and quantify resilience have stemmed from differing interpretations of resilience, with many drawing from and expanding upon others ideas with the key verbs and principles identified by Patterson et al. appearing frequently as fundamentals.

2.2.2 Quantifying Resilience

A well-known framework for representing the seismic resilience of communities (although also considered appropriate for other disturbances in addition to earthquake activity) was developed by the Multidisciplinary Center for Earthquake Engineering Research (MCEER). Four defining properties of resilience were defined by MCEER, as well as four primary dimensions to measure community resilience. MCEER defines a resilient system to be one that shows reduced failure probabilities, reduced consequences from failures, and reduced time to recovery (Bruneau et al. 2003). The four fundamental properties of resilience identified by MCEER are referred to as the *Four R's* (R^4): robustness, redundancy, resourcefulness, and rapidity (Bruneau et al. 2003; MCEER 2006). Robustness is a measure of the strength or ability to withstand the impact of a disaster strike. Redundancy is the repetition or the availability of multiple elements or systems that are the same to act as a backup or failsafe to perform the same functions. Resourcefulness is the ability to identify problems and supply resources when a disaster strikes. Lastly, rapidity is how fast goals can be achieved to combat a disaster when it strikes in order to minimize and contain losses. Resourcefulness and redundancy are typically viewed as the means of resilience, while rapidity and robustness are considered the ends of resilience. According to MCEER, improving upon each of the R^4 properties should be done in order to enhance resilience. In addition to the R^4 properties, four dimensions of resilience were identified as a way to evaluate the resilience of various physical and organizational systems within a community, such as physical infrastructures or government institutions. These dimensions are technical, organizational, social, and economic. Technical refers to physical systems and all interconnected components, of which buildings would fall under. Organizational refers to the capacity of an organization to make decisions and take actions. Social are the measures undertaken by communities and government bodies to increase resilience. And economic is the capacity to reduce direct and indirect economic losses from a disaster.

Using the MCEER R^4 framework, resilience can be graphically represented to aid in the evaluation and measurement of the resilient capacities of systems as shown in Figure 5. The formula used to mathematically define resilience is:

$$R = \int_{t_0}^{t_1} [100 - Q(t)]dt$$ (Bruneau et al. 2003)

Q(t) represents the quality of a system or component from 100% quality or functionality to 0% varying over time from when a disaster strikes, and showing degradation and recovery time. R represents the loss of resilience; t_0 is the instance when a disaster strikes, causing a disruption and/or damage; and t_1 represents the time when the system or element has completely recovered. Figure 5 depicts a graphical representation of the resilience of a system or component showing when a disaster hits, and the resilience and recovery to complete functionality. This concept and formula has been adapted and used in a study to quantify the seismic resilience of facilities in response to earthquakes in an effort to further research in

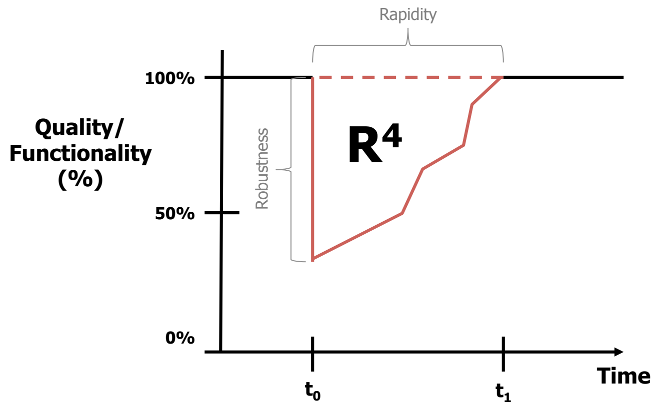


Figure 5 Graphical representation of resilience adapted from MCEER resilience framework (Bruneau et al. 2003)

developing guides or decision-making tools for achieving resilience on a broader level (Bruneau and Reinhorn 2006). The study provided an understanding of damage and its relation to different response and recovery scenarios for facilities following an earthquake.

In another interpretation of resilience into a framework, cost is an additional explicit factor included in the quantification of resilience. Sandia National Laboratories (Sandia) formulated a framework for the resilience of critical infrastructure systems through the quantification of systemic impacts (SI) and total recovery effort (TRE), known as the resilience cost measurement approach (Vurgin et al. 2010). Sandia defines a resilient system to have the properties of absorptive capacity, adaptive capacity, and restorative capacity. SI encompasses both absorptive and adaptive capacity, which is a measure of the difference between a target system performance level and the actual system performance level following a disruptive event. While TRE encompasses the restorative capacity, which represents the amount of resources expended during the recovery processes following the disruptive effort, and includes resilience costs incurred as a measure of the recovery effort. In summary, the sum of SI and TRE equals the resilience of a system. SI and TRE can be mathematically represented with the following equations:

$$SI = \int_{t_0}^{t_f} [TSP(t) - SP(t)]dt \qquad TRE = \int_{t_0}^{t_f} [RE(t)]dt$$ (Vurgin et al. 2010)

In Figure 6, SI and TRE are presented graphically to represent Sandia's framework for resilience. Quantifying the shaded areas of each curve in graphs (a) and (b) will provide a measure for each aspect used to determine the resilience. Cost is explicitly included in this framework to distinguish between identical systems. Where, for example, if one of the identical systems in a pair required less recovery costs, this system would be considered as more resilient, even though both systems are identical in performance. In graph (a), the notation SP for the solid line represents the actual system performance, while TSP for the dashed line represents the targeted system performance. In graph (b), the RE solid line represents the recovery effort that took place following a disruption to achieve a complete recovery.

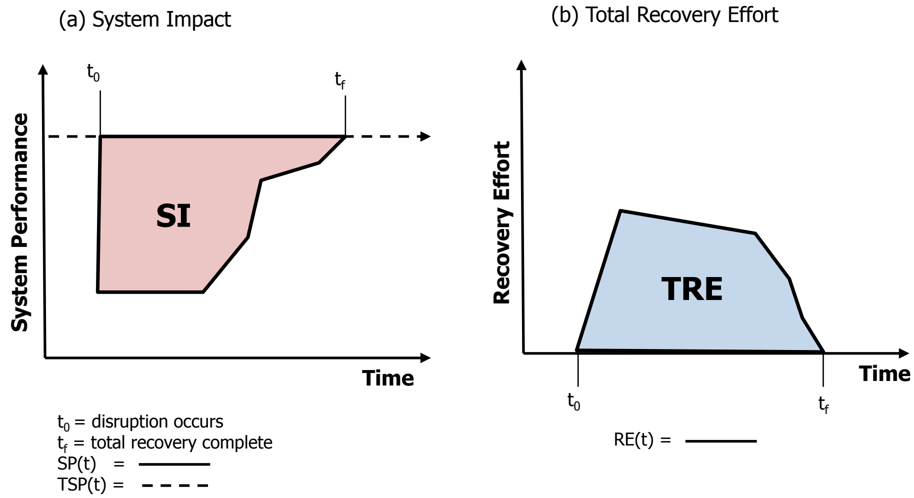


Figure 6 Graphical representation quantifying SI and TRE to measure the resilience of a system. Adapted from Sandia resilience cost measurement framework (Vurgin et al. 2010)

An *Operational Framework for Resilience* is another similar resilience framework developed as a basis to incorporate resilience into critical infrastructure and society defined by three main objectives: resistance, absorption, and restoration (Kahan et al. 2009). This framework developed by Kahan et al., explains that the interconnected principles and features planners can use to make a system resilient and achieve the resilience objectives should be comprised of: threat and hazard limitation, robustness, consequence mitigation, adaptability, risk-informed planning, risk-informed investments, harmonization of purposes, and comprehensiveness of scope. A profile, branded a "resilience profile", of a system allows for the visualization of the effects of implementing the resilience principles used to achieve the overall objectives defined by three essential dimensions of 1) performance, general level of capacity and quality; 2) time, chronology of the whole life cycle of any disruption; and 3) gravity, the degree to which any function plays a key role within a system. Performance and time are again used as key dimensions to quantify resilience as the previous frameworks discussed in this section have also included in visualizing and quantifying resilience. For a more defined resilience profile using the Kahan et al. framework, the additional dimensions of function, latency limit, and minimum performance boundary can be included. Function being the elements that play one or more roles within a system. Latency limit meaning the maximum amount of time allowable for a function to remain degraded before recovery. And minimum performance boundary represents the lowest acceptable level of performance allowable for a function. Figure 7 illustrates the Operational Framework of Resilience developed by Kahan et al., which graphically shows an example of a resilience profile of a system where the resilience principles have been implemented to achieve the resilience objectives.

As an additional example of a resilience framework, Longstaff et al. proposed a community-based approach to assess resilience through the means of resource robustness and adaptive capacity in the context of five community subsystems: ecological, economic, physical infrastructure, civil society, and governance (Longstaff et al. 2010). Resource robustness would be assessed through the measures of performance, diversity, and redundancy. While adaptive capacity would be measured through institutional memory, innovative learning, and connectedness. Encompassing both high adaptive capacity and resource robustness achieves the most resilience. Assessing for these attributes can lead to the identification of key evaluative criteria of resilience needed by decision-makers to evaluate vulnerabilities and preparedness (Longstaff et al. 2010). However, the authors noted that further research is needed to identify key functions and resilience attributes quantitatively and qualitatively in various sectors to aid this effort.

As exemplified here, much of the research conducted and developed has been focused toward quantifying resilience to seismic activity, and has been focused on infrastructure, large civil and commercial buildings, and larger community-wide contexts. The frameworks described here are all useful examples of guides that can be used when aiming to implement and measure the resilience of systems and disruptions of many kinds. While they may vary in definition, representation, quantification, and terminology, the application of each can be beneficial in developing resilient measurements and decision-making tools when appropriately adapted for specific contexts. In the built environment, resilient technologies and strategies have been incorporated into various projects and plans to reduce vulnerabilities from a wide range of hazards such as earthquakes or flooding. In the following sections, this will be discussed in terms of building practices that can be used to achieve resilience, methods used to measure and quantify resilience adapted from frameworks, and next steps that can be taken in order to enhance the realm of disaster resilient buildings and systems.

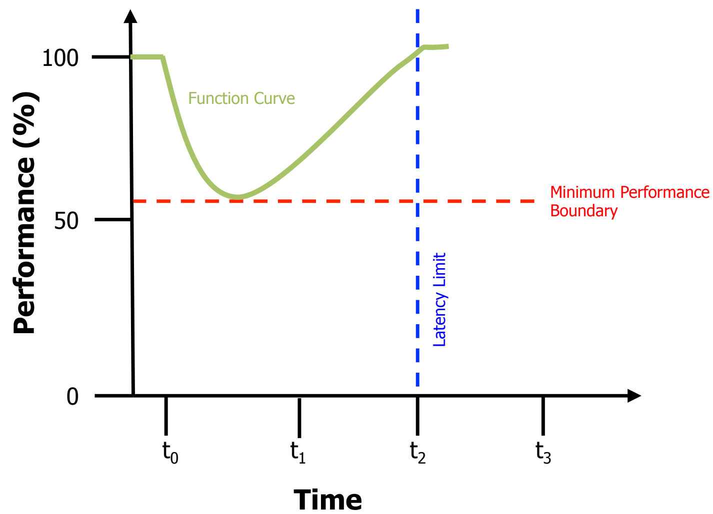


Figure 7 Example graphical representation of a "resilience profile" of a resilient system. Adapted from Operational Framework for Resilience (Kahan et al. 2009)

2.2.3 Disaster Resilient Strategies for the Built Environment

There are common strategies and best practices that exist to achieve resilience from multiple hazards in building construction that have and are being implemented worldwide. Recently, a task force assembled in response to Superstorm Sandy developed 33 actionable proposals for making New York buildings more resilient to natural disasters, which included a broad set of strategies for resiliency (Urban Green 2013). The resilient building practices discussed in the proposals included the use of wind-resistant windows, and the anchoring of framing to foundations/basements to prevent storm damage; relocating suitable building systems above flood levels, and elevating lower floors above flood levels; designing below grade walls and slabs to resist hydrostatic forces from floods; using light-colored, and self-cleaning roof coatings; prioritizing electrical equipment for backup power, and using cogeneration solar power systems as reliable generator sources designed to operate in the event of blackouts; air sealing and upgrading insulation to allow for buildings to remain habitable through extreme temperatures during power outages; and requiring that drinking water can be supplied solely by the street main pressure during power failures. These strategies, and many more, can prove valuable in maintaining the operation and protection of building integrity, performance, and connections to critical resources in the event of event extreme weather and natural disaster occurrences. Guides and community resource plans developed by organizations such as FEMA (Baxter et al. 2013) are also freely available to aid individuals such as community planners, architects, and builders in implementing disaster mitigation building technologies. Many of the above mentioned disaster resilient technologies are again referred to in these plans as viable solutions to combat harsh weather and naturally occurring events that create hazards and disruptions.

Disaster resilient technologies have also been evaluated as applicable for climate change vulnerabilities in resiliency plans and guides to encourage adaptation. In a resiliency plan prepared for the city of Boston, Massachusetts, best practices for resilience and adaptation were identified for multiple natural hazards and building types specific to the Boston climate and housing stock (Newman et al. 2013). Prior to this, a similar process was implemented on a coarser, more generalized nationwide scale, where a large inventory of adaptation strategies for buildings within the 8 U.S. climate regions were identified that have the potential to make projects more resilient (Larsen et al. 2011). While reports such as these can be very helpful to guide builders, owners, designers, and planners, where they fall short includes not being able to provide meaningful order or evaluations of the resilience solutions in regards to their performance for specific climate hazards and buildings to aid in selection. This also includes the need for evaluations of their interactions and interdependencies that could potentially impact the applicability and performance of each solution's ability to function as desired in regards to various building features, and multi-hazard environments. This lapse in information can also lead to an abundance of choices for resilience technologies, which can be counterintuitive and lead to solution failures and/or superfluous decision-making. These issues require more focused, detailed efforts, and further investigations could significantly enhance decision-making and the implementation of resilient building practices in a more efficient and sound way.

While many building resilience technologies are known and recommended, measuring the effectiveness of these strategies is still challenging and not widely understood. This is where resilience frameworks and principles are useful in guiding the quantification and evaluation of what methods are best for a variety of hazards and vulnerabilities to aid in selection and prioritization. Some studies have attempted to measure resilience doing just that, which have again been more focused toward seismic disruptions. There is still a great need for further resilience research and diffusion of efforts into other disciplines combating a diversity of disasters.

Using some of the previously discussed resilience measurement frameworks in section 2.2.2, resilience has been quantified for different systems and building types in research studies attempting to assist decision-making processes as one of their goals. After adapting the MCEER resilience framework developed by Bruneau et al., Chang and Masanobu conducted a case study which measured and quantified the resilience of different retrofit strategies for a water delivery system in Memphis, TN impacted by an earthquake (Chang and Masanobu 2004). As a result, the study showed how the resilience of different retrofit strategies to disaster events could be compared against one another through the application of the framework. Probability and loss estimation models were included in this framework to measure functionality and resilience in relation to meeting or exceeding predefined performance standards of robustness and threshold recovery times (rapidity). Performance metrics and standards used in this study were used only as examples and were not identified through formal investigation. However, the authors noted that performance metrics are central to accurate quantification of resilience, and should ideally be sought out through formal investigation and consultation with stakeholders, decision-makers, and other important members of the public for a specific situation being evaluated. This has also been noted as an area that is in need of further research, to identify appropriate performance standards in various fields so resilience measurement frameworks can be implemented more suitably (Chang and Masanobu 2004; McAllister 2013). Different facilities, building types and systems will have diverse sets of performance indicators, along with their ability to withstand and function prior to a disastrous event. While measuring resilience using the MCEER resilience principles as a basis would be beneficial, without accurate inclusion of important measures of performance, the process would be futile if needed for actual meaningful decisions and evaluations.

In another study which also extended from the MCEER resilience framework, Cimellaro et al. quantified the resilience of hospital buildings using a comprehensive model measuring the ability to function and recover from extreme events (Cimellaro et al. 2010). Functionality, or performance standards, of hospital buildings were defined as the quality of service in terms of waiting times. The resilience of different rehabilitation strategies applied to hospital buildings were quantified and subsequently compared in terms of the resilience they can offer. This framework could potentially be used or adapted to be a decision support tool to increase the resilience of systems and facilities as noted by the authors. The same researchers proposed a common reference framework for quantifying the seismic resilience of health care facilities in another study which also expanded upon the MCEER framework (Cimellaro et al. 2010). Specific functionality standards and influences were analyzed and defined, and resilience was quantified for different retrofit techniques applied to hospital facilities to determine the best strategy.

2.2.4 Moving Forward with Disaster Resilience and Buildings

Much is known and discussed about new construction and retrofit technologies that can be used in an attempt to achieve disaster resilience as detailed in many reports, proposals, and guidance plans. However, there is still limited data and we find gaps of knowledge in regard to ensuring applicability, and assessing the performance of implementing such technologies in different contexts. As argued in a report addressing necessary steps forward needed to build resilience, a closer integration between climate and disaster resilience is required to further knowledge in building resilience to weather-related disasters, and potentially lead to a robust decision-making framework (World Bank 2013). As discussed in the previous sections, seismic resilience seems to be the popular focus leaving other natural disasters out of the conversation. Extreme temperatures, flooding, hurricanes, and winter storms are all examples of natural disasters that can occur more frequently, and cause great danger and damage, and thus also require higher resilience. Further investigation of performance standards, functionality, and applicability of disaster resilient technologies for various building types and systems in varying climates is still needed in order to quantify the resilience they can provide and move forward with decision-making. A recent report by the National Institute of Standards and Technology Engineering Laboratory identified research needs for developing resilience in the built environment (McAllister 2013). These needs included filling gaps that align with those mentioned here such as establishing performance goals, standards, and metrics for resilience measurement, comparison and planning; consideration of infrastructure and system interdependencies and dependencies on resilience; defining resilience terminology to aid in communication of new concepts; and develop tools to support technical assessments, policy development, and decision-making (McAllister 2013).

Residential buildings are a domain not widely explored in resilience studies due to their small scale in the larger scheme of the built environment. However, they are critical structures in need of more protection in the wake of climate change as they are consistently devastated and their occupants displaced by severe weather events. Disaster resilient houses can aid in alleviating disaster strains on other critical interconnected systems at multiple scales within and outside of a community, such as power supply and rescue efforts. However, frustration by stakeholders in the home building industry has been expressed in regards to a lack of scientific research to help identify practices to achieve resiliency (ICLR 2012). Achieving and improving the resilience of homes needs further investigation to allow for disaster resilient building technologies to be applied effectively for various vulnerabilities in multiple climates. But first, a clear and succinct definition of disaster resilience must be created for this particular context of residential buildings to aid evaluations. Then, further research can take place including the identification and compilation of data linked to risks such as climate hazards, vulnerabilities and impacts that can cause disruptions and devastation, so that appropriate technologies can be identified. In this regard, downscaled, localized data and analysis should be used and sought out from investigations, databases, and/or prior studies to ensure accuracy is increased where possible to avoid generalization. Performance standards and baselines for disaster resilient technologies in residential buildings and systems must also then be identified so resilience can be measured, then prioritized for different climates and housing types and features.

2.3 HIGH-PERFORMANCE BUILDINGS

Disaster resilient building strategies can at times double as high-performance building technologies used to achieve goals such as enhanced energy and thermal performance as well as natural disaster resilience. For example, in an effort to assess the dangers poor thermal enclosures pose to occupants remaining or stranded in homes during extended blackouts in the wake of severe heat or cold weather conditions, Leigh et al. performed building simulations, which compared different building enclosure thermal performance levels. It was determined that an improved thermal performance, such as increased insulation and/or air sealing, would improve the habitability of a building when compared to the existing building stock and code built homes, thus dramatically reducing threats to people's health (Leigh et al. 2014). This was found to be true for both summer and winter conditions, that high-performance building enclosures can dramatically improve building resilience to extreme temperatures. Cogeneration power systems and enhanced building enclosure insulation were both techniques proposed as technologies to make New York buildings more disaster resilient (Urban Green 2013). These technologies can also be excellent ways to improve the energy performance of buildings and communities if implemented effectively regardless of the occurrence of a natural disaster or disturbance event. This overlap of combing the efforts of high-performance building features and disaster resilience has been acknowledged as a strongly connected and complimentary need. This pairing can also address two important goals society is currently trying to achieve, sustainability and resilience (Asprone et al. 2014). Others have similarly come to agreement over this close, yet not identical, link between the two concepts (Hassler and Kohler 2014). Sustainability (which can overlap with high-performance building) and climate change adaptation have also been discussed as complimentary goals to reduce short and long term vulnerabilities (IPCC 2007). The link between resilience and sustainability has been defined by Asprone et al. to be a structure that is able to minimize the negative impacts of potential disasters both during and after an event, in terms of social, environmental and economic burden. To put it simply, a structure is sustainable if the disaster event phase in the life cycle is resilient. Therefore according to this definition, resilience can be considered a characteristic contributing to sustainability (Asprone et al. 2014). While in another explanation it has been argued that disaster resilience is the pathway that links disaster risk management and the long-term sustainability of communities (Cutter 2013).

While the initial costs associated with disaster resilient building may sometimes be significant, the long-term cost effectiveness of sustainability that can be achieved with resilient high-performance building technologies can allow for substantial energy savings and return of investment, all while simultaneously protecting a building from harsh environmental dangers. The incentives from there can continue to pile up making this combination an attractive strategy to pursue. However, despite attractive benefits, the interaction and relationship between systems and strategies that can provide both disaster resilience and sustainability or high-performance has not widely been explored in depth before, and can be very complex due to the varied interpretations of the singular concepts (Asprone et al. 2014).

Actions needed to improve the understanding and further research between the combined aspects of sustainability, high-performance building, climate change, and disaster resilience needs to be further pursued (Hassler and Kohler 2014). This gap of research needs to be filled to ensure effective implementation of such technologies can be achieved to avoid costly mistakes and poor performance that could arise from ill-informed presumptions of performance. Investigation of the impacts building technologies could have on the objectives of achieving both resilience and high-performance standards, in terms of application, context, and functionality is in great need and demand. Prior to this, a clear meaning of high-performance buildings must be defined for this context, as well as the potential impacts they can have when providing disaster resilience as an additional goal.

2.3.1 Defining High-Performance Building

The meanings of the terms “green building”, “high-performance building”, and “sustainable building” have become notably mainstream and thus vague as the use of each word has been done so haphazardly on multiple occasions. Although they are similar, they are not synonyms for each another (BSC 2008; Prum 2010). The many definitions, labels, and standards that exist today using these terms have aided this common misconception and misuses. This issue has also added to the difficulty in classifying what each type of building should represent in evaluations, and has also possibly lead to important environmental issues being treated superficially as a result of the popularity the terms have garnered in recent years (Lerum 2008).

It is understood here that green building can be considered as a type of environmentally responsible construction; high-performance building as a type of construction where the key goal is increased system performance that, for example, typically reduces energy consumption and increases durability; and sustainable building is then understood to encompass both long- and/or short-term zero impact technologies and behaviors. All three can at times overlap, but remain separate facets of construction. Figure 8 illustrates this relationship further and depicts each circle’s area to represent a distribution of technologies found in each type of construction.

There are multiple interpretations for what a high-performance building can be, as well as established standards of construction each varying in characteristics and calculation methods for quantitative evaluation if included (Erhorn and Erhorn-Kluttig 2011). The Energy Independence and Security Act (EISA) of 2007 brought about a definition for high-performance building that is well known and commonly referred to today by many. The definition states that a high-performance building is one that "integrates and optimizes on a life-cycle basis all major high-performance attributes, including energy conservation, environment, safety, security, durability, accessibility, cost-benefit, productivity, sustainability, functionality, and operational considerations" (HPBC 2007). This can also include reducing or eliminating the negative impacts natural disasters can have on building systems, energy production and supply, and occupancy as discussed in the previous section 2.1.5. Sustainability is included in the EISA definition as a core attribute, although this is not necessarily always an attainable quality based upon the definition of sustainability (refer to Figure 8), and this is similarly true for the other attributes included in this definition. Sustainable buildings can be defined as buildings and technologies that have zero impacts in the long-term and/or short-term, where 100% of the resources are renewable and reduce impacts in the three specific aspects of the environment, economy, and society known as the three pillars of sustainability. Finally, green buildings can be broadly defined as environmentally responsible and resource-efficient buildings.

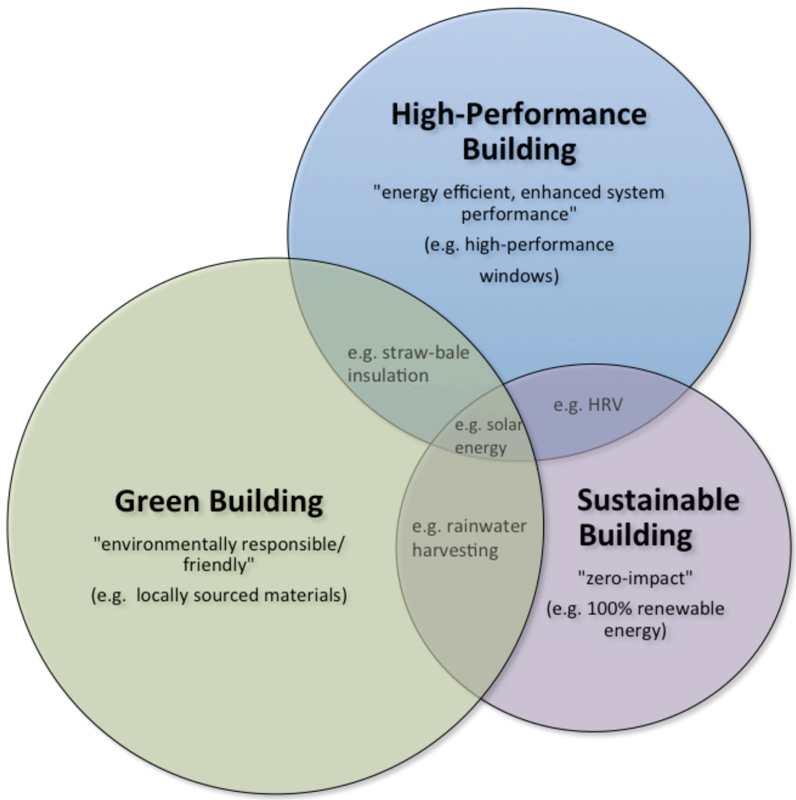


Figure 8 Relationship between sustainability, green, and high-performance building

The focus of this study was high-performance buildings, and therefore, for consistency and clarity, *High-Performance* was the sole term used to describe the related technologies regardless of potential overlaps between green and sustainable building. However, it was still understood that high-performance building technologies could overlap with green building and/or sustainable building technologies. Specific definitions for high-performance building attributes were devised in this study, which were utilized in this research for the context of high-performance residential buildings.

2.3.2 High-Performance Building Technologies and Evaluation Metrics

It is important to know what exactly qualifies as a high-performance building technology or standard, especially for residential buildings, where varied standards and definitions exist to represent this area. There is not one common standard to identify what a high-performance building is or should entail, which is evident by the plethora of definitions that can be found for high-performance buildings through a simple internet keyword search. Adding some difficulty to this task, when it comes to measuring and evaluating building performance, technologies and standards are seldom defined in objective and measurable terms (Woods 2008), or instead provide crude, arbitrary benchmarks (Erhorn and Erhorn-Kluttig 2011). Even so, there are a variety of technologies and standards used today that are considered to be high-performance, some with rigorous quantitative metrics to ensure achievement of certain performance requirements, while others go without.

The PassivHaus standard, considered one of the most rigorous high-performance building standards available, is one of the few standards that offer quantitative metrics for evaluating the performance of a building in regards to energy consumption, thermal comfort, and airtightness. Technologies used to achieve this can include enhanced building enclosure thermal performance with increased insulation, and the elimination of thermal bridges. The PassivHaus standard brings attention to an issue where some high-performance technologies and standards may respond and perform differently depending on the context, thus producing varied results in performance and may need certain adjustments prior to implementation. This can include for example, location, specifically the local climate and its associated impacts. For example, with the PassivHaus standard being originally intended for the Central European climate, is often not a simple “copy and paste” task to implement in dissimilar climates. This, among other performance attributes, should be considered in evaluating high-performance technologies, some of which may not have previously needed to be considered but are imperative today. But what these attributes are and how they are evaluated, is still an area of debate and uncertainty.

In an attempt to define and measure what a high performance home should be, Marburger et al. identified quantifiable and non-quantifiable attributes (Marburger et al. 2010). The quantifiable attributes include cost effectiveness, sustainability, safety/security, and occupancy. While the non-quantifiable attributes include productivity, functionality/operational/accessibility, historical preservation and aesthetics. These attributes in fact reflect all those mentioned in the 2007 EISA definition of high-performance building. Performance metrics to evaluate all attributes for similar and dissimilar building technologies or standards is still in need to allow for comparison and benchmarking (Marburger et al. 2010).

With resilience having close ties to high-performance, this is an additional aspect that can be considered and evaluated as a goal to achieve both high-performance and disaster resilience.

2.3.3 High-Performance Building for Disaster Resilience

It is a common belief that unsustainable development is the root cause of increasing costs and devastation from natural disasters, and that increasing resilience to disasters can be done so through enhancing environmental, economic, and social aspects of communities, thus making them more sustainable (FEMA 2000; Mileti 1999). Similar views have since been put forth, that disaster resilience can be considered an attribute of high-performance building as an essential contributor to a sustainable future (Asprone et al. 2014; Cutter 2013; Hassler and Kohler 2014; Houlihan 2007). This notion of using high-performance buildings as a way to adapt to climate change through resilience and sustainability is a popular topic of discussion. Few have investigated technologies comprised of this connection, and there is a growing need for more research in this area. Nevertheless, some strides have been made to progress forward with this issue.

In a notable study conducted by the U.S. Green Building Council (USGBC) and University of Michigan researchers, the first known attempt was made to examine future, regional level climate change impacts throughout the U.S., and identify green building strategies and LEED credits that have the potential to provide resilience to the risks identified by the impacts (Larsen et al. 2011). 81 strategies were identified within the six categories of (1) Enclosure (2) Site and Landscape (3) Heating, Cooling, and Lighting (4) Water and Waste (5) Equipment and (6) Process and Operations. The strategies were each evaluated for attributes such as if they are a high priority, low priority, or not applicable technologies in the eight U.S. climate regions; the purpose of the strategy and how it would respond to climate change; if it provides resilience, or "no regrets", which implies it produces social and/or economic benefits regardless of climate change; the useful life of the strategy; and any associated LEED credits the strategy could provide if implemented. This document serves as an initial guide and basis for builders to begin thinking about green building strategies to achieve disaster resilience specific to project location regions. However, as noted by the authors, there is still more research that can be done to strengthen the knowledge in this area. Gaps in research noted by the authors included the generalized nature of the climate data used, which requires further downscaling of global climate models used to the local level to better understand direct impacts on neighborhoods and buildings. While the study was able to prioritize strategies for the broad eight U.S. climate regions by giving high, low, or N/A priority classifications, this analysis remains coarse and vague in providing tangible details for informing decision-makers in the selection process due to the method and scale used. Furthermore, the study was not able to evaluate specific benefits, nor levels of resilience and performance for each solution if implemented solely or in conjunction with other strategies, which were additional gaps noted by the authors.

Figure 9 Schiestlhaus, alpine PassivHaus at 2145m altitude withstands extreme cold and operates on 100% renewable energy and cogeneration power

High-performance building technologies that are implemented successfully in order to provide resilience to natural disasters exist as exemplary demonstration of integrating high-performance, resilience, and climate. For example, the Schiestlhaus, a PassivHaus standard building in an alpine climate located on the Hochschwab Mountain in Austria was built to withstand extreme low temperatures and essentially operate off-grid. Figure 9 depicts the Schiestlhaus almost completely frozen over and buried in snow, yet still remaining fully functional and maintaining habitable interior temperatures due to its highly thermally resistant enclosure and 100% renewable energy generation sources from photovoltaic cells and cogeneration keeping systems functional. This facility was built to withstand extreme low temperatures, provide shelter and refuge to hikers and climbers, and essentially operate year round off the grid. In Boston, Massachusetts, the LEED Gold certified Spaulding Rehabilitation Hospital implemented high-performance building technologies in response to prior flood devastation caused by Superstorm Sandy and the potential for the building's location to see a rise in sea level in the future. All critical mechanical and electrical systems required for the hospital to remain operational in the event of a flood were placed on the penthouse floor. In addition to this, a dedicated cogeneration plant produces power and generates heat for hot water and heating loads, and due to its independent capabilities from the grid, allows the facility to maintain functionality should there be regional power outages. This provides robustness to the building systems in place, and thus increases facility and community resilience.

It is important to also note that understanding other potential risks that could impede the results of high-performance building technologies on resilience and other aspects building performance and integrity. In a report released by FEMA, some insight into the interactions to be cautious of when implementing common residential green building practices to achieve resilience from natural disasters was provided (Gromala et al. 2010). Green building ratings, such as LEED for Homes, were evaluated for their positive or negative interactions with a building structure in order to identify areas that could compromise a buildings resistance to a natural disaster. For example, if a building installs a green roof, this may be excellent towards stormwater management and sustainable building goals. However, if this building is also located in an area prone to extreme heat causing droughts and wildfires, the risk of wildfire damage is increased from having vegetation in close proximity to the structure. In another example, PV cells placed on a building in a location with large solar gain potentials may be a very good solution to generate energy during grid wide power outages due to overload (e.g. heat waves). Yet, if this location were also subject to harsh weather-related events such as intense hail and windstorms that could severely damage the system, this solution would not be a practical system in terms of achieving resilience. Interactions such as this, as well as multiple system interactions, are important to explore and assess for effective decision-making and implementation of high-performance building and disaster resilience for specific locations. The inclusion of such interaction assessments is an important factor that should be included in green building rating systems, standards, and decision-making tools to aid in climate change adaptation.

Green building rating systems are however beginning to take note of society concerns regarding climate change adaptation, and incorporating important considerations into revisions and new tools for industry use. A tool to help users identify LEED credits that are sensitive to changing climate conditions and aid in prioritizing credits that can offer resilience to such conditions in a project location has been developed by the USGBC. The LEED Climate Resilience Screening Tool is its name. It has a Microsoft Excel based platform, and it is available to guide policy makers, construction project teams, and rating systems developers on climate change adaptation (Jaudel 2013). This is certainly a good step forward by now addressing the need for resilience and beginning to incorporate future climate conditions into rating systems, but with LEED alone, this isn't enough. Less than 20% of LEED for New Construction Rating System credits are climate sensitive solutions, so using LEED credit solutions alone will not get one far towards achieving resilience (Randolph 2014). It is important that stakeholders do not confine themselves to familiarities and achieving arbitrary credits from rating systems, some of which with solutions that are not even applicable to certain hazards, provide no tangible energy performance or sustainable benefits, or are no longer effective for certain projects and/or locations. They should rather strive to go beyond this by considering and seeking more tangible and prescribed evidence of performance for guidance when looking to implement solutions to achieve high-performance building and disaster resilience goals.

The DHS has been developing a performance based tool to aid in the construction of high-performance buildings, which also takes into account resilience to multi-hazards (NIBS 2011). The tool allows for building owners to identify and set performance targets based on the attributes of high-performance defined in the 2007 EISA definition for high-performance building. Performance results produced by the tool are based upon various attributes (safety, security, energy, environment, durability), demands (man-made and natural hazards, environmental conditions), systems (architectural, mechanical, fenestration, structural), and performance targets (baselines, improved, enhanced, or high performance). Performance outcomes/results are expressed in terms of risk, resilience, and operation. Resilience is measured by cost and time to recover from an event in the OPR tool for comparative purposes. However, this tool does not identify prescriptive technologies to achieve the levels of performance desired by the owner using this model. That additional task is left to the design team to identify and decide which technologies to use that will hopefully achieve the desired results.

2.3.4 Moving Forward with High-Performance Buildings

The connection that exists between high-performance building, disaster resilience, and climate change adaptation is relatively clear, however such known building technologies remain a challenge in terms of limited knowledge regarding effective selection and application for various local contexts. Defined metrics to evaluate high-performance and resilience lack consistency and are in need specifically in the residential construction industry to effectively implement technologies across building standards. This will require developing clear classifications and performance attributes allowing for accountability, quantification of impacts and benefits, and benchmarking. Incorporating resilience as an aspect that can additionally be evaluated for performance is an essential component in this process. When it comes to identifying high-performance buildings, disaster resilience technologies for specific buildings and applications, incorporating localized area characteristics and climate data into decision-making is more important than ever in regards to climate change adaptation concerns. Builders, designers, owners, and policy makers need to consider this now and forthcoming towards creating a resilient and sustainable future for the built environment.

2.4 Natural Hazard Vulnerability

Thus far, the term vulnerability has been mentioned several times, however, its meaning remains vague and unexamined in regard to the topic and problem that has been posed. So what does vulnerability mean? And how can vulnerabilities be determined? The answer to these questions are highly reliant upon the context of the situation in regard to stakeholders, location, object and situational characteristics, and many other variable features and situations that can influence decisions and outcomes. For example, the context of a home's vulnerability to natural disasters can be negatively or influenced by a multitude of conditions. This can include housing construction and technology standards implemented, socio-economic conditions such as age, education and social class of the occupants and location, and perhaps most obviously, the type of climate a home is located in and exposed to. The definition of vulnerability was explored in this section in order to explain how it relates to the risk of a disaster, and how vulnerabilities can and will be identified and measured for the research proposed here.

2.4.1 Vulnerability's Relation to Risk

Similar to the previously discussed terms "resilience" and "high-performance" , vulnerability has been defined in many different ways due to the multifaceted nature of its application to a plethora of disciplines and circumstances. In a review of vulnerability definitions, Birkmann compiled a list of vulnerability definitions while also discussing the need to be able to identify, measure, and rank vulnerabilities for effective risk reduction and promotion of a disaster resilient culture (Birkmann 2006). Some definitions complied by Birkmann included the following:

The United Nations International Strategy for Disaster Reduction (UNISDR) defines vulnerability as the *"conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards."* (UNISDR 2004)

The United National Development Programme (UNDP) defines vulnerability as a *"human condition or process resulting from physical, social, economic and environmental factors, which determine the likelihood and scale of damage from the impact a given hazard."* (UNDP 2004)

Cannon et al. discussed how although vulnerability can be mainly hazard oriented, the type of hazard only partially defines vulnerability, and it is instead driven by the degree of self or social protection, qualifications, and institutional settings the define the overall context people or communities experience and respond to hazardous events (Cannon et al. 2003)

And similarly to Cannon et al., Vogel and O'Brien discuss the importance of context and the ever-changing nature of vulnerability. They define vulnerability as multi-dimensional and differential, scale dependent, and dynamic (Vogel and O'Brien 2004).

It is a common view that risk, the antithesis to resilience, is a function of the combination of hazard and vulnerability (Naudé et al. 2009; Wisner et al. 2003), and can thus be used to determine vulnerability with the following equation:

$$Hazard + Vulnerability = Risk$$

It can also be defined with the additional aspect of adaptive capacity included in the equation as follows:

$$Adaptive\ Capacity - (Hazard + Vulnerability) = Risk$$

Furthermore, risk has been defined by the Department of Homeland Security (DHS 2011) with consequence *(C)* as a main component in addition to vulnerability *(V)* and threat *(T)*, also considered as hazard, as follows:

$$R = f\ (T \bullet V \bullet C)$$

In these definitions and equations, the hazard can typically be associated with a natural disaster, adaptive capacity can refer to a variety of resources and/or planning strategies used to mitigate risk as a result of the combination between hazards and vulnerability, and consequences can represent the impacts caused as a result of a disaster.

The TVC definition of risk was most closely associated with the research that was conducted here, as climate induced natural hazards, impacts (e.g. damages and consequences), and vulnerabilities were investigated, as well as potential solutions to mitigate natural disaster risk and enhance disaster resilience.

Vulnerability, as mentioned in the definitions above, still remains very dynamic and contextual. In the case of housing in response to natural disasters, probing into housing market conditions, as well as housing construction and technology characteristics implemented in particular locations and communities can help identify vulnerability indicators that contribute to the driving forces behind the risks and potential impacts caused by hazards to homes and associated infrastructure. Understanding and identifying what these vulnerabilities are and what their importance is to assessing risk can also provide assistance in creating and selecting appropriate solutions to reduce risk and increase the adaptive capacity needed for protection against potentially catastrophic impacts.

2.4.2 Housing Vulnerability Indicators

The residential building industry, or housing market, can be characterized by a multitude of attributes. In regard to determining the risk exposure of a particular housing market, these attributes can be specifically pinpointed as most important to determining vulnerabilities to hazards posed to the population and its contents, as well as establishing baseline conditions necessary for monitoring change, comparisons, and progress towards resilience (Cutter et al. 2010). Literature has revealed insight into attributes of vulnerability that are important to include in assessing risk and potential impacts to hazards such as natural disasters.

Naudé et al. discussed how household vulnerability can be measured and what household assets are important to coping with hazards and striving for resilience. These assets include the categories of natural (e.g. land), physical (e.g. infrastructure), financial (e.g. insurance, savings), human (e.g. know-how, health), and social (e.g. networks) (Naudé et al. 2009). If these categories are broadened in scope, they can come to represent a model for assessing natural disaster vulnerabilities, which considers immediate household assets as well as boundary conditions that are also important contributors to consider. For example, natural assets can also align with the environment and climate of a household's location, which is important to assessing hazard specific vulnerabilities. Physical assets can be closely associated with the structure, technologies, and infrastructure of a building, as well as the building codes and regulatory environment associated with constructing and governing the home and land. The financial, human, and social assets all relate to the economics, demographics and overall market area of the people, home and/or community contributing to natural disaster vulnerabilities.

When dissecting these attributes into even more detail, housing natural disaster vulnerabilities can then begin to be more easily identified for this context. Literature review and insight that will discussed further here has led to the proposed theory that housing natural disaster vulnerabilities can be indicated by the attributes associated with categories of the natural environment, market area, construction standards and regulation, and high-performance building (HPB) technology implementation. Figure 10 summarizes the proposed vulnerability indicators.

Natural Environment: The climate and natural environment surrounding a home are important factors that can positively or negatively influence the level of vulnerability and risk faced with in regard to natural disasters. Current as well as prior history with a climate and natural disasters is perhaps one of the most obvious indicators of vulnerability when considering the natural environment, and the future climate is now becoming an even bigger consideration. Frequency and intensity of past and anticipated natural hazards can help estimate the type and amount of exposure and vulnerability that exists for a location. This type of vulnerability is named here as hazard exposure and potential, and are specific to a particular type of hazard. This type of data can be obtained from climate assessments that provide information regarding past, present, and future climate conditions. Additionally, historical accounts of natural disasters are important to consider when assessing hazard potential. For example, a location that has had a larger history of hurricane activity compared to average occurrences of other locations that seldom experiences such weather extremes, are considered much more vulnerable to the impacts of hurricanes. The Disaster Risk Hotspots project conducted by Columbia University and the World Bank used this approach by assessing and incorporating hazard exposure, hazard frequency, as well as associated human and economic loss rates to represent vulnerability and identify areas in most need of risk management (Dilley 2005).

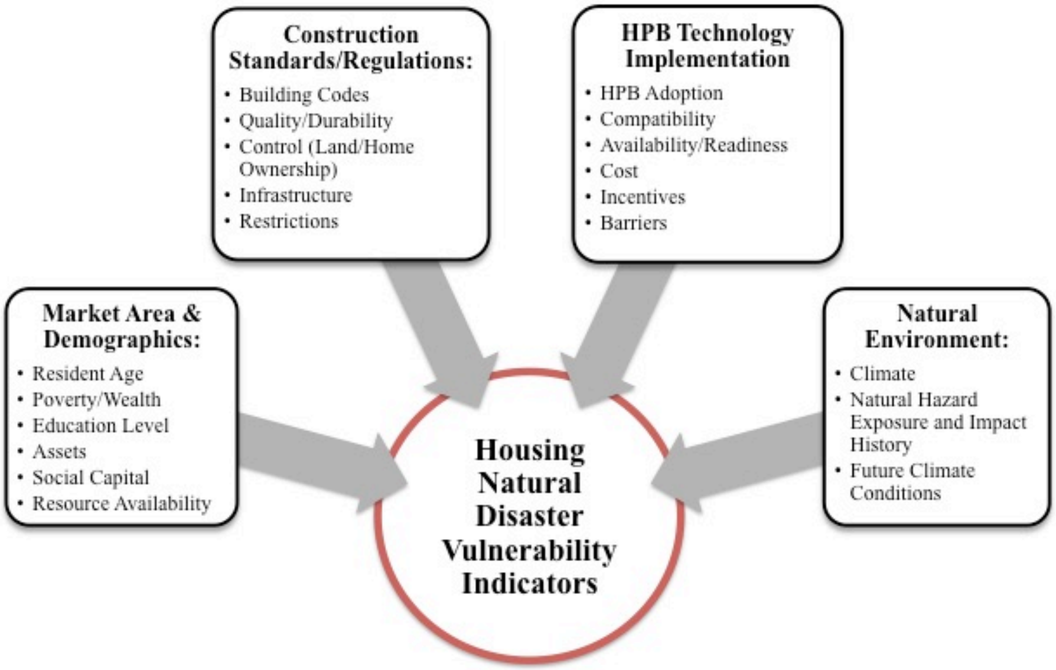


Figure 10 Proposed model of housing natural disaster vulnerability indicators

Market Area and Demographics: The type of area where a home is situated can also be an important indicator of vulnerability. In regard to disaster resilience, it has been proven that in the southeastern region of the U.S. a spatial variation exists between rural an urban areas, were urban metropolis areas were found to have higher levels of resilience than that of rural areas (Cutter et al. 2010). This can imply that rural areas are more vulnerable to disasters, as antonym of resilience. The attributes included in Cutter et al.'s evaluation were social, economic, institutional, and community capacities, which varied widely between the two groups. All of which fall into the category of market area characteristics.

Individuals and households living in poverty have often been considered to be more vulnerable to their environment as they can be exposed to more risks and lack resources and services that are available to those situated in areas with higher incomes (IBHS 2012; Martin-Breen and Anderies 2011; Wisner et al. 2003). This can include access to local, affordable goods and services such as builders, planners, and/or retrofit professionals needed to increase adaptive capacity and resilience to adverse conditions. It has been found that in a study of low-income communities, assets such as labor, employment, and human capital (education, health, and food), housing, and social capital (community connectivity and networks) were all found as important factors contributing to economic adversity, or in other words, assets important to building resilience (Martin-Breen and Anderies 2011). However, not all that live in poverty are vulnerable. For example, lacking social capital even in a wealthy area can increase vulnerability (Martin-Breen and Anderies 2011). Areas with fewer elderly and disabled individuals have also been considered to have higher levels of resilience (Cutter et al. 2010) thus lower levels of vulnerability (IBHS 2012).

Data regarding market area characteristics can be gathered from sources such as the U.S. Census statistics, and/or other national data sources to develop composite indicators of market vulnerabilities for various locations and contexts being assessed.

Construction Standards and Regulations: The presence, quality, and enforcement of certain building codes and regulations can have a significant influence on the protection and performance a home in the wake of adverse climate conditions such as natural disasters. Building codes are put in place and enforced to establish the minimum acceptable level of construction standards allowing for the adequate construction, protection, and safety necessary for buildings and its occupants (EPA 2015). This can include enforcing laws such as structural standards for seismic activity, or construction proximity restrictions near flood lines. Older homes and low-income communities are often considered to be at greater risk than newer buildings and higher income areas because older and lower-income homes are typically not updated, and thus not protected by the most up to date building codes that offer the protection necessary to withstand various hazards. Other challenges that lower-income communities face with building codes can be related to skewed views regarding the costly nature of enforcing building codes, and lack of education over building code requirements, which can lead to hesitance in seeking the required work, and contracting unlicensed and unskilled workers for renovation, construction, and/or inspection work (IBHS 2012).

Building codes can vary in the minimum requirements enforced, where "code-plus" or advanced building codes exist that go beyond the typical minimums enforced by the state and local government level model codes required. These types of code-plus construction provide more protection and natural disaster resistance than typical model building codes, and are not always more expensive, refuting the claims that advanced building codes are not targeted for low-income communities (IBHS 2012; IBHS 2013).

The ownership and control over one's property and land can also have an impact on the amount of vulnerability to natural disasters that exists for a building and its occupants. For example, having no legal title or ownership to your home or land means increased outside regulation, which can lead to decreased incentive to maintain the property and decrease aspects causing vulnerability. Where in contrast, having ownership, thus lack of outside regulation, can create more stability and incentive to increase resilience and lower vulnerabilities of a property (Martin-Breen and Anderies 2011). Therefore, even if a home is located in a low-income area, if the occupants have significant ownership over the property and have autonomy in regard to regulation, vulnerability can be decreased more readily and easily even for individuals located in close proximity to older, more vulnerably constructed homes.

Evaluating various building code requirements and other code-plus standards implemented by a home can provide data towards comparing and contrasting the amount of rigor and tact communicated in each mandate to address natural hazard vulnerability.

High-Performance Building (HPB) Technology Implementation: As discussed in prior sections regarding HPB (section 2.3.3 High-Performance Building for Disaster Resilience), HPB technologies can offer natural disaster resilience remedies for buildings if implemented strategically. HPB technologies, which can be found in various advanced or code-plus building standards, can increase environmentally, economically, and socially vulnerable aspects of construction and building occupancy. This is also one of the main theories and initiatives proposed by this research. For example, renewable combined heat and power systems used by a community of homes can decrease social and economic vulnerability by increasing social capital assets and decreasing the financial burden on a community, while also reduce environmental vulnerability due to its ability provide energy and heat in the wake of a natural disaster hazards that could cut off connection to grid power.

Although the implementation of HPB technologies can decrease natural disaster vulnerability, there are barriers that can prevent innovation, diffusion, and effective use of such technologies, and thus, still allow for housing vulnerabilities to prevail. Innovation refers to the adoption or implementation of new products, processes, and services, while diffusion refers to the rate of adoption of innovations (Holmen Enterprises Ltd. 2001). Innovations in the housing industry applies to building materials and products, construction techniques, construction equipment, building equipment, business services, and business operations (Holmen Enterprises Ltd. 2001). HPB technologies are included in this list as construction products, processes, and services that go beyond the traditional housing construction codes and standards enforced today and historically. Barriers discussed to impede innovation are factors such as regulatory authorities, rejection or incompatibly with existing labor forces/skills, high costs of adoption, un- or ill-informed consumers, lack of incentives, risk of performance, and liability perceived by lenders (Holmen Enterprises Ltd. 2001). Identifying where these barriers may exist in various locations, as well as rates of adoption and the presence of various HPB standards and labels, can aid in the identification of where HPB innovation exists and where it lacks. This would display evidence of disparities in natural disaster resistance vulnerabilities among differing housing communities where HPB innovation is either more prevalent or notably absent.

2.4.3 Evaluating Local Climate Induced Natural Disaster Vulnerabilities

While implementing high-performance building technologies to make homes less vulnerable to natural hazard impacts is a strategy that can be a significant contributor to increasing disaster resilience, it's application, or lack thereof, should not be the only indicator used to assess their need in regards to increasing resilience and decreasing vulnerability. As noted, socio-economic factors such as the market area and demographics, construction standards and regulations, and the natural environment of a home or housing community's location are all additional indicators to be considered for natural disaster vulnerability and the need for increased disaster resilience. All of these mentioned aspects should be considered when assessing local vulnerabilities of housing in regards to natural disasters and the hazards they pose.

2.4.4 Vulnerability and Resilience at Multiple Scales

The Greek god Pan's persona is known to represent unpredictable change. Relating this concept to the notion of linked interdisciplinary hierarchies at different scales completes the meaning and idea behind what is known as Panarchy (Gunderson and Holling 2002). Panarchy in resilience is used to define complex adaptive systems, which are composed of multiple linked systems operating at different scales. These linked systems are each composed of their own adaptive cycles and successively linked to other systems adaptive cycles (Walker and Salt 2006). Each system moves through four cycles in an adaptive cycle phase consisting of the front loop phases: rapid growth and conservation; and the back loop phases: reorganization, and release (Gunderson and Holling 2002). The front loop represents the phases in which resilience is decreasing due to maintaining a status quo and capitalizing on strengths rather than exploring and implementing new strategies or resources to function and thrive. While the back loop represents the phases of increasing resilience following a disturbance or disaster where a system is now adapting to a new state to function (Walker and Salt 2006). These links between systems and their cycles play a major role in how a system reacts and respond to disasters, as well as how it influences system operations at other scales. Considering systems as single entities is not taking into account the cross-scale effects that exist in the environment being studied (Walker and Salt 2006).

While this study focused on the building scale and the specific resilience of that system and its' components, understanding its linkages and influences to and from other systems within its panarchy is important towards expanding the work to other scales of resilience for future research and collaboration.

Building scale disaster resilience to climate-induced natural disaster risks is interdependent on multiple variables. Vulnerability indicators of housing on the building scale were highlighted in the previous subsection (2.4.2.). These variables can also be viewed as resilience indicators, the antithesis to vulnerability. As other system linkages to the building scale are explored, these indicators begin to change as the scales decrease or increase. Figure 11 represents an example of similar resilience variables, or indicators, that can be considered at multiple scales within a panarchy of complex adaptive systems. For example in Figure 11, when moving from the building scale to the larger community scale, similar variables for resilience are represented but are now analyzed at a much larger scale. The building itself is now included as a variable in an interpretation of community resilience indicators by Cox and Hamlen (2015). This is the similar case when moving to variables at the city or town scale (Razafindrabe et al. 2009). Examining this scale can reveal the influence the building system can now have on higher order systems. To demonstrate this thinking, consider the task of increasing the resilience of individual buildings using high-performance technologies. This in turn could increase the resilience of a community if it were then composed of high-performance resilient buildings, depending on how technologies and strategies are implemented. Thinking in even broader scales, a now high-performance community consisting of high-performance resilient buildings can then influence an entire city or town's resilience through physical capital, which is increased by enhanced community building performance and resources for self-sufficiency in the event of a disaster. This thinking also can work in reverse when these variables are now considered as vulnerabilities. For example, state or city building codes and policies that inhibit building performance measures that could reduce disaster impacts at the building scale where these policies are enforced, is an example of how linkages between scales can influence system cycles negatively. Lack of awareness by institutions in regards to the local needs of what is being governed can sometimes be detrimental to other systems below in a panarchy.

It is also important to note that at the building scale, the data needed to represent this level and subsequently evaluate its vulnerability or resilience may not be available in its entirety. Therefore, looking at the linkages to the community, city, or county level is sometimes the only available alternative scale to draw data from to assess resilience. This can be true for natural environment climate data, various demographic data, and very often governance and policy information such as building codes and standards as discussed. While this is limiting in the level of detail sought after, this is also an opportunity for future work. Using larger (or smaller) system scale data, which are linked to the scale of focus, can be a way to expand the scope of work to other systems and the interdependencies within the Panarchy. One example of how this can be demonstrated in regards to looking at the building resilience variable HPB technology implementation. When assessing the vulnerability of a home to climate-induced natural disasters, imagine that it is revealed that for the building's county or region there is a lack of HPB technology incentives and technology availability, which is increasing a home's vulnerability to disasters. Looking at this larger scale data in the panarchy and evaluating its effect on the smaller building scale now reveals how addressing this lack of incentive and technology availability could be targeted to increase resilience of the area. Strategies to spur the investment in the HPB market before disasters strike in the building's locality could increase the economic resilience of the area through release and reorganization in new resources, and additionally increase the disaster resilience potential of the buildings in the area, now with reduced barriers towards HPB technology implementation.

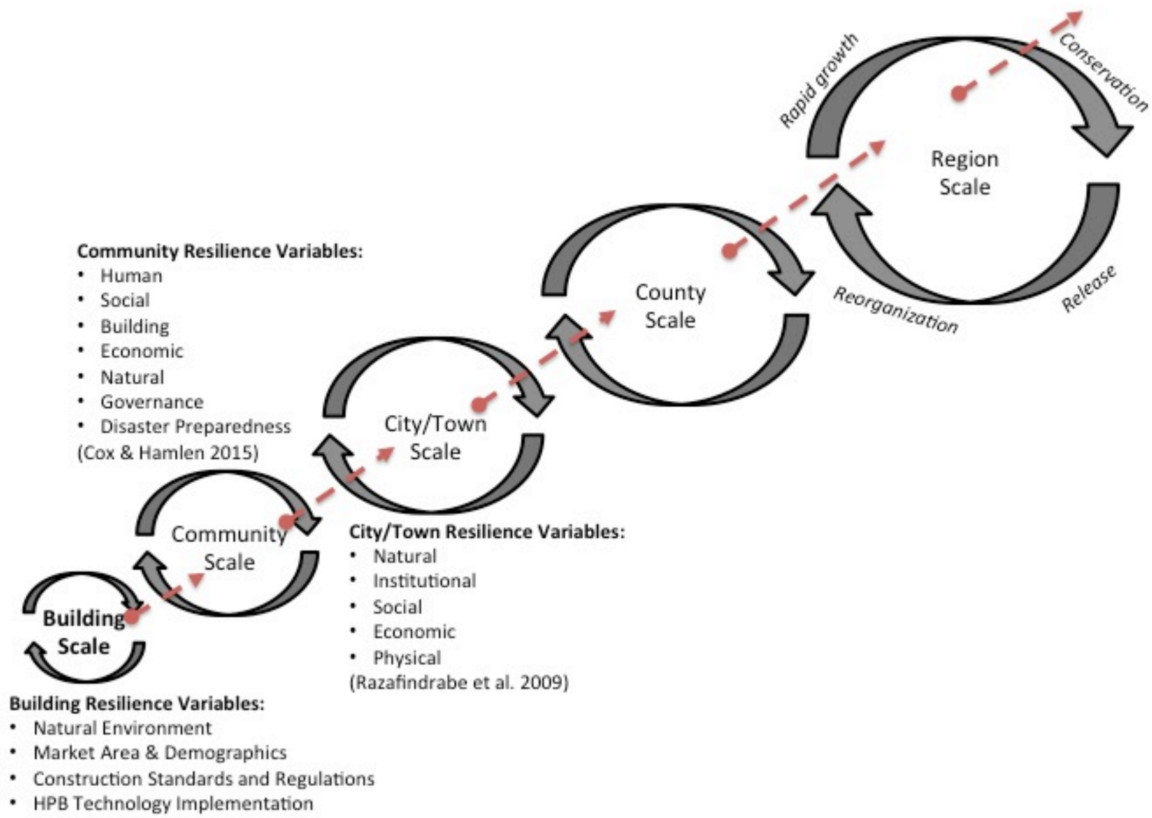


Figure 11 Panarchy example of linked adaptive cycles related to building scale disaster resilience

2.5 Research Gaps

Research efforts and discussions that link high-performance building, resilience, and climate adaptation is concerted with efforts being made such as identifying LEED credits that can potentially provide disaster resilience to climate change impacts on a regional level (Larsen et al. 2011); or FEMA, providing an assessment of natural disaster impacts on high-performance building ratings strategies implemented for resilience (Gromala et al. 2010); and developing tools to assist the implementation of high-performance building to achieve multi-hazard resilience (NIBS 2011). Although research such as mentioned before has and is being conducted to address the combination of high-performance building and disaster resilience, there are still gaps in these efforts where the opportunity is still there for further investigation.

Gap 1. Firstly, using local level building characteristics, market area and demographic data, as well as localized climate model data to identify natural hazards and vulnerabilities that may exist for residential buildings is in great need for locations across the U.S. In the past, the assessment of climate impacts and associated vulnerabilities to buildings has been conducted using coarser levels of data, but this now requires more in depth inquiry to ensure higher accuracy can be achieved. The United States Global Change Research Program's (USGCRP) second National Climate Assessment report published in 2009 entitled Global Climate Impacts in the United States, was used for studies such as the investigation conducted by USGBC and University of Michigan researches to identify climate impacts on the regional level (Larsen et al. 2011). The latest version of this report, and its associated technical input reports released in 2014 have incorporated more downscaled climate assessments where possible to improve accuracy. This is a step in the right direction, and reports and assessments such as these should be used, further focused state/city level impact assessments should be conducted, and other efforts should be made to move from the larger regional level to the smaller local decision-making level by accounting for local building, community, and climate differences.

Gap 2. Secondly, definitions that exist for residential high-performance building lack consensus, as do classifications of the attributes of performance in relation to it. This makes comparing and prioritizing high-performance technologies a considerably difficult task to achieve and to communicate.

Gap 3. Thirdly**,** seismic activity resilience is the natural hazard that has garnered the most attention and research efforts thus far when it comes to measuring resilience. Resilience toward "climate induced" hazards such as extreme heat and cold, or blizzards, and intense winds from hurricanes are mostly missing from these efforts. Similarly, the focus has also been directed more towards infrastructure and large buildings such as hospitals. While these are important structures requiring protection, residential buildings are also essential, as they provide the primary sources of shelter for the general population, and can also reduce the burden on connected infrastructure operation and recovery. Thus, being able to quantify resilience for residential buildings and technologies requires inclusion in this process.

Gap 4. Fourth and finally, according to the undertaken literature review, a framework or model that aids the decision-making process of selecting residential construction technologies that incorporate features of both high-performance building and disaster resilience for climate induced natural disaster risks while being applied at the local scale could not be found. Such an inventory of information accompanied by a decision tool would be a strong asset to individuals looking to mitigate natural disaster risks that exist in their location, and access a prioritized set of technologies to reduce those risks.

These gaps are the next steps to be investigated in order to enhance the areas of high-performance building, disaster resilience, and climate change adaptation in residential construction as an all-inclusive goal. The research that was conducted and discussed in the upcoming sections was performed with the intention of addressing and filling these identified gaps.

3 Research Design and Overview

3.1 Research Question

How can we identify and prioritize high-performance building technologies that can effectively provide residential buildings resilience towards local level climate induced natural disaster risks currently experienced and anticipated throughout the diverse U.S. climate regions?

The increasing costs and devastations as a result of natural disasters have been attributed to unsustainable development as a contributor. The combination of high-performance building technologies and programs as well as the increased use of disaster resilience strategies contribute to important goals that society currently faces in regards to climate adaptation, occurrence of natural disasters, and achieving greater sustainability. Few have evaluated the link between high-performance building technologies and disaster resilience towards identifying viable strategies and assisting decision-makers with effective implementation into the built environment. Nor have such technologies been evaluated and prioritized specifically for residential construction in relation to localized climate induced natural hazards, vulnerabilities, and impacts. Without a doubt, residential buildings need to become more resilient for the climates they are located in, and in addition to this they need to become higher performing. Currently only a scarce number of tools and resources exist to aid in progressing toward this goal. Additionally, the incorporation of regional and local climate differences into existing high-performance building standards is lacking, which is also contributing to this need. Climate change is exacerbating natural hazards and extreme weather event intensity and frequency, requiring a more in-depth evaluation of climates, vulnerabilities, and potential impacts where conditions will vary. High-performance, disaster resilient building technologies should be identified, evaluated, and prioritized to address important factors such as natural hazard risks, building performance, and disaster resilience for specific residential buildings contexts.

The above-mentioned research question has been addressed by this research, and a process has been developed to prioritize residential building technologies that encompass both, high-performance and resilience qualities that can be implemented for a variety of contexts at the local residential building scale to mitigate natural disaster risks. This process allows individuals in the residential building industry to use it as a tool towards making informed risk-based decisions that help to achieve disaster resilient and higher performing homes.

3.2 Research Goal

The overall goal of this research was to develop a decision-making process model that can be used to identify, evaluate, and prioritize residential building technologies that provide attributes of high-performance and disaster resilience in response to natural disaster risks for a variety of contexts at a local level. Figure 12 provides an overview of the important facets of this research that were integrated to identify and evaluate an inventory of high-performance resilient building "HPRB" technologies that were prioritized for a variety of natural disaster risks.

The results of this research meaningfully organized HPRB technologies that can be implemented to address a residential building's climate induced natural disaster risks, which included the consideration of multiple natural hazards, vulnerabilities, and impacts, according to specific building characteristics and other variables such as the local climate, local demographics, and implemented building standards. Location and climate characteristics, natural disaster vulnerabilities and impacts were assessed using housing stock and market data, evidence based literature such as prior disaster impact reconnaissance reports, subject matter experts, and regional climate impact assessments that have incorporated downscaled climate model data where possible. The HPRB technologies identified were based upon an in-depth analysis of their ability mitigate natural disaster risks as a result of the disaster resilience and high-performance building attributes they can be associated with, which in turn was supported by literature.

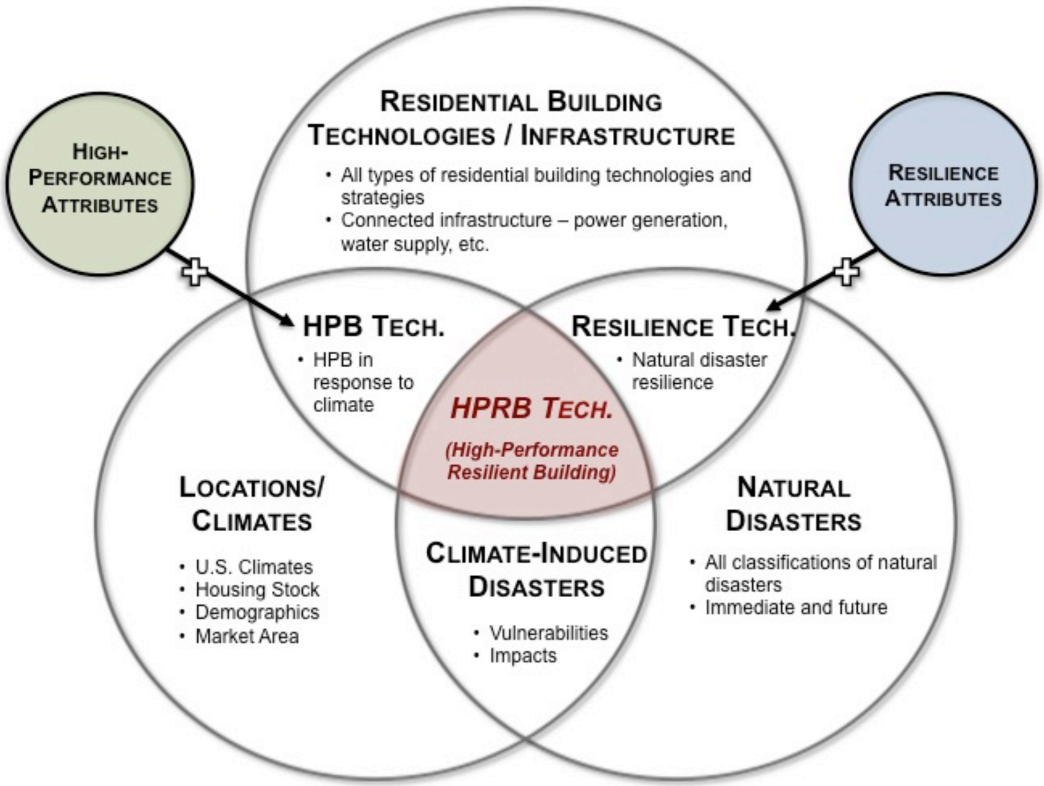


Figure 12 Research goal overview diagram (HPB = high-performance building)

For the purpose of demonstrating the applicability of the process developed, the scope of this study was limited to the southeast climate region of the U.S. Further research scope limitations are discussed in the Research Limitations and Assumptions section to follow.

The stakeholders focused on for this research included building auditors, retrofitters, and disaster mitigation officials, who assess building performance in regards to natural disaster risk. These are the professionals that can use this process as a tool to evaluate residential buildings and communicate strategies to homeowners, government agencies (e.g. FEMA or HUD), homebuilders, and community planners to educate them on how to improve building performance and resilience that is most efficient for their particular situations. The process developed in this research can become a tangible tool when taking action in response to the need for increased resilience and building performance. Ultimately, this research hopes to benefit stakeholders by providing new research data and tools in regards to climate hazard vulnerabilities and impacts to residential construction, as well scientific research towards strengthening the integration of resilience and high-performance buildings. New findings and further research in this area can prove valuable towards policymaking, community resilience planning, resource efficiency, and quality of life, as well as reduced risk for builders, designers, homeowners, and insurance firms.

3.3 Research Objectives

To achieve the research goal, the following research objectives and tasks were proposed and carried out. Three objective categories of A, B, and C, were further broken down into tasks (e.g. A1, A2, etc.). Each objective/task is explained in regards to its purpose, how it was achieved, and how it related to the overall research goal.

Objective A: Identify and assemble data and tools needed to support a decision-making process for evaluating climate induced natural disaster risks and a selection of appropriate high-performance, resilience solutions.

Task A1: Identify immediate and future climate induced natural disaster hazards, which will be included in a data inventory

- ✓ *Addresses Research Gap 1*
- ✓ *Method(s): Systematic Literature Review*

This initial objective was an important step towards understanding what the current and future climates throughout the southeast region of the U.S. will potentially entail. This step contributed to the goal of identifying appropriate disaster resilience strategies in response to various natural hazards that exist and that are expected. This task involved the analysis of climate assessments for the southeast climate region located within the U.S. in order to create a classification of existing and future climate induced natural hazards. The southeast portion of the U.S. was the focus of this study to begin with in order to narrow down the scope, as well as to ensure the research approach was achievable at a smaller scale before expanding research efforts to additional regions.

Studies and reports were reviewed in which climate data and models have been assessed and subsequently used to communicate current and future projections for climate hazards. Sources of literature included assessments such as the regional technical input reports used for 2014 National Climate Assessment, in which RCM datasets were included in impact and vulnerability assessments.

Task A2: Identify and categorize residential high-performance building technologies that can be effective in providing disaster resilience in response to climate induced natural disaster risks, which will be included in an HPRB technology inventory

- ✓ *Addresses Research Gap 1*
- ✓ *Method(s): Systematic Literature Review*

An inventory of high-performance building technologies that are considered to be effective at providing resilience to the climate induced natural hazards that were identified in Task A1 was compiled in this task. High-performance building standards, which included PassivHaus, LEED, EarthCraft, Energy Star, and the National Green Building Standard, were thoroughly analyzed by assessing each prescriptive requirement, strategy, and/or credit that offers residential building resilience to climate induced natural disasters. All of the identified technologies were classified according to the types of natural disasters they can for which apply to, and how they can potentially offer resilience. This inventory and analysis of technologies was beneficial towards climate adaptation and disaster mitigation planning for various locations, especially for those most vulnerable to the impacts of natural disasters and climate change, looking for direction on how to improve housing performance while also incorporating disaster resilience.

The result of this objective was the assembly of an inventory of residential HPRB technologies categorized for multiple natural hazards and the associated adverse impacts to buildings that they can mitigate. Sources of where each technology can be found in various high-performance building standards were also revealed, with a broad analysis performed regarding what sole standard could best address a specific hazard.

Task A3: Conduct FMECAs and FTAs to reveal the relationships that exist between the identified HPRB technologies and climate-induced natural disaster hazards by analyzing hazard impacts to housing, and identifying common failure modes and the contributing vulnerabilities/causes

- ✓ *Addresses Research Gap 1*
- ✓ *Method(s): Failure Mode, Effects, and Criticality Analysis (FMECA), Fault Tree Analysis (FTA)*

Failure Mode, Effects, and Criticality Analyses (FMECAs) were performed to identify common building system failure modes (i.e. direct damages), or impacts, to residential buildings as a result of the identified natural hazards in Task A1. The criticalities of the failure modes were quantified, and all possible associated effects (i.e. indirect damages) of each failure were identified using FMECAs. Fault Tree Analyses (FTAs) were be performed to identify the root causes and vulnerabilities that lead to the failure modes identified by the FMECAs, as well as any prevention or mitigation options, which were the HPRB technologies identified in Task A2.

The inventory of HPRB technologies, natural hazards, building failure modes and causes, were linked together in a graphical representation of a series of FTAs. This provided a visualization of climate induced natural disaster hazards, building failure modes, and specific causes that can lead to each failure that can be commonly experienced by residential buildings exposed to the specific hazards investigated, in addition to the HPRB technologies that can potentially be effective risk mitigation solutions.

Case studies and building damage forensic reports, which detail actual events of when and/or how natural hazards have negatively impacted residential buildings were reviewed, and subject matter experts were consulted to produce the results of this task.

Objective B: Define the attributes and metrics needed for measuring levels of disaster resilience and high-performance for the residential building context

Task B1: Define the attributes of disaster resilience for residential buildings

- ✓ *Addresses Research Gap 3*
- ✓ *Method(s): Thematic Analysis*

Before buildings and technologies could be compared and contrasted, attributes and performance metrics needed to be consistently defined so that expected level of performance and resilience could be quantified. These metrics needed to address attributes considered essential to achieving high-performance building and disaster resilience for the residential building context. This would strengthen decision-making in regards to allowing for a more convenient comparison of building technologies across multiple construction standards.

Attributes and metrics for quantifying disaster resilience were defined for the residential building context. Disaster resilience planning strategies and proposals, and residential building standards for achieving disaster resilience that were developed by various subject matter experts, were drawn upon for thematic analysis. These data were thoroughly reviewed and coded in order to identify common themes for disaster resilient homes. These themes were then used to devise a comprehensive list of attributes and metrics, which were used to characterize and quantify disaster resilience applicable to the dimensions of residential buildings.

Task B2: Define the attributes of high-performance for residential buildings

- ✓ *Addresses Research Gap 2*
- ✓ *Method(s): Thematic Analysis*

Similar to Task B1, high-performance building standards and technology functions detailing high-performance building features and principles were reviewed in order to develop a list of attributes and metrics used to classify high-performance applicable to the context of residential building performance. The texts analyzed and coded included high-performance building standards that have been widely acknowledged in research, and accepted and/or implemented with evident cases of use in residential construction.

<u>Objective C:</u> **Develop a process model that conceptually demonstrates how climate induced natural disaster risks and HPRB technologies can be prioritized for effective decision-making.**

Task C1: Define the necessary steps for the entire process, including inputs and outputs

- ✓ *Addresses Research Gap 4*
- ✓ *Method(s): Systematic Literature Review*

National, state, and local building resilience and disaster risk mitigation planning reports, proposals, and needs assessments were reviewed in order to define the necessary process steps, and to ensure that it aligns with commonly communicated needs of stakeholders.

Task C2: Demonstrate how to define baseline levels of building performance and disaster resilience needed to prioritize risks and technologies for differing housing contexts

- ✓ *Addresses Research Gap 1 & 4*
- ✓ *Method(s): Demonstration Cases, Multi-Criteria Decision-Making (MCDM)*

A series of "demonstration cases" were carried out for Tasks C2 and C3 to demonstrate the viability of the process developed, and to also represent the variability in the type of homes the process can be applied to.

For Task C2, an analysis of various building characteristics and housing natural disaster vulnerability indicators was performed for two conceptual demonstration case homes. As a result of this analysis, various natural hazard risks (which were identified in Objective A) were prioritized for each case home, then baseline residential performance and disaster resilience for the demonstration cases were quantified using Multi-Criteria Decision-Making (MCDM). The baseline performance and resilience levels of the case homes were quantified using the attributes and metrics of residential building performance and resilience defined in Objective B.

Task C3: Demonstrate the MCDM prioritization process by prioritizing HPRB technologies in response to specific housing natural disaster risks.

- ✓ *Addresses Research Gap 1 & 4*
- ✓ *Method(s): Demonstration Cases, Multi-Criteria Decision-Making (MCDM)*

Finally, Task C3 involved demonstrating how HPRB technologies can be prioritized for specific contexts using MCDM. The technology prioritization was based upon the prioritized risks identified for each case home in the preceding task, as well as the baseline levels of performance and disaster resilience quantified for each case, and the applicable HPRB technologies to address each risk. A clear graphical visualization of prioritized risks and associated HPRB technologies was produced for each case. The graphs presented the most critical climate induced natural disaster risks that exist for a specific home in regards to the level of vulnerability they exhibit and the potential adverse impacts that could occur; and also revealed the HPRB technologies that could be the most effective at mitigating these risks by providing enhanced disaster resilience and building performance from baseline levels.

This objective conceptually demonstrated the application of the process developed in this research, which is used to identify and prioritize HPRB technologies for residential buildings. It was the goal that the results produced in this objective will show the potential to further develop this process and apply it to various locations nationwide.

3.4 RESEARCH METHODOLOGIES

Table 2 show each of the research methods was associated with the respective objectives and tasks discussed in the prior section. In the following text, each method is explained in terms of its general purpose and prior applications, its relevance to the conducted research, and how it is utilized towards meeting one or more of the research objective(s).

Table 2 Research methods used for each research objective and task

	Objective/Task							
Method	A1	A2	A3	B1	B2	C1	C2	C3
Systematic Literature Review	✓	✓				✓		
FMECA			✓					
FTA			✓					
Thematic Analysis				✓	✓			
Demonstration Cases							✓	✓
MCDM							✓	✓

Systematic Literature Review

The systematic review of literature is a research methodology commonly used to gather evidence and develop research theories by learning from, consulting, and synthesizing the findings of other researchers in lieu of undertaking new research (Gough et al. 2012). Gough et al. (2012) defines a systematic review of literature as a process of "using systematic and explicit, accountable methods." A systematic review can involve several stages, which includes developing a specific and focused search strategy (e.g. screening the literature with keywords) before a review takes place, and data is synthesized.

Systematic literature review was one of the main methods that was used to compile and synthesize data regarding climate hazards and impacts to residential building, housing vulnerabilities, and HPRB technologies. This was the primary method used to conduct tasks A1, A2, and C1. It entailed an extensive search by specific keywords and other target metrics, followed by a review of specific focus types of literature, which encompassed the information needed to compile the inventory of data, and to identify the process needs.

For example, searching for and reviewing various climate impact studies and assessments required a systematic search of targets such as the Regional National Climate Assessment reports, which helped to identify climate hazards; or when identifying HPRB technologies this required the systematic review of various high-performance building standards and their technology functions.

Overall, the systematic literature review targeted existing case studies, concepts, definitions, and principles regarding vulnerability, natural hazards, hazard impacts on residential buildings, high-performance buildings, and disaster resilience.

Failure Mode, Effects, and Criticality Analysis (FMECA)

FMECA is an extension of failure mode and effects analysis (FMEA) method with the addition of a criticality analysis component. Both types of methods have been used in research to analyze processes or products for potential failures, effects of the failures, causes of failures, risk of failure, and additionally, the criticality of failures if performing an FMECA (Wilhelmsen and Ostrom 2012). Criticality can be valuable for prioritization efforts by assessing how bad the effects of failures can be. Some typical steps of an FMECA include:

- Learn about the product or process being evaluated
- Setting the level at which the analysis is performed
- Describing and rationalizing the functions
- Listing and rationalizing all possible failures
- Describing the potential effects, causes, and controls of each failure
- Assessing the criticality of each failure

(Wilhelmsen and Ostrom 2012)

A common application of FMECA includes identifying safety hazards and problem areas in products and/or processes, and determining failures that could impact the desired qualities or results (Warwick Manufacturing Group 2007). While FMECAs cannot be used to form an FTA because FMECAs are bottom-up processes where faults are linked to the end effects and impacts, they can however be useful to check FTAs or develop them by beginning with impacts, or failure modes, identified in the FMECA as FTA top events (Stamatelatos et al. 2002). Table 3 provides a summary of the information and steps documented with an FMECA. FMECA was one of the main methods used to complete task A3, in which common failure modes to buildings as a result of natural hazard impacts were identified and ultimately assessed for criticality.

Table 3 Example steps of FMECA product or process analysis, adapted from Wilhelmsen and Ostrom 2012

Item	**Potential failure mode**	**Cause of failure**	**Possible effects**	**Severity of Consequence**	**Probability of Occurrence**	**Criticality**	**Prevention**
Product, component, process step, etc.	How can it fail? / What could possibly go wrong?	What could happen to have caused the failure?	What is the outcome of the failure?	How severe is the consequence?	How possible is it?	How bad are the results? (e.g. severity x probability)	What can be done to prevent either failures or results of failures?

Fault Tree Analysis (FTA)

An FTA can be described as an analytical method used to discover the root causes of failures or potential failures of undesired events (Čepin 2011; Marquis 2008). It begins with a top-level approach, where one starts with a particular failure, or impact, and works downward to evaluate all possible causes and faults contributing to the failure in question. This analysis can be represented with a diagram, the fault tree, and is used to identify countermeasures to eliminate the causes of the failure at the top level of the tree (Marquis 2008). FTAs can be used for many different applications and contexts. For example, it has been used to model potential flood causes in urban areas by using data from complaint registers, rainfall gauges, and hydrodynamic model calculations to support risk assessments (ten Veldhuis et al. 2009). Čepin explains that the scope of the fault tree indicates what faults and fault contributors are included in the tree and analysis (Čepin 2011), thus making it important that boundaries and limits are set for the analysis. Marquis (2008) describes the steps of an FTA to include the following:

1. Top-level event selection for analysis
2. Identification of all possible faults that could lead to the top event
3. List all possible causes for each fault identified
4. Use logic gates (i.e. and/or) to represent the sequencing and grouping of faults, causes, and events
5. Continue identifying causes for faults until a root cause has been reached
6. Identify countermeasures that can be applied for each root cause

In order to form and visualize the relationships that exist between the climate-induced natural hazards, impacts, causes, and HPRB technologies identified in objectives A1 and A2, FTAs were conducted. FTA was one of the primary methods used to achieve task A3. The FTAs carried out are also among the major contributions of this research. It reduced the large volume of qualitative data that were compiled in objective A into a consolidated and simplified representation of findings for other researchers and interested stakeholders seeking to use this information. Figure 13 provides a diagram that exemplifies the elements included in the FTAs performed in this research.

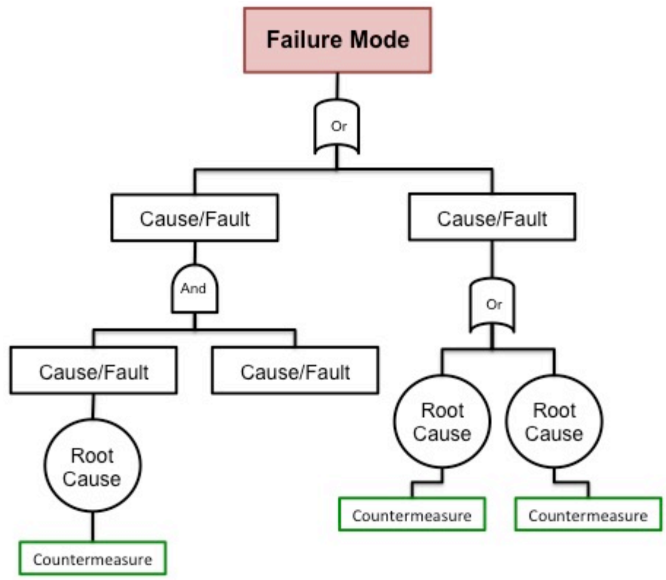


Figure 13 FTA process example

Multi-Criteria Decision-Making (MCDM)

Multi-Criteria Decision Making (MCDM) is a method used to make decisions with multiple dimensions in which various quantifiable or non-quantifiable criteria, attributes, or objectives play a role. MCDM has been used in multiple industry sectors and research disciplines such as sustainable energy planning (Pohekar and Ramachandran 2004), project prioritization (Karydas and Gifun 2006) (Miller 2014), and assessing climate change vulnerability (Kim and Chung 2013). MCDM consists of various approaches, or sub-methods, which among this group is perhaps the most commonly known and used MCDM approach, the *Weighted Sum Method* (WSM). The WSM was used and adapted for this study to demonstrate how climate induced natural disaster risks and HPRB technologies can be prioritized accordingly for a specific home.

The WSM involves defining weights to identified attributes considered important to making a selection between alternatives. The typical steps to this process include defining the key attributes and their values that are important to making a decision, determining the weight of importance of each attribute, and then taking the product of the attributes value and weight to identify the WSM score of each alternative (Pohekar and Ramachandran 2004). The WSM method can be expressed with the following formula:

$$A_i^{WSM} = \sum_{i}^{j} w_j \, a_{ij}, for\ i = 1,2,3, \dots, n$$

a_{ij} is the actual value of alternative i in terms of criterion j, whereas w_j is the weight of importance of criterion j. The total value, or WSM score, for alternative A_i is equal to the sum of the product of the weight and the actual value. In order to determine the appropriate weights and values for each attribute, seeking stakeholder input is important in order to increase buy-in, decrease variability, and to resolve the different interests that may exist. Discussions and surveys distributed to industry experts and stakeholders to attain this input has been implemented by prior studies (Kim and Chung 2013; Miller 2014).

For this study, the indicators and attributes for hazard vulnerability and impacts, building performance, and disaster resilience specific to a particular housing context were quantified with numeric weights and values on a comparable scale. This was achieved through literature research, building performance modeling, and consultation with subject-matter experts. Each identified attribute for hazard vulnerability, impact, performance, and disaster resilience in this study was evaluated according to values and weights defined using the WSM for comparison and subsequent prioritization.

To prioritize the data in a way that would be visually friendly and easy to interpret and compare alternatives for the decision-maker, a *Criticality and Vulnerability Matrix* has been used to prioritize assets by the greatest level of criticality and vulnerability for implementing countermeasures (AASHTO 2002), and the *Project Scoring Tool* conceptualized by Miller (2014), in which a quadrant consisting of two dimensions of a decision (e.g. vulnerability and impact) are scored from high to low. This method was piloted as part of demonstration cases to prioritize localized climate induced disaster risks and HPRB technologies specific to a location and its many characteristics and influences.

Demonstration Cases

A conceptual demonstration of the application of the developed processes was executed in order to verify its functionality as a viable tool. This method was called *Demonstration Cases*. Conceptual case homes were defined for the purposes of this research, and were evaluated using the developed prioritization process. In addition to the data collected and analyzed in this research that was integrated into the process, further data analyses were executed to support the performed demonstration case assessments. This included a systematic literature review of current and past building and energy codes for residential construction, various market area data for the case locations, case studies, and energy and resource modeling. The demonstration cases were also carried out to show the variability in the type of sample that the process can be applied to at a local level based upon differences in various building and occupant characteristics.

Thematic Analysis

Content Analysis has been described as "a research method for making replicable and valid inferences from data to their context, with the purpose of providing knowledge, new insights, a representation of facts and a practical guide to action" (Krippendorff 1980). The data, or content, used in this method of analysis has been described to include various sources of either quantitative or qualitative data such as texts, documents, and films used to identify themes, categories, and/or patterns in a particular body of materials pertinent to answering research questions or objectives (White and Marsh 2006; Williams 2007). The aim of using content analysis as a research method is to distil words analyzed in content into fewer categories and broad descriptors of the phenomenon being studied, thus building a model or conceptual system/map of representative categories (Satu and Kyngäs 2008). Three common phases of the content analysis process include:

1. *Preparation* – selecting content to analyze from a representative sample guided by the research question
2. *Organization* – open coding of the content through descriptions and creating categories and groups from the content
3. *Reporting* – modeling and conceptualizing the categories into a system or map (Satu and Kyngäs 2008).

Content analysis is typically regarded as a more quantitative approach to text analysis, where the presence and frequency of specific words are counted

The more appropriate term for the type of textual content analysis method that was used for Objective B, is rather more accurately referred to as inductive *Thematic Analysis*. Similar to the more quantitative based text analysis method of content analysis, thematic analysis is a "content-driven" approach that involves rigorously searching for key implicit and explicit themes in textual data (Guest et al. 2012). Themes are identified through codes developed by interpreting meaning from relevant excerpts of text, which will be the unit of analysis. This method is also a preceding task to the grounded theory method (Corbin and Strauss 2008). *Inductive Thematic Analysis* was the primary method used for objective B.

To ensure credibility and trustworthiness could be gained for the results produced in the thematic analyses, *Purposive Sampling*, which is a common method used in qualitative research, was used to select appropriate texts for the sample. This sampling method requires that the researcher select individuals or items for a sample because they can purposively inform the research problem at hand as a result of inherent knowledge and/or experience (Creswell 2007). The type of purposive sampling used for this research was *Criterion Sampling*, which ensured that all the texts selected meet some established criteria. This sampling approach works particularly well when the individuals studied (in this case, the authors/texts) represent people who have extensive knowledge and experience of the subject matter (Creswell 2007).

The population of texts that were analyzed in this research were related to high-performance building and disaster resilience relevant to the residential building context. The texts were selected according to a purposive sampling technique, which was guided by a set of criteria established as they related to the research questions defined for each thematic analysis performed. The texts were thoroughly reviewed and coded in order to identify themes, which came to represent the attributes and metrics used to evaluate performance and disaster resilience for residential buildings.

3.5 Research Design Overview

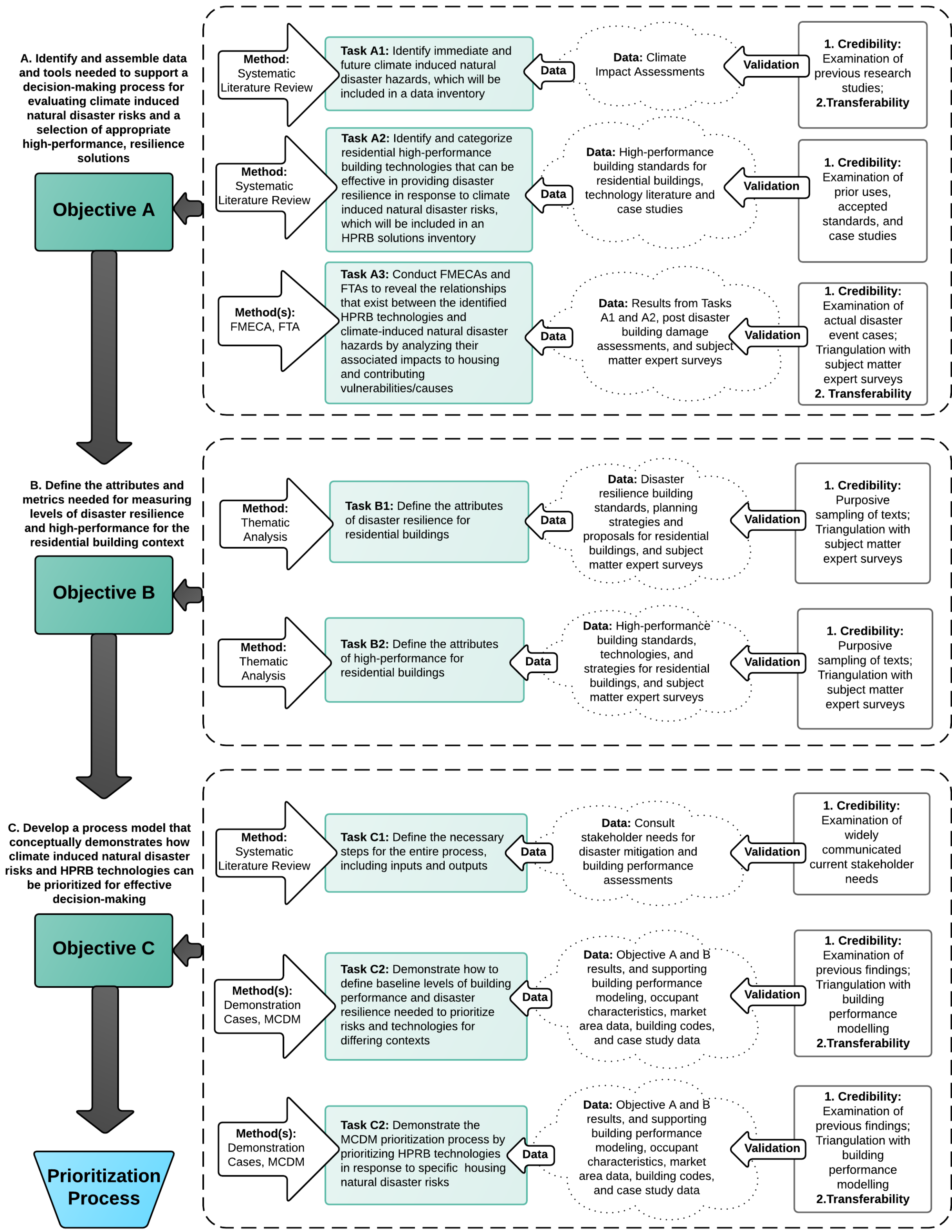


Figure 14 Final research design overview diagram

3.6 RESEARCH VALIDATION

To address the validity and reliability of the findings of this research, the following methods were used, where many of which align with Guba's widely accepted four criteria for assessing trustworthiness in qualitative research. This includes ensuring credibility (internal validity), transferability (external validity and generalizability), dependability (reliability), and confirmability (objectivity) (Guba 1981). Provisions of how qualitative researchers can attempt to achieve validity and reliability by abiding by this criteria as outlined by Shenton (2004), are explained here in regards to how they related to this research. The process map of the final research design, which is presented in Figure 14 in the previous Research Design Overview section, depicts how each task was validated using Guba's four criteria for trustworthy qualitative research.

3.6.1 Validation Methods

Credibility (Internal Validity): One of the most important factors for trustworthiness is credibility, which addresses the question: "How congruent are the findings with reality?" (Shenton 2004). The following strategies were implemented to bring credibility to the data collected and analyzed.

Triangulation – This involved using multiple methods to collect data for the same objective. For this research, an example of triangulation that was used specifically entailed using a variety of literature sources in which data was extracted for analysis, and by further surveying a group of individuals who were identified as subject matter experts to collect the same type of information. The results produced from each method were then compared to see how the data aligned with one another, and to also make conclusions regarding areas for further investigation where gaps or mismatches were revealed.

Frequent Committee Debriefing and Peer Scrutiny – Members of the research committee were frequently consulted and given periodic updates regarding the progress and methods used for this research. The individuals on the research committee were carefully selected and experienced advisors for the project who each brought many years of expertise to the subject matter and for the scientific research process in general. This ensured that any researcher biases and preferences were recognized and eliminated as much as possible; methods for data collection were refined as needed; and in general, ensured that any additional research flaws and/or barriers were addressed so that a sound and credible study was achieved.

Examination of Previous Research Findings – Research findings were related back to existing bodies of knowledge where possible to bring credibility to the results. For example, the HPRB technologies identified in this research to address mitigate certain natural disaster risks were supported with cases detailing prior uses and functions that relate to the conclusions drawn for this research. This approach was also used when analyzing hazard impacts and conducting the FMECAs and FTAs by relating all of the results to actual events and case studies documented in literature to increase internal validity. This type of data served as a form of evidence needed for credibility in this research.

Transferability (External Validity/Generalizability): Due to the unique and highly contextual nature of this research, as is the case with many other qualitative research studies, transferability is difficult to obtain. This refers to the extent at which the study can be applied to other situations and wider populations (Shenton 2004). However, it was one of the goals of this study that with future research, the objectives and methods used can be replicated and applied to other geographic regions and housing populations. In an effort to achieve this, the research undertaken here is thoroughly documented and communicated. This includes the entire research design, data collection methods and sources used, and the results produced, so that the information can be used to conduct the same or similar research under different contexts. The demonstration cases performed in this research were included to specifically show the potential for this research and the results to be applied to various contexts on a wider scale.

Dependability (Reliability): If the same research was repeated keeping all the information and steps unchanged, similar results would be obtained and dependability would be achieved (Shenton 2004). To add dependability to this research, the entire process was thoroughly documented with the following information as suggested by Shenton:

a) The research design and how it was implemented
b) How data was collected
c) Reflective commentary and discussion of the results produced in each objective, as well as for the research conduction overall

Confirmability (Objectivity): Finally, confirmability ensures that the researcher's findings are the result of the data and experiences collected, rather than personal assumptions and preferences (Shenton 2004). To achieve this, all of the assumptions and preliminary theories of this research were admitted and communicated prior to the start of the data collection process and also before the results were produced and discussed. Additionally, an "audit trail" (Shenton 2004) was crafted that shows diagrams of how exactly all of the contributing data that was collected lead to the final results and conclusions.

3.7 RESEARCH LIMITATIONS AND ASSUMPTIONS

The following research limitations describe the assumptions and scope of work defined for the data that was collected and analyzed.

Limit 1: The focus of the building structure, systems, and technologies identified and evaluated for this research was limited to the residential building type. More specifically, this refers to individual privately occupied residences as a single entity along with the technologies and features they are composed of, and not the community wide development scale, which can include multiple buildings and landscapes that need to be considered. While individual residential buildings were the primary focus, there was a possibility for overlap when considering connected infrastructure to utilities and other community based building technologies, as well as when analyzing the location characteristics of a home for vulnerability. This presents an opportunity for expanding the research efforts to a community wide scale in the future, which will be discussed later in the Discussion section.

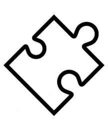
Limit 2: Residential buildings with high vulnerability to natural disasters are at most risk and in need of solutions to create and enhance disaster resilience. This is why they were a target population considered when collecting and communicating data. A vulnerable residential building was a focus for this research when conducting the demonstration cases and evaluating the relationships between disaster risks and HPRB technologies to identify and prioritize technologies to mitigate disaster risks. Vulnerable housing was chosen to limit the characteristics used to select the case homes, and to also clearly define what a vulnerable house can entail for the context of this research.

Limit 3: The natural hazards/disasters included in this research were limited to those that are "climate-induced". This included the natural disaster subgroups of meteorological and climatological disasters as classified by the CRED (refer to Table 1). Furthermore, the natural hazards focused on were limited to hurricanes, when performing in-depth risk analyses. This included wind, precipitation, storm surge, and any other sub-hazards found to be associated with hurricanes.

Limit 4: Due to the vast size of the U.S. and the multiple climate zones it encompasses, the southeast geographic region of the U.S. was the location and climate selected as the primary focus for approaching the research objectives. This also allowed for a more manageable amount of data to ensure that the objectives were completed in a feasible time frame. Future research will involve replicating the study in other regions where climates, as well as housing and other important characteristics differ.

Limit 5: A residential building is comprised of multiple technologies, systems, materials, and influences that dictate its structure and performance in many different ways. For this reason, a whole house considered as a single system cannot immediately be assessed for performance or resilience, but instead the systems that make-up the house should be evaluated separately due to their differing functions before assessing total house performance and resilience. Each technology or influence that a house encompasses can be multi-faceted in itself with various aspects to its composition, such as the building enclosure, which can include walls, fenestration, foundation, and a roof. To further limit the scope of this research, when evaluating disaster risks to housing and identifying HPRB technologies to address the risks, the building enclosure was the focus system in order to make the data and work more manageable within in the allotted research timeframe. Other building systems and components of residential buildings will be considered in future research efforts to expand the scope.

Limit 6: As previously mentioned, the stakeholders considered for this research included building auditors, retrofitters and surveyors, and/or disaster mitigation officials or assessors who evaluate building performance in regards to natural disaster risk. These are the professionals that can utilize this process as a tool to evaluate residential buildings and communicate strategies to homeowners, government agencies, homebuilders, and community planners to educate them on how to improve building performance and resilience most efficiently for their particular situations. This is the tangible tool needed to take action in response to the need for increased resilience and building performance where guidance is missing.



***Note**: When this symbol appears in the margins, it marks the discussion of **Major Findings** for quick reference. Results from these sections have significantly influenced the Major Contributions (8.1) of this research*

***Note:** When this symbol appears in the margins, it marks the discussion of a **Major Contribution** (8.1) of this research as a result of Major Findings*

4 Hazards, Impacts, and HPRB Technology Identification and Analysis

Identifying and evaluating hazards and impacts was the first step towards developing the decision-making support process for prioritizing climate induced natural hazard risks, and identifying appropriate high-performance resilient building (HPRB) technologies as potential solutions. The work discussed here includes

- assessing the current and future outlook of climate hazards to be expected in the southeast region of the U.S.;
- identifying and then categorizing a group of high-performance building technologies that can provide disaster resilient solutions to the identified hazards;
- performing hazard impact analyses to determine the potential failure modes (i.e. physical building damages) that can occur as well as how critical the impacts can be;
- and finally, conducting analyses which revealed the contributing causes of how each failure mode can occur and the HPRB technologies that are potentially viable resilience solutions for each.

As mentioned in the research limitations section, the focus area for climate-induced natural hazards was hurricanes, which allowed for an in-depth analysis regarding various sub-hazard aspects and the impacts to residential building enclosures. The focus on hurricanes was chosen due to current availability of data that can be used to develop the proposed process, as well as for the southeast regions exposure and history of disastrous events due to this hazard, and the expected increase of such events to take place in the near future.

4.1 Climate Induced Natural Hazards in the Southeast U.S.

The goal of this first task was to gain an understanding for the current and future outlook of the climate in the southeast region of the U.S., and more specifically, the expected frequency and intensity of various climate-induced natural hazards the region is exposed to. This allowed for vital information to be gathered that was used to subsequently assess the vulnerability of particular locations to hazards in later tasks, as well as to identify the type of sub-hazards that must be further assessed in regards to their potential impacts to residential building enclosures.

4.1.1 Climate Assessment Analyses

The 2014 National Climate Assessment (NCA) and the NCA southeast regional technical input report were reviewed in order to extract data providing information about the current and projected climate outlook for the southeast region of the U.S. The implications of climate change are also provided in each assessment.

A team of over 300 experts and stakeholders from private and public organizations worked together to assemble the NCA to provide an assessment of the U.S. climates. The assessment has been rigorously reviewed by expert panels and federal agencies of the U.S. Global Change Research Program, and the Federal Committee on Environment, Natural Resources, and Sustainability (Melillo et al. 2014). The NCA report includes inputs from peer-reviewed research and several regional and coastal technical input reports. However, the primary source of data here was the southeast U.S. regional technical input report created for the NCA, which was individually reviewed for this research in addition to the NCA report. The regional report was reviewed individually and in addition to the NCA report because it provides a much more extensive and rigorous assessment, which goes far beyond that of what was included in the NCA. The southeast regional technical input report was developed by a diverse group of experts and over 100 contributors, which included individuals in academia, government and non-governmental agencies, and private industry (Ingram et al. 2013). The regional report covers the U.S. states of Virginia, Kentucky, North Carolina, South Carolina, Tennessee, Arkansas, Louisiana, Mississippi, Alabama, Georgia, and Florida, and also includes Puerto Rico and the U.S. Virginia Islands in the analysis.

The climate assessment reports utilized both, global climate model (GCM) and downscaled regional climate model (RCM) datasets, to produce future climate projections. Data detailed by each assessment includes past, present, and projected climate trends for the hazard categories of precipitation, sea level and sea surface temperatures, heat, cold, severe thunderstorms, tornadoes, winter storms, tropical cyclones and hurricanes, and wildfires.

4.1.2 Current and Future Climate Induced Natural Hazards for the Southeast Region

According to the International Energy Conservation Code (IECC), the southeast region of the U.S. is predominantly categorized as a moist climate, and can be specifically divided into two types of climate zones, mixed-humid toward the top of half of the region, and hot-humid at the bottom half (ICC 2012). The region is also exposed to a range of various types of storms, extreme temperatures, wildfires, and drought. As depicted in Figure 15, the type of storms the region is exposed to includes winter storms, severe thunderstorms, and tropical cyclones and hurricanes. Hurricanes and its associated sub-hazards are highlighted in the figure as the subsequent focus of this research, excluding tornadoes (highlighted in red) from the analysis as rare events. Arrows denote the additional sub-hazards each hazard is associated with or contributes to.

The following information presented in Table 4, provides an overview of the current and expected trends of climate induced natural hazards for the southeast region extracted from the climate assessments. This includes a description of the hazard trends, severity, and frequency of occurrence according to the conducted climate assessments. A focus on hurricanes will be presented later in finer detail, where the various sub-hazards (i.e. aspects of hurricanes such as wind and storm surge) are discussed in regard to how they could impact residential structures in the southeast region.

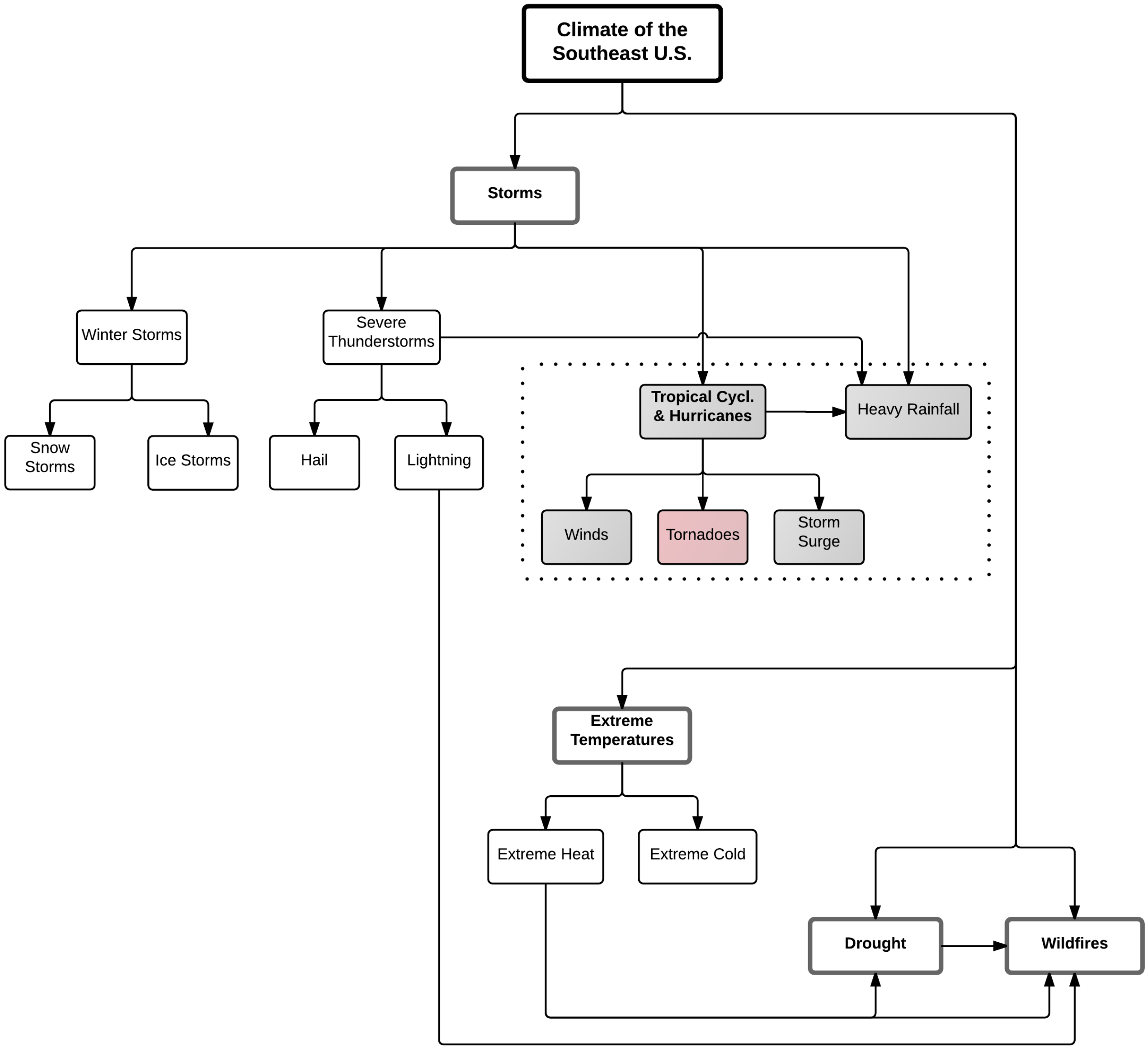


Figure 15 Climate of the Southeast Region of the U.S.

Table 4 Current and future climate trends for the southeast region of the U.S.

Hazard Potential Future Trends Key: ↓ = *Decrease* ↑ = *Increase* → = *Uncertain*

Hazard	Current Trends		Future Trends
Storms and Precipitation			
Winter Storms	Primary hazard type for the northern states in the region. Storms exceeding 6" of snow occur 1-3 times per year, more so across the southern Appalachians. 3-4 days of freezing rain per year occurs, most commonly in west-central Virginia and North Carolina, and least commonly in the Gulf Coast.	↓	The average snowfall totals and the occurrence of winter storms have been declining since the start of the 20th century. There is a trend towards warmer winters.
Severe Thunder-storms	Occur more frequently in the warmer months of the year, with higher occurrences in Alabama, Mississippi, Arkansas, western Tennessee, and Northern Louisiana. 1" hail occurs in late winter and spring. Lightning is most frequent in the southeast region, specifically in the Gulf Coast and the Florida Peninsula.	↑	Has been increasing over the last 50 years. The convective available potential energy (CAPE) needed for severe thunderstorms is projected to increase throughout the 21st century.
Hurricanes	**The region is very vulnerable to hurricanes. Hurricanes are the primary hazard type for the coastal states. The greatest impact occurs along the coast of the region and several hundred miles inland. Landfall is most frequently along southern Florida and Louisiana, and North Carolina. Hurricane activity has been high over the last two decades, with an increase in severity over the Atlantic basin.**	↑	**An overall increase in the frequency of major hurricanes (category 3-5) is projected, with the greatest increase expected over the western Atlantic basin, and a decrease in the Caribbean and Gulf of Mexico sub-basins.**
Heavy Rainfall	Heavy rainfall and flooding has increased across the region, with imminent threat of increased flooding occurring during heavy rainfall periods in low-lying coastal areas.	→	Overall projections are uncertain, however, in all seasons except for the summer, there is an expected increase in heavy rainfall for most states in the region, but with less change across the southern portion. A significant further increase in the annual number of days with extreme rainfall is expected.
Extreme Temperatures			
Extreme Heat	High temperatures have increased across the region, with significant local variability. Extreme heat is more frequent and pronounced during the summer especially along the coast. The region is very vulnerable to extreme heat and its impacts to water resources.	↑	Overall increase in intensity, duration and frequency is expected across the region, with significantly more cooling degree-days and consecutive hot days projected. Interior states of the region will experience higher temperatures than the coastal states.
Extreme Cold	The region is prone to extremely cold temperatures during the winter. However, cold temperatures have declined during the winter season.	↓	The demand for heating will decrease as the number of extremely cold days is expected to continue to decline.
Droughts			
Drought	Most frequent hazard for the Caribbean, but with shorter durations occurring compared to the west and central U.S. states.	→	Overall uncertainty due to precipitation projection uncertainty. However, hydrological drought is projected to increase across the majority of the country.
Wildfires			
Wildfire	The southeast has the highest occurrence of wildfire events, which has been increasing.	↑	Increase in wildfire events is expected as extreme high temperatures continue to rise and drying occurs.

In regards to the future of the southeast region's climate, the biggest threats are hurricanes, extreme heat, severe thunderstorms, and wildfires with expected increases in frequency of occurrence and severity of events posing considerable challenges. Winter storms and extreme cold temperatures are expected to decline as higher temperatures and longer spells of warmer weather are anticipated throughout the region, which can be viewed as reduction in the overall risk associated with these natural hazards. Extreme precipitation and droughts are more uncertain in the future projections for the region, but can still be considered as a potentially growing concerns.

The hazards expected to increase in frequency and intensity for the region should be considered as higher priorities in regards to adaption and preparation concerns for the likely impacts that they will have on the built environment. Further analysis of potential impacts each hazard can have on buildings is important towards identifying vulnerabilities. Such vulnerabilities could increase the risk of the hazards becoming disaster scenarios due to their potential influence, which could lead to damaged physical systems and have adverse consequences on the health and safety of individuals. Realizing what types of technologies and strategies are available and needed to address various hazard impacts can contribute to risk mitigation and disaster resilience.

4.1.3 Hurricane Hazards and Enclosure Systems

The southeast region of the U.S. faces increased risk of major hurricanes, which is a natural hazard the area is familiar with, but at the same time, it nonetheless consistently creates severe devastation in the region. The sub-hazards of hurricanes include severe winds, storm surge, and precipitation, which in turn can lead to additional hazardous conditions such as flooding, wind- and water-borne debris, and erosion.

The building enclosure is very vulnerable to these forces as it is the primary barrier between the exterior environment and interior spaces of a home. The multi-hazard nature of hurricanes (i.e. the combination of wind, precipitation, and surge) creates a challenging task for an enclosure system to efficiently mitigate all the associated threats simultaneously. Precipitation in the form of rainfall can cause water damage to enclosure components as rain is driven into openings and cavity spaces by wind pressure, which can be further exaggerated as a result of poor air sealing and/or deficient moisture management details. Floodwater resulting from storm surge and/or heavy rainfall can become an issue especially for homes located in close proximity to large bodies of water. Rising levels of water that surround a structure can quickly inundate homes. The hydrostatic and hydrodynamic pressure exerted by standing and moving water across an enclosure can lead to detached non-structural materials, as well as severe structural damage, or even completely move a building off its foundation. Debris thrown by wind and water can further impact enclosures, and with enough speed and momentum, even penetrate through the entire system, which in turn can lead to a dangerous build-up of internal pressure and large pathways for water intrusion.

In order to contribute to the risk mitigation of hurricane damages to residential structures and increase their resilience to the multi-hazard conditions the hazard presents, technologies should specifically address all aspects of the threats a hazard poses. This includes encompassing the following qualities:

- Components with sufficient resistance to withstand high velocity debris impacts
- Superstructure connections and material attachments with adequate strength to resist severe wind and water pressures, as well as debris impact forces
- Enhanced water resistant and/or moisture control qualities enough to prevent or reduce the effects of water exposure and/or intrusion
- Air sealing quality that can reduce the likelihood of dangerous levels of air and water infiltration

While these qualities specifically address hurricane hazard impacts that should be considered and aid technology selection, resilience and high-performance building technologies in general will include additional attributes that are not currently discussed in this analysis. The qualities that have been investigated here will integrate into the high-performance building and resilient technologies as identified in the upcoming sections. The attributes of high-performance building and resilience technologies are then later defined so that metrics can be used to quantify their applicability and performance.

4.2 HPRB Enclosure Technologies for Hurricane Hazard Resilience

Technologies that can be found in a set of common high-performance building standards were identified and selected as HPRB technologies. Their selection coincided with the essential qualities the technologies should encompass in order to provide resilience from hurricane hazards. These qualities were discussed in the previous section. The qualities and functions of each of the HPRB technologies have been defined to illustrate why they are appropriate, and have additionally been categorized according to the high-performance qualities they exhibit and their resilience characteristics for particular hazard aspects associated with hurricanes.

4.2.1 High-Performance Building Standards Analysis

A set of high-performance building standards and certifications were reviewed to identify a pool of HPRB enclosure technologies specific to hurricane hazards. The building standards and certifications mentioned below were included because of their applicability to residential construction, extensive prior use in the built environment, and specific building goals that includes commitment to construction beyond typical minimum building code compliance levels in order to enhance building performance specifically in regards to energy consumption, durability, and occupant comfort. The following five standards and certifications were selected for inclusion in this process:

- Passivhaus (Passive House) Institute Standard
- Leadership in Energy and Environmental Design (LEED) for Homes, Version 4
- EarthCraft House, Version 2015.4.28
- ENERGY STAR Certified Homes, Version 3
- 2012 National Green Building Standard (NGBS) Single-Family Green Home Certification

It should be noted that for some of the certifications included herein, there are at times overlapping objectives between high-performance, green building (i.e. environmentally friendly) and sustainability (i.e. zero impact). However, all these technologies will be referred to as high-performance technologies for consistency. A description of each standard or certification is provided in the following section, which presents an overview of each standard's respective construction goals and certification processes.

Passive House Institute Standard:

The Passive House standard is perhaps one of the most aggressive building standards in existence today in regards to energy efficiency objectives. Commonly referred to as Passivhaus in German, the country in which the first passive house was constructed, the Passive House standard was developed in Europe and became an officially certifiable building standard with the Passive House Institute (PHI) lead by its founder Dr. Wolfgang Feist. Thousands of passive houses have since been successfully constructed and occupied around the world, with the predominant population of passive houses existing in Europe. The concept of passive house is governed by five principles and four prescriptive requirements that are primarily the result of enhancing the building enclosure system (PHI 2015). The five principles of constructing a passive house include 1) superior thermal insulation, 2) high-performance windows (e.g. low u-value and low-e), 3) airtightness, 4) thermal-bridge free, and 5) heat recovery ventilation. While the strategies and technologies used to construct a passive house may differ and are appropriately adapted for specific climates, the prescriptive criteria to achieve the standard are always the same. However, recently in response to issues with cost and occupant comfort when applying the original German standard in the diverse climate zones of the U.S., the prescriptive criteria has been reevaluated specifically for U.S. climates in the newly formed Passive House Institute U.S. standard (PHIUS+), which has become a completely separate standard from the PHI (Wright and Klingenberg 2015).

The original German standard's prescriptive criteria requires that 1) the space heating and cooling energy demand does not exceed 15 kWh per square meter of net living area, 2) the primary energy demand does not exceed 120 kWh per square meter, 3) a maximum of 0.6 air changes per hour is achieved in regards to airtightness, and 4) thermal comfort is achieved in all areas of the building throughout the year. Specific differences between PHIUS+ and PHI include an airtightness limit that is now based upon building size; energy limits altered based upon the global carbon emission budget; and adjusted space-conditioning criteria that is now set on the basis of economic feasibility (Wright and Klingenberg 2015). By achieving the Passive House requirements, the expected results include an ultra-energy efficient building when compared to standard code compliant construction, with the additional resulting benefit of supreme occupant comfort experienced year round.

LEED for Homes:

LEED is one of the most well-known and implemented building standards in the U.S. for a variety of construction types. Developed by the U.S. Green Building Council (USGBC), LEED is a points-based certification system in which various levels of certification (e.g. certified, silver, gold, and platinum) can be achieved according to the amount of points attained in several categories. These categories include an integrative process, location and transportation, sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation, and regional priority. The mission of LEED is focused on promoting environmental stewardship through the use of materials and construction that contribute to this goal, while it is also concerned with the health and well-being of building occupants, as well as improving building performance through energy efficiency and durability enhancements (USGBC 2013). The standard includes both mandatory and optional points to achieve the standard related to improving various aspects of the construction process and/or the building itself. As a result of this, the performance of LEED buildings can be highly variable based on the preferences and priorities of building owners and designers. LEED for Homes is focused specifically on residential single-family and multi-family building construction.

EarthCraft House:

Developed specifically for the southeast region of the U.S., the EarthCraft certification was created by the Greater Atlanta Home Builders Association and Southface Energy Institute with the goal of protecting the natural environment and its resources, and improving indoor air quality, as well as the energy and water efficiency of buildings (EarthCraft 2015). Since its establishment as a building standard in 1999, over 30,000 building units have achieved certification in the southeast, which relates to an estimated 30% reduction in energy consumption compared to standard code compliant construction (EarthCraft 2015). Similar to LEED, EarthCraft is also a points-based certification standard, with mandatory and optional points available in the categories of site planning, construction waste management, resource efficiency, durability and moisture management, indoor air quality, high performance building envelope, energy efficient systems, water efficiency, education and operations, and innovation. The EarthCraft standard can be applied to various types of new or existing construction. EarthCraft House in particular is focused on single-family detached homes, townhouses, and duplexes.

ENERGY STAR Certified Homes:

ENERGY STAR is a label created by the U.S. Environmental Protection Agency (EPA) that promotes energy efficiency and environmental protection in the built environment. ENERGY STAR Certified Homes is a building certification standard that carries this label and abides by these principles through improvements made to the building enclosure system, occupant comfort, durability, and indoor air quality of a home (ENERGY STAR 2015). The certification offers either a prescriptive path or performance path to achieve the label, which can reduce total energy consumption by up to 30% in comparison to standard code compliant homes. Beyond being a stand-alone construction standard, other high-performance building standards such as LEED for Homes, EarthCraft House, and the Department of Energy (DOE) Zero Energy Ready Home standard include ENERGY STAR as a mandatory perquisite for certain credit categories.

National Green Building Standard:

The National Home Building Association's (NAHB) National Green Building Standard (NGBS) is another certification for creating high-performance homes. There are currently over 62,500 NGBS certified homes in the U.S. that have achieved high-performance through the improvement of the core categories included as part of the standard. These categories include site development, resource efficiency, water efficiency, energy efficiency, indoor environmental quality, and operation, maintenance, and owner education (NAHB 2015). The NGBS standard is a points-based similar to LEED and EarthCraft, and the single-family green home NGBS certification option is applicable for single-family homes, townhouses, and duplex homes.

Zero Energy Standards:

The DOE Zero Energy Ready Home (ZERH) standard and the Living Building Challenge (LBC) Net Zero Energy Building (NZEB) certification were originally included, however, it was found that they did not provide enough information and variability from the other standards that were included. For example, the ZERH standard is based heavily upon achieving the ENERGY STAR certification and complying or exceeding IECC code requirements specific to the climate in which the building is located. For this reason, the ZERH standard was excluded as to not duplicate efforts. The LBC NZEB standard was also excluded, as it was completely performance based with only one core requirement to fulfill, which is to produce 100% of the required annual energy demand on site with renewable sources. Due to this, the certification does not specify specific technologies or strategies to achieve the certification.

4.2.2 HPRB Enclosure Technology Identification and Categorization

Technology Identification

A list of several HPRB technologies was assembled from the analyzed high-performance building standards, which can be found in Table 5. These technologies were limited to the building enclosure, which includes the roof, exterior walls, fenestration (windows and exterior doors), and foundations. They were additionally limited by their applicability to mitigate the potential of hurricane hazards damaging a home resulting from the exposure to severe levels of precipitation, storm surge, and wind. As previously stated, the exact criteria used to screen each enclosure technology, in addition to already being categorized as a high-performance building technology, included encompassing one or more of the following hurricane resilience qualities:

- Components with sufficient resistance to withstand high velocity debris impacts
- Superstructure connections and material attachments with adequate strength to resist severe wind and water pressures, as well as debris impact forces
- Enhanced water resistant and/or moisture control qualities; enough to prevent or reduce the effects of water exposure and/or intrusion
- Air sealing quality that can reduce the likelihood of dangerous levels of air and water infiltration

Each HPRB technology included in the current shortlist has been aligned with the high-performance building standards that stipulate implementation of the technology either on a mandatory basis (i.e. required in order to achieve the standard), or on an optional basis (i.e. a recommended or specifically mentioned as a suggestion towards earning credits) in order to evaluate how each standard fares in regards to offering resilience options as they currently stand. The findings are presented in Table 5.

Table 5 HPRB technologies extracted from residential high-performance building standards

◆ = Mandatory ◆ = Optional

HPRB Enclosure Technologies for Hurricane Hazards	High-Performance Building Standard				
	Passive House	LEED for Homes	ENERGY STAR	EarthCraft House	NGBS Single-Family
Advanced Framing Techniques[a]		Optional	Optional	Mandatory	Optional
Continuous Insulation	Mandatory	Optional	Optional	Optional	
Insulated Concrete Forms (ICF)		Optional	Optional	Optional	
Autoclaved Aerated Concrete (AAC)		Optional		Optional	
Green Roof		Optional		Optional	Optional
Roof Water Management		Mandatory	Mandatory	Mandatory	Optional/Mandatory
Integrated Drainage Plane		Mandatory	Mandatory	Mandatory	Mandatory
Redundant (i.e. Double) Weather Resistant Barrier (WRB)				Mandatory	
Vented/Ventilated Drainage Plane				Optional	Optional
Foundation Moisture Protection		Mandatory	Mandatory	Mandatory	Mandatory
Continuous Airtight Layer	Mandatory	Optional	Mandatory	Mandatory	Mandatory
High-Performance Windows/Doors[b]	Mandatory	Optional	Mandatory	Mandatory	Mandatory
Building Commissioning	Mandatory	Mandatory	Mandatory	Mandatory	Mandatory
Mandatory Technologies	**4**	**4**	**6**	**8**	**6**
Optional Technologies	**0**	**7**	**3**	**5**	**4**

[a] Must make specific considerations for hurricanes and implement techniques in accordance with local code requirements for hurricane hazards
[b] Refers to high-performance windows and doors, which should also be high impact and pressure rated

Technology Categorization

The hurricane hazard aspects of rain, flood, debris, and wind have been used to categorize each of the HPRB technologies. This categorization, which is presented in Table 6, represents a broad description of hazards to which their resilience qualities apply. These hazards will be made more specific in the later following impact analyses. The technologies have additionally been explicitly defined in terms of their high-performance building characteristics, and the hazard resilience qualities they offer. This is an important step towards appropriately assembling and subsequently assigning and ranking HPRB technologies for various hurricane risks experienced by residential buildings. A demonstration of how to quantify the high-performance and resilience qualities that these technologies exude will be discussed and performed in later objectives.

It is important to note here that while the technologies identified and included in the current shortlist are categorized as HPRB enclosure technologies for hurricane hazards, further physical testing of each technology is recommended in order to verify their potential benefits as viable resilience technologies. However, background literature with testing and case study support have been provided where possible for each technology to strengthen the basis for why each technology has been selected.

Table 6 HPRB enclosure technologies categorized by hurricane hazard applicability

	Rain	**Flood**	**Debris**	**Wind**
Advanced Framing Techniques		◆	◆	◆
Continuous Insulation	◆	◆	◆	◆
Insulated Concrete Forms (ICF)	◆	◆	◆	◆
Autoclaved Aerated Concrete (AAC)	◆	◆		
Green Roof	◆	◆		
Roof Water Management	◆			
Integrated Drainage Plane	◆	◆		
Redundant (Double) WRB	◆	◆		
Vented/Ventilated Drainage Plane	◆	◆		◆
Foundation Moisture Protection	◆	◆		
Continuous Airtight Layer	◆	◆		
High-Performance Windows/Doors		◆	◆	◆
Building Commissioning	◆	◆	◆	◆

Technology Qualities

Advanced Framing Techniques:

High-Performance – Advanced framing is also typically referred to as either energy efficient framing or optimum value engineering (OVE) framing because of the improvement to a buildings life-cycle costs and energy performance that it can offer. It involves the reduction of non-essential framing members, which in turn reduces the resources expended for construction and minimizes the framing factor (i.e. space occupied by framing), and as a result, provides more cavity space for insulation. This strategy allows for an increase in the thermal performance of exterior walls, and reduces the energy consumed on space conditioning when compared to conventional framing practices (APA 2014). Common techniques used in advanced framing, particularly in exterior walls and roofs, includes aligning all load paths to make structural connections continuous and stronger; increasing the stud size from 2x4 spaced 16 inches on center to 2x6 spaced 24 inches on center; switching from double headers to single headers in load bearing walls and removing headers entirely from non-load bearing walls; minimizing the use of jack studs and cripples; and using continuous OSB or plywood sheathing, which can also be fixed with exterior rigid insulation to become insulating or insulated sheathing (APA 2014; Lstiburek).

Resilience – Flood, debris, and wind resilience are all qualities advanced framing techniques can provide for a home seeking to reduce the likelihood of damage and other adverse impacts and consequences of a hurricane. Floodwater and winds can exert a large amount of lateral force and negative and positive pressures from water and wind against an enclosure that can compromise the structural integrity of a building. Additionally, wind- and/or water-borne debris can impact the enclosure with great force due to high-velocities associated with hurricane wind and surge water. With this in mind, and while also taking engineering and design precautions when deciding on and implementing advanced framing techniques, resilience to these effects can be addressed with specific advanced framing techniques. This can include increasing the strength of the buildings structure by proving continuous load paths for enhanced resistance to high wind and water velocities; using stronger strapping, fasteners, and anchor ties at framing connections; and installing a thicker or stronger material used for continuous sheathing in order to increase reinforcement and shear load resistance (FLASH 2014). Insulating/insulated sheathing can also provide enhanced impact resistance of flying debris. The addition of exterior rigid insulation to OSB sheathing in an advanced framed wall system (complete with high density closed cell spray foam cavity insulation) has proven to be able to provide increased resistant to wind-borne debris impact, and prevent penetration at a higher design velocity when compared to conventional wall assemblies that exclude exterior insulation and higher performing cavity insulation and air sealing (Lstiburek and Baker 2006).

Continuous Insulation:

High-Performance – The objective behind continuous insulation is to create an uninterrupted layer of insulation (excluding service openings and fasteners) within an exterior enclosure. This insulation configuration drastically reduces thermal bridging, reduces air leakage, and thus increases the overall thermal performance of the enclosure system in doing so. This insulation layer can be used in a variety of different enclosure types and is either placed on the interior side or more commonly on the exterior side of an enclosure. Continuous insulation also improves the durability of an enclosure in regards to managing moisture. When placed on the exterior side, the dew point is moved outside of the wall cavity, which reduces the risk of moisture damage during cold weather (Straube 2011). This technology is a key strategy for the Passive House standard as a means of creating a thermal bridge free design, and is also a defining characteristic of some structurally insulated panel systems and exterior insulation and finish systems (EIFS).

Resilience – With the appropriate material properties, component configuration, and/or placement within an enclosure system, continuous insulation can offer resilience from rain, flood, debris, and wind associated with hurricanes. One particular example of this is a high-strength drainable EIFS. This type of system is protected from moisture intrusion by a drainage plane which includes a strong water-resistant basecoat; has an exterior surface reinforced by high tensile strength fiberglass reinforcing mesh to prevent cracking and resist strong wind and water pressures; and can additionally withstand the impacts of high velocity debris as demonstrated in large missile impact tests (Martens 2012).

Insulated Concrete Forms (ICF):

High-Performance – An ICF consists of cast-in-place concrete walls using permanent layers of rigid insulation attached to the interior and exterior sides. The interior portion of an ICF, which consists of the concrete, includes steel reinforcement bars that increase the structural performance of the system (NAHB 2001). ICFs also have enhanced durability, thermal and sound performance, and energy efficiency when compared to traditional stick-built frame construction, which is a result of the increased insulation and air tightness provided by the permanently fixed continuous layers, and also due to the fire, wind, insect, and water resistant qualities of the concrete mass (NAHB 2001).

Resilience – ICFs offer many benefits in regards to natural disaster resilience due to its superior strength and durability over traditional wood frame residential construction, and has proven to survive severe extreme weather events such as tornado and hurricane events that have occurred within the U.S. (ICFA 2008; NAHB 2001). It qualifies as an HPRB technology in response to the hurricane hazards of rain, wind, flood, and debris. ICF construction provide significantly more racking strength (i.e. resistance to lateral wind loads) with 5-10 times more capacity than wood frame construction (NAHB 2001). The continuous load paths between the foundation, walls, and roof provided by the embedded concrete reinforcement bars and connection straps strengthen the superstructure and help a building to further resist strong winds and uplift forces (ICFA 2008). The bending strength of ICFs is between 200-400 psf, which is equivalent to withstanding winds between 280-395 mph, much higher than the wood frame construction 50-100 psf bending strength (140-200 mph wind) (NAHB 2001). While wood frame construction can provide enough resistance to withstand high wind loads associated with hurricanes, the extra strength provided by ICFs provides an adaptive quality that standard wood frame construction cannot, where it allows for the resistance of potentially higher loads that can be faced in future, stronger hurricane events. ICFs also have a much higher compressive strength that prevents a building from collapsing, and can additionally withstand impacts from debris (without penetrating the concrete core) that are heavier and move at velocities in excess of 100 mph (TTU 2006), where wood frame walls impact resistance is significantly less, with thresholds between 8-26 mph for debris with a lighter weight (NAHB 2001). Finally, concrete offers significantly higher fire ratings than wood frame construction, as well as moisture and flood resistance, which can prevent the severity and risk of damage and adverse impacts to the health and safety of building occupants.

Autoclaved Aerated Concrete (AAC):

High-Performance – As another form of precast concrete construction, AAC offers high-performance benefits similar to that of ICF construction. AAC does not however consist of permanent layers of insulation, but instead combines insulation and structural properties into a single component, and is free of the thermal bridging that would be present with the use of stud framing. Some of the main performance advantages of AAC include its extremely high fire rating as well as its excellent moisture durability as a result of its high resistance to water and the associated risks of mold and other types of moisture damage (PCA ; Schnitzler 2006). AAC also has enhanced air tightness in comparison to conventional wood frame construction, and excellent noise control. Qualities of AAC that contribute to energy efficiency include reduced air leakage, which also enhances occupant comfort as a result of reduced noise infiltration (PCA ; Schnitzler 2006). Life-cycle costs in regards to material use, are also reduced when implementing AAC, as it requires a significant amount of air (approximately 80%) to manufacture the technology, which in turn dramatically reduces the needed quantities of other raw materials (PCA ; Schnitzler 2006).

Resilience – AACs resilience applies specifically to water hazards associated with hurricanes, more particularly, rain and flooding. Due to its excellent durability in regards to water resistance, the resilience it can offer in terms of exposure to water surpasses that of traditional wood frame construction. Therefore, the longevity of AAC is higher and maintenance/repair costs associated with the technology are lower (Rutgers 2011).

Green Roofs:

High-Performance – Vegetation planted and grown on top of an otherwise bare roof membrane surface, commonly known as green roofs, can have several benefits that help to increase a buildings' thermal and energy performance (Jaffal et al. 2012; Liu and Baskaran 2003), acoustic performance (Van Renterghem and Botteldooren 2011), and water management capabilities (Morgan et al. 2013). Green roofs provide direct shade, evaporative cooling, and insulation to a roof membrane, all of which can significantly reduce daily roof temperature fluctuations and heat flow through the roof in comparison to that of an exposed membrane, which is especially beneficial in the warmer months experienced during the year. As a result of these qualities, average daily energy consumption expended on space cooling can be reduced by more than 75% during the summer (Liu and Baskaran 2003).

Resilience – Green roofs offer rain and flood resilience primarily due to their ability to retain water more effectively than traditionally bare roof membrane surfaces used in residential construction. Because of a green roofs plant growth medium, which has the ability to retain water, green roofs can also significantly reduce the amount of storm-water runoff that flows off of a building and into nearby stormwater systems (Morgan et al. 2013). This can reduce the likelihood of local stormwater system overflow and probable resulting flooding that could surround, rush past, and/or inundate a nearby building. It can additional reduce the likelihood of water exposure and infiltration into enclosure components, which can occur as a result of roof water runoff if not properly controlled. The effectiveness of reducing storm-water runoff is however influenced by the type and depth of the growth medium used, the use of a drainage layer, the amount of plant coverage, and the general quality of the system design (Morgan et al. 2013).

Roof Water Management:

High-Performance – While managing the flow and drainage of rainwater to prevent water from penetrating through the roof system is a required function of a typical residential house design, the minimum stipulations written in the IRC can at times leave room for errors and deficiencies. The 2012 IRC calls for mandatory flashing to be installed on the roof "in a manner" that prevents moisture intrusion at wall to roof joints and intersections, eave and vertical sidewall intersections, around roof plane openings and penetrations, changes in roof slope or direction, and moisture permeable materials (ICC 2012). Although flashing is mandatory as a minimum for code compliant buildings, implementation details described in the code itself are not always sufficient enough to ensure proper protection (Home Innovation Research Labs 2014), as is evident with the language used (e.g. install "in a manner"). However, high-performance building requirements can be more specific in regards to managing water on the roof, which provides additional durability with its required construction details. In order to prevent or minimize water entry past the roof, high-performance roof water management requires that all roof valleys direct and discharge the flow of water away from all vertical surfaces of any kind; that step and kick-out flashing be installed at all roof to wall intersections and be integrated with the roof drainage plane; and a self-sealing bituminous membrane (or equivalent) is used underneath the roof underlayment to completely seal the roof deck, which should also be integrated with the roof drainage plane. Integrating flashing with the drainage plane as well as sealing the roof deck are two key details that can add a great deal of value to a roof system by ensuring protection is continuous so that the roof is sufficiently shielded from water intrusion that manages to bypass the flashing and underlayment and reach the roof deck. Flashing that is not integrated with the drainage plane often times does not offer complete moisture protection in an enclosure system (Dorin 2006).

Resilience – Rain, and more specifically wind-driven rain, are the hazards high-performance roof water management can provide increased resilience for. During a hurricane, wind can exacerbate the potential for rainwater intrusion with the added pressure behind it. In a test that demonstrated the benefits of properly sealing a roof deck, it was found how this strategy could significantly reduce the amount of wind-driven rain entering through the roof during a hurricane modeled from a real-world event (IBHS 2011). The test compared the difference between an unsealed and sealed roof deck during a hurricane, and the results showed that the sealed roof deck experienced one-third of the amount of water intrusion than that of the unsealed roof deck. The financial losses as a result of the water damage experienced by test home with the unsealed roof deck was estimated to be triple the amount of the cost compared to the test home with the sealed roof deck, with this home also not requiring any furniture to be replaced, which could displace the occupants for an extended period of time.

Integrated Drainage Plane:

High-Performance – A drainage plane is used within a building enclosure to control and drain rainwater out of the assembly to the exterior. It prevents wetting of materials and prolonged exposure to moisture that could cause water damage. The drainage plane typically consists of a weather resistant barrier (WRB) installed behind cladding. An integrated drainage plane ensures that the WRB is continuous throughout the enclosure at all points, which includes between wall intersections with the roof, windows, doors, and foundation, all flashings, and any other openings or penetrations (DOE 2013). Testing has proven that this continuous system for drainage and moisture protection throughout the enclosure is critical to the successful performance of enclosures (Dorin 2006) as it provides enhanced durability and reduced risk of enclosure water damage, especially at vulnerable intersections between building components prone to water intrusion, such as window to wall connections.

Resilience – higher flood and rain resilience are provided with an integrated drainage plane with its ability to provide a continuous water control layer and protection from moisture penetration. It is a truly unifying technology between enclosure components while also increasing the robustness of the enclosure system as a whole by allowing it to better withstand the exposure to water than that of an enclosure system that lacks proper integration of flashings and a drainage plane.

Redundant WRB:

High-Performance – The weather-resistant barrier (WRB) inside an enclosure is used as a protective layer from moisture as well as to prevent air infiltration. As described as a component in the previously discussed technologies of roof water management and integrated drainage planes (as well as some other technologies to follow), it provides durability to an enclosure system and can also reduce air leakage if installed appropriately. While one layer of a WRB is commonplace in residential construction, two layers can increase its performance as a backup layer of protection and by increasing the capacity to control and withstand exposure to moisture. In stucco-clad walls specifically, investigations found that two layers of a

WRB, as opposed to one, provides better moisture control by significantly reducing the amount of water penetration to the sheathing layer (Karagiozis 2002). This outcome is however dependent on the local environment and vapor control strategy implemented in an enclosure.

Resilience – Two layers of a WRB offer resilience to water exposure and reduce the risk of water damage from hurricanes. It does so by increasing the robustness of the water control layer in an enclosure with its enhanced ability to withstand moisture. This technology can potentially speed up the typical drying time (i.e. recovery process) as a result of such a quality. Furthermore, in the event of hurricane winds stripping away the outermost WRB layer from an enclosure, a backup layer adds redundancy to the system where the remaining layer can deliver the same or at least partial function that a WRB is intended to provide.

Vented/Ventilated Drainage Plane:

High-Performance – The space between an exterior wall's finish cladding (e.g. brick veneer) and the air-sealed drainage plane (e.g. WRB) can consist of an air cavity to accommodate an effective space and passage way to drain water out to the exterior. This cavity space can also increase the durability of the wall due to the capillary break between the cladding and WRB that it provides, and depending on the local weather and materials used within the wall, the cavity space can accelerate the rate of drying inside the wall (Salonvarra et al. 2007). As an additional advantage, the cavity space between the cladding and WRB can be vented or ventilated to further increase the drying potential (Straube 2001), which has been found to be generally beneficial for all wall types (Salonvarra et al. 2007). Ventilating a cavity wall creates a pressure equalized wall system that can almost completely prevent wind-driven water infiltration into the cavity itself. This ability to pressure equalize an exterior wall system is commonly referred to as a pressure-moderated or pressure-equalized rainscreen (PER). A PER system can prevent wind-driven rainwater infiltration into a wall system by controlling the airflow through sufficient ventilation, and thus virtually eliminating the pressure difference across a wall that can drive rain inside it by keeping the pressure differential between the exterior and the air cavity at or near zero (Rousseau et al. 1998; Straube 2001).

Resilience – A vented/ventilated drainage plane or PER system is especially beneficial in providing resilience to wetting from water infiltration into an enclosure, as well as wind pressure acting against a wall that can additionally strain cladding material attachments and push rain inside wall openings and imperfections. PER systems can increase the robustness and recovery rate of an exterior wall system by improving moisture durability with enhanced drying capabilities following exposure to water, and by reducing the amount of water infiltration through a reduction in the pressure differential between the exterior and cavity. In addition to this, and depending on the type of layers in the wall construction, investigations have shown that a PER system can increase the design wind speed capacity of a wall over non-PER wall systems, which allows it withstand higher wind pressure without experiencing wall failures such as detached cladding or sheathing (Kopp and Gavanski 2012; Straube 2001).

Foundation Moisture Protection:

High-Performance – Many of the minimum requirements for foundation moisture protection, such as those described in typical residential building codes (e.g. the 2012 IRC), are similar to those required by high-performance building standards. These requirements are enforced to improve the durability of the system, maintain good indoor air quality, and to also make sure they are appropriate for the site location. Foundation moisture protection strategies include site drainage requirements to divert groundwater away from the foundation and to approved collection points; installing drains below-grade to direct water away from foundation walls and floors; and damp-proofing and water-proofing foundation walls and floors with porous layers of gravel and vapor barriers to provide capillary breaks and prevent harmful gases from infiltrating the living space. However, provisions can be made to go above and beyond these minimum requirements in high-performance buildings. For example, third-party verification of the design and installation of foundation moisture protection is required for high-performance buildings to ensure methods are appropriate and that construction is of high quality. Increasing the coverage and capacity of capillary breaks to withstand moisture, and implementing an increased number of strategic points for drainage are also ways to improve upon minimum standards of protection. In addition to this, avoiding materials that are prone to water damage and mold growth such as the use of wood below-grade, which is expressly prohibited by EarthCraft requirements.

Resilience – Increased resilience to all sources of moisture during a hurricane is provided with this technology. Ensuring homes are also up to date in abiding by local hazard regulations (e.g. National Flood Insurance Program, and Flood Insurance Rate Maps), and that there is sufficient protection of their foundation from moisture, is critical to prevent or reduce the severity of consequential damages associated with wet foundations.

Continuous Airtight Layer:

High-Performance – Rigorously sealing all openings, joints, and connection details throughout an enclosure can dramatically reduce the amount of air infiltration, which creates a continuous airtight layer between the interior of a home and the exterior. In doing so, the energy efficiency of a home is improved beyond typical code construction as a result of minimized air leaks and the subsequent reduced use/need for larger mechanical heating and cooling equipment, which in turn reduces operational costs. The airtight layer also decreases noise transmission that comes from the exterior, as well as moisture intrusion and air pollution originating from the exterior and unconditioned spaces adjoining to the living areas. Incorporating a continuous airtight layer into the design and construction of a home is one of the key requirements for the Passive House standard with its significant contributions to the comfort and energy reduction requirements. This technology has also been incorporated in other low-energy buildings where they exemplify the discussed high-performance benefits they can offer as an example (Carey 2013). It is also important to note that ensuring a home is properly ventilated, and controlled for water vapor and humidity in order to maintain good indoor air quality and durability, is essential with airtight construction.

Resilience – A properly designed and constructed continuous air barrier surrounding an enclosure can block the pathway of water intrusion from rain and flooding, which offers increased resilience to the potential damaging impacts of such exposures. This reduced risk of water intrusion into otherwise unsealed gaps in the enclosure keeps it dryer and reduces the chance of interior material layers being damaged by water. However, as infiltration of some water inside of an enclosure system is inevitable (even with steps taken to reduce the potential volume), pathways for bulk water and vapor to dissipate via drainage, evaporation, or storage, is always a critical detail that must be incorporated in airtight construction.

High-Performance Windows/Doors:

High-Performance – Openings throughout an enclosure that accommodate space for windows and doors can be problematic building components if they are not appropriately selected, designed for, and installed correctly. Windows are especially a higher concern due to the large surface area they can consume on the exterior of the home. Windows and doors have significantly higher U-values (i.e. poor insulating value) than the surrounding exterior walls, and they can provide easy pathways for air infiltration and moisture migration and accumulation at joints and surfaces. High-performance windows and doors provide solutions to these issues to ensure higher energy efficiency, durability, air tightness, and comfort can be maintained. They offer lower U-values with options such as triple- or even quadruple-pane windows over the standard double-pane options used in residential buildings. These types of windows can also come with low-emissivity (low-E) coatings and gas films to further reduce the U-values and increase the insulating performance. By also ensuring that the surrounding frame is sealed, integrated into the drainage plane, and the framing materials provide a thermal break, this will further increase the thermal performance of the component and enclosure as a whole. Reducing cold sensations experienced by large areas of windows and/or doors can be achieved by using high-performing windows/doors to enhance the indoor thermal comfort. Using high-performance windows/doors also reduces the risk of condensation accumulating on otherwise colder surfaces and frames, which tends to be a problem area in many homes if not addressed. The Passive House specifically requires high-performance windows with low U-values because of their contribution to the required vigorous energy efficiency and comfort goals. Dynamic windows with smart or switchable glass have been developed and are an available high-performance window option in which the glass changes transparency to adapt to the climate and reduce energy used on lighting, heating and cooling (Baetens et al. 2010). High impact windows with debris impact and high-pressure ratings can also be specified as qualities incorporated in a high-performance window or door. Both dynamic and high impact windows have been reported to be available for residential applications through various manufactures (Diez).

Resilience – High-performance windows/doors that also provide resistance to hurricane strength wind pressure, large levels of water pressure, and wind- and water-borne debris impacts, increases the ability for these vulnerable openings to withstand the impacts of such hazards. Incorporating this quality in the windows/doors used in an enclosure can reduce the likelihood of one or more of those components failing. Such a failure could lead to other catastrophic damages such as water damage, dangerous internal air pressure build-up, and structural failure to surrounding enclosure components that could displace residents. The Florida Building Code (FBC) already recognizes the vulnerability of windows to hurricanes and requires specific performance requirements for test approved impact resistant glass windows and doors for residential homes in high wind velocity areas (Building a Safer Florida and University of Florida 2006).

Building Commissioning:

High-Performance – A new or existing building can go through a commissioning process, which is a series of inspections and tests performed on various components and systems to ensure quality of installation and operation (Mills 2009). This process can take place during the design, construction and/or occupancy phase of a building. Commissioning activities can include construction plan reviews; ongoing construction meetings and walkthroughs at various stages of the building process; verifying installation at various construction phases; performing tests to ensure equipment functions as intended; and training and educating the occupants of the building in regards to operation and maintenance required for various systems. Making future plans for retro-commissioning (i.e. commissioning post-occupancy and at a later date during the buildings life time) is another task that can be included in the commissioning process with the goal of remedying any problems that may surface and improving the buildings performance (Mills 2009). Commissioning is often required as part of attaining a high-performance building standard to ensure that all requirements are meet. However, the main benefit of implementing a commissioning plan and undergoing the process, whether or not a high-performance building standard is the goal, is the assurance of durable, safe, and energy efficient buildings, depending on the technologies implemented. It can additionally provide builders and occupants with a sound understanding of the technologies installed and how to operate them effectively to avoid sub-optimal performance and/or costly, or even dangerous, errors in the future.

Resilience – Building commissioning can increase resilience to hurricanes in regards to wind, rain, flood, and debris. This is because, regardless of the technologies implemented, it is the goal that commissioning will ensure that they are installed and operating as intended, and that they are also appropriate for the context (e.g. location, building type), thus reducing the risk of failure as a result of poor design, installation, or operation. Retro-commissioning also allows for intervention during the buildings lifetime to adapt performance to changing environments that may require alterations such as higher design thresholds to withstand larger impacts anticipated with future events. A commissioning plan implemented for the enclosure of an expansion to an existing hotel in Florida has been credited as the reason the hotel addition survived Hurricanes Charley, Frances, and Jeanne without sustaining any severe wind or water damage, while the existing portion of the hotel and nearby facilities however, were not so fortunate (Parzych and MacPhaul 2005). The hotel expansion implemented a series of commissioning tasks during the design, construction, and occupancy phases, which included activities such as holding commissioning workshops, conducting submittal and constructability reviews, peer reviewing drawings, performing onsite inspections, building and testing mockup wall assemblies, and testing the performance of final installations, all with specific focuses on the moisture control and air barriers of the enclosure system. Following the hurricanes, no water intrusion could be identified in the hotel addition, as the rigorous enclosure commissioning process ensured it remained sealed off from water and air infiltration.

4.2.3 Recommended Standards for High-Performance, Hurricane Resilient Enclosures

The analysis performed here in section 4.2 as has revealed which high-performance building standards explicitly offer the most technology options towards potentially increasing hurricane resilience as well as building performance. At first glance, EarthCraft seemed to be the standout performer in offering HPRB technology options for high-performance and hurricane resilient building enclosures. Most of the HPRB technologies identified in this analysis are mandatory for a EarthCraft Certified House in comparison to the other standards analyzed, making it a good option for homeowners looking to select a high-performance building standard while addressing concerns of hurricane impacts.

While the other standards included in this list may not prescribe as many mandatory HPRB hurricane enclosure technologies as identified here, many of these technologies can still be used while pursuing other high-performance building standards, or even no standard at all. However, caution should always be taken to ensure they are installed and operated correctly so that they do not impede on the performance of other technologies or the goals of achieving the building standard sought after. Furthermore, weighing the costs and benefits of implementing one or more the technologies over the other is important in order to ensure the various hazards and associated impacts of hurricanes to a specific building are considered wisely to avoid poor decision-making. This is why an effective method to prioritize the technologies considering such concerns is essential.

4.3 HURRICANE IMPACTS TO ENCLOSURES

Common failure modes (i.e. physical damages) experienced by residential building enclosures were identified by performing impact analyses. This included performing failure modes, effects, and criticality analyses (FMECAs), and fault-tree analyses (FTAs) for a residential building enclosure when considering hurricanes as the instigating phenomenon. These analyses were not only performed to determine the types of damage that hurricanes can trigger on residential building enclosures, but were additionally carried out to investigate the contributing causes of the failures associated with each enclosure component so that applicable HPRB technologies could be assigned as potential solutions. The analyses also evaluated the criticality of each identified failure mode to aid in subsequent prioritization of risks. Forensic reports and damage assessments detailing how residential building enclosures have historically been impacted by prior hurricane events that have taken place within the U.S. were used as a primary source of data for this investigation.

In summary, the results here included the identification and analysis of the common causes and effects of residential building enclosure failure modes as a result of hurricane hazard impacts; an assessment of the criticality of each identified failure mode; and the identification of available and future needs for HPRB technologies to address each failure mode.

4.3.1 Residential Building Enclosure Component Functions and Interactions with Hurricanes

Prior to analyzing the impacts that a hurricane can have on an enclosure, it was important to first understand the basic functions of residential building enclosure components as well as comprehend how they influence one another and interact with hurricanes. This prompted some initial background literature research to identify these functions and interactions. As previously mentioned, hurricanes can consist of a severe combination of rain, storm surge, and wind. Each of these hazards can have a tremendous amount of influence on the integrity of a building enclosure either as individual hazards or combined, which can lead to minor and/or catastrophic damages.

This section will provide an overview of the primary functions and typical construction details of residential exterior walls, roofs, exterior windows and doors, and foundation systems. It will also describe the interactions these components have with hurricanes, which could eventually lead to the failures that were identified and analyzed.

Exterior Walls

Basic Components and Functions:

The exterior walls of a residential building create the primary shape of a home while also forming the buildings separation of the interior from the exterior climate, which protects and provides comfort to its occupants. Situated on and connected to the foundation system, exterior walls also provide support for the roof, floors, windows, and doors. According to the 2012 International Residential Code (IRC), exterior walls are required to accommodate dead and live loads, which includes loads from the roof, and also loads that originate from the environment such as rain, flood, snow, wind and seismic forces (ICC 2012). Additionally, exterior walls should be able to appropriately transfer such loads to the supporting structure as necessary.

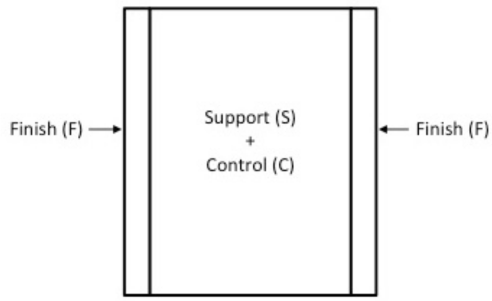


Figure 16 Exterior wall functional diagram

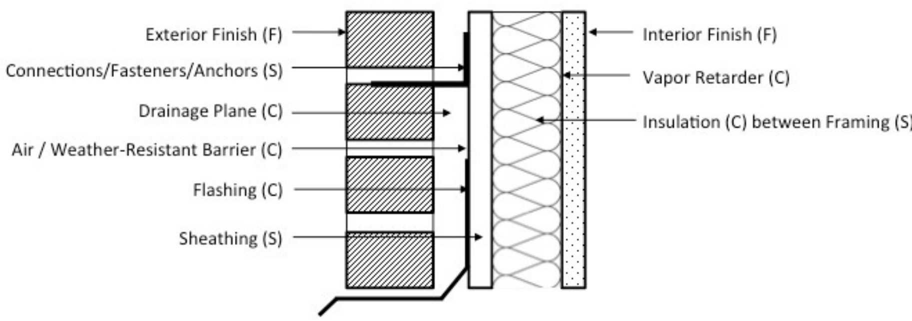


Figure 17 Example of typical brick veneer cavity wall detail

Exterior walls are composed of several materials all with specific purposes to provide these functions, which can be grouped into four major categories: 1) Support, 2) Control, 3) Finish, 4) Distribution of services (Straube 2006). The first three categories will be the focuses described here. Figure 16 and Figure 17 illustrate these functions in a diagram and an example detail of a basic brick veneer exterior wall assembly.

The Support component of an exterior wall provides the majority of the walls structural strength, and must support, transfer and resist the loads that the wall encounters. It is typically composed of the structural framing or backup wall, sheathing, anchors, and connections (e.g. fasteners, ties, and anchors). The control component consists of various layers that are put in place to regulate the flow and transfer of heat, air, water, and vapor, as well as resistance to fire, noise, and other aspects of the environment in order to prevent undesired effects such as building damage, physical or psychological harm, or just discomfort to occupants. This component generally includes materials such as thermal insulation, air barriers, water control components (e.g. drainage planes, WRB, flashing, etc.), and vapor barriers or retarders. The third category consists of the finish layers, which enclose the control and support components of the wall, and form the outermost layers of the wall. The finish layers provide aesthetic qualities as they are visible from the interior and exterior, but can additionally act as control layers, e.g. when used as a rainscreen on the exterior of the wall.

Hurricane Interactions:

Exterior walls interact with hurricane winds, which induce positive (pushing) or negative (pulling) pressures against the walls, or lateral shear forces within walls, depending on the direction of the walls and the location of the

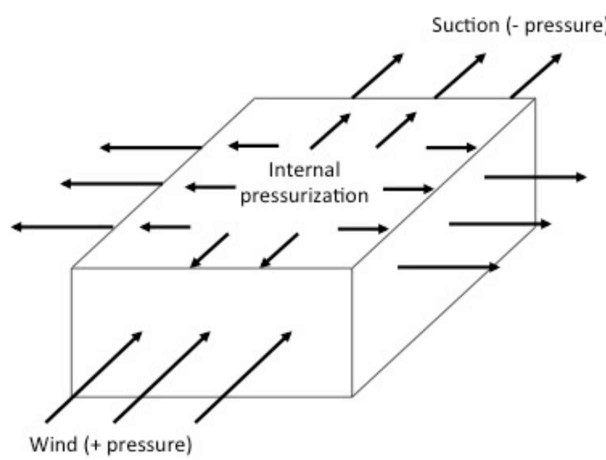


Figure 18 Exterior wall interactions with wind pressure. Adapted from the Whole Building Design Guide (Smith 2010)

majority of the enclosure openings (e.g. windows, doors, small holes). The positive wind pressure that pushes on the windward side of the wall exerts a load that must be overcome by the exterior walls and its components, or otherwise suffer damage. As depicted in Figure 18, wind flows and pushes against and around the windward side of a building. While this occurs, air also enters in through small openings on the windward side of the enclosure into the interior of the building, which can cause dangerous internal pressure build-up, otherwise known as internal pressurization (note: this only occurs if the windward side is more porous than the leeward side i.e. has more openings, otherwise the opposite would occur – depressurization) (Smith 2010). This internal pressurization of the building creates positive pressure on the interior, which pushes the walls out further as air is also being pulled out by suction, and as a result, this exacerbates the wind load applied to the exterior walls. If not designed for, or if unexpected openings appear that cause large holes, such as debris penetrating through a wall or window, severe damage could occur to the structure. Wind can also pull or blow off exterior wall cladding materials as it flows past and around the building.

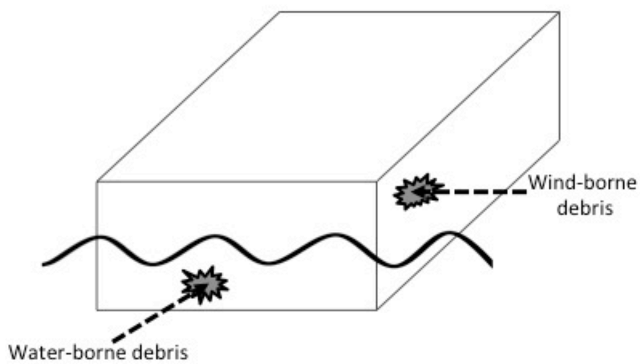


Figure 19 Exterior wall interactions with wind- and water-borne debris

Debris from the surrounding area of a building can enter the wind stream and become wind-borne debris. This now air-borne missile moves at a portion of the wind velocity, which can subsequently impact exterior walls and cause damage. If the wind velocity is very severe, debris could move with enough force to penetrate through an exterior wall to the interior side of the building. Debris can also enter floodwater streams that can similarly impact or penetrate exterior walls. Figure 19 illustrates this interaction.

Furthermore, exterior walls interact with water associated with hurricanes in the form of floodwater and rain (Figure 20). Floodwater typically flows around and potentially through the enclosure, and also exerts pressure against exterior wall surfaces. Though specific floodwater design in flood prone areas design for interior flooding to equalize pressures, this practice is not implemented in all regions.

Rain, which is typically driven by wind during a hurricane (i.e. wind-driven rain), can infiltrate openings and cavities in a wall. The wetting that can occur as a result of flood and rainwater interaction if not properly designed for or repaired in a timely manner, can be very severe and harmful to the durability of building materials, contents, and the health of building occupants.

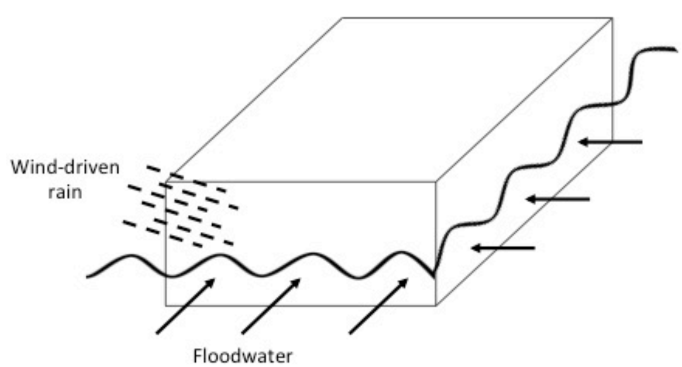


Figure 20 Exterior wall interaction with floodwater and wind-driven rain

Roof

Basic Components and Functions:

Sloped roofs are often found in residential roof applications. Similar to exterior walls, the 2012 IRC mandates that they must also accommodate dead and live loads such as flood, snow, wind, and seismic forces (ICC 2012). The roof is also required to transfer these loads to the supporting structure. Sloped roofs should additionally control water so that it can be directed and disposed of in a way that will not cause damage to the building. This is achieved by using appropriate methods for drainage, water resistance, and/or water retention.

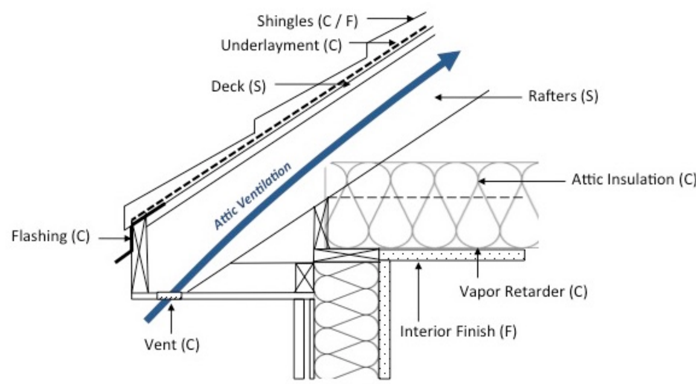


Figure 21 Example of a sloped roof demonstrating control, support, and finish functions

The basic components of a roof include the roof shingles, underlayment, deck, rafters, insulation, flashings, connections, and if required by the climate, ice dam protection (Mehta et al. 2008). Figure 21 depicts each component in an example detail of a sloped roof. These components provide various functions much like that of an exterior walls support, control, and finish categories (Straube 2006). The roof framing (rafters and trusses) and deck are support components of the roof, which provides structural support for the roof system and a substrate for other materials to be attached to. Underlayment, which is the WRB, is directly attached to the roof deck. It is a control layer that is used as an air and water barrier for the roof. Roof shingles are fastened to the roof deck above the underlayment. Flashing installed on the roof also provide a control function as an additional water protection method required on roof systems. Shingles are considered as both a finish and control layer for a roof as they provide water resistance and aesthetic appeal as the outermost material of the roof surface. Insulation, a thermal control layer, is typically found either between roof rafters, or in the ceiling above the highest floor separating the attic as unconditioned space from the conditioned space below.

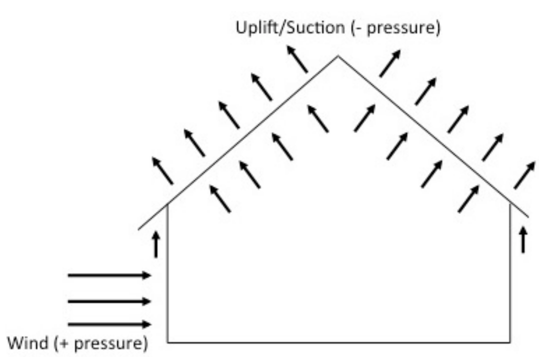


Figure 22 Roof interaction with wind pressure

Hurricane Interactions:

Wind induces a similar effect on the roof as it does on exterior walls. The positive pressure exerted on the windward side of the building pushes against those surfaces, but as it flows around and over the roof, the pressure becomes negative and pulls the components away from their attachments to underlying elements. This is called uplift, and it is most severe at the corners of a roof (Smith 2010). An example of how uplift can occur at a roof is shown in Figure 22. Uplift can pull away cladding and components such as shingles, sheathing, and underlayment, or even the entire roof system if the force is excessive enough (URI 2015).

The roof can also be impacted or penetrated by wind-born debris. If breached by debris, this can cause internal pressurization and provide pathways for water intrusion (URI 2015). The roof also interacts with rainwater that falls during a hurricane. This water can infiltrate past the roof system if not properly designed and controlled for.

Exterior Windows and Doors

Basic Components and Functions:

Exterior windows and doors provide visual and physical openings to the exterior. They should be integrated appropriately to the surrounding exterior walls, and be able to resist a certain amount of wind load (ICC 2012). Frames provide structural support for each system that is anchored within the exterior walls. Windows provide access to daylight and also provide an aesthetic quality to the exterior. In addition to this, the control functions of windows include providing thermal control with insulation and emissivity of the materials, air control using weather-stripping and sealants to prevent unwanted air infiltration, and moisture control by blocking the infiltration of water and draining liquid away from areas in which it can enter the enclosure. Exterior doors provide much of the same function as windows.

Hurricane Interactions:

Wind and floodwater can exert pressure on windows and doors, and with enough force, cause damage or complete destruction of their connections, frames and/or surfaces. Debris that enters the wind stream or water stream can be thrown against windows and doors and potentially breach through the openings to the interior of a building, which in turn induces internal pressurization and water infiltration. Rainwater combined with wind also interacts with windows and doors, which can cause water to infiltrate at component joints, frames, and connections with the exterior walls if they are not adequately sealed off and drained (FEMA 2007).

Foundation

Basic Components and Functions:

Foundations can come in a variety of configurations such as a slab-on-grade, basements, crawlspaces, or piers to form the base structure of a building. No matter what configuration is used, it must be able to accommodate all vertical loads coming from the building (dead, live and environmental) as well as horizontal loads from the surrounding soil and water, and successfully transmit these to the supporting soil (ICC 2012). Foundations complete the load path of all the other connected enclosure components of a superstructure in order to transfer these loads. For this reason, it must be engineered and constructed appropriately to provide the required structural support. Foundation systems are also comprised of several control layers to protect against moisture, soil gases, heat flow, and pests.

Hurricane Interactions:

Depending on the type of foundation configuration (e.g. slab-on-grade, piers, etc.), it may or may not be directly exposed to all the hazards associated with hurricanes. If elements of the foundation are exposed, it could be impacted by wind- or water-borne debris causing structural damage. Wind and water pressure can also be exerted to the foundation and similarly cause structural damage. Floodwater that flows around a buildings foundation can cause erosion and scour, which depletes the ground surface and soil around and/or below the foundation and its elements (FEMA 2009). The effects of erosion and scour can be severe, with impacts such as exposing the foundation to higher flood loads that it was not designed for, and weakening the embedment of the foundation in the soil, making the building more vulnerable to movement or collapsing (FEMA 2009).

4.3.2 Failure Modes, Effects, and Criticality Analysis

This section discusses the identification and assessment of the physical impacts that hurricanes can have on a residential building enclosure using failure modes, effects, and criticality analyses (FMECA). This bottom up analysis was used to identify typical failure modes experienced by exterior walls, roofs, windows and doors, and foundations as a result of hurricane hazard interactions discussed before. The effects (i.e. consequences) of the identified failure modes to a building were also identified, and the criticality of each failure mode was assessed in order to quantify the negative impact of each failure. The FMECA process undertaken is described in this section using the exterior wall as an example to illustrate the involved steps. The final list of identified failure modes ranked by their criticality (i.e. impact ratings) for all enclosure components is then presented and discussed in detail.

Hurricane Damage Assessment Data Sources

Several post-hurricane reconnaissance efforts in which damage assessments were performed and forensic reports were assembled for residential buildings were used as the primary source of data to identify enclosure failure modes caused by hurricanes. The majority of the reports were provided by FEMA's Mitigation Assessment Team (MAT) Program, who assesses the performance of buildings in response to various hazard events that have taken place within the U.S. The MAT team investigators each have at least 10 years of experience performing post-disaster investigations and evaluating building performance (FEMA 2015). The National Institute of Standards and Technology (NIST) Reconnaissance Team composed of scientists and engineers in the Materials and Construction Research Division, Building and Fire Research Laboratory, was also referred as a source of data. The National Association of Home Builders (NAHB) Research Center was additionally included as a source of data, and they provided the only available data that could be found for this study with a statistical analysis of various types of damages experienced by residential building enclosures based upon observations. A summary of all the sources of data, as well as their coinciding hurricane events in which damage was observed, are listed in Table 7. The criteria that was defined for each source to meet in order to be included in the impact analyses are as follows:

- Post-event damage assessments of actual hurricane events that have taken place in the U.S. between 1989-2014
- The hurricane event(s) corresponding to each damage assessment must be categorized as a hurricane according to the Saffir-Simpson hurricane scale (category 1-5)
- Damage assessments includes specific focuses on residential building enclosures
- Investigators demonstrate expert knowledge and/or include review from technical experts

Each report was thoroughly reviewed, and necessary data was extracted to perform the subsequent FMECAs for residential building enclosure components.

Table 7 Hurricane Damage Data Source

	Data Source	*Hurricane Event(s)*	*Category*[a]
1	Hurricane Damage to Residential Structures: Risk and Mitigation (Ayscue 1996)	Hugo (1989), Andrew (1992), Iniki (1992)	4, 5
2	The damaging impacts of hurricanes upon coastal structures (Patterson and Ford 2009)	Hugo (1989), Andrew (1992), Iniki (1992), Fran (1996)	3, 4, 5
3	FEMA 549, Hurricane Katrina in the Gulf Coast: MAT (FEMA 2006)	Katrina (2005)	3
4	Assessment of Damage to Single-Family Homes Caused by Hurricane Andrew and Iniki (NAHB 1993)	Andrew (1992), Iniki (1992)	4, 5
5	Performance of Physical Structures in Hurricane Katrina and Hurricane Rita: A Reconnaissance Report (NIST 2006)	Katrina (2005), Rita (2005)	3
6	FEMA 281, MAT Report: Hurricane Opal in Florida (FEMA 1996)	Opal (1995)	3
7	FEMA 290, MAT Report: Hurricane Fran in North Carolina (FEMA 1997)	Fran (1996)	3
8	FEMA 338, Building Performance Assessment Team Report: Hurricane Georges in the Gulf Coast (FEMA 1999)	Georges (1998)	2
9	FEMA 488, MAT Report: Hurricane Charley in Florida (FEMA 2005)	Charley (2004)	4
10	FEMA 489, Hurricane Ivan in Alabama and Florida: Observations, Recommendations and Technical Guidance (FEMA 2005)	Ivan (2004)	3
11	FEMA P-757, Hurricane Ike in Texas and Louisiana: MAT Report (FEMA 2009)	Ike (2008)	2
12	FEMA P-942, MAT Report: Hurricane Sandy in New Jersey and New York (FEMA 2013)	Sandy (2012)	1

Enclosure Failure Modes, Causes, and Effects Analysis

Upon reviewing each reconnaissance report, specific aspects of hurricane hazards were identified as the main contributors to the failure modes of residential enclosure systems as observed from hurricane events. These hazard aspects include: rain, wind-driven rain, flood, wave erosion/scour, water-borne debris, wind-borne debris, wind pressure, and uplift. Each hazard aspect identified was found to be associated with one or more types of failure modes, which were grouped into categories. The failure mode categories were defined to represent a common type of damage that can be associated with either a specific enclosure component or various enclosure components. Eight types of failure mode categories were identified in the reconnaissance reports and were defined for clarity. The failure mode categories identified and defined (in no particular order) are as follows.

[a] Saffir-Simpson hurricane scale category at landfall

Enclosure Failure Mode Categories:

I. **Penetration/crack** – a hole or crack to an enclosure component caused by debris impact or puncture through to the interior

II. **Exterior wall structural failure** – exterior wall structural components fail resulting in significant or irreparable structural damage requiring extensive repair or complete replacement (e.g. displaced or disconnected structural framing connections)

III. **Detached non-structural components** – non-structural components (e.g. wall cladding, roof shingles, etc.) are removed from an enclosure component

IV. **Roof structural failure** – roof structural components fail resulting in significant or irreparable structural damage requiring extensive repair or complete replacement

V. **Blown-in window/door** – complete loss of an exterior door/window surface or surface and frame resulting in significant or irreparable damage and requires extensive repair or complete replacement

VI. **Water damage** – water damage to materials caused by the wetting of enclosure components such as material saturation, accumulated and trapped moisture, and/or inundation in the building space and/or between enclosure components

VII. **Foundation structural failure** – foundation structural components fail resulting in significant or irreparable structural damage requiring extensive repair or complete replacement

VIII. **Flotation** – the building is swept off of its foundation as a result of flood water and waves

To visualize how each failure mode category relates to each hazard aspect of a hurricane, a diagram, as presented in Figure 23 Initial (direct) hurricane hazard failure mode categories for residential building enclosures, was created to represent the relationships revealed upon reviewing the reconnaissance reports. This diagram was beneficial towards understanding the many influences that can contribute to the various types of damage that hurricanes can provoke on building enclosures. At this point the hazards and failure mode categories shown in the diagram represent initial impacts (i.e. direct damages), and do not show consequential damages (i.e. indirect damages) of each type of failure.

When considering the exterior wall components of a residential building enclosure as an example, the main hazard loads that caused damage were wind- and water-borne debris, wind and water pressure, and wetting as a result of exposure to moisture. The reconnaissance reports revealed that there are four common direct failure modes experienced by exterior walls as a result of these loads:

Exterior Wall Failure Modes and Causes:

A.I. Exterior Wall Penetration/Crack

- Causes:

  Cracks or penetrations to walls caused by flying or floating debris that impact or puncture through walls

A.II. Exterior Wall Structural Failure

- Causes:

  Pressure from wind or floodwater forces exerted on the superstructure cause structural wall connections to separate and fail

A.III. Detached Non-Structural Exterior Wall Components

- Causes:

  Pressure from wind or fast moving floodwater against exterior walls remove or separate non-structural wall components

A.VI. Exterior Wall Water Damage

- Causes:

  Prolonged wall inundation and/or wind-driven rain intrusion at wall cavities and openings makes materials wet and traps moisture, which damages materials due to altered structural and thermal properties

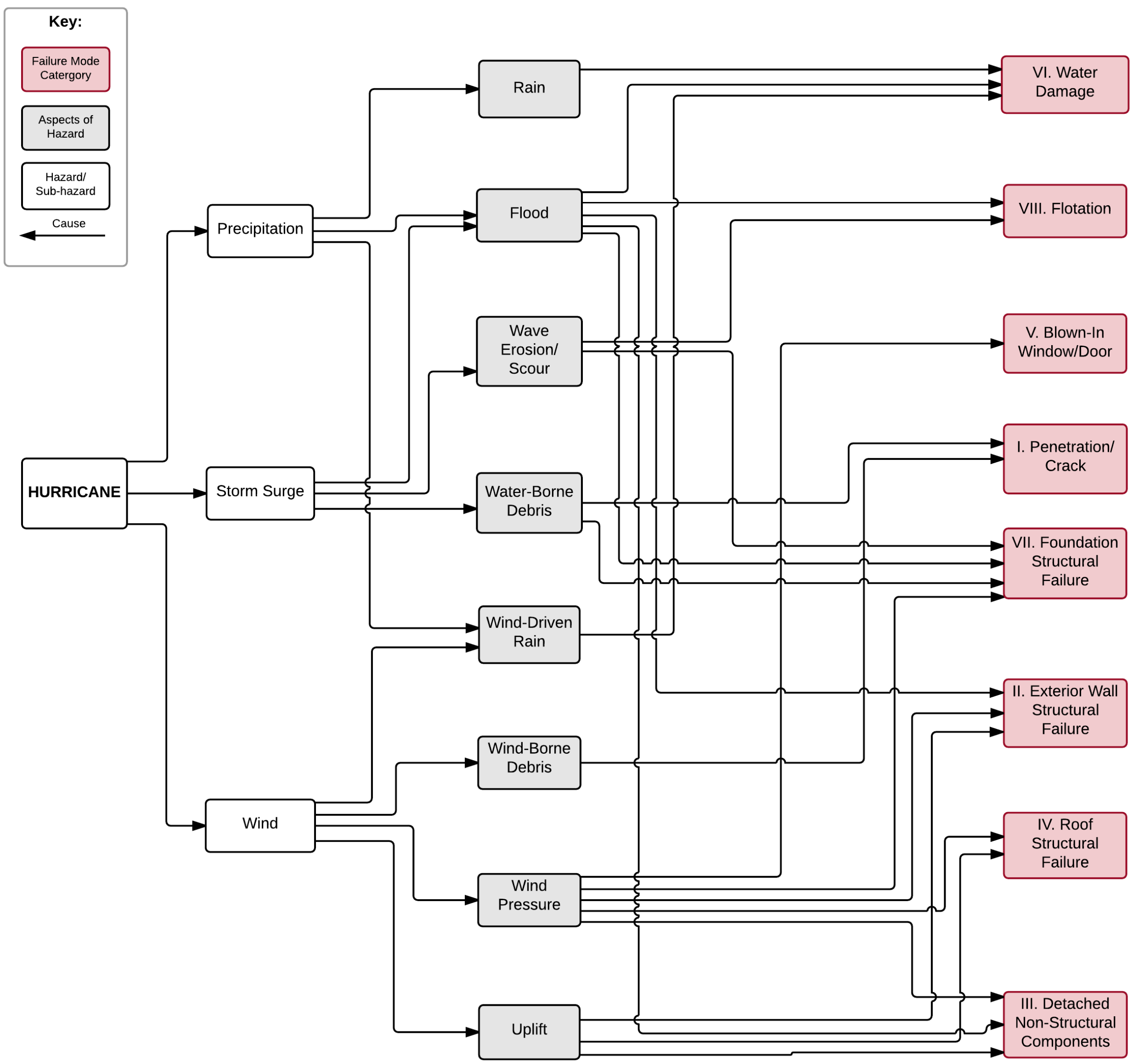


Figure 23 Initial (direct) hurricane hazard failure mode categories for residential building enclosures

The indirect damages, otherwise known here as the "effects" of each of the identified exterior wall failure modes, were identified in order to subsequently aid in the assessment of the criticality of each failure in the next steps of the FMECAs performed. The reconnaissance report data as well as building science knowledge helped to assemble and supported the basis of a list of potential minor and severe consequential failures that could occur. These effects are currently limited to physical damage of the building:

Exterior Wall Failure Modes and Effects:

A.I. Exterior Wall Penetration/Crack

- Effects:

  Internal pressurization – small or large holes in the exterior wall leave pathways for wind to infiltrate the building and create a large, dangerous pressure build-up inside of the building. This can significantly increase the pressure exerted on various building components that may not have been designed to withstand such loads. This effect can cause distress to and weaken various building components, and could eventually set-off a domino effect of other enclosure component failures if it becomes excessive.

  Wall and roof structural failure – a combination of internal pressure that exerts a large amount of negative pressure on the enclosure and an already weak wall system now damaged by debris, leaves the structure vulnerable to failure. Additionally, the impact location of debris can contribute to subsequent structural failure if the target is at superstructure connection or structural framing members.

  Water damage – openings and cracks left on the wall after a debris impact breaks the seal that blocks unintended water infiltration, leaves a walls materials susceptible to water damage. If it is raining during a hurricane event, or does so after the fact, and the wall has not been repaired, water can continue to enter the wall. Wetting of materials from water can change the structural and thermal properties of a wall that are essential to the functions and success of a component (e.g. corroded or molded structural components, or saturated insulation)

  Blown-out windows/doors – as a result of a breach in the envelope causing internal pressurization, windows and doors are at risk of being overloaded with negative wind pressure pushing from the interior. With enough force, this could cause these openings to fail (e.g. window surfaces shatters)

  Total building collapse/loss – In extreme cases, a building can completely collapse if the uncontrolled internal pressure build-up created by a breach of the envelope is excessive enough to lift the roof off and push sidewalls completely out of place. An opening of only 5% of the enclosure can be sufficient enough to fully pressurize a building during a hurricane.

A.II. Exterior Wall Structural Failure

- Effects:

  Water damage – when the structure of an exterior wall fails, it can cause damage such as displacing materials, form holes or cracks, and compromise control layers. This could allow pathways for uncontrolled water infiltration into the wall, especially if the wall were to completely collapse. This water infiltration could eventually damage materials.

  Roof structural failure – the structural integrity of the exterior walls is very important for the roof, as these components are directly connected to one another as part of the superstructure of a building. The walls must support the load of the roof, so, if one or more of the exterior walls are no longer able to carry this load due to structural failure, this load will be redistributed to other areas of the walls, which may go beyond what they were originally designed for. This puts the roof at risk of structural failure and potentially collapsing if the walls can no longer support it.

  Total building collapse/loss – in the event that the exterior walls suffer extensive structural damage, which prevents it from sustaining any type of load, the walls could collapse as well as the other loads it supports (roof, floors, ceiling, windows and doors). This would essentially cause a total loss of the building, at least above the foundation level.

A.III. Detached Non-Structural Exterior Wall Components

- Effects:

  Water damage – detached non-structural wall components, such as the exterior finish cladding, could compromise the air and water control layers of a wall. As layers are pulled off beginning with the exterior surface, other underlying materials such as the WRB, sheathing, and/or insulation become more susceptible to becoming detached or damaged now that they are exposed to external forces that they were not designed to interact with or resist. With an exposed exterior wall, and lost or deficient control layers, water can easily infiltrate the walls and cause water damage to materials.

A.VI. Exterior Wall Water Damage

- Effects:

  Detached non-structural wall components – walls that experience water damage contain wet materials that have lost some or all of its prior strength due to altered material properties. This makes them more vulnerable to detachment either from environmental interaction (e.g. wind pulls of materials) or due to weakened connections (e.g. corrosion or rot).

  Exterior wall structural failure – water damage to a wall can negatively impact the structural integrity of a wall if wetting, corrosion, and/or mold occur at critical structural components, such as wood framing and load path connections.

Figure 24 provides a summary of the failure modes, causes, and effects analysis performed for exterior walls impacted by hurricanes. This analysis was also performed for roofs, foundations, windows and doors, and similar tables for each component can be found in Appendix A.

Component	Hazard Loading(s)	Failure Mode	Causes of Failure Mode	Potetnial Effects of Failure Mode
A. Exterior Wall	Wind/water-borne debris	I. Penetration/ crack	Wall punctured by water-borne debris and/or wind-borne debris, or wall impacted by water-borne debris and/or wind-borne debris	Internal pressurization; Roof structural failure; Exterior wall structural failure; Water damage; Blown-out windows/doors; Total building collapse/loss
	Wind/water pressure	II. Exterior wall structural failure	Wind pressure and uplift forces separate structural wall connections, or moving flood water forces seperates connections	Water damage; Roof structural failure; Total building collapse/loss
		III. Detachaed non structural components	Wind pressure removes/seperates non-structural materials, or moving floodwater removed/seperates materials	Water damage
	Wetting	VI. Water damage	Wind-driven rain enters wall cavities and openings causing water damage to matierals, or prolonged inundation causes water damage	Detached non-structural components; Exterior wall structural failure

Figure 24 Exterior wall hurricane failure modes, causes, and effects table

Criticality Analysis

The criticality of each failure mode was quantified by evaluating the severity of the worst-case effect of each failure (i.e. severity factor – *SF*), and by also considering the probability of each failure mode occurring (i.e. probability factor – *PF*). While these are the sole factors currently included and evaluated for this research according to the selected method, which can be considered a limitation, additional factors can be incorporated in the future to broaden the scope and evaluate what influence they may have on the results produced (e.g. direct failure mode severity).

Each aspect (probability and severity) was given numeric values on a scale of 0-1, where 1 is equal to the highest level of severity or probability, and 0 as the lowest level. The equation used to determine criticality factor (CF) is:

$$CF = PF\ x\ SF$$

Severity Factor (SF):

The exterior wall failure modes that were identified each have one or more potential effects as previously discussed. Each effect can result in consequences that can be related to repair cost, occupant displacement, and/or health and safety, among many other potential considerations. Such consequences can be minor or very severe. For this evaluation, repair/replacement costs for residential enclosures were considered as the sole factor to evaluate the severity of each failure mode. Additional factors, such as safety to the occupants, were initially considered, however, it was decided upon to exclude it at this point in time, but it will be considered for future research in order to broaden the scope of the research.

Percentage breakdowns of enclosure component costs for residential building enclosures were used to estimate the repair/replacement costs for materials and processes associated with construction of exterior walls, roof, foundation, windows and doors. A building enclosure takeoff for a southwest Virginia single-family home located outside of a metropolitan area was compared to the 2015 Craftsman National Building Cost (NBC) Manual for residential enclosures. The NBC manual provides national averages for various locations throughout the U.S. in order to estimate construction or replacement costs for different types of buildings, such as single-family residences (Moselle 2015). A comparison of these costs is presented in Table 8. Typically, construction or replacement cost estimates can vary by 10% or more, and for buildings located outside of a metropolitan area, costs can be 2-6% lower if cheaper and less skilled labor is available (Moselle 2015). In addition to this, costs following a natural disaster event that puts pressure on construction deadlines can significantly inflate estimates (Moselle 2015). In creating and presenting this cost comparison, such limitations have been considered. However, these values were used in order to determine reasonable values for replacement costs considering various averages to represent a broad range as a baseline. For more accuracy, cost estimates more specific to a buildings location can be used to adjust values. As shown by the % difference in Table 8, the difference in costs for each major component for a non-metropolitan area VA home in comparison to national averages is between approximately 4-10%, which is reasonable considering the variability associated with location.

Table 8 Enclosure component cost estimate comparison

<table>
<tr><th>Enclosure Component</th><th>Southwest VA Home</th><th>NBC Average</th><th>% Difference</th></tr>
<tr><td>Foundation</td><td>43.2%</td><td>47%</td><td>- 3.8%</td></tr>
<tr><td>Exterior Wall Framing</td><td>10.5%</td><td rowspan="3">31%</td><td rowspan="3">- 6.3%</td></tr>
<tr><td>Exterior Wall Finish</td><td>5.7%</td></tr>
<tr><td>Windows and Doors</td><td>8.5%</td></tr>
<tr><td>Roof Framing</td><td>29.7%</td><td rowspan="2">22%</td><td rowspan="2">+ 10%</td></tr>
<tr><td>Roof Shingles</td><td>2.3%</td></tr>
<tr><td>Total Enclosure</td><td>100%</td><td>100%</td><td>- 0.1%</td></tr>
</table>

The enclosure component cost percentages for the southwest VA home were used here to represent baseline SF values for the southeast U.S. region when estimating replacement costs associated with the damage and repair required for each failure mode effect. For example, replacement costs for water damaged exterior walls could require the complete replacement of walls as a worst-case scenario, which includes the framing and finish of the system (i.e. approx. 11% + 6% = 17%). The SF for each identified enclosure failure mode effect is presented Table 9.

While internal pressurization is an effect of a failure mode, it is not an actual physical damage. For this reason, it does not have a SF until it is associated with other damages that can occur, in which case those damages have a SF.

Table 9 Severity Factors (SF) for enclosure failure mode effects

Failure Mode Effect	***SF***
Internal Pressurization	N/A
Roof Structural Failure	0.30
Exterior Wall Structural Failure	0.11
Exterior Wall Water Damage	0.17
Roof Water Damage	0.32
Foundation Water Damage	0.43
Blown-Out Windows/Doors	0.09
Detached Non-Structural Exterior Wall Components	0.06
Detached Non-Structural Roof Components	0.02
Total Building Collapse/Loss	1.00

Considering these SFs, the severities of the worst-case effects for the exterior wall failure modes identified are:

A.I. Exterior Wall Penetration/Crack

- Worst-case SF: Total Building Collapse/Loss = 1.00

A.II. Exterior Wall Structural Failure

- Worst-case SF: Total Building Collapse/Loss = 1.00

A.III. Detached Non-Structural Exterior Wall Components

- Worst-case SF: Exterior Wall Water Damage = 0.17

A.VI. Exterior Wall Water Damage

- Worst-case SF: Exterior Wall Structural Failure = 0.11

Probability Factor (PF):

The likelihood of each enclosure component experiencing damage, as well as the possibility of various types of enclosure failure modes occurring, were evaluated in order to determine the PF for each failure. Hurricane damage forensic reports assisted with this assessment, which provided a basis for conclusions made regarding the PFs determined. Insurance damage data was initially sought after, however, the availability of such data is often proprietary and it could not be obtained for this research. Nonetheless, the sources of data used to obtain damage data (refer to Table 7 Hurricane Damage Data Source) provided valuable information based upon direct damage observation, and in one case, damage statistics that were applicable to develop PF ratings. The probability of each enclosure component experiencing damage (CPF) and the probability of each enclosure component failure mode (FMPF) were determined and used to identify the final PF for each enclosure component specific failure mode. The equation to represent this evaluation is:

$$CPF \ x \ FMPF = PF$$

The likelihood of each enclosure component experiencing some sort of damage, which includes the exterior walls, roof, foundation, windows and doors, is ranked as follows in Table 10 by their CPF, with 1 being the most likely, and 0.25 being the least likely to experience a failure mode:

Table 10 Enclosure component probability factor (CPF)

Enclosure Component	***CPF***
Roof	1.00
Windows/Doors	0.75
Exterior Walls	0.50
Foundation	0.25

As shown in Table 10, the roof of a residential building was documented to be the most likely to experience some sort of damage (severe or minimal) during a hurricane event. Windows and doors are second, followed by exterior walls, and foundations.

Failure modes associated with each enclosure component were then ranked in terms of how probable they were to occur according to damage observations (Table 11). A detached non-structural component was found to be a very common occurrence during a hurricane event for residential building exterior walls and roofs. Impact or penetration by flying or floating debris was the next common failure to occur for exterior walls, followed by structural failure, and water damage respectively.

According to the CPFs and FMPFs determined for each enclosure component and failure mode, the final PF (CPF x FMPF) for each are listed in Table 12 ranked by most probable at the top for each component.

Table 11 Enclosure component failure mode probability factors (FMPF)

Exterior Wall Failure Mode	***FMPF***
Detached Non-Structural Components	1.00
Penetration/Crack	0.75
Structural Failure	0.50
Water Damage	0.25
Roof Failure Modes	***FMPF***
Detached Non-Structural Components	1.00
Water Damage	0.75
Structural Failure	0.50
Penetration/Crack	0.25
Windows/Door Failure Modes	***FMPF***
Penetration/Crack	1.00
Blown-In	0.67
Water Damage	0.33
Foundation	***FMPF***
Flotation	1.00
Structural Failure	0.50

Table 12 Final probability factors (PF) for each enclosure component failure mode

Exterior Wall Failure Mode	***CPF***	***FMPF***	***PF***
Detached Non-Structural Components	0.50	1.00	0.50
Penetration/Crack		0.75	0.38
Structural Failure		0.50	0.25
Water Damage		0.25	0.13
Roof Failure Modes	***CPF***	***FMPF***	***PF***
Detached Non-Structural Components	1.00	1.00	1.00
Water Damage		0.75	0.75
Structural Failure		0.50	0.50
Penetration/Crack		0.25	0.25
Window/Door Failure Modes	***CPF***	***FMPF***	***PF***
Penetration/Crack	0.75	1.00	0.75
Blown-In		0.67	0.50
Water Damage		0.33	0.25
Foundation	***CPF***	***FMPF***	***PF***
Flotation	0.25	1.00	0.25
Structural Failure		0.50	0.13

Criticality Factor (CF):

Finally, the overall criticality was estimated and quantified by using the values determined for probability and severity for each enclosure component's failure modes. The CFs for each exterior wall failure mode are presented in Table 13 as well as all the other identified enclosure failure modes determined for each enclosure component (roof, foundation, windows and doors). Considering just exterior walls, a penetration/crack to exterior walls is considered most critical, followed by exterior wall structural failure, detached non-structural components, and water damage in that order.

As listed in Table 14, the final criticality ranking for all the identified enclosure failure modes for the FMECAs are presented. The exterior wall failure modes, which were previously discussed as specific examples of this analysis, are included in this final ranking. The same method discussed for the exterior walls was used to determine the CFs for all the failure modes for each enclosure component. FMECA tables for each component can be found in Appendix A, which lists the information used to determine the SFs and PFs that quantify criticality. Figure 25 depicts the final FMECA table for residential enclosures.

Table 13 Enclosure failure mode criticality factors (CF)

Exterior Wall Failure Mode	***SF***	***PF***	***CF***
Penetration/Crack	1.00	0.38	0.38
Structural Failure	1.00	0.25	0.25
Detached Non-Structural Components	0.17	0.50	0.09
Water Damage	0.11	0.13	0.01
Roof Failure Modes	***SF***	***PF***	***CF***
Structural Failure	1.00	0.50	0.50
Detached Non-Structural Components	0.32	1.00	0.32
Penetration/Crack	1.00	0.25	0.25
Water Damage	0.30	0.75	0.23
Window/Door Failure Modes	***SF***	***PF***	***CF***
Penetration/Crack	1.00	0.75	0.75
Blown-In	1.00	0.50	0.50
Water Damage	0.11	0.25	0.03
Foundation	***SF***	***PF***	***CF***
Flotation	1.00	0.25	0.25
Structural Failure	1.00	0.13	0.13

Table 14 Enclosure failure modes ranked by criticality

Enclosure Failure Modes		*CF*	*CF Scaled*
C.I.	Windows/Doors Penetration/Crack	0.75	1.00
C.V.	Blown-In Windows/Doors	0.50	0.67
B.IV.	Roof Structural Failure	0.50	0.67
A.I.	Exterior Wall Penetration/Crack	0.38	0.50
B.III.	Detached Non-Structural Roof Components	0.32	0.43
A.II.	Exterior Wall Structural Failure	0.25	0.33
B.I.	Roof Penetration/Crack	0.25	0.33
D.VIII.	Flotation	0.25	0.33
B.VI.	Roof Water Damage	0.23	0.30
D.VII.	Foundation Structural Failure	0.13	0.17
A.III.	Detached Non-Structural Exterior Wall Components	0.09	0.11
C.VI.	Water Damage at Windows/Doors	0.03	0.04
A.VI.	Exterior Wall Water Damage	0.01	0.02

Component	Hazard Loading(s)	Failure Mode	Causes of Failure Mode	Potetnial Effects of Failure Mode	Severity of Consequence (SF)	Probability of Occurrence (PF)	Criticality (SFxPF)	Needs to Prevent/Reduce Risk of Failures
A. Exterior Wall	Wind/water-borne debris	I. Penetration/ crack	Wall punctured by water-borne debris and/or wind-borne debris, or wall impacted by water-borne debris and/or wind-borne debris	Internal pressurization; Roof structural failure; Exterior wall structural failure; Water damage; Blown-out windows/doors; Total building collapse/loss	1.00	0.38	0.38	Materials with high impact resistance properties
	Wind/water pressure	II. Exterior wall structural failure	Wind pressure and uplift forces separate structural wall connections, or moving flood water forces seperates connections	Water damage; Roof structural failure; Total building collapse/loss	1.00	0.25	0.25	Stronger superstructure connections at walls for high wind/water pressures
		III. Detachaed non structural components	Wind pressure removes/seperates non-structural materials, or moving floodwater removed/seperates materials	Water damage	0.17	0.50	0.09	Non-structural material properties and attachement methods that can withstand esposure to high pressures and moisture
	Wetting	VI. Water damage	Wind-driven rain enters wall cavities and openings causing water damage to matierals, or prolonged inundation causes water damage	Detached non-structural components; Exterior wall structural failure	0.11	0.13	0.01	Enhanced water control methods to mitigate water exposure risks

Figure 25 Exterior wall hurricane FMECA table

4.3.3 Fault Tree Analysis

As an extension of the FMECA process, fault tree analyses (FTA) were performed for each enclosure failure mode in order to identify contributing causes to each failure, and to uncover the root causes. In doing so, countermeasures (i.e. HPRB technologies) were assigned to failure mode's root cause(s) as potential solutions in each fault tree. The exterior wall is used here again as an example to demonstrate the FTA process that was performed.

FTA and FMECA Correlation

In contrast to the bottom-up approach of an FMECA where failure modes were identified, analyzed, and linked to the consequential effects of the impacts, FTAs are top-down, where the failure modes are analyzed and linked to all contributing causes and possible solutions. The failure modes identified for each enclosure component's FMECA were used to begin each FTA as a top event. Damage assessments and forensic reports (refer to Table 7 Hurricane Damage Data Source) were again used to assist with this analysis to identify the root causes of each failure mode.

Failure Modes, Root Causes, and Countermeasures

The first step in performing an FTA is to define the scope of the analysis. According to the damage assessments reviewed for the impact analyses performed for this research, when described, many of the surveyed homes were wood-framed structures; relatively uniform in design and age within certain communities; constructed between the 1970s and 1980s with no significant upgrades to mitigate potential storm damage; and were constructed below or at current building codes for their location at the time of the hurricane event. Due to these observations, it is assumed here that the initial states of enclosure components defined in the scope of the FTAs are for residential, wood-framed, single-family homes constructed at or below typical building (IRC) code. Each component is also assumed to perform basic functions as defined in section 4.3.1. The failure modes analyzed are limited to those identified in the previously performed FMECAs, and the sources of data were those previously defined to represent actual post-hurricane event damages.

The next step was to define the top event of each FTA. Using exterior walls as an example, the top events for each FTA are the failure modes

- A.I. Exterior Wall Penetration/Crack,
- A.II. Exterior Wall Structural Failure,
- A.III. Detached Non-Structural Exterior Wall Components, and
- A.VI Exterior Wall Water Damage.

From there, the damage assessment data was thoroughly reviewed to extract information identified by investigators as contributing causes to each failure mode in question. Using logic gates, the FTAs were then graphically constructed, which linked each failure mode to the identified causes and extended downwards until the root cause was left remaining at the bottom of the tree. To demonstrate this process, failure mode A.III. for exterior walls is described below.

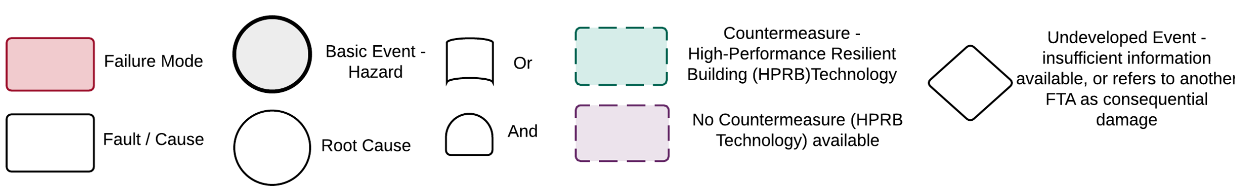
FTA – A.III. Detached Non-Structural Exterior Wall Components:

When analyzing failure mode A.III. Detached Non-Structural Exterior Wall Components, one of the initial causes identified for this failure was wind pressure removing non-structural components from a wall. Further investigation revealed that in combination with hurricane wind, several other underlying causes could eventually lead to this failure. This could include stud failure, failure of non-structural fasteners, or inadequate material strength to resist the wind load. Additional investigation into these causes revealed root causes of each. To illustrates this, consider inadequate material strength, it was found that the root cause of this could have been due to wind speeds that exceed what the walls were originally designed for, or materials could have previously been damaged by water as a consequential damage from another failure mode. This process was performed until causes could no longer be developed any further. Each root cause was then aligned with the previously identified hurricane specific enclosure HPRB technologies. For example, for the root cause "wind exceeds design speeds", which could eventually lead to detached non-structural wall components, two HPRB technologies could potentially offer viable solutions for the tree that lead to the failure. These were to install a pressure equalized drainage plane to reduce the pressure differential across the wall, or the install a high strength exterior insulation finish system to resist the high wind loads.

While many of the root causes identified for the exterior wall failure modes were found to align with HPRB technologies, this was not always the case. Some causes were found to not currently have an HPRB technology available from the inventory identified in this research. Therefore, the tree reveals the need of further HPRB technologies and identifies those that may benefit from future research and development. It is important to note that, while some FTAs have areas where no HPRB countermeasures could be identified, this does not mean that a solution does not exist to address the failure. For the context of this research, it alludes to the fact that no "high-performance" and "resilient" technology could currently be identified at this time. Solutions may exist that do not provide the combination of such qualities.

The following figures (Figure 26 to Figure 29) are the final FTAs constructed for the exterior wall failure modes identified. FTAs for the roof, foundation, windows and doors can be found in Appendix A.

FTA Symbols Key:



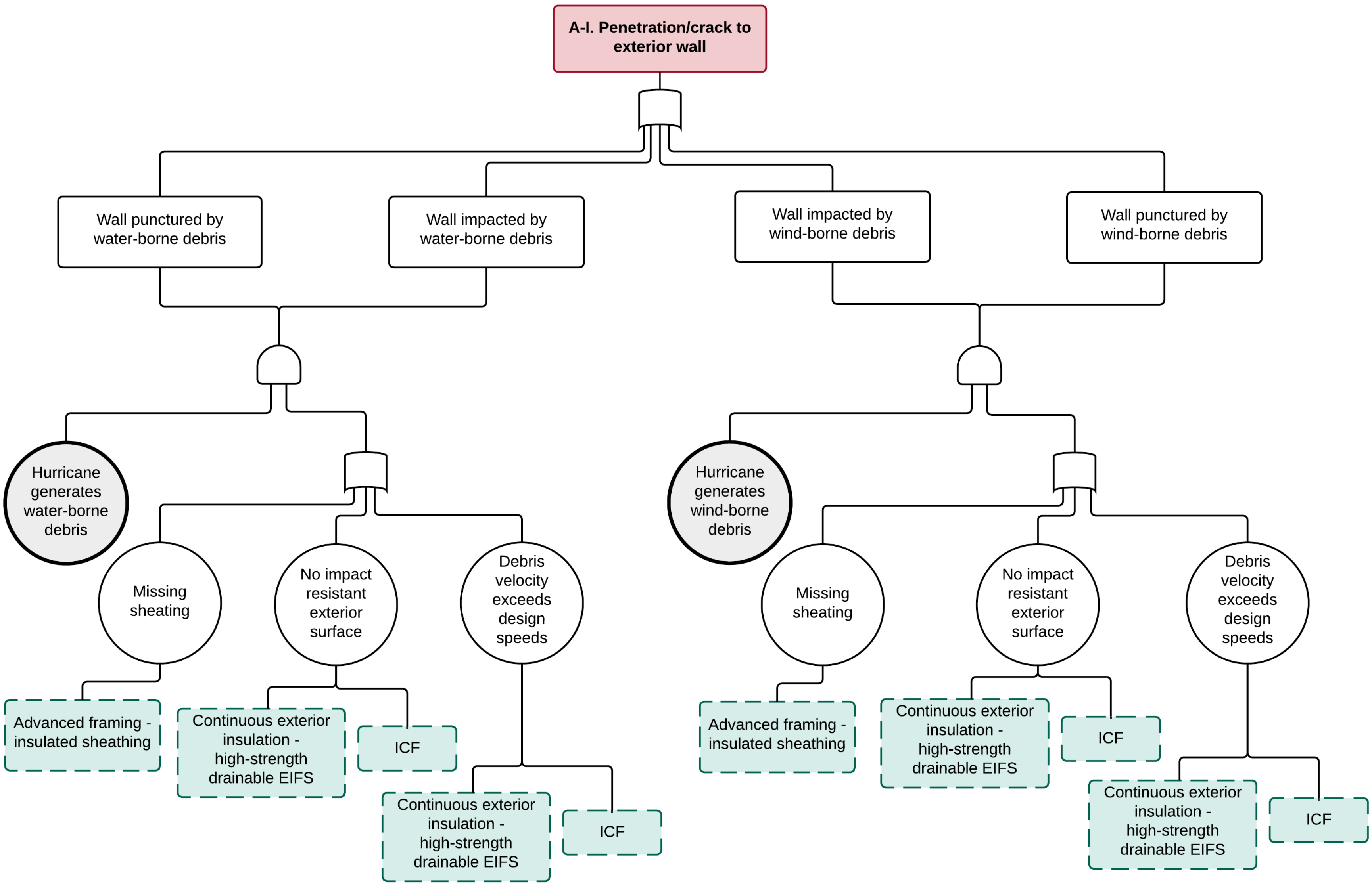


Figure 26 A.I. Exterior Wall Penetration/Crack FTA diagram

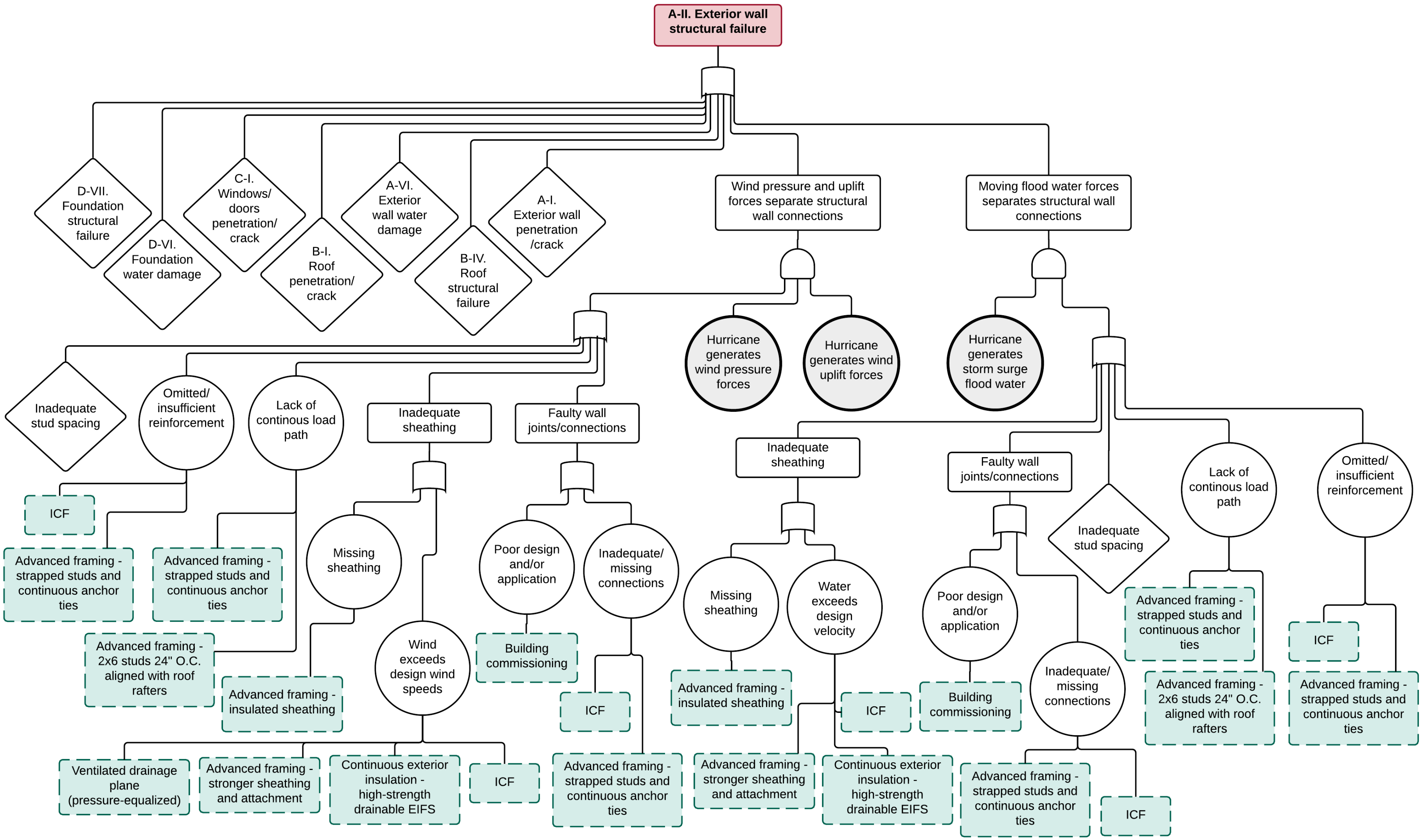


Figure 27 A.II. Exterior Wall Structural Failure FTA diagram

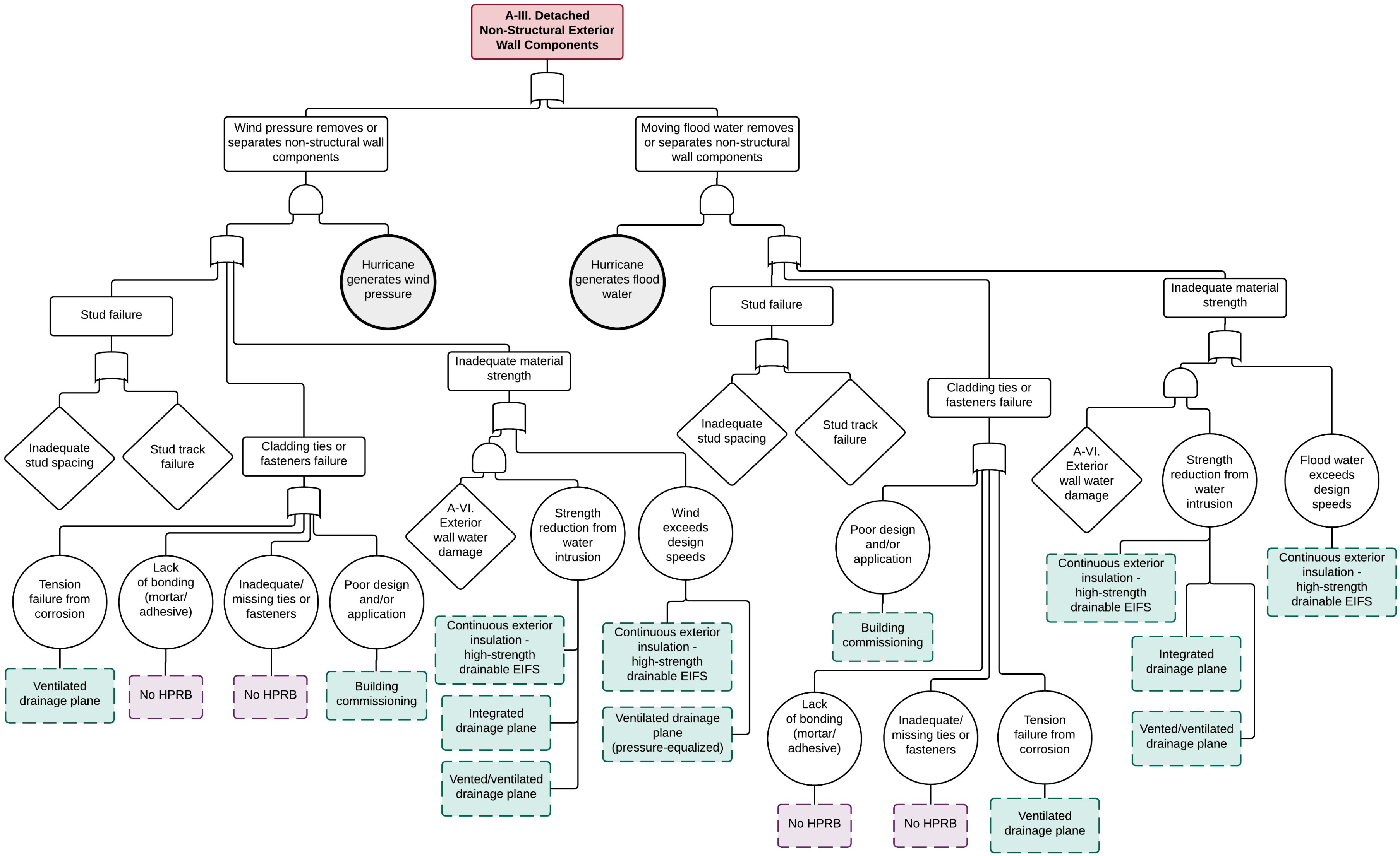


Figure 28 A.III. Detached Non-Structural Exterior Wall Components FTA diagram

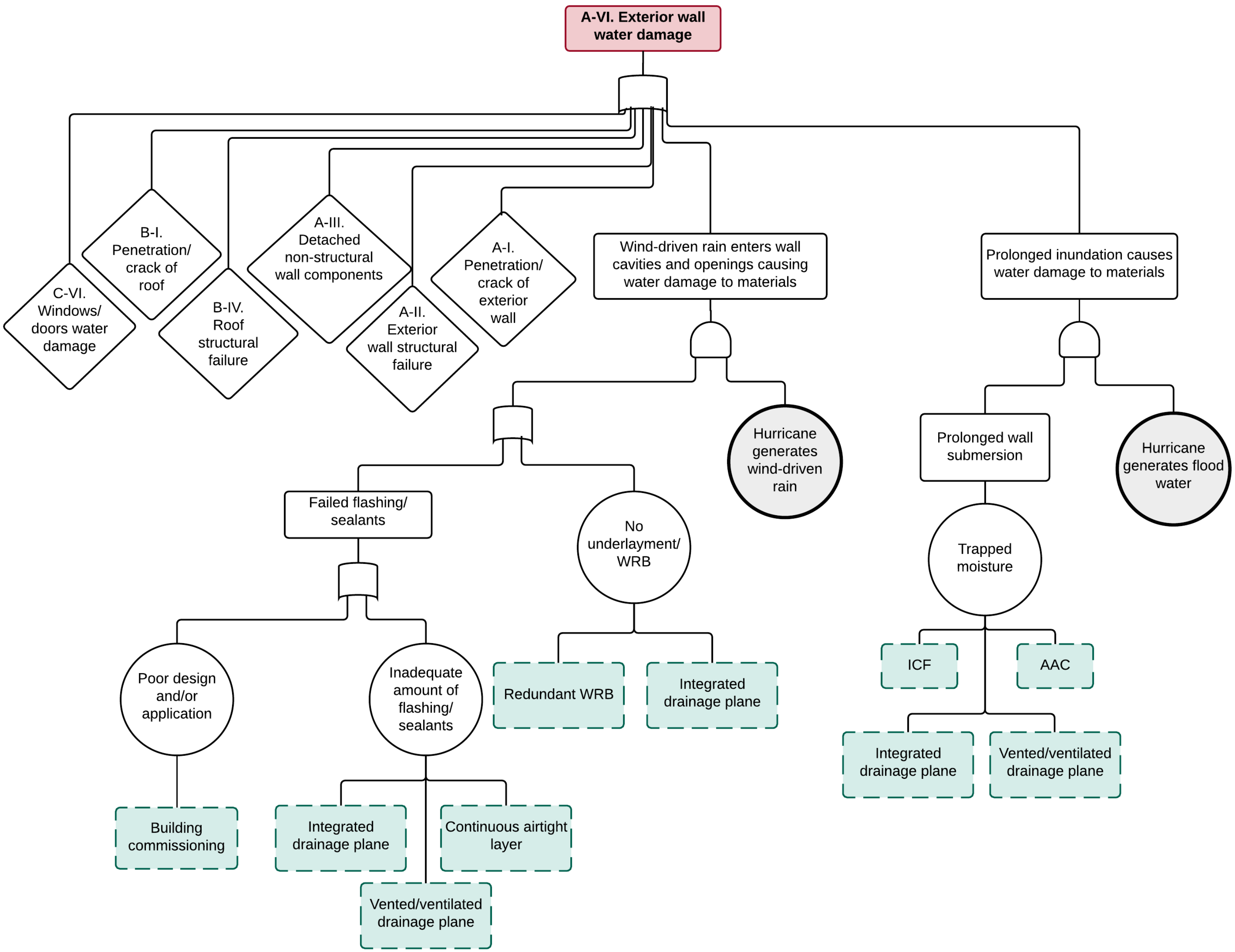


Figure 29 A.VI. Exterior Wall Water Damage FTA diagram

4.4 Summary of Results and Reflection

An analysis of current and future climate conditions for the southeast region of the U.S. was performed. It was found that hurricanes are one of the most prevalent and destructive natural disasters that occur in the region, and it is anticipated that they will become more frequent and stronger in the future as the climate continues to change. Hurricane hazards were used as a basis to identify and evaluate high-performance building technologies for residential building enclosures that can simultaneously offer enhanced building performance and disaster resilience to the hazards that hurricanes are comprised of. Several high-performance building standards were reviewed, and an inventory of HPRB enclosure technologies was extracted. This HPRB technology inventory includes viable candidates that can be implemented as solutions for the potential impacts hurricanes can have on enclosure systems. FMECAs and FTAs were performed to uncover common failure modes, and their causes and effects as a result of hurricanes interacting with residential enclosure systems. The criticality of each failure mode was quantified, and where possible, HPRB technologies were assigned as potential solutions to the root causes identified for each failure. Where HPRB technologies were not available to address certain failures, the opportunities for such technologies have been revealed. Figure 30 presents a diagram summarizing the work and results of this chapter, which corresponds to Objective A.

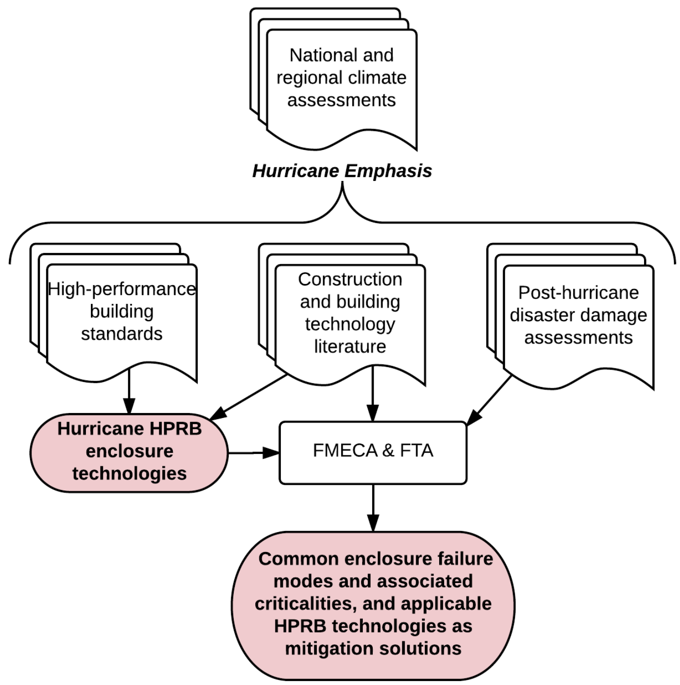


Figure 30 Summary diagram of Objective A work and results

The performed hurricane impact analyses have identified and evaluated important data towards assessing the impacts that hurricanes can have on residential building enclosure systems in hurricane prone locations. An evaluation of several high-performance building standards identified enclosure technologies that can potentially increase residential building performance while at the same time provide higher levels of resilience to hurricanes.

The results from these tasks alone can be beneficial to decision-makers seeking quick, condensed, and informative guidance towards understanding what, and how failures can occur to enclosures during hurricanes, and how to mitigate the potential of hurricane damage to residential buildings. However, this information can be made even more useful in conjunction with a cohesive process that considers additional factors associated with natural hazard risk, such as local and household vulnerabilities. In addition to this, prioritizing the identified HPRB technologies in this task for homes, which considers specific vulnerabilities that make the risk of certain building component failures more of a concern, would enhance this decision-making process. This integration and evaluation is explored in upcoming sections.

5 Attributes and Metrics of High-Performance and Disaster Resilience

The HPRB technologies that have been identified for subsequent prioritization according to context specific risks, offer various benefits in terms of increasing building performance and resilience. However, the potential benefits offered by each technology can vary greatly (e.g. a primarily energy oriented technologies vs. durability oriented technologies), and implementing such technologies on different buildings can lead to diverse outcomes as a result of differentiations in planned or existing construction features and quality. Therefore, in order to comparatively evaluate and compare the overall building performance and resilience of homes, it necessitates metrics that distinguish the contributing attributes for each aspect of performance and resilience. This allows for benchmarking and comparisons between dissimilar homes, and additionally permits the quantification of potential improvements, or lack-there-of, when implementing building technologies in efforts to specifically increase both, performance and resilience.

The work and results produced here addressed this need by carrying out a thematic analysis of relevant texts to define attributes used to measure high-performance and resilience specific to the context and goals of this research. Metrics were also defined to quantify each coinciding attribute, which consisted of developing values and weights of importance.

5.1 ATTRIBUTES OF DISASTER RESILIENT HOUSING

The attributes and metrics for measuring the disaster resilience of housing are discussed in this section. The thematic analysis of a purposive sample of texts was performed to identify common attributes communicated by various organizations and stakeholders regarding the definition, requirements, and needs sought after for disaster resilient housing. A total of nine attributes were defined to represent disaster resilience for the residential building context. The research question that guided this thematic analysis was as follows:

"What are the defining attributes of a residential building that is resilient to natural disasters?"

5.1.1 Thematic Analysis Text Sample

To ensure credibility and trustworthiness could be gained for the results produced in the thematic analysis, purposive sampling was used to select the appropriate texts for the sample. To aid in the assembly of this sample, selection criteria were established, which are specific to the aforementioned research question stated for the texts. The criteria set for the sampling were:

(1) Authors or contributors to the texts provide expert input (based upon disclosed knowledge, qualifications, and objectives) on the subject matter of disaster resilience and residential buildings

(2) Texts are related to the built environment, with specific mentions/focus given to residential buildings or communities

Table 15 provides details of the final list of texts included in the sample to identify the attributes of a disaster resilient home. The sample was varied in that it included proposals to increase the resilience of housing, scientific discussion in literature, and developed standards of construction for resilient housing.

Table 15 Disaster resilient housing text sample

Text	***Description***	***Criterion Sampling Compliance***
FORTIFIED Home™ - What is FORTIFIED? (IBHS 2014; IBHS 2014)	Describes the standard that is used to design and strengthen new and existing homes to reduce potential damage from natural hazards such as hurricanes.	(1) The IBHS, which is the organization that developed the FORTIFIED building standard, conducts scientific research to increase and promote the natural disaster resilience of residential buildings. (2) FORTIFIED Home is specifically focused on residential construction.
A Stronger, More Resilient New York – Buildings pg.78-86 (ORR 2013)	A comprehensive plan of initiatives created by the city of New York to combat climate change and increase the city's resilience and sustainability.	(1) The report was created by the New York City Mayor's Office of Recovery and Resilience (ORR), which is an organization established to guide the city towards greater resilience. Additional contributors to the plan included individuals from government agencies, public officials, and the general public in NYC. (2) Increasing the resilience of homes and communities are topics of focus in regards to the proposed initiatives.
Resilient Design Institute (RDI) – Resilient Design Principles and Resilient Design Strategies (RDI 2015)	Principles of resilience and design strategies to achieve resilience in the built environment.	(1) RDI is an organization consisting of experts in the design and construction of buildings, resilience, and high-performance building. Their mission is to create solutions that can enable buildings to survive and thrive against natural disasters, climate change, and other disruptive threats to the built environment. (2) Resilience of buildings at the community scale and individual building scale are addressed.
The City Resilience Framework (ARUP 2015)	A literature review, case study, and fieldwork based framework developed to understand the drivers of resilience in cities (ARUP 2014)	(1) The authors, Arup International Development, is an organization of experts for sustainable building, resilience, and disaster response for systems encompassed in cities (e.g. infrastructure and buildings) (ARUP 2015). (2) Focus given to the built environment and its contents, such as households.
Building Resiliency Task Force (Urban Green Council 2013)	Proposals and strategies for increasing the resilience of buildings impacted by Hurricane Sandy.	(1) The taskforce that assembled the report consisted of over 200 contributors who are leading experts in their fields and focused on improving the resilience of buildings as a main objective. This included architects, engineers, contractors, and building codes consultants. (2) Specific focus given to residential buildings (multi-family and single-family homes).
Housing in America: Integrating Housing, Health, and Resilience in a Changing Environment (Mcllwain et al. 2014)	Report exploring how housing responds to extreme weather events, and the need for greater resilience to such events.	(1) Urban Land Institute's Terwilliger Center for Housing assembled the report. The Center conducts research and provides technical assistance for a wide range of topics and needs related to housing in the U.S. This report was focused on housing and community resilience to a changing climate. (2) Focus is specifically on housing.

5.1.2 Disaster Resilient Housing Attributes

The texts included in the sample were coded by going through relevant excerpts selected from each. The identified excerpts were reviewed more than once to ensure codes were not overlooked or made in error. Excerpts varied in length and in the amount of codes developed, with some containing only one code, and other containing two or more. Examples of excerpts taken from the texts include the following:

> *"Resilience is the capacity to adapt to changing conditions and to maintain or regain functionality and vitality in the face of stress or disturbance. It is the capacity to bounce back after a disturbance or interruption. At various levels —individuals, households, communities, and regions — through resilience we can maintain livable conditions in the event of natural disasters, loss of power, or other interruptions in normally available services Relative to climate change, resilience involves adaptation to the wide range of regional and localized impacts that are expected with a warming planet: more intense storms, greater precipitation, coastal and valley flooding, longer and more severe droughts in some areas, wildfires, melting permafrost, warmer temperatures, and power outages. Resilient design is the intentional design of buildings, landscapes, communities, and regions in response to these vulnerabilities. As used by the Resilient Design Institute, resilient design focuses on practical, on-the-ground solutions."* (RDI 2015)

> *"Backup power should be a part of any resiliency plan… Providing enough backup power for full operation during a blackout can be expensive, so owners will need to prioritize their backup power uses so that basic safety and sanitation needs are addressed first. When installed, onsite power should be designed to be available during blackouts. Choosing the right backup power source for reliability and cost-effectiveness means considering power sources that run continuously, such as cogeneration units or solar, increasing the chances power will work when the grid fails. To avoid reliance on potentially unreliable fuel deliveries during an emergency — and to reduce cost and air pollution — natural gas may be a better choice than diesel fuel. Emergency generators are currently required to power heavy loads and to start up with."* (Urban Green Council 2013)

> *"Sustainable design and construction constitute a cornerstone for developing healthy and resilient communities. To maximize its ability to mitigate the impacts of climate change and withstand future extreme weather events, housing must be designed to be resource-efficient and durable. Resource-efficient housing uses green design and construction techniques and is optimized to reduce energy and water use, thereby lowering utility bills for building occupants. On-site renewable generation can provide reliable power supply in the event of grid failure. Furthermore, durable housing is not only designed to withstand extreme weather events, but also consciously constructed to be geographically sensitive to anticipated impacts of climate change."* (Mcllwain et al. 2014)

A total of 134 codes were identified from all of the reviewed texts. Each code was then grouped into one or more common themes (later re-named sub-attributes). A code could be grouped into more than one theme in cases where the code contained multiple meanings. For example, the following code: "*Alternative strategies in place and ready to be implemented to speed up recovery processes*", was grouped into three themes based upon the meaning interpreted from the coded excerpt, which were: 1) resourceful in times of need, 2) provides backup or failsafe resources or technologies/strategies, and 3) quicker recovery time. The identified themes were then compiled under nine larger attribute labels. These nine attributes came to represent the final list of disaster resilient housing attributes. Table 16 lists each identified attribute and their sub-attributes from the coding process. The number of codes grouped under each sub-attribute is also listed the table to show the prevalence of certain themes that arose within the texts reviewed.

Table 16 Disaster resilient housing thematic analysis attributes

Disaster Resilient Housing Attributes	***Sub-Attributes***	***Number of Codes***
Recovery	Returns to normalcy or better quality following a shock/stress	8
	Quicker recovery time	7
Robustness	Enhanced durability and resistance to shocks/stress	35
	Maintains functionality during shocks/stresses	4
	Keeps conditions habitable during shocks/stresses	12
	Enhanced protection and/or sheltered away from the exposure to shocks/stresses	23
	Reduces the severity of impacts (e.g. damage, cost)	13
Redundancy	Provides backup or failsafe resources or technologies/strategies	21
	Does not rely solely on the grid, non-renewable and/or non-local resources to function	12
Resourcefulness	Resourceful in times of need	10
Adaptivity	Adapts to sudden shocks/stresses and short- or long-term changes	20
	Learns from previous experiences to improve	4
Energy Efficiency	Efficiently uses and distributes energy	11
Resource Efficiency	Reduces or does not cause harm to the environment	9
Simple	Simple operation, control, and repair	5
Complementary	Encompasses and is associated with comprehensive and/or collaborative strategies to reduce vulnerabilities	4

Attribute Descriptions

Recovery:

The ability to *Recover* was the first attribute identified, and it has been defined here as:

The ability to bounce-back (i.e. return to normalcy) or -forward (i.e. improve beyond normalcy) following a sudden shock/stress that alters typical performance, and do so with a quicker rate of recovery than what is typically expected.

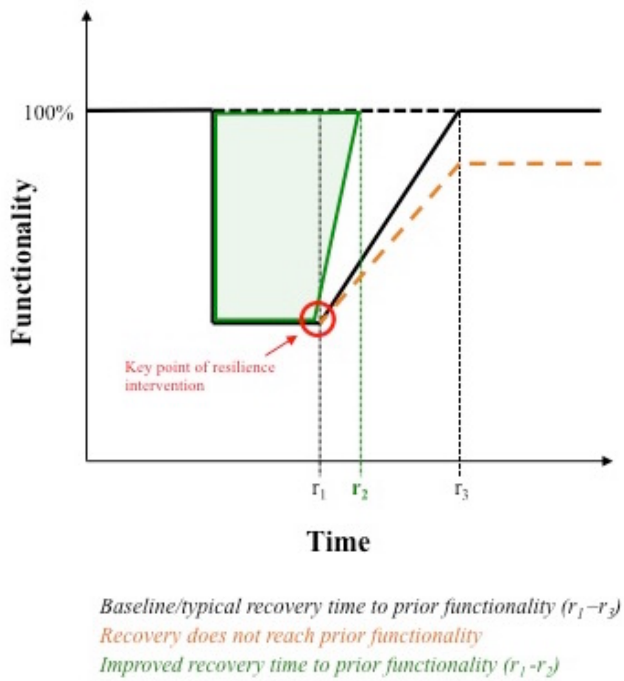


Figure 31 Improved recovery time to prior functionality

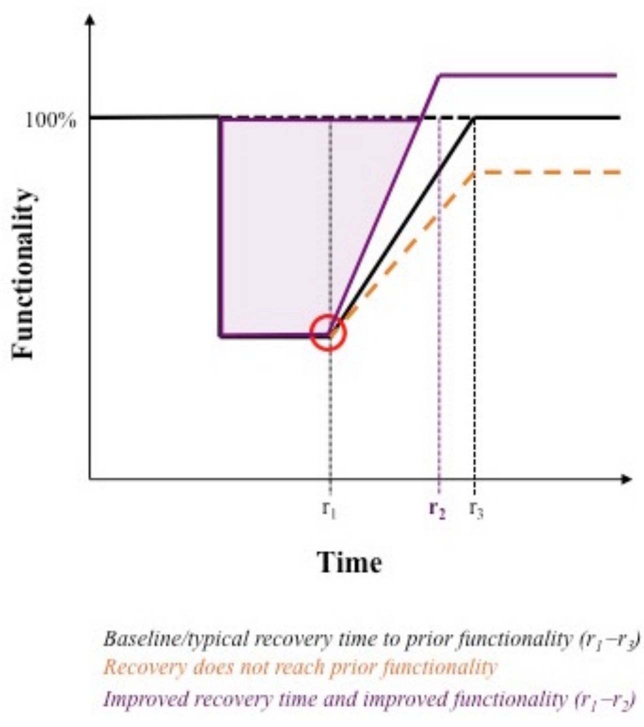


Figure 32 Improved recovery time and improved pre-impact functionality

This definition describes several aspects that can occur with a resilient recovery. The first, and perhaps most apparent aspect, is a reduction in the typical recovery time to pre-event functionality. Figure 31 depicts this characteristic of a resilient recovery. From here on out, a **red circle** is used to highlight key points in figures at which **a resilience intervention** takes place. For the recovery attribute, this takes place where the recovery process begins, as the recovery time is the altered aspect. The black line represents the recovery path of a typical or baseline performing home if it was impacted by a sudden shock or stress. This typical recovery track returns to prior functionality, however, it is also likely that a complete recovery is not attainable, which is represented by the orange dashed line. In comparison to this, the green shaded area represents a resilient recovery, where a home bounces back to pre-impact functionality at a faster rate of recovery. Figure 32 illustrates some additional aspects of a resilient recovery that can occur. In comparison to the baseline recovery, a resilient recovery cannot only improve at a quicker rate, but it can additionally improve to a better state than the pre-impact functionality as shown by the shaded purple areas. This is essentially the ability to "bounce-forward" rather than "bounce-back" by essentially improving a system's robustness (see next attribute).

An example of a resilient recovery using an HPRB technology is a vented/ventilated drainage plane. The use of this technology can provide an enhanced ability to dry out faster than that of an unventilated exterior wall following heavy wind-driven rain exposure. After the wall has been able to recover to pre-impact functionality, additional steps can be taken to further increase its capacity to dry out or reduce the walls exposure to wetting. This can involve upgrading the system in response to areas of weakness found (e.g. weakened sealants, or missing flashing) as a way to improve pre-impact functionality.

Robustness:

The second attribute of disaster resilient housing identified was *Robustness*, and it has been defined here as:

The improved ability to withstand an impact that reduces the overall severity of an event.

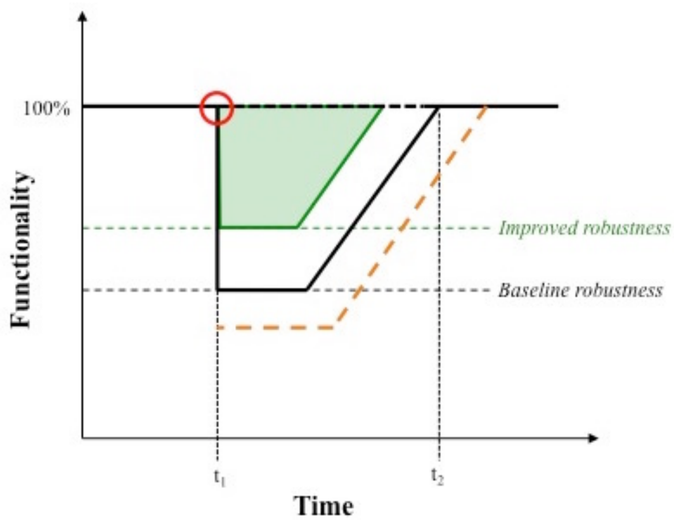


Figure 33 Improved robustness to an impact

The key aspect of robustness as depicted in Figure 33, is the decreased severity of an impact as indicated by the increase in maintained functionality following an impact. This coincides with a reduction in the necessary repair/recovery to restore pre-impact performance. The key point of resilience intervention for resilient robustness occurs at the point of impact, where steps have been taken prior to a disruptive event to mitigate the severity of potentially harmful effects. The green shaded area in comparison to the area for baseline robustness (black line) as well as the robustness that is below baseline levels of performance (orange dashed line), is less, which illustrates that the ability to better withstand or resist impacts can reduce damage, recovery time, and associated costs, among other disruptions it could cause to homeowners and building performance. Enhancing the robustness of a system can be done in many ways, and for this reason it can be considered to be one in the same as durability, which is also very multi-faceted, especially in respect to housing and the many performance influences that exist for it.

An HPRB technology that represents resilient robustness is insulated concrete forms (ICF). For example, in comparison to traditional wood framed exterior walls, ICF walls offer significantly more robustness in terms on an increased resistance to wind pressure loads, a better ability to withstand faster and larger debris impacts, and additionally, superior water resistance qualities that reduce the likelihood of damage that can occur from the exposure to moisture.

Redundancy:

The third attribute of disaster resilient housing identified was *Redundancy*, and it has been defined here as:

Having backup or failsafe technologies/strategies in place as an alternative means of maintaining functionality and/or accessing critical resources.

Redundant technologies in place to prevent the complete loss of functionality can increase the resilience of a system, and this can occur in various ways with differing levels of effectiveness. This specifically refers to influences on the amount of resilience that can be achieved as a result of when a redundant technology mobilizes, and to what level of functionality can be maintained by the technology upon mobilization. Figure 34 illustrates the level of resilience that can be attained in two examples of redundant technologies that are mobilized after some time has passed following an impact that results in the complete loss of functionality. As depicted in these examples, a redundant technology that mobilizes some time after an initial impact and restores partial functionality, can amount to less resilience than that of a redundant technology that similarly mobilizes with a delay, but is able to restore full functionality until a complete recovery has occurred.

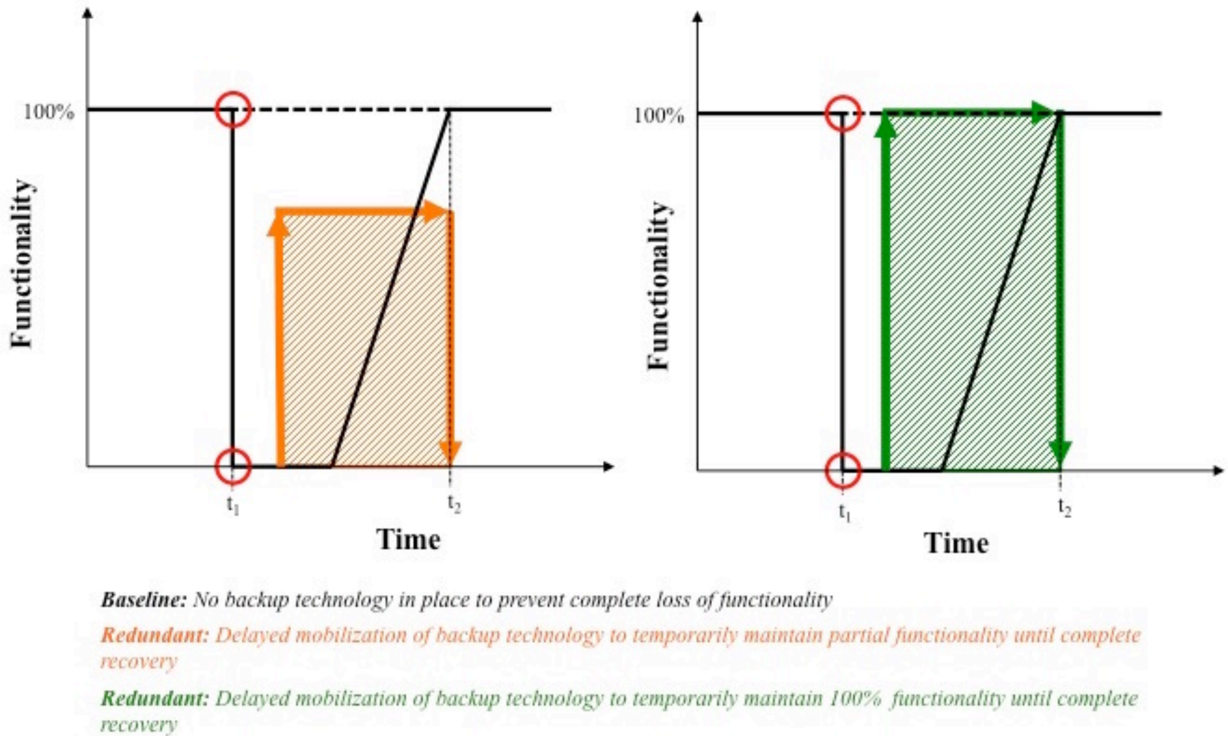


Figure 34 Delayed mobilization of redundant technology

In contrast to the redundancy examples presented in Figure 34, Figure 35 illustrates additional levels of resilience that can be attained if redundant technologies are able to mobilize immediately following an impact that causes a complete loss of functionality. As shown in Figure 35, even if a technology were to restore and maintain only partial functionality, the amount of resilience that can be achieved can surpass that of a technology that were to mobilize on a delay and maintain partial or even complete functionality. Additionally, there are redundant technologies that can mobilize immediately and restore complete functionality until recovery takes place as shown in the right diagram of Figure 35.

It is important to note that the amount of resilience that can be obtained in each of the redundancy scenarios presented can vary, with more or less levels of resilience being possible in each when simply comparing the patterned/shaded areas in each figure (i.e. the shaded areas enclosed by the colored arrows in the redundancy figures represents the amount of functionality maintained). However, the important aspects of comparison to consider for redundancy as discussed here should be, 1) the time it takes for the redundant technology to mobilize (e.g. delayed or immediate), and 2) the amount of functionality that can be restored and/or maintained until complete recovery has occurred (e.g. partial or full). It can be generally assumed that the immediate mobilization of backup technologies, and/or fully restored and maintained functionality, is the most favorable scenario.

A redundant weather-resistant barrier (WRB) is an example of resilient redundant qualities found in an HPRB technology. If the first WRB layer inside a wall were to unexpectedly fail, the backup WRB layer is in place to immediately mobilize and maintain functionality of the enclosure system.

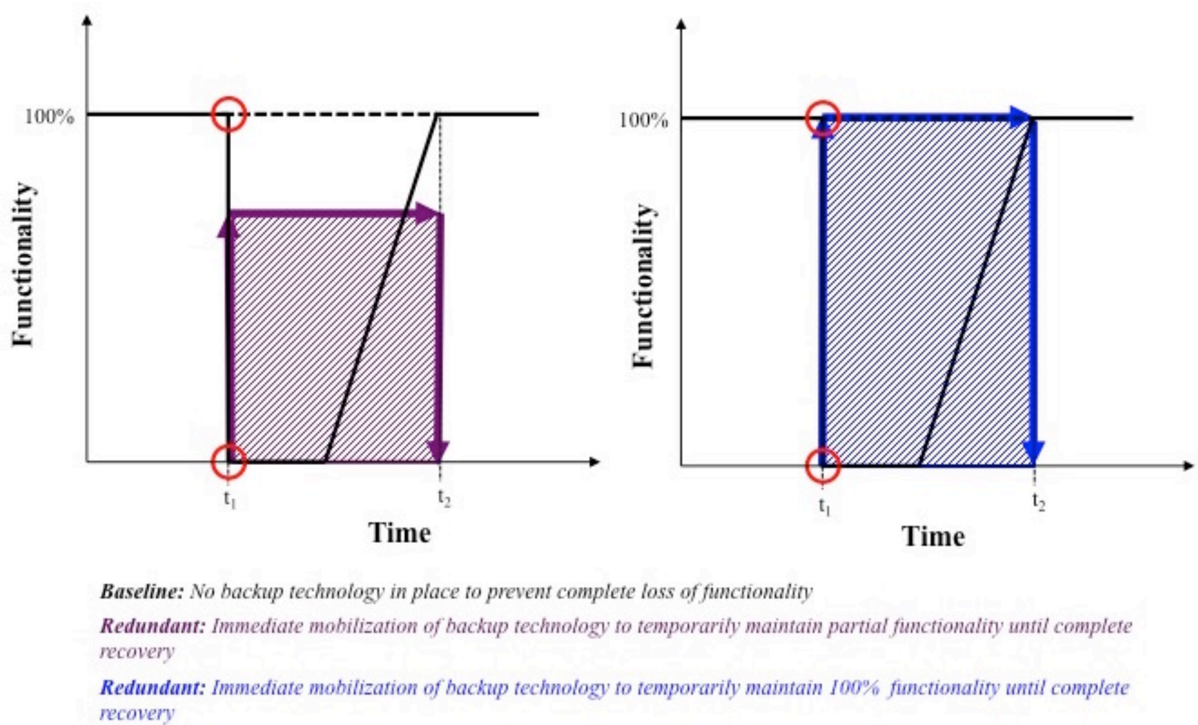


Figure 35 Immediate mobilization of redundant technology

Resourcefulness:

The fourth attribute of disaster resilient housing identified was *Resourcefulness*, and it has been defined here as:

Having resources readily available in times of need, and the ability to prepare for and anticipate an event by reorganizing and implementing resources as needed.

Mobilization time towards the start of the recovery process is one the main aspects of *Resourcefulness* that is influenced here by this attribute of resilience. As shown in Figure 36, the key point of resilience intervention can take place after an impact has occurred. Here, the mobilization time for technologies or resources to reduce the downtime that takes place prior to the start of recovery is altered to allow for a quicker recovery to pre-impact functionality. Another key point of resilience intervention for *Resourcefulness* can be prior to an impact. As illustrated in Figure 37, anticipating, and thus preparing for an impact, which has similarity to robustness, but it contributes to a reduction in the severity of an impact

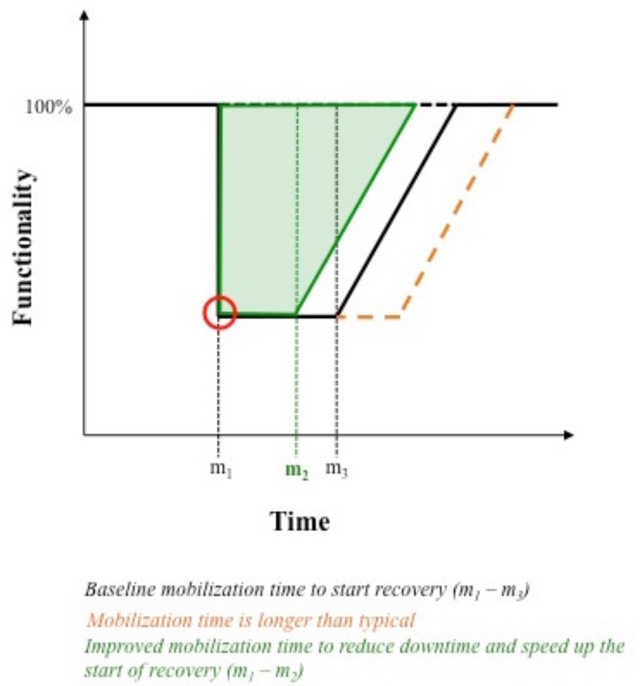


Figure 36 Resourcefulness improves mobilization time to speed up typical recovery

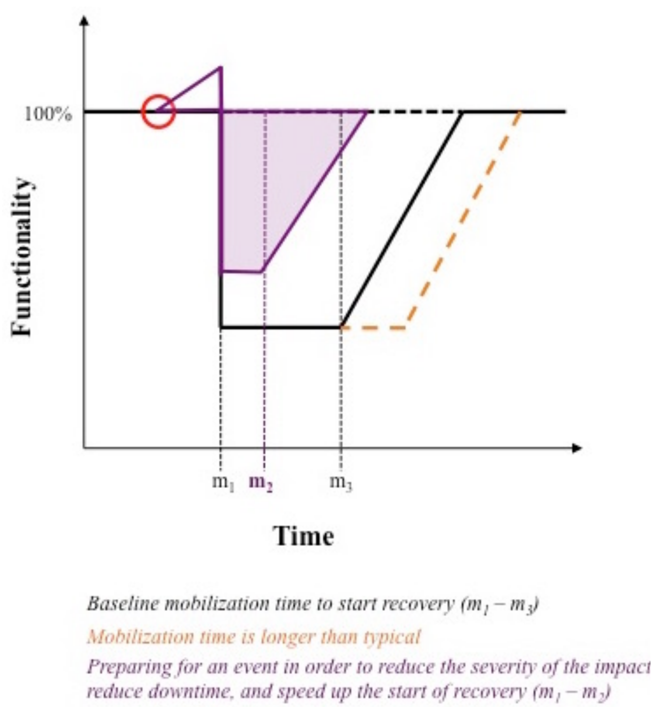


Figure 37 Resourcefulness allows for preparedness in order to reduce severity and improve mobilization time

that reduces loss of functionality by mobilizing resources more quickly (e.g. even before the disaster strikes as part of a preparation plan) to make the ultimate recovery process start and complete sooner.

As discussed with redundancy, having a diversity of backup resources and technologies readily available to implement during times of critical need is highly dependent on the ability to mobilize such technologies in a timely manner. In doing so, it also has the potential to benefit the recovery process.

Resourcefulness can be demonstrated with a damaged enclosure system. For example, should exterior walls become damaged by debris and require repair, having materials available that can be sourced quickly and locally as a way to maintain resource efficiency could contribute to a faster recovery start time in comparison to essential resources being unavailable locally.

Adaptivity:

The fifth attribute of disaster resilient housing identified was *Adaptivity*, and it has been defined here as:

The ability to improve with experience by appropriately reflecting on, then adapting performance during and/or following an event in order to better withstand current and future impacts.

Adapting involves the ability to learn from experience in order to improve performance. This ability is termed hereafter as “reflective learning”. As represented in Figure 38, when reflective learning is implemented following or during an event that causes a loss of functionality necessitating a recovery process to occur, using this experience and reflection to make appropriate temporary or permanent adaptations to the performance of a system can reduce the severity of current and anticipated impacts to the same system. Additionally, permanently adapting performance can lead to the alteration of current design/damage limits in an effort to accommodate more severe impacts anticipated in the future and ensure that functionality can be recovered.

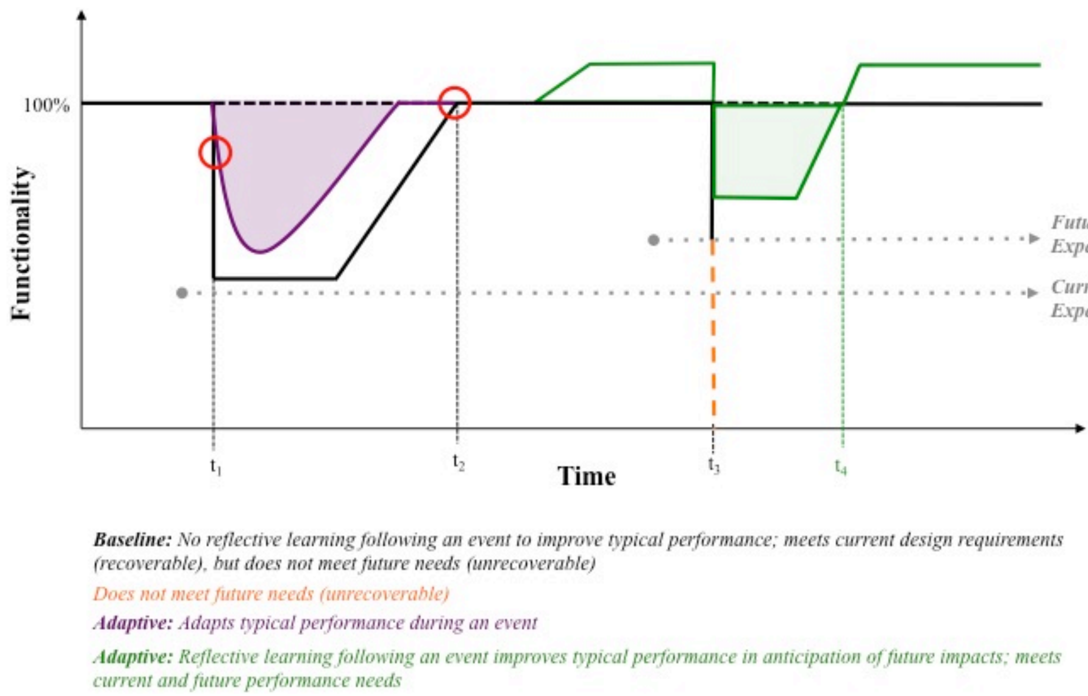


Figure 38 Reflective learning adapts performance to anticipate future impacts and ensures functionality is recoverable

Retrocommissioning (RCx) is an HPRB technology that exemplifies adaptive qualities. RCx strategies can enhance and alter the performance of various building systems to ensure functionality is updated and operates as desired. For example, a RCx survey of a building following a period of severe weather could identify that various building technologies no longer meet current code requirements due to the year the home was constructed or because of damages incurred. Retrofitting the home to correct such shortcomings is not only an opportunity to adapt the existing building to current requirements, but it can additionally be the chance to exceed standard code levels with other HPRB technologies.

Energy Efficiency:

The sixth attribute of disaster resilient housing identified was *Energy Efficiency*, and it has been defined here as:

A reduction in energy consumption needs by means of efficient use, production, and/or distribution.

Energy Efficiency was identified as an attribute of resilience as it provides a way to reduce the reliance on energy intensive mechanical systems and prioritize energy use effectively, especially in times of need. A resilient home should have lower annual energy consumption per square foot when compared to non-resilient or typical code constructed homes. This energy consumption comparison should take into account the energy demand, as well as any energy that may be produced on site to off-set external energy supply. Additionally, being able to conserve and/or distribute energy to critical systems in a home, or even throughout the local community, in the event of power failure or grid disconnection, is a characteristic of *Energy Efficiency* that contributes to resiliency, as it contributes to keeping spaces habitable.

An HPRB technology that contributes to *Energy Efficiency* is continuous insulation. This technology can increase the thermal performance of an enclosure by reducing unintended air leakage, break thermal bridges, and reduce the u-value of the entire assembly. A comprehensive layer of continuous insulation on the enclosure should reduce the annual energy consumption of a home, and reduce the need for large energy intensive heating and cooling equipment to achieve desired interior comfort.

Resource Efficiency:

The seventh attribute of disaster resilient housing identified was *Resource Efficiency*, and it has been defined here as:

A reduction in greenhouse gas (GHG) emissions associated with construction materials and processes.

Similar to energy efficiency, reductions in the use of resources (e.g. material quantities, and the increased use of recycled and/or local resources) increases the potential for homes to be self-sustaining, and they are also more material and cost efficient to construct and/or reconstruct. *Resource Efficiency* can involve requiring fewer materials and/or processes to manufacture, construct, and operate a building, and similarly use less material to rebuild or repair damaged systems that may have been exposed to severe weather. Additionally, by using locally sourced and renewable resources in lieu of non-renewable resources to construct and operate a building, it contributes to a home's potential to maintain functionality should non-renewable resources become scarce or depleted. Therefore, a home with a lower carbon footprint is more resilient than homes with larger footprints.

Advanced framing is an example of a resource efficient HPRB technology. This technology eliminates non-essential materials from the enclosure in order to reduce the resources required for the construction of a home as one of its key benefits.

Simple:

The eight attribute of disaster resilient housing identified was *Simple*, and it has been defined here as:

Technologies are simple to operate with the ability to be manually overridden if necessary, and repair is not complex.

The ability to control and repair a technology with minimal complexity can contribute to better recovery times, faster mobilization of resources, a readiness to more easily adapt performance, and/or an increased potential to maintain functionality following a hazardous impact. The attribute of *Simplicity* could include strategies such as overriding mechanical controls when necessary with passive systems such as ensuring that windows remain operable in the event of mechanical system failures; or making sure that building occupants and installers are properly educated and familiar with how to operate and maintain the technologies installed within a home during normal conditions, and in the event of a severe weather.

Complementary:

The ninth and final attribute of disaster resilient housing identified was *Complementary*, and it has been defined here as:

Technologies/strategies are connected, integrated, and/or comprehensive in reducing vulnerability and increasing resilience.

This definition is broadly termed *Complementary*. *Complementary* technologies and systems can ensure that multiple threats are addressed simultaneously at multiple scales. At the building scale, this interaction between building technologies makes sure that they do not impede on the performance or intended purposes of one another in a way that could result in a decreased resilience to various hazards, but rather increase resilience. Commissioning during the design and construction phases for a building could address such issues that could arise in regards to unfavorable interactions between technologies that increase vulnerability to various hazards not otherwise considered.

5.1.3 Disaster Resilient Housing Metrics

Evaluating a home for disaster resilience using the identified attributes from the thematic analysis required the definition of metrics to coincide with each attribute. Each attribute metric was also assigned a range of values in order to subsequently quantify resilience in evaluations. The metrics defined here are based upon norms or established methods for quantifying each attribute as to remain consistent with industry standards. However, where existing metrics could not be found to coincide with the remaining attributes identified, they have nevertheless been defined accordingly for the definitions devised in this research, and background support and/or expert judgment has been provided where possible at this stage of the research for the proposed metrics. Weights of importance for each attribute have also been developed, as a way to prioritize each attributes contribution to the overall disaster resilience of a home.

Attribute Metrics and Values

The metrics and values determined for each attribute are listed in Table 17. Detailed explanations as to how each metric and the coinciding values were determined follow this table. The ranges of values are used to quantify the level of resilience that can be obtained in each attribute. The range is typically between 1-5, and in one case, between 1-2. When the range of values is between 1-5, a value of 1 represents "poor resilience" and is below typical building code compliant or standard new residential construction; 2 represents "fair resilience" for standard new construction, which can be considered here as baseline construction; 3 represents "good resilience"; 4 represents "very good resilience"; and 5 is "excellent resilience", which is the best level of disaster resilience that can be achieved out of the available range. In some cases, numbers between the value range have been omitted (e.g. 1, 3, 5 or 1, 3, 4, 5), this was because the metric did not currently require additional variation of levels to quantify the attribute, or further elaboration could not be completed at this time to reasonably represent meaningful variations in disaster resilience that can be achieved beyond the range presented.

Table 17 List of disaster resilient housing attributes, metrics, and values

Attributes	***Metrics***	***Values***	
Recovery	**Recovery/ Repair Time**	**1**	Unrecoverable or > typical recovery time
		2	Typical recovery time
		3	10-25% < typical recovery time
		4	Over 25% < typical recovery time
		5	Over 10% < typical recovery time and exceeds pre-impact performance
Robustness	**Strength Design Loads/Limit States**	**1**	< Design load requirement
		2	Meets design load requirement
		3	10-20% > design load requirement
		4	21-30% > design load requirement
		5	Over 30% > design load requirement
	Water Control & Drying Capacity	**1**	Can withstand or manage minimal levels of wetting and/or the onset of moisture damage
		3	Can withstand or manage moderate levels of wetting and/or the onset of moisture damage
		5	Can withstand or manage excessive levels of wetting and/or the onset of moisture damage
	Estimated or Remaining Useful Life (EUL or RUL)[a]	**1**	< 10 years (very short)
		2	10-25 years (typical)
		3	26-40 years (medium-long)
		4	41-50 years (long)
		5	50+ years (very long)
Redundancy	**Backups**	**1**	No backups in place
		2	Delayed mobilization of backup to restore and maintain partial functionality
		3	Delayed mobilization of backup to restore and maintain full functionality
		4	Immediate mobilization of backup to restore and maintain partial functionality
		5	Immediate mobilization of backup to restore and maintain full functionality
Resourcefulness	**Pre-Recovery Mobilization Time**	**1**	> Typical mobilization time
		2	Typical mobilization time
		3	10-25% < typical mobilization time
		4	Over 25% < typical mobilization time
		5	Pre-event preparedness reduces impact severity, and mobilization time is over 10% < than typical
Adaptivity	**Reflective Learning Behaviors**	**1**	Does not adapt typical performance
		3	Adapts typical performance to reduce impact severity by 10-20%
		4	Adapts typical performance to reduce impact severity by 21-30%
		5	Adapts typical performance to reduce impact severity > 30%
Energy Efficiency	**Energy Use Intensity (EUI)**	**1**	Over 5% > local EUI average
		2	Equals +/- local EUI average
		3	10-20% < local EUI average
		4	30-40% < local EUI average
		5	Over 40% < local EUI average

[a] Range of years should be adjusted appropriately by the evaluator to reflect the specific building/component or material being evaluated

Resource Efficiency	**Equivalent Carbon Dioxide (CO_2e/ft^2)**	**1**	Over 5% > local CO_2e/ft^2average
		2	Equals +/- local CO_2e/ft^2 average
		3	10-20% < local CO_2e/ft^2 average
		4	30-40% < local CO_2e/ft^2 average
		5	Over 40% < local CO_2e/ft^2 average
Simple	**Complexity**	**1**	Operation, installation or repair/maintenance requires additional education; system operation cannot be manually overridden
		2	Operation, installation or repair/maintenance is readily accessible; system operation can be manually overridden
Complementary	**Interaction**	**1**	Technologies/systems reduce the resilience of others
		3	Technologies/systems have no impact on the resilience of others
		5	Technologies/systems increase the resilience of others

Recovery/Repair Time:

As construction is commonly scheduled by tasks that take place over a unit of time (e.g. hours, days, or weeks), the same logic for using time was applied to measure the *Recovery* attribute of a building or system in regards to the reconstruction/repair tasks required to restore or improve pre-impact functionality. Values were set in between the range of being unrecoverable, recovering at a rate below what is typically expected, up to recovering at a rate that is 10-25% or more quicker than what is typically expected. Additionally, a higher level of disaster resilience can be achieved if recovery includes an improvement beyond prior pre-impact functionality (i.e. bounce-forward).

Repair Time should be based upon various performance aspects of a system in regards to the type of hazard impact, the extent of damage experienced, as well as access to critical resources such as labor and materials that can influence the effort and time needed for recovery and repairs. When evaluating recovery, it may also require consultation with local repair contractors to gain accurate recovery time estimates in order to make informed decisions.

Strength Design Loads/Limit States:

When measuring the *Robustness* attribute, it is assumed here to be one in the same as durability, which consists of many factors important to maintaining sufficient building performance and expected functions during an items service life. While remaining focused on disaster resilience to climate hazards, the sub-attributes currently used to measure residential building *Robustness* here include: *Strength to Resist Design Loads, Water Control and Drying Capacity*, and *Estimated Useful life* of a building and its components. This is consistent with other interpretations of durability, where evaluations consider various physical environmental factors, such as water and wind, which can lead to the deterioration of a building; and the general estimation of expected service life while accounting for factors such as quality, material properties, and environmental exposure (Yu and Bull 2006).

A strength, or ultimate, limit state, which is commonly used in structural design, refers to the amount of strength required to resist certain loads in order to avoid damage or failure to perform expected functions (Paik and Thayamballi 2003). This requires various elements to be designed to resist certain loads (i.e. design loads) to avoid surpassing the limit state. Similar to structural components of a building, non-structural building components also have design loads prescribed in building codes that they must meet to resist potential failure from various hazard loads such as wind pressure.

Depending on the applicable building code provisions, and the type of hazard that causes an impact on functionality (e.g. debris deformation, wind pressure deflection, etc.), design loads can be used to measure strength durability for wind pressure or debris impact resistance requirement. Designing beyond the minimum load requirements can increase the Robustness of a system by improving its ability to withstand larger impact loads.

Water Control & Drying Capacity:

Evaluating water infiltration and exposure requires a comparison of the presence and/or effectiveness of water control methods, and the drying capabilities of building components This will depend on various performance aspects of building components and assessing extra measures taken to enhance moisture durability, such as evaluating wall materials, configuration, and the specific moisture control/drying strategies used such as drainage, evaporation, mass storage, or wall or floor elevation. Building science fundamentals of moisture transport, and the use of modeling tools (e.g. hygrothermal simulations such as WUFI) can be used as an aid for this evaluation, which may also require a considerable amount of expert judgment.

An example of enhancing *Robustness* in this attribute can include implementing a combination of the ENERGY STAR moisture management checklist, advanced moisture management technologies (e.g. ventilated cavities or enhanced moisture resistance materials), or designing a foundation for extreme flood events, can qualify as beyond minimum code requirements.

Estimated or Remaining Useful Life (EUL or RUL):

The EUL can be used to give an overall estimation for the life expectancy of building materials and components in calendar years. Various sources or methods can be used to determine the EUL of a building component, which can include historical or professional judgment, manufacturers specification, independent organization evaluations, or government data sources. For example, Lstiburek (2006) lists some EULs for various building enclosure elements such as shingles, OSB, brick, and flashing based upon their exposure to different climates, generic material properties, and past experience assessing durability. Fannie Mae also provides EUL tables that can be used to aid property condition assessments when estimating the remaining useful life (RUL) of building components for existing properties, which would require considering other factors that have influenced the durability of the component during the course of its elapsed lifetime so far (Fannie Mae 2014).

The range of years currently presented here in Table 17 for each value is based upon a preliminary review and consideration of EUL estimates for typical materials used to construct enclosure components of a home. However, these value ranges will vary and can be adjusted based upon the local climate, building age, experience of the building evaluator, and the building components being assessed. It was found that frequently installed building enclosure materials with the lowest EULs are estimated to last between 10-25 years (InterNACHI 2015; Lstiburek 2006; NAHB 2007), which was used to establish a current baseline value. Increasing certain qualities of building materials, installation, maintenance, and the configuration of enclosure components can increase durability and subsequently the EULs.

Backups:

Similar to its use in reliability engineering as a way to tolerate system faults or failures (National Instruments 2008), the presence and mobilization of an alternative technology or technologies that can provide the same or similar functions by acting as a backup if default/original technologies were to fail, is used here to measure *Redundancy*. This can also include access to resources such as energy or water when grid supplied power or other resource services are disrupted. *Backups* can either maintain partial functionality or complete functionality, and are either implemented immediately or on a delay. A backup system that can provide complete redundancy, in that is mobilizes immediately and maintains full functionality as a buffer while recovery takes place, is considered to provide the highest level of resiliency in regards to *Redundancy*.

Pre-Recovery Mobilization Time:

Time is used here again as it was for the recovery time metric, however, it is now focused on *Pre-Recovery Time*, which is more specifically the time it takes to mobilize a technology or resource before and/or immediately following a shock/stress that aids towards improving the start and duration of the recovery process. This measure of time is used to evaluate *Resourcefulness*. The objective is to implement pre-recovery technologies/resources strategically and in a timely manner in order to reduce adverse impacts such as uninhabitable interiors, and the downtime that takes place before recovery to or beyond pre-event conditions can begin. This should ultimately result in an earlier recovery time, and increased resilience. This evaluation would require a comparison to the typically expected downtime that takes place following an impact before recovery and repairs can begin.

Reflective Learning Behaviors:

Using experience and lessons learned to react or make future plans to adapt the status quo of a system in order to allow for measured changes in performance during or following an event, is used here as a method to evaluate *Adaptivity*. The adapted performance should exhibit signs of improvement in typical pre-impact functionality, impact response, recovery, and/or future functionality with respect to specific current and/or future hazards. Therefore, when using *Reflective Learning Behaviors* to measure *Adaptivity*, the intention is that a system exhibits an adaptive capacity through an ability to change behaviors/performance accordingly, either temporarily or permanently, and that this adaptation has the potential to reduce the severity of an impact. Evaluating how much of a reduction in impact severity can be achieved through such reflective learning behaviors (e.g. such as a physical change in material properties during an event, or a planned retrofit following an event) aids in the quantification of resilience for this attribute.

Energy Use Intensity (EUI):

A common measurement of energy consumption used for buildings is the *EUI*, sometimes also referred to as Energy Usage or Utilization Index, which is the amount of annual energy consumed per square foot of floor area (e.g. $kWh/ft^2/yr$) (ENERGY STAR 2016). EUI is used here as a metric for *Energy Efficiency*. Household EUI data for various locations around the U.S. can be found using sources such as the Energy Information Administration (EIA). If site measured energy usage is not available via monitoring devices, using typical residential EUI data to represent a local baseline average (e.g. county, city, region, or state level) in comparison to the home being evaluated can be used to quantify improvements or shortcomings in energy use. An EUI over 5% higher than the local average is considered non-resilient, while having and EUI over 40% lower is considered highly resilient in regards to the *Energy Efficiency* attribute.

Equivalent Carbon Dioxide (CO_2e/ft^2):

The resulting GHG emissions from various materials and processes associated with the manufacturing, construction, and operation of a residential building can be measured using *CO_2e per square foot*. This is a common metric that has been used when performing life cycle assessments of buildings (Augustsson 2014; Grönvall et al. 2014). An evaluation of the CO_2e/ft^2 for various components associated with a home in different stages of a buildings lifetime in comparison to a typical CO_2e/ft^2 emissions of a standard local baseline home or typical code built home, is proposed to quantify *Resource Efficiency*. This evaluation would require gathering knowledge about the materials and processes (converted into CO_2e/ft^2) used to construct the building being evaluated, as well as for the building being considered as the baseline for comparison. Similar to EUI, the lower the CO_2e/ft^2, the more resilient the system or building is in regards to *Resource Efficiency*.

Complexity:

The amount of additional education required to install, operate, and/or repair technologies (e.g. a contractor's familiarity with the required system repair process, and an occupant's familiarity with system controls and their influences on building performance), and the ability to manually override complex technologies as an alternative means of operation, are both ways to evaluate the *Simplicity* attribute of a system. This evaluation is specific to the capabilities and knowledge of the building occupants and local labor force, as well as the characteristics and presence of active and passive building systems in a home.

Interaction:

Design and construction verification that technology interactions do not impede on the performance of one another in a way that could increase vulnerability and decrease resilience to various natural hazards will be used to measure the *Complementary* attribute. Expert judgment or resources such as FEMA P-798 (Gromala et al. 2010) can be used, which provides a guide useful in the evaluation of building technology interactions in regards to natural hazards that should be considered when selecting and implementing building technologies. For example, increasing the stud spacing in a wall using advanced framing to allow for more insulation could increase thermal performance of the exterior walls if extreme temperatures are a main concern, however, if hurricanes are also a common hazard for the building's location, this could negatively impact the walls structural performance to withstand wind if not properly considered and designed appropriately. Considering this, with only one hazard in mind during an evaluation, a non-resilient score is awarded for the *Complimentary* attribute if technology interactions are found to increase the vulnerability of building components to other hazards, a moderate resilience score if interactions neither decrease nor increase vulnerability, and a high resilience score is awarded if interactions also decrease vulnerability to other hazards.

Attribute Weights

To allow for priorities to be given to various attributes over others when evaluating the disaster resilience of homes, weights can be applied and adjusted for each attribute. Table 18 lists the current default weight values for each attribute, where all the weights are equally distributed among each attribute and sub-attribute. The evaluator can adjust the weights accordingly if higher priority is sought after from one or more attributes. For example, if recovery is considered to be the most important attribute in an evaluation, then it should carry a larger weight than all the other attributes.

Table 18 List of disaster resilient housing attribute weights (currently unadjusted)

Attributes	*Metrics*	*Weights*	*Sub-Weights*
Recovery	Recovery/Repair Time	**0.111**	-
Robustness	Design Loads/Limit States	**0.111**	0.037
	Water Control & Drying Capacity		0.037
	Estimated or Remaining Useful Life (EUL)		0.037
Redundancy	Backups	**0.111**	-
Resourcefulness	Pre-Recovery Mobilization Time	**0.111**	-
Adaptivity	Reflective Learning Behaviors	**0.111**	-
Energy Efficiency	Energy Use Intensity (EUI)	**0.111**	-
Resource Efficiency	Equivalent Carbon Dioxide (CO_2e/ft^2)	**0.111**	-
Simple	Complexity	**0.111**	-
Complementary	Interaction	**0.111**	-
	Total =	**1.000**	

5.2 Attributes of a High-Performance Residential Building Enclosure

Similar to the process undertaken to identify disaster resilient housing attributes and metrics, a thematic analysis of texts relevant to high-performance residential building was performed. A total of nine attributes were defined to represent a high-performance residential building enclosure, where some attributes were also found to overlap with the previously identified disaster resilient attributes. The research question that guided this thematic analysis to identify the attributes was as follows:

"What are the defining attributes of a high-performance residential building enclosure?"

5.2.1 Thematic Analysis Text Sample

Purposive criterion sampling was used again to select an appropriate text sample. The selection criteria for the texts included here were specific to the above-mentioned research question stated. The criteria set for the sampling were as follows:

(1) Authors or contributors to the texts provide expert input (based upon disclosed knowledge, qualifications, and objectives) on the subject matter of high-performance buildings

(2) Texts are related to residential buildings with specific mention/focus given to enclosure system performance

(3) Texts have been used to achieve/support the construction of high-performance building standards or certifications for residential buildings

Table 19 provides details of the final list of texts included in the sample used to identify the attributes of a high-performance residential building enclosure.

Table 19 High-performance residential building enclosure text sample

Text	***Description***	***Criterion Sampling Compliance***
Passipedia – The Passive House Resource (iPHA 2015)	A knowledge database of scientific articles used for the design and construction of Passive Houses	(1) The International Passive House Association (iPHA) develops the Passipedia, which is specific to the high-performance building standard Passive House. The iPHS consists of a global group of architects, planners, scientists, suppliers, manufacturers, contractors and property developers who promote, disseminate, and advance knowledge about the Passive House standard worldwide (iPHA 2015). (2) The Passipedia includes articles specific to the design and construction of a Passive House building enclosure components. (3) Passipedia coincides with the Passive House standard, which is a certifiable standard for high-performance building in the U.S. and worldwide.
LEED Reference Guide for Homes Design and Construction v4 (USGBC 2013)	A reference guide used to support the design and construction of LEED certified homes. The guide provides explanations behind the intent and requirements of the various categories and credits.	(1) Authors and contributors are expert in the LEED Technical and Advisory Committees, USGBC consultants, and Technical Advisory Group members for each credit category who belong to numerous third-party organizations in the residential building and high-performance building industries. (2) LEED for Homes is geared specifically towards residential construction with credits and sections in the guide focused on the building enclosure. (3) LEED for Homes is a standard used to certify homes throughout the U.S. as achieving performance beyond typical building code compliance.
EarthCraft House Technical Guidelines (EarthCraft 2015)	A guide that provides detailed explanations and support for the design and construction of new and renovated EarthCraft House certified single-family homes, duplexes, and townhomes.	(1) Southface Energy Institute developed the EarthCraft standard and technical guidelines. Southface is a non-profit organization that specializes in the residential home building industry and offers various high-performance building services (EarthCraft 2014). (2) EarthCraft House is for either new construction or renovated single-family home, duplex, and townhome projects, and the guide provides specific focuses on requirements for the building enclosure. (3) EarthCraft House is a high-performance building standard use to certify residential buildings in the southeast region of the U.S.
ENERGY STAR Certified Home Features Fact Sheets (ENERGY STAR 2015)	Articles that provide explanations behind the intent of the features of an ENERGY STAR certified home.	(1) Developed by the U.S. Department of Energy and the U.S. Environmental Protection Agency. (2) The articles are specific to residential buildings and achieving high-performance enclosure systems. (3) The articles are intended to inform the intended purposes and benefits behind ENERGY STAR Home standard construction.

5.2.2 High-Performance Residential Building Enclosure Attributes

Guided by the thematic analysis research question, the texts were reviewed for relevant excerpts and then coded. Examples of excerpts taken from the sample included the following:

> *"The most important principle for energy efficient construction is a continuous insulating envelope all around the building, which minimises heat losses like a warm coat. In addition to the insulating envelope there should also be an airtight layer as most insulation materials are not airtight. Preventing thermal bridges is essential – here an individual planning method has to be developed, according to the construction and used materials, in order to achieve thermal bridge free design. Independently of the construction, materials or building technology, one rule is always applicable: both insulation and airtight layers need to be continuous." (iPHA 2015)*

> *"ENERGY STAR certified homes are built with features designed to safely drain water off roofs, down walls, and away from the home. To help achieve this, ENERGY STAR builders wrap the walls of the home from top to bottom in a continuous layer of overlapping moisture-resistant material to create a "drainage plane." In areas that are particularly susceptible to water problems, such as roof-wall intersections and openings around windows and doors, the drainage plane is supplemented with a second layer of protection, called flashing. Flashing consists of water-resistant material that directs water away from the areas of concern and onto the drainage plane, where it can be safely drained away." (ENERGY STAR 2015)*

> *"…minimize waste of energy caused by uncontrolled air leakage into and from conditioned spaces… Benefits from reducing air leakage include increased energy efficiency; less dust, pollen, and other outdoor pollutants entering the house; and reduced sound transmission from the outside and between units in multifamily buildings. Well-sealed buildings typically require smaller HVAC equipment, which costs less to install and operate." (USGBC 2013)*

A total of 196 codes were identified from the analyzed texts included in the sample. Similar to the previous thematic analysis performed to identify disaster resilient housing attributes, some of the codes identified here contained multiple meanings, and were grouped into multiple themes. These themes became the attributes of a high-performance residential building enclosure as listed in Table 20. Additionally, three attributes identified here overlapped with the disaster resilient housing attributes. These attributes were *Energy Efficiency, Resource Efficiency*, and *Robustness*. However, Robustness is named here as *Enhanced Durability*.

Table 20 High-performance residential building enclosure thematic analysis attributes

High-Performance Enclosure Attributes	*Sub-Attributes*	*Number of Codes*
High Levels of Insulation	Insulation levels and quality is enhanced to reduce thermal transmission	57
Minimal Air Leakage	Air leakage is significantly reduced	47
Enhanced Occupant Comfort and Health	Interior comfort is enhanced and/or maintained	12
	Contributes to improved indoor air quality (IAQ)	9
	Noise transmission is minimal	2
Energy Efficiency	Contributes to energy efficiency	33
	Utilizes renewable energy (e.g. passive solar)	3
Resource Efficiency	Reduces green house gas (GHG) emissions	3
	Conserves and uses resources efficiently	17
Minimized Life-Cycle Cost	Contributes to reduced life-cycle costs (e.g. design, construction, operation, and maintenance)	15
Verified Quality Assurance	Quality and operation of the final construction is verified	12
Enhanced Durability (i.e. Robustness)	Moisture durability is enhanced	42
	Protected from and resistant to pest damage	5
	Service life is improved	10
Climate Appropriate	Designed and installed appropriately for the local climate	15

Attribute Descriptions

High Levels of Insulation:

The first attribute identified was *High Levels of Insulation*, and it has been defined here as:

A reduction in the amount of thermal transfer through an enclosure component

As one of the most prevalent themes to appear throughout the thematic analysis, a high-performance enclosure should have higher levels of insulation than what is typically prescribed in building codes. They should have higher R-values, or lower U-values, than the standard code built enclosure, so much so that it further reduces the amount of heat transmission that can occur between the exterior environment and the interior environment of a building. To achieve this, it can include selecting materials that have a high resistance to heat transfer, eliminating areas of heat loss, and/or increasing the amount of physical insulation in enclosure components. By increasing the levels of insulation in an enclosure it can benefit the thermal performance of a home, and can additionally reduce the amount of energy consumed for space conditioning by reducing the need for large heating and air conditioning units to compensate for excessive heat loss and gains.

An example of an HPRB technology that exemplifies this attribute is Continuous Insulation. The intent is that this technology eliminates interruptions (e.g. thermal bridges) in the thermal control layer of an enclosure in order to reduce the amount of heat flow through an enclosure.

Minimal Air Leakage:

The second attribute identified here was *Minimal Air Leakage*, and it has been defined here as:

A reduction in the amount of air leakage past the enclosure

This theme was also very prevalent in the analysis. Decreasing the amount of unwanted air leakage between the interior and exterior can similarly increase the thermal performance and energy efficiency of a building. Gaps and holes in the enclosure provide easy escape routes for heated or cooled air that must then be regained with use of mechanical equipment to maintain acceptable levels of thermal comfort. By reducing the amount air leakage past an enclosure, it will reduce the need for large heating and cooling equipment to maintain comfortable interiors. Minimizing air leakage can also benefit noise comfort and air quality by reducing air and noise pollution between conditioned and unconditioned spaces separated by the enclosure. Even more important, it also significantly reduces the risk of condensation and moisture related damages within the enclosure system.

The HPRB technology Continuous Airtight Layer minimizes the air infiltration rate past an enclosure. It achieves this by rigorously sealing off areas throughout an enclosure that allows air to escape, which can result in significantly lower air changes per hour (ACH) than what is typically required for code-compliant construction.

Enhanced Occupant Comfort and Health:

The third attribute identified here was *Enhanced Occupant Comfort and Health*, and it has been defined here as:

Improved and maintained indoor air quality and thermal comfort, and reduced noise transmission through the enclosure

This attribute consists of several aspects that all relate to the comfort and/or health of the building occupants. The choice of materials and the quality of the construction of an enclosure can have detrimental impacts to the well-being of individuals confined within an enclosure if not considered and addressed appropriately. A high-performance enclosure can contribute to *Enhanced Occupant Comfort and Health* by reducing heat loss and improve surface temperatures that can make interiors uncomfortable (e.g. eliminate drafts and/or increase insulation levels); specifying low- or non-toxic chemicals in the materials to prevent harmful off-gases (e.g. low-VOC materials); increasing the sound transmission rating of enclosure materials to improve acoustic performance and physical comfort; preventing harmful air pollutants (e.g. radon) from passing through the enclosure; and ensuring that materials are dry before installation to make sure that moisture is not trapped within components.

HPRB technologies that contribute to this attribute can include Continuous Airtight Layer and Insulation, High-Performance Windows/Doors, and AAC. Continuous layers of insulation and air tightness benefit IAQ by reducing the likelihood of air pollutants entering a home and by also increasing thermal comfort. High-Performance Windows/Doors with lower U-values than standard single- or double-glazed surfaces can similarly increase the thermal comfort in a home by increasing surface temperatures throughout the enclosure (e.g. mean radiant temperature). Windows and doors typically have much higher U-values than exterior wall insulation, which can create uncomfortable sensations near those areas if not compensated for with heavy blinds or local mechanical heating/cooling. AAC construction provides enhanced sound performance than traditional wood frame construction, and can additionally increase the air tightness of an enclosure due to its material composition.

Energy Efficiency:

The fourth attribute identified here was *Energy Efficiency*, and it has been defined here as:

A reduction in energy consumption by means of reducing heat loss/gains that contribute to increased mechanical system needs

This attribute was also identified for Disaster Resilient Housing; however, the definition here is specific to how the enclosure contributes to this trait in regards to building performance. A high-performance enclosure that can reduce the need for mechanical systems to maintain comfortable interiors will reduce the amount of energy needed and consumed to do so. Increasing insulation levels, reducing the amount of air leakage, and/or using passive strategies to collect and store heat (e.g. passive solar design) can typically achieve this for an enclosure.

Resource Efficiency:

The fifth attribute identified here was *Resource Efficiency*, and it has been defined here as:

A reduction in the GHG emissions associated with the construction materials and process used for the building enclosure

Similar to the energy efficiency attribute, *Resource Efficiency* was also identified to represent disaster resilient housing. When *Resource Efficiency* is defined specifically for an enclosure in relation to building performance, the material quantities, content, and processes used to manufacture and build an enclosure are considered. A reduction in the amount of resources used and sourced from non-local areas, and consciously selecting them in an effort to reduce detrimental environmental impacts is the ultimate goal.

Minimized Life-Cycle Cost:

The sixth attribute identified here was *Minimized Life-Cycle Cost*, and it has been defined here as:

A reduction in the costs associated with material manufacturing, procurement, construction, operation, maintenance, and/or demolition of the building enclosure

Life-cycle costs (LCC) takes into account the initial design and construction cost, as well as all other long-term costs associated with the operation, maintenance, and demolition of a building or component throughout it's expected lifetime. Implementing an LCC assessment for a building enclosure can help to identify and evaluate alternatives and strategies to reduce these costs in various stages of its lifetime to maximize potential overall savings (Fuller 2010). Strategies could include minimizing the amount of material quantities, using locally sourced materials, enhancing durability to reduce maintenance costs, and/or making energy efficiency a priority in the design to reduce operation costs in the long-term.

HPRB technologies that contribute to M*inimized LCC* include those that increase energy and resource efficiency by reducing initial construction and operating costs, as well as technologies with the ability to better withstand harsh environments so that repair or replacement costs can be kept to a minimum.

Verified Quality Assurance:

The seventh attribute identified here was *Verified Quality Assurance*, and it has been defined here as:

Implementing rigorous inspections and commissioning processes to ensure construction and systems function effectively and as intended

The design, construction, and operation of a high-performance enclosure must be inspected and tested at various stages to ensure design requirements are met, and it functions properly for its intended purposes. In high-performance building, this required process is typically called commissioning, and it can be applied to many aspects of a building with different test and inspection methods utilized as appropriate. Some typical tests used to verify the quality of the enclosure includes a Blower Door Test, which is used to measure the air tightness; and water tests to ensure that the enclosure is properly detailed and constructed to prevent unintended water intrusion.

Enhanced Durability (i.e. Robustness):

The eighth attribute identified here was *Enhanced Durability*, and it has been defined here as:

An improved ability to withstand exposure to the stresses of a building's external and internal environment

This attribute also overlaps with an attribute identified for Disaster Resilient Housing, which in this case is *Robustness*. Similar to robustness, enhancing the durability of an enclosure entails increasing the ability to withstand adverse impacts and exposures that the system may face. This includes various hazards (e.g. fire, wind, snow, and pests) with prescriptive design loads set by building codes; exposure to normally expected wear and tear (e.g. occupants); and of course, one of the major aspects of a successful enclosure, the control of bulk water and moisture. For these reasons, when evaluating *Robustness* and *Enhanced Durability* they are currently considered one and the same with respect to the entire building or individual building components that are exposed to the exterior environment.

Climate Appropriate:

The ninth and final attribute identified here was Climate *Appropriate*, and it has been defined here as:

Designed and installed accordingly for the designated IECC climate zone requirements

The IECC has created a map that divides the U.S. into 8 climate zones (e.g. hot, cold, mixed, humid, etc.). Each zone specifies various design requirements that must be abided by, such as insulation levels, vapor barrier placement, heating and cooling efficiencies, and infiltration rates. These maps and associated requirements are periodically updated and incorporated into residential building codes and high-performance building standards. It is essential that a high-performance building enclosure is well suited for its climate in order to function properly and provide a long lifetime of service. Not paying attention to the influence of the local climate on the performance of an enclosure could lead to issues with durability and occupant health and comfort.

5.2.3 High-Performance Residential Enclosure Metrics

Metrics were defined to coincide with each identified attribute for a high-performance enclosure. Ranges of values quantify each metric to demonstrate the level of performance that can be achieved in each attribute. This process follows the same logic as what was performed for the disaster resilient housing metrics classifications, where metrics have been defined to remain consistent with industry standards as well as the definitions conceived in this research. Weights of importance were also distributed among each attribute, which can be adjusted to prioritize each attributes contribution to the performance of an enclosure.

Attribute Metrics and Values

The metrics and values identified for each attribute of a high-performance enclosure are listed in Table 21. Following the table, explanations are provided to support how each metric and range of values were determined. The ranges of values for each metric varies, but are typically between 1-5 or 1-2. A value of 1 represents "poor performance"; 2 generally represents "fair performance" for standard new residential construction, which can be considered here as baseline construction; 3 represents "good performance"; 4 represents "very good performance"; and 5 represents "excellent performance". As with the disaster resilient housing thematic analysis previously performed, there are some cases where numbers between the 1-5 range have been omitted (e.g. 1, 3, 5, or 1, 3, 4, 5). Again, this was because the metric did not currently require additional variation of levels to quantify the attribute, or further elaboration could not be completed at this time to reasonably represent meaningful variations in enclosure performance that can be achieved beyond the range currently presented.

The metrics used to quantify the overlapping attributes of *Energy Efficiency, Resource Efficiency*, and *Enhanced Durability* (i.e. *Robustness*) remain the same as what was described in the previous section for the disaster resilient housing attributes and metrics, and have therefore been omitted from the following metrics discussion. The only difference is that they are specific to the building enclosure and its components, and/or their impact to the entire building depending on the measurement method used (e.g. EUI metric for Energy Efficiency). All other metrics identified for high-performance enclosure attributes are described in the follows.

Table 21 List of high-performance enclosure attribute metrics and values

Attributes	***Metrics***	***Values***		
High Levels of Insulation	**Total UA**	**1**	> IECC Total UA	
		2	Meets IECC Total UA	
		3	10-25% < IECC Total UA	
		4	26-50% < IECC Total UA	
		5	Over 50% < IECC Total UA	
Minimal Air Leakage	**ACH50**	**1**	> IECC ACH50	
		2	Meets IECC ACH50	
		3	25-50% < IECC ACH50	
		4	51-75% < IECC ACH50	
		5	Over 75% < IECC ACH50	
Enhanced Occupant Comfort and Health	**ASHRAE 55 or Resident Satisfaction**	**1**	ASHRAE 55 Non-compliant	**1** Very dissatisfied
		2	ASHRAE 55 Compliant	**2** Dissatisfied
				3 Somewhat satisfied/Neutral
				4 Satisfied
				5 Very Satisfied
	STC Rating	**1**	< STC 45	
		2	STC 45	
		3	STC 45-50	
		4	STC 51-55	
		5	STC 56+	

	IAQ	**1**	Non-compliant
		2	Compliant
Energy Efficiency	**Energy Use Intensity (EUI)**	**1**	Over 5% > local EUI average
		2	Equals +/- local EUI average
		3	10-20% < local EUI average
		4	30-40% < local EUI average
		5	Over 40% < local EUI average
Resource Efficiency	**Equivalent Carbon Dioxide (CO_2e/ft^2)**	**1**	Over 5% > local CO_2e/ft^2average
		2	Equals +/- local CO_2e/ft^2average
		3	10-20% < local CO_2e/ft^2average
		4	30-40% < local CO_2e/ft^2average
		5	Over 40% < local CO_2e/ft^2average
Minimized Life-Cycle Cost	**LCC/ft^2**	**1**	Over 5% > local LCC/ft^{2}average
		2	Equals +/- local LCC/ft^{2}average
		3	10-20% < local LCC/ft^{2}average
		4	30-40% < local LCC/ft^{2}average
		5	Over 40% < local LCC/ft^{2}average
Verified Quality Assurance	**Cx**	**1**	None
		3	Cx performed
		5	Cx and RCx performed
Enhanced Durability (i.e. Robustness)	**Strength Design Loads/Limit States**	**1**	< Design load requirement
		2	Meets design load requirement
		3	10-20% > design load requirement
		4	21-30% > design load requirement
		5	Over 30% > design load requirement
	Water Control & Drying Capacity	**1**	Can withstand or manage minimal levels of wetting and/or the onset of moisture damage
		3	Can withstand or manage moderate levels of wetting and/or the onset of moisture damage
		5	Can withstand or manage excessive levels of wetting and/or the onset of moisture damage
	Estimated or Remaining Useful Life (EUL or RUL)[a]	**1**	< 10 years (very short)
		2	10-25 years (typical)
		3	26-40 years (medium-long)
		4	41-50 years (long)
		5	50+ years (very long)
Climate Appropriate	**IECC Climate Zone**	**1**	Non-compliant
		2	Compliant

Total UA:

In the most currently adopted version of the IECC (2012), prescriptive U-values and R-values are provided as minimum requirements for enclosure components according to the climate zone the home is constructed in. A home's enclosure must be constructed using those values as minimum, or as an alternative, the *Total UA* of an enclosure (i.e. the sum of the enclosure component U-values multiplied by the component areas) should be less than or equal to the U-values specified by the code multiplied by the

[a] Range of years should be adjusted appropriately by the evaluator to reflect the specific building/component or material being evaluated

same areas of the home's enclosure. Meeting the current code prescribed *Total UA* has been defined here as the baseline value for this metric. It will be used to make comparisons against it in terms of increases or decreases in performance for the *High Levels of Insulation* attribute. The highest level of performance that can be achieved is a *Total UA* that is over 50% lower than the code prescribed *Total UA*.

ACH50:

The current IECC (2012) also now prescribes mandatory levels of maximum air leakage that must be achieved for the enclosure measured in air changes per hour at 50 Pascal pressure (ACH50). Air leakage maximums are defined according to the climate zone of the building, where a maximum of 5 ACH50 is required for climate zones 1 and 2, and a maximum of 3 ACH 50 is required for climate zones 3 to 8. Meeting the maximum prescribed *ACH50* rate for the appropriate climate zone has been set here as the baseline value to measure the *Minimal Air Leakage* attribute. The highest performance level that can be achieved for this attribute is an air leakage decrease of over 75% less than the code requirement. This level of decrease was defined to coincide with very rigorous air leakage levels that can be achieved with high-performance building standards such as the ultra-tight Passive House standard, were the required maximum air leakage rate is 0.6 ACH50.

ASHRAE 55 or Resident Satisfaction Survey:

The *Enhanced Occupant Comfort and Health* attribute can be measured in various ways because of the multiple influences it can entail in relation to the building enclosure. According to the sub-themes that emerged during the thematic analysis, three types of metrics have been defined to evaluate this attribute, which includes quantifying thermal comfort, noise comfort, and indoor air quality (IAQ).

To measure thermal comfort, either the *ANSI/ASHRAE Standard 55* methods can be applied, or the perceptions of resident satisfaction with comfort using a survey can be analyzed. *ASHRAE 55* is a standard that defines minimum acceptable thermal environmental conditions for the occupied spaces of a building (ASHRAE 2013). The standard provides various methods that can be used to evaluate thermal comfort. One method involves assessing thermal comfort according to temperature variations with time that is not controlled by the occupants (e.g. temperature fluctuations caused by cycling of the thermostat). In order to comply with this level of comfort, cyclic variations of the temperature in the space from peak to peak amplitude should not exceed 2.0˚F in 15 minutes. Alternatively, the temperature should not exceed the maximum specified temperatures for periods greater than 15 minutes in 1 hour (e.g. the temperature should not surpass 4.0˚F in 1 hour). Radiant temperatures of surfaces can also be measured as a means to evaluate local thermal discomfort to comply with *ASHRAE 55*. If such methods are not applied, an occupant survey can be used as an alternative means to measure comfort satisfaction or dissatisfaction. Either of the methods can be used as a metric for the thermal comfort sub-attribute defined in this research.

STC Rating:

Sound can create a physically uncomfortable environment for occupants if it is not properly controlled, and it has been included here as one of the metrics to evaluate the *Enhanced Occupant Comfort and Health* attribute. A *Sound Transmission Class (STC)* is a rating in decibels used to measure how well a building component or material can absorb or reduce the transmission of sound. The higher the STC rating, the better the component is at attenuating sound. The currently adopted IRC (2012) requires that wall insulation and floor-ceiling assemblies separating dwelling units and adjacent townhouse units should have minimum STC rating of 45. For this reason, the code value to quantify noise comfort in this research is an STC of 45. The highest level of performance that can be achieved for this sub-attribute is an STC of 56 or more. This value was determined as the highest performance level because, according to a study conducted in which acceptable levels sound insulation in walls was investigated for residential buildings, and STC of 55 was found to be a more realistic value for acceptable sound attenuation, while 60 was identified as the ideal level to eliminate unwanted sound (Bradley 2001).

IAQ:

As a third metric that can be used to measure the *Enhanced Occupant Comfort and Health* attribute, *IAQ* has been defined as a sub-attribute metric, which is specific to the health aspect of this attribute. Having acceptable and safe levels of *IAQ* requires that measures be taken to effectively reduce and/or eliminate sources of air pollutants through and in an enclosure. Various steps can be taken to achieve this, and standards have been established to certify compliance of such efforts. Such a standard includes the EPAs Indoor airPlus, which is often required for some high-performance building standards such as ENERGY STAR Certified Homes. Indoor airPlus requires that a set of additional construction practices and specifications be implemented to further reduce indoor pollution in order to achieve the standard. It includes implementing additional control systems for moisture, HVAC, pests, combustion gas venting, gas emitting materials, and radon (EPA 2015). Additionally, for existing homes, inspecting and measuring building materials and components for signs of deterioration and damp, such as rot, to ensure there are no sources of mold and bacteria that could impact the health of occupants can be implemented to evaluate the *IAQ* of a home.

Achieving the Indoor airPlus label or implementing equivalent strategies specific to various building systems (e.g. the enclosure), and passing a building inspection for signs of building component contamination, is the metric used to evaluate *IAQ* here. Complying or not complying with such practices detailed in the standard or recommended practices, and/or having sound building components (e.g. healthy materials), are used at this time to evaluate achievements in this attribute.

LCC/ft^2:

The costs associated with various aspects of a building or building enclosure's life cycle can be compared in cost/ft^2 over a period of time. In this case the cost amount is equivalent to the LCC amount being measured. Therefore, *LCC/ft^2* is the metric used to quantify the *Minimized LCC* attribute. When considering the local area of a building, the average *LCC/ft^2* should be considered as a baseline value. This could encompass multiple aspects of a life cycle (e.g. initial cost, operation, and maintenance) or individual aspects (e.g. operating cost only) depending on the rigor desired and amount of information available. Referencing construction cost databases such as RSMeans and Craftsman, collecting actual energy use data or modeling utility costs with energy modeling tools, and/or surveying local costs would be required to gather sufficient data to be able to measure increases or decreases from baseline values identified. Local data could come from the surrounding community, county, city, region, or state level as available.

Cx:

Either performing or not performing *Commissioning (Cx)* and/or *Retrocommissioning (RCx)* activities for a building enclosure is used as a metric to evaluate the *Verified Quality Assurance* attribute. Having the enclosure commissioned during and immediately following construction earns a value representing good performance. To score beyond this value, if initial *Cx* of the enclosure is performed and *RCx* of the enclosure is planned at later dates to monitor and improve enclosure performance, this earns the highest level of performance for this attribute.

IECC Climate Zone:

As the final metric used to evaluate the attributes of a high-performance enclosure, *IECC Climate Zone* compliance evaluates the *Climate Appropriate* attribute. The IECC requires that specific specifications (e.g. insulation levels, system efficiencies, etc.) be meet according to the climate zone the building is located in. Designing and constructing a building enclosure accordingly for the appropriate and updated *IECC Climate Zone* as a minimum is used to quantify this attribute with either compliance or non-compliance being achievable.

Attribute Weights

Table 22 lists the current default weight values for each attribute of a high-performance residential building enclosure, where all the weights are currently equally distributed for each attribute and sub-attribute. If a higher priority is desired for one or more attribute or sub-attribute, the evaluator can adjust the weights accordingly to allow such attributes to carry a greater weight of importance.

Table 22 List of high-performance enclosure attribute weights (currently unadjusted)

Attributes	*Metrics*	*Weights*	*Sub-Weights*
High Levels of Insulation	Total UA	**0.111**	-
Minimal Air Leakage	ACH50	**0.111**	-
Enhanced Occupant Comfort and Health	ASHRAE 55 or Resident Satisfaction	**0.111**	0.037
	STC Rating		0.037
	IAQ		0.037
Energy Efficiency	EUI	**0.111**	-
Resource Efficiency	CO_2e/ft^2	**0.111**	-
Minimized LCC	LCC/ft^2	**0.111**	-
Verified Quality Assurance	Cx	**0.111**	-
Enhanced Durability	Design Loads/Limit States	**0.111**	0.037
	Water Control & Drying Capacity	**0.111**	0.037
	EUL or RUL	**0.111**	0.037
Climate Appropriate	IECC Climate Zone	**0.111**	-
	Total =	**1.000**	

5.3 Summary of Results and Reflection

Thematic analyses were performed for texts purposively sampled as relevant to the qualifying criteria set for disaster resilient housing and high-performance residential building enclosures. As a result of the performed analyses, common attributes were defined to represent each aspect. A total of nine common attributes were defined to represent disaster resilient housing, and a total of nine common attributes were defined to represent a high-performance residential building enclosure. The thematic analysis uncovered common overlapping attributes between both disaster resilience and high-performance. These attributes were Energy Efficiency, Resource Efficiency, and Robustness/Enhanced Durability. Each identified attribute was also given metrics and values that can be used to quantify levels of resilience and performance that can be achieved. Figure 39 depicts a summary diagram of the work and results of this chapter, which corresponds to research Objective B.

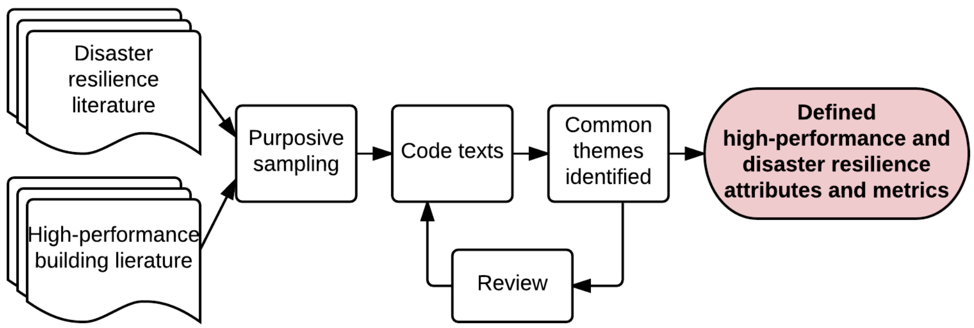


Figure 39 Summary diagram of Objective B work and results

The results produced in here can be used to evaluate residential buildings in regards to both disaster resilience and performance across multiple construction and high-performance building standards used to design and build a new or existing home. The defined attributes and metrics provide common values across dissimilar attributes and standards to allow for such evaluations and comparisons to be performed at a local level. Building evaluators can use this information when seeking a method to both qualitatively and quantitatively measure the overall resilience and performance of homes in various locations. They can also use the attributes and metrics to evaluate technology alternatives in efforts to simultaneously improve resilience or performance in one or multiple attributes.

Identifying the attributes of high-performance for additional systems of a residential building (e.g. HVAC systems) can be conducted in the future to increase the scope of evaluations that can be performed for a home. Additionally, while verifying the established metric value ranges with actual case studies of homes will further refine the achievable quantification.

6 Risk and HPRB Technology Prioritization Model

Various stakeholders in the built environment are seeking guidance towards reducing the risk of natural disaster devastation by using resilient and high-performance building technologies and strategies. A process to address this need at the local, housing level was developed in this research, which integrates the collected and analyzed data from the previous results sections.

To review, an evaluation of the potential physical impacts that residential building enclosures face with respect to hurricane hazards was performed. This evaluation

- identified and assessed the outlook of hurricanes for the southeast region of the U.S. in terms of its current and expected frequency and severity;
- identified common failure modes to residential building enclosures due to a hurricane and its multi-hazard nature;
- and analyzed the impacts they could have on an enclosure by evaluating the criticality (i.e. the severity and probability) of each failure mode.

While such analyses are beneficial to risk assessments, to complete a holistic natural disaster risk assessment for residential buildings (e.g. considering hurricanes), an assessment of vulnerability is also necessary to contribute to such an evaluation. This can be achieved when a specific home, or homes, are known, which allows for a context to define a decision space for an assessment by taking into account various housing natural disaster vulnerability indicators. The previously defined attributes and metrics for enclosure performance and disaster resilience can be implemented in such assessments to assist with quantification and comparisons of risks, performance and disaster resilience, and ultimately prioritize applicable HPRB technologies as potential risk mitigation solutions for homes.

By brining each of these aspects together with additional supporting data, a prioritization process for climate induced natural disaster risks and HPRB technologies was developed. Such a process for residential buildings is currently non-existent, and can thus be considered to be one of the first attempts made. The development and application of this process is demonstrated with conceptual scenarios in the following sections. As an example of its application and usefulness, the process model is conceptually demonstrated to show how hurricane risks can be prioritized accordingly for homes and their associated context, which includes an assessment of a home's location, age, building features, energy and resource consumption patterns, as well as building occupant and local area characteristics.

6.1 Prioritization Process Model

The prioritization process developed for this research and currently defined here includes two key steps: **Step 1 – Risk Assessment**, and **Step 2 – HPRB Technology Prioritization.** Each step includes several underlying tasks, which involves various data inputs and outputs. The process was also developed with the intent of aligning with national and local needs for natural disaster mitigation and resilience planning as communicated by several industry and research experts, policy makers, and national planning strategies. This process is specifically intended for decision-makers who assess housing performance in an effort to better recognize the threat of natural disasters to buildings, and to identify the most pertinent mitigation options to reduce the identified hazard risks.

Table 23 provides a summary of the literature that was reviewed to ensure that necessary and beneficial steps were included in this process, and to also confirm that it addresses and aligns with widely communicated stakeholder goals and needs. Additionally, this review demonstrates that this process is applicable and needed on a larger scale, and has the potential to be further developed and integrated into local and nationwide disaster resilience planning strategies and goals.

Table 23 Literature review of disaster resilience and building performance assessment needs

Source	***Contributor(s)***	***Report Purpose***	***Resilience Goals/Proposals/Needs***
Housing and Urban Development (HUD) Climate Change Adaptation Plan (HUD 2014)	HUD Resilience Council	Proposed actions to address climate change risks to residential buildings	In response to concern over the potential lack of resilient HUD-assisted residential buildings to climate-related hazards and climate change, it is proposed that easy-to-use guidance for building design, construction, and retrofit for sustainability and resilience be developed or adapted.
National Mitigation Framework (DHS 2013)	U.S. Department of Homeland Security, FEMA	To establish and encourage a common forum for coordinating and addressing the nations management of risk and mitigation to develop and build resilient communities	Core capabilities required for mitigation include identifying the threats and hazards a community faces as well as the associated vulnerabilities and consequences, and organize and translate the data into meaningful and actionable information to aid others. Also, assess various risks and disaster resilience to better inform decision-makers with data and analysis tools used in planning for such risks to achieve resilience.
Developing Guidelines and Standards for Disaster Resilience of the Built Environment: A Research Needs Assessment (McAllister 2013)	NIST, and leaders in engineering, research, building standards and codes	Research gaps and needs assessment performed to assess critical infrastructure facilities, systems, and other buildings for resilience to hazards in support of community resilience in the built environment	There is a need for quantitative tools and metrics to support decision-making in assessing building and system performance in regards to hazards and resilience, resilience planning guidance, and risk-based performance goals for resilient communities.
Adopting Disaster Resilient Construction at the Local Level: Recommendations from the 2012-2013 Workshops (NRMCA 2013)	Design and construction professionals, state and local government agency officials, and over concerned and interested stakeholders in communities	To produce recommendations for improving disaster resilience of infrastructure to natural and man-made hazards	Resilience to natural hazards should be included as a criterion in high-performance building standards. Disaster planning and implementation should be based upon assessments and prioritization of hazards and risks in regards to vulnerability and abilities/inabilities to cope with such risks.
Designing for a Resilient America: A Stakeholder Summit on High Performance Resilient Buildings and Related Infrastructure (DHS 2010)	Building industry and national hazard experts from government agencies, universities, and professional and trade organizations	To produce recommendations for resilient design in the U.S.	Research and development of tools and techniques to improve building and infrastructure resilience from all types of hazards, with specific efforts to integrate resilience into risk assessment processes. Certification programs and professional societies and trades should integrate resilience into building design, construction, and operation with resiliency assessment tools.

6.1.1 Step 1: Climate Induced Natural Disaster Risk Assessment

The first step of this process involves a risk assessment of climate induced natural hazards for a particular home. The goal of this step is to provide an understanding and assessment of the natural hazard vulnerabilities and impacts that contribute to a higher or lower risk of damage to a home and the associated consequences such as occupant displacement, significant repair costs, and/or loss of life. The following data and analyses described are included in this process step, with the overall outcome leading to the prioritization of climate induced natural disaster risks for a specific building.

Step 1A. – Context inputs set the decision space:

Initially gathering data that describes the context of a building and its surrounding area is of utmost importance before beginning the risk assessment. This includes information about the building's location, climate, age, size, energy consumption, and physical features and technologies (e.g. enclosure characteristics, mechanical systems, etc.), occupants, and market area. This data is collected to localize the decision space. It makes sure that enough detail is available to ensure that decisions are being made as specific as possible to the home being evaluated in an effort to reduce over generalization.

Step 1.1. – Identification of critical hazards and associated impacts:

Using the context inputs defined, critical hazards for the building's climate can be determined and evaluated. This step draws upon a database of applicable hazard impact analyses conducted, in which potential failure modes have been predetermined and ranked in regards to how critical their impacts can be. The FMECAs and FTAs previously performed in this research are used as databases to supply the data needed to fulfill this step. As a result, failure modes with impact scores are produced, as well as an applicable list of HPRB technologies.

Step 1.2. – Evaluation of vulnerabilities to the critical hazards and failure modes:

Various housing vulnerability indicators are assessed for a home and household using the context inputs defined. This evaluation consists of a multi-criteria decision-making (MCDM) assessment of a set of general natural hazard housing vulnerability indicators, as well as failure mode specific vulnerability indicators, which apply to the failure modes identified in the prior step. The MCDM vulnerability assessment produces a quantitative score that coincides with each failure mode's impact score on a comparable scale (0-1).

Step 1 Results – prioritized risks:

Finally, when the identified critical hazard(s) failure mode's impact and vulnerability scores have been determined for the building being evaluated, they can be prioritized accordingly. Those risks (which are labeled as failure modes) with the highest impact and vulnerability scores are considered high-priorities for the building in question. It is recommended that these high-priority risks be addressed above others using the list of HPRB technologies identified as applicable mitigation options if both enhanced resilience and building performance is desired.

Should an extensive list of HPRB technologies be produced, and/or multiple high-priority risks emerge from an assessment, prioritization of the HPRB technologies will further aid decision-makers with their selection of risk mitigation options. This is performed in Step 2.

6.1.2 Step 2: Prioritized Risk Mitigation Options

The second step of this process assesses building performance and disaster resilience to the previously identified risks in Step 1 using developed MCDM metrics and benchmarks for quantification. In addition to this, Step 2 also prioritizes risk mitigation options, in the form of HPRB technologies, by assessing how they can improve upon building performance and disaster resilience in comparison to previously assessed baseline levels. The data and analyses required for this step are described as follows:

Step 2A. – Original and additional context inputs set the decision space:

In addition to the originally defined context inputs for a home as identified in Step 1, Step 2 also requires the results produced from Step 1 as additional inputs. This specifically refers to the high-priority risks identified, and the applicable HPRB technologies to address each of the risks. Each risk is individually evaluated and used as a basis to assess building performance and disaster resilience, with and without the implementation of HPRB technologies in order to make comparisons and prioritize options accordingly.

Step 2.1. – Determination of baseline levels of performance and resilience for the building/building system:

With a specific risk being considered, the baseline performance of a building (or specific system, e.g. the enclosure) and disaster resilience as it stands is evaluated using MCDM metrics, which quantify each aspect. These metrics were previously identified and developed in this research to represent attributes of building enclosure performance and disaster resilience for residential buildings. The baseline evaluation that takes place during this step creates a benchmark for the building being assessed in regards to specific risks. As a result of this, a comparison can be made between different HPRB technology options by evaluating how beneficial each technology could be in regards to improving baseline performance and resilience if implemented.

Step 2.2. – Determination of top priority risk mitigation option (i.e. HPRB technologies):

Following the quantification of baseline performance and resilience, HPRB technologies should then be considered in re-evaluations of performance and disaster resilience. This re-evaluation will use the same MCDM process and metrics to measure the performance and resilience of the same building/system. Adjusted performance and resilience scores are determined which can then be used to compare with original baseline evaluations produced in the prior step.

Step 2 Results – prioritized risk mitigation options:

The final outcome of this step is a set of prioritized HPRB technologies. Each technology is compared against baseline values of resilience and performance, as well as other HPRB technologies identified as potential mitigation options to address the same risk(s). This assessment provides decision-makers with localized, risk-based guidance for selecting applicable building performance and disaster resilience technologies.

6.1.3 Final Model of the Prioritization Process

Figure 40 provides a summary of the entire process and the associated steps involved. Following this figure, the process will be demonstrated with conceptual case homes created for the purposes of this research.

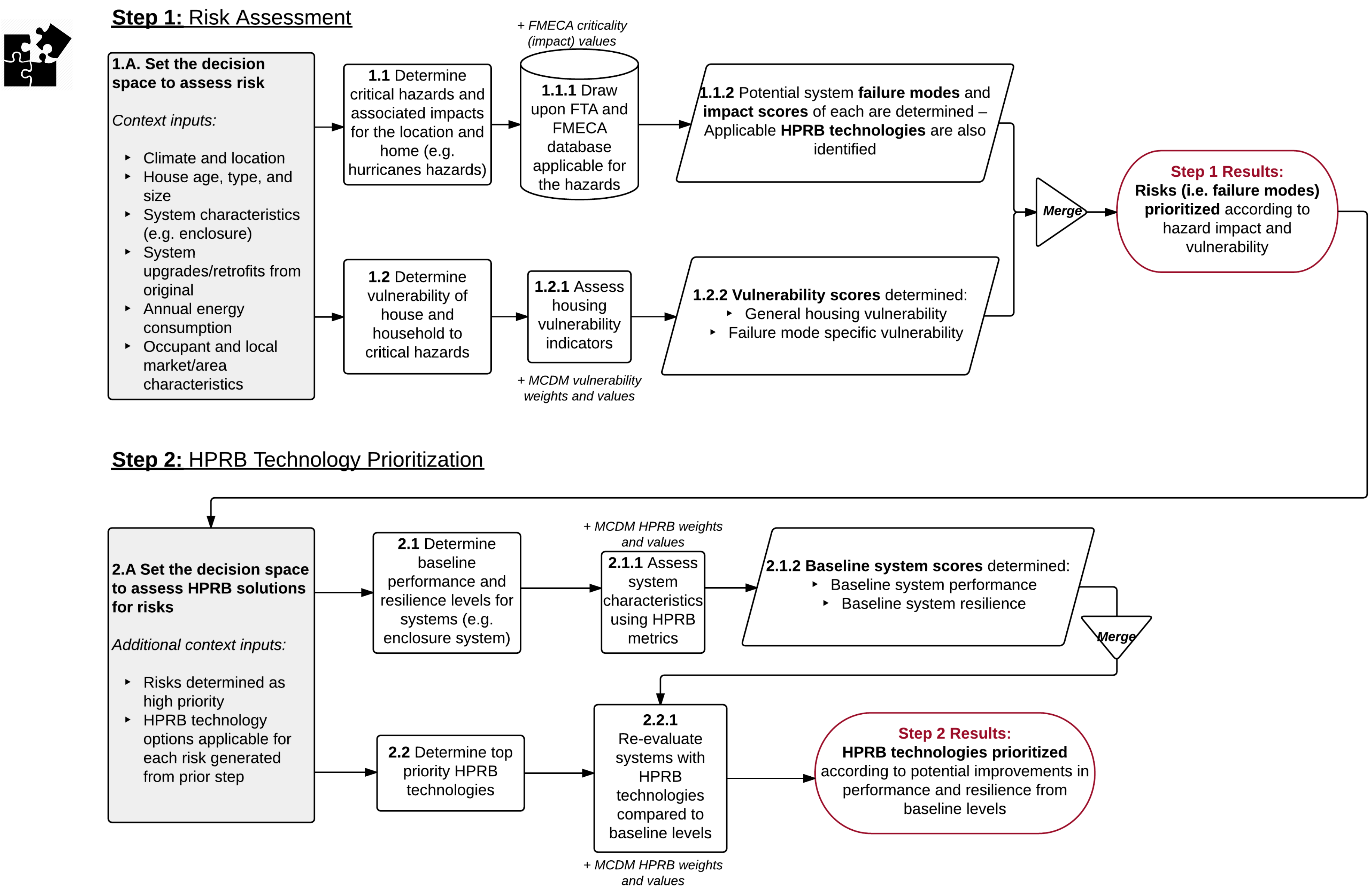


Figure 40 Prioritization process model overview

6.2 Demonstration Cases – Risk Assessment

Two conceptual homes were used as demonstration cases for this research in order to provide examples of how risks and HPRB technologies can be prioritized specifically for a home and its context. In addition to this, the demonstration cases also provide a comparison of the risks they face, and the levels of enclosure performance and disaster resilience that they exhibit based upon certain differences between the case homes, which included building age, physical condition, construction standards and quality, occupancy type, socio-economic status, energy and resource consumption. Factors that remained constant for both cases included the location, climate zone, house type, footprint area, and foundation. A detailed description of the demonstration case homes will be provided in the following section, which summarizes all assumptions made for each home as a means to demonstrate the prioritization model. A risk assessment is then performed, followed by a prioritization of applicable HPRB technologies for a selection of high-priority risks.

6.2.1 Demonstration Case Home Characteristics

The demonstration cases defined here, **Case 1** and **Case 2**, are both located in coastal communities in Charleston, South Carolina (SC), which is an area located in the southeast region of the U.S. that is prone to hurricane activity. The main difference between the case homes being demonstrated and investigated is that Case 1 is an existing home constructed to a now outdated building code, and Case 2 is a newly constructed home that was built to an above building code, high-performance standard. Table 24 summarizes key characteristics of each case home followed by a more detailed overview of each case and the assumptions considered for the assessments performed.

Table 24 Demonstration case home characteristics summary

Building Characteristic	***Case 1: Existing Code Home***	***Case 2: New High-Performance Home***
Location	Charleston, SC	
IECC Climate Zone	3A (warm-humid)	
Additional Zoning	FEMA flood zone AE[a], wind speed zone 110-116 mph	
House Type	Townhome	
Condition Area	1690 ft^2	
Number of Stories	Three-story	
House Age	6 years old (constructed in 2009)	< 1 year old (new construction, 2015)
Building Codes[b]	IRC 2006, IECC 2006	IRC 2012, IECC 2009
High-Performance Certification/Features	N/A	ENERGY STAR version 3, net-zero energy ready, Cx, RCx planned
Retrofits/Renovations	N/A	N/A
Occupancy	Renters, Low-income family	Owners, Middle-income family
Average Annual Energy Consumption[c]	12.16 kWh/ft^2/year	4.76 kWh/ft^2/year
Average Annual Operating Cost[d]	$1.69/$ft^2$/year ($238.71/month)	$0.66/$ft^2$/year ($93.44/month)
HVAC	Split system, electric cooling 13 SEER, natural gas heating 78% AFUE	Split system, electric cooling 16 SEER, balanced HRV, dehumidification
Water Heating	Natural gas, storage tank	Hybrid hot water heater, 2.9 EF
Air Leakage	7 ACH50 [e]	< 1 ACH50
Structural Framing	Wood framing, 2x4, 16” O.C.	Advanced wood framing, 2x6, 24” O.C., hurricane engineered connections
Wall Exterior Finish	Vinyl siding	High-strength drainable EIFS
Wall Insulation	R-13 (fiberglass batts)	R-40 (blown cellulose and 4” of exterior rigid insulation)
Wall Configuration	Drained, cavity walls	Drained, cavity walls
Roof Exterior Finish	Asphalt shingles	Asphalt shingles
Roof Insulation	R-30 (fiberglass batts)	R-60 (blown cellulose)
Window Performance	U-0.65 (R-1.54), standard double glazing with storm shutter protection	U-0.13 (R-7.69), high-impact triple glazing (ASTM missile test level D)
Foundation Type	Open, deep, concrete piers, raised above BFE	Open, deep, concrete piers, raised above BFE
Foundation Insulation	R-0	R-10

[a] FEMA flood zone AE is defined as a high risk area where Base Flood Elevations have been determined
[b] Building codes that were adopted and in effect at the time of construction. Current residential building codes adopted and implemented for South Carolina are the IRC 2012, and IECC 2009
[c] Case 2’s average annual energy consumption was estimated using REM/Rate energy modeling software. Case 1 was estimated using 2009 EIA average household energy consumption data for South Carolina EIA (2009). "Table CE1.4 Summary Household Site Consumption and Expenditures in South Region, Divisions, and States - Totals and Intensities, 2009." U.S. Energy Information Administration._
[d] Estimated using Charleston, SC residential utility rates $0.13939/kWh (SCE&G power company)
[e] No prescriptive maximum air leakage is required for IECC 2006, so it is assumed here to be 7 ACH50 as a reasonable representation based upon prior estimates used for IECC 2006 construction (Taylor, Z. T., and Lucas, R. G. (2010). "An Estimate of Residential Energy Savings From IECC Change Proposals Recommended for Approval at the ICC’s Fall, 2009, Initial Action Hearings." Pacific Northwest National Laboratory.)

Case 1 – Overview

This townhome was constructed in 2009 according to the required residential building and energy codes that were in effect for that year and location, which were the IRC 2006 and IECC 2006. Both codes have since been updated to the IRC 2012 version and IECC 2009 version now implemented statewide. The house is located near the Atlantic coast in a high-risk flood zone. This required the house to be constructed on a raised foundation/floor of concrete piers that abides by FEMA flood zone maps and the BFE for the location. The home is also designed for high wind speeds (110-116 mph) as required by the designated wind speed zone in the IRC 2006 building code.

Charleston, SC is very prone to hurricane activity, with a history of devastation as a result of prior hurricane events. While the last major hurricane to hit that local area was in 2004, the state and local area has since experienced severe thunderstorms, which has imparted some wear and tear on the enclosure of this home, as well as some of the other surrounding existing homes in the close vicinity. As the occupants are renting this home, they are forbidden from making any renovations and additions to the home, with additional homeowners association (HOA) restrictions in place also limiting the building owner from making substantial changes to the homes exterior.

This townhome is rented and occupied by a young family of 4 (two adults and two teens/children) who are classified as low-income, as they earn below the median household income for the location according to 2014 census data (80% HUD User Limit).

Additionally, the house is not constructed to any high-performance building standard, and only meets the code requirements enforced during the time of construction, which now makes some features outdated for certain hazards.

An existing condition report of this home assumes the following for the building enclosure:

Exterior Walls – Walls are finished with vinyl siding on top of continuous layers of structural sheathing, with a cavity space in-between to facilitate drainage. Walls are 2x4 wood framed, spaced 16" O.C. There are some signs of a deteriorated weather barrier and flashing defects as a result of exposure to the exterior environment and installation deficiencies. Walls are elevated above the ground accordingly for the area BFE. Continuous load path detail deficiencies are also present due to a lack of adequate anchors and stud strapping at top and bottom plates to resist required wind loads for the area.

Roof – The roof is standard construction for a high-pitched residential building. The roof is finished with asphalt shingles, and one layer of 15 lb. asphalt building paper underlayment over a continuous sheathed roof deck. There are minor, visible signs of wear and tear from past weather exposure and installation deficiencies, which includes some loose roof shingles, flashing defects, and poor sealing, however, no fasteners are corroded. The roof also has inadequate strength required for the minimum wind loads for the area due to building code updates.

Windows and Doors – Windows and doors are equipped with storm shutters that can be put in place in the event of a severe storm or hurricane to protect the glazing and opening surfaces from debris and high pressure loads. Glazing and surfaces are not rated to withstand high impacts, and meet minimum requirements. Sealing and flashing show signs of minor deterioration at windows, as well as some gasket deterioration as a result of exposure to prior severe weather in the area.

Foundation – The foundation is appropriately constructed and raised for the flood zone risk. There is concern for continuous load path deficiencies as noted with the exterior walls and roof, but it is considered to be in a good condition otherwise.

Case 2 – Overview

The second case home is also a townhouse. It is located in the same area as Case 1, and thus is exposed to the same type and amount of natural hazard threats as designated for the climate zone. The house has the same layout as Case 1, is the same size, and has the same number of stories. However, this house is a high-performance home as it has achieved the ENERGY STAR Home certification. In addition to this, several other design modifications have been made to this home ensure the house is net zero energy ready, which means that if photovoltaic (PV) cells are installed on the home's roof, it can produce enough energy on-site to be self-sufficient and become independent from the grid.

This home is new construction, and abides by the current building and energy codes enforced in South Carolina, which includes the IRC 2012, and IECC 2009. The family that occupies this home is also a family of four, but they are above the low-income status limit for Charleston, SC, and are classified as a middle-income family. As homeowners, and with approval from their local HOA, they can readily make renovations to the exterior or interior of the home to accommodate upgrades and new technologies, such as renovating the roof to support the installation of a PV array on the exterior should the household decide to produce on-site energy, which is a common technology implemented in their community of similar high-performance homes.

The completed design documents and pre-occupancy condition report for this home assumes the following characteristics for the enclosure:

Exterior Walls – The walls have superior thermal performance with high levels of insulation throughout, and thermal bridges have strategically been eliminated. They are finished with a high-strength drainable EIFS system, which utilizes a reinforced mesh system over two layers of exterior rigid insulation, allowing the walls to withstand large impacts. The walls are finished in stucco for aesthetic appeal. Underneath the finish material and exterior insulation, the walls are constructed using advanced framing techniques. The wood frame structure is 2x6 construction, spaced 24" O.C. Additional design and engineering was implemented to make stronger connections throughout the structure to accommodate large wind loads. Similar to Case 1, the walls are elevated above the ground accordingly for the area BFE to better withstand potential flood events. An integrated drainage plane is installed throughout the walls to ensure that complete coverage is provided with the WRB and flashing. The walls are also airtight, allowing very minimal air leakage in and out of the conditioned spaces. The enclosure was commissioned and several inspections took place for the enclosure design and construction, which included physically measuring the airtightness of the home, and inspecting all load paths to ensure all connections were continuous and engineered accordingly for the additional strength desired to resist wind forces.

Roof – A high-pitched roof is installed for this home, finished with asphalt shingles and one layer of 15 lb. asphalt building paper underlayment over a continuous sheathed roof deck. The roof is typical for most residential homes with the exception that the roof deck has been sealed below the underlayment to provide additional protection from severe precipitation that could occur during thunder storms or hurricanes. The roof was designed and constructed according to the IRC 2012, and meets current minimum requirements to withstand wind pressure and other live and dead loads.

Windows and Doors – Triple pane windows that have also been tested and rated as high-impact are installed on this home. Not only do the windows improve durability and comfort by increasing surface temperatures, which further reduces energy consumption and condensation risks, they can also withstand larger amounts of pressure and debris impact when compared to customary double glazed window surfaces commonly installed on residential buildings. The window and door connections to the surrounding walls have been sufficiently sealed and flashed, and are integrated into the drainage plane installed throughout the enclosure.

Foundation – The foundation system is equivalent to the foundation used in Case 1, with the exception of the foundation insulation applied for Case 2. This foundation is also appropriately constructed and raised for the flood zone risk designated by FEMA flood maps. Load paths are continuous throughout, and it meets building code requirements.

6.2.2 Impact Scores

A critical hazard identified for the demonstration case homes are hurricanes. By drawing upon a database of impact analyses conducted for hurricane hazards and their interaction with residential buildings (i.e. FTAs and FMECAs), potential failure modes were compiled for the case homes, which include impact scores that rank each failure mode in regards to their criticality. Additionally, a list of HPRB technologies that can be implemented to address each failure mode was produced.

As both case homes in this demonstration are located in the same area, and the same hazard is being investigated in this research, the failure modes identified for each case, as well as the associated impact scores for each home, were the same. In the future, when more hazards are included in this process (e.g. snow storms, heat waves, etc.) and homes are located in various climates, the list of failure modes and HPRB technologies will inevitably be different depending on the evaluations taking place. Nevertheless, while the impacts are currently the same for each case at this stage in the process, the risk assessment is not complete, as it does not yet include an assessment of vulnerability. Once this has been included, it will differentiate the cases in terms of a holistic assessment of failure mode risks, which ranks each potential failure for the case homes accordingly by considering the hazard, impacts, and vulnerabilities.

Table 25 lists the potential failure modes that each case home can experience in the event of a hurricane. The most critical failure mode is listed at the top according to the developed impact scores, which are scaled criticality factors out of a total range of 1 to 0. HPRB technologies identified to mitigate each failure are also listed below each failure mode.

Table 25 Enclosure hurricane failure modes and associated HPRB technologies ranked by impact score

Impact Score	***Enclosure Failure Modes and HPRB Technologies***
1.00	**C.I. Windows/Doors Penetration/Crack**
	HPRB: Low-U, high-impact and pressure rated openings
	HPRB: Commissioning/retrocommissioning
0.67	**C.V. Blown-In Windows/Doors**
	HPRB: Low-U, high-impact and pressure rated openings
	HPRB: Commissioning/retrocommissioning
0.67	**B.IV. Roof Structural Failure**
	HPRB: ICF
	HPRB: Advanced framing – hurricane strapping and anchoring
	HPRB: Advanced framing – 2x6, 24" O.C., aligned with roof
	HPRB: Advanced framing – stronger sheathing attachment
	HPRB: Advanced framing – enhanced substrate fastening
	HPRB: Commissioning/retrocommissioning
0.50	**A.I. Exterior Wall Penetration/Crack**
	HPRB: Advanced framing – insulated sheathing
	HPRB: Continuous, high-strength exterior insulation
	HPRB: ICF
0.43	**B.III. Detached Non-Structural Roof Components**
	HPRB: Commissioning/retrocommissioning
0.33	**A.II. Exterior Wall Structural Failure**
	HPRB: Advanced framing – hurricane strapping and anchoring
	HPRB: Advanced framing – 2x6, 24" O.C., aligned with roof
	HPRB: Advanced framing – insulated sheathing
	HPRB: Advanced framing – stronger sheathing attachment
	HPRB: Continuous, high-strength exterior insulation
	HPRB: Ventilated drainage plane (pressure-equalized)
	HPRB: ICF
	HPRB: Commissioning/retrocommissioning
0.33	**B.I. Roof Penetration/Crack**
	HPRB: ICF
	HPRB: Continuous, high-strength exterior insulation
	D.VIII. Flotation
0.33	HPRB: ICF
	HRPB: Commissioning/retrocommissioning
0.30	**B.VI. Roof Water Damage**
	HPRB: Commissioning/retrocommissioning
	HPRB: Integrated drainage plane
	HPRB: Continuous airtight layer
	HPRB: Roof water management
	HPRB: Redundant WRB
	HPRB: Green roof
0.17	**D.VII. Foundation Structural Failure**
	HPRB: Commissioning/retrocommissioning
	HPRB: ICF

0.11	**A.III. Detached Non-Structural Exterior Wall Components**
	HPRB: Ventilated drainage plane
	HPRB: Commissioning/retrocommissioning
	HPRB: Continuous, high-strength exterior insulation
	HPRB: Integrated drainage plane
0.04	**C.VI. Water Damage at Windows/Doors**
	HPRB: Commissioning/retrocommissioning
	HPRB: Integrated drainage plane
	HPRB: Continuous airtight layer
0.02	**A.VI. Exterior Wall Water Damage**
	HPRB: Commissioning/retrocommissioning
	HPRB: Integrated drainage plane
	HPRB: Continuous airtight layer
	HPRB: Ventilated drainage plane
	HPRB: ICF
	HRPB: Redundant WRB
	HPRB: AAC

6.2.3 Vulnerability Scores

A set of housing vulnerability indicators to climate-induced natural hazards were identified for the categories of Construction Standards/Regulation, Market Area and Demographics, Natural Environment, and High-Performance Building Technology Implementation. These categories are consistent with those previously defined for this research (refer to section 2.4.2 Housing Vulnerability Indicators), and were used to assess "general" hazard vulnerability. As each hurricane failure mode is being assessed for risk, where vulnerability scores coincide with impact scores, it necessitates that an additional vulnerability category be included in addition to the general hazard vulnerability indicators. The additional category for vulnerability indicators is specific to each identified failure mode being prioritized in the risk assessment, and thus differentiates each failure mode being assessed for risk.

Two indicators of general vulnerability for each category were defined and included in this evaluation as a demonstration (additional indicators of vulnerability can be included and assessed in the future). As part of the MCDM process, each attribute was given a weight of importance, which was applied to possible values that can be achieved to characterize the vulnerability that the home exhibits. The possible values that could be achieved were either a 1 for high vulnerability, or a 0 for low vulnerability. Justification for why each vulnerability indicator was selected and included in this evaluation is summarized in Table 26, which also explains what is regarded as high or low vulnerability as it relates to what has been documented in literature. Failure mode vulnerability indicators were derived from the hurricane failure mode FTAs, where the identified contributing causes of each failure were used as indicators for assessing failure mode specific vulnerability. FTAs for each failure mode were reviewed in order to identify the necessary indicators that should be used to assess failure mode vulnerability. The failure mode vulnerability indicators assessed for exterior walls are provided in Table 27 to Table 30, which demonstrates a hurricane vulnerability assessment for each case home. The remaining hurricane vulnerability assessments performed for each case home can be found in Appendix B.

Table 26 Housing vulnerability indicators assessed

Vulnerability Indicator	*Indicator Description*	*Assessment Question*	*Value (V)*	*Weight (W)*
Construction Standard/Regulation				**0.125**
Construction Year	Older homes are more vulnerable to damage from natural hazards due to several factors such as aged components, and building features, quality, and state-of-the-art practices and standards that have improved over time where awareness of natural hazard impacts after major disasters has increased (AIR Worldwide 2010; Hays 1999).	Was the home built prior to the most recent major hurricane event? Or pre-TBD? (e.g. select a year when certain hazard specific codes became mandatory)	1 = yes 0 = no	0.063
Building Code/Quality	Homes of low quality or constructed to no/outdated building codes are more vulnerable to destruction (AIR Worldwide 2010; Cutter et al. 2003; Hays 1999).	Was the home constructed or retrofitted using a now out of date building code or no building code for hazard safety at all?	1 = yes 0 = no	0.063
Market Area & Demographics				**0.125**
Occupancy Type	Homes primarily occupied by seniors or young children are more vulnerable to environmental hazards (Cutter et al. 2003).	Is this household composed primarily of senior/elderly residents?	1 = yes 0 = no	0.063
Income Status	Low-income status increases vulnerability (Cutter et al. 2003; Masozera et al. 2007).	Is the household classified as low-income for the area? Or located within a low-income community?	1 = yes 0 = no	0.063
Natural Environment				**0.125**
Location/ Climate	The climate in which the home is located in regards natural hazards of that region can increase of decrease vulnerability to certain natural hazards.	Is the home located in a climate prone to hurricanes?	1 = yes 0 = no	0.063
Hazard Exposure	A home is further exposed to the potential of natural hazard impacts depending on its proximity to certain hazard origins or stressors (e.g. coastal home, proximity to a flood plain, the density of debris sources) (Hays 1999).	Does the home have an increased exposure to potential hazards of the climate? (e.g. when considering hurricanes, is it located near the coast, or in a high wind speed zone)	1 = yes 0 = no	0.063
High-Performance Implementation (Proposed theory of the research)				**0.125**
Certifications/ Features	A home constructed to a high-performance building standard, or with high-performance features can decrease certain natural hazard vulnerability.	Is the home constructed to a high-performance standard or to the minimum required building code?	1 = code 0 = HPB	0.063
Barriers	Lack of ownership, zoning, and/or HOA restrictions can prevent alterations of the home or installation of technologies to improve performance (Schmidt 2008)	Are there restrictions that prevent home/land alterations to accommodate HPB technologies?	1 = yes 0 = no	0.063
Failure Mode				**0.50**
FTA Causes	If the home exhibits vulnerabilities that coincide with failure mode causes identified in FTAs, the home is considered more vulnerable to a failure.	E.g. Failure Mode A.I: Exterior walls are rated as high-impact resistant to debris.	1 = false 0 = true	

In the demonstration cases presented here, weights were equally distributed among the general housing vulnerability indicators, except for the failure mode indicators, which were heavily weighted in this assessment with the assumption that considering vulnerabilities that can directly influence the occurrence of a specific failure has greater importance. However, weights can be adjusted accordingly for an evaluator's preference, or similarly adjusted if it is found that specific vulnerabilities have a heavier influence on the assessed risks.

Vulnerability scores for each failure mode were generated for each case home, which involved the MCDM, weighted sum method (WSM) assessment of the general vulnerability indicators, which remained constant throughout, and the failure mode specific vulnerability indicators, which changed accordingly for each failure mode being assessed. A total vulnerability score close to 1 (the highest total vulnerability score achievable) indicates having a higher vulnerability to the assessed failure mode, while a total vulnerability score close to 0 (the lowest total vulnerability score achievable) indicates lower vulnerability. The formula used for the MCDM vulnerability assessment is presented and described as follows:

$$\boldsymbol{V_T} = wv_{g1} + wv_{g2} + wv_{g3} \ldots + wv_{fm1} + wv_{fm2} + wv_{fm3} \ldots$$

In this equation, the total vulnerability score (V_T) for a failure mode being assessed for a home is equal to weighted sum of all the vulnerability indicators evaluated (general and failure mode specific). To determine the total vulnerability score, the general vulnerability indicator scores, which is the sum of the product of each general vulnerability indicator value and its weight (wv_g), are added to the failure mode specific vulnerability indicator scores (wv_{fm}).

Table 27 Failure mode A.I vulnerability assessment

Vulnerability Indicator	*Weight*	*Case 1*	*Value*	*WV*	*Case 2*	*Value*	*WV*
General Vulnerabilities:							
Construction Year	0.063	No	0	0.000	No	0	0.000
Building Code/ Quality	0.063	Yes	1	0.063	No	0	0.000
Occupancy Type	0.063	No	0	0.000	No	0	0.000
Income Status	0.063	Yes	1	0.063	No	0	0.000
Location/Climate	0.063	Yes	1	0.063	Yes	1	0.063
Hazard Exposure	0.063	Yes	1	0.063	Yes	1	0.063
High-Performance Certifications/Features	0.063	Code	1	0.063	HPB	0	0.000
High-Performance Barriers	0.063	Yes	1	0.063	No	0	0.000
Failure Mode A.I Vulnerabilities – Debris Penetration/Crack to Exterior Wall:							
Walls have continuous sheathing	0.250	True	0	0.000	True	0	0.000
Walls are rates as high-impact resistant	0.250	False	1	0.250	True	0	0.000
Failure Mode A.I Vulnerability Totals:			**Case 1 V_T =**	**0.625**		**Case 2 V_T =**	**0.125**

Table 28 Failure mode A.II vulnerability assessment

Vulnerability Indicator	***Weight***	***Case 1***	***Value***	***WV***	***Case 2***	***Value***	***WV***
General Vulnerabilities:							
Construction Year	0.063	No	0	0.000	No	0	0.000
Building Code/ Quality	0.063	Yes	1	0.063	No	0	0.000
Occupancy Type	0.063	No	0	0.000	No	0	0.000
Income Status	0.063	Yes	1	0.063	No	0	0.000
Location/Climate	0.063	Yes	1	0.063	Yes	1	0.063
Hazard Exposure	0.063	Yes	1	0.063	Yes	1	0.063
High-Performance Certifications/Features	0.063	Code	1	0.063	HPB	0	0.000
High-Performance Barriers	0.063	Yes	1	0.063	No	0	0.000
Failure Mode A.II Vulnerabilities – Exterior Wall Structural Damage:							
The enclosure has continuous load paths	0.167	False	1	0.167	True	0	0.000
Walls have continuous sheathing	0.167	True	0	0.000	True	0	0.000
Walls are reinforced	0.167	False	1	0.167	False	1	0.167
Failure Mode A.II Vulnerability Totals:			**Case 1 VT =**	**0.708**		**Case 2 VT =**	**0.292**

Table 29 Failure mode A.III vulnerability assessment

Vulnerability Indicator	***Weight***	***Case 1***	***Value***	***WV***	***Case 2***	***Value***	***WV***
General Vulnerabilities:							
Construction Year	0.063	No	0	0.000	No	0	0.000
Building Code/ Quality	0.063	Yes	1	0.063	No	0	0.000
Occupancy Type	0.063	No	0	0.000	No	0	0.000
Income Status	0.063	Yes	1	0.063	No	0	0.000
Location/Climate	0.063	Yes	1	0.063	Yes	1	0.063
Hazard Exposure	0.063	Yes	1	0.063	Yes	1	0.063
High-Performance Certifications/Features	0.063	Code	1	0.063	HPB	0	0.000
High-Performance Barriers	0.063	Yes	1	0.063	No	0	0.000
Failure Mode A.III Vulnerabilities – Detached Non-Structural Exterior Wall Components:							
Wall cladding can withstand large amounts of wind/water pressure	0.125	False	1	0.125	True	0	0.000
Walls are drained and/or ventilated	0.125	True	0	0.000	True	0	0.000
All wall cladding is securely fastened	0.125	True	0	0.000	True		0.000
No signs of corroded cladding fasteners	0.125	True	0	0.000	True	1	0.000
Failure Mode A.III Vulnerability Totals:			**Case 1 VT =**	**0.500**		**Case 2 VT =**	**0.125**

Table 30 Failure mode A.VI vulnerability assessment

Vulnerability Indicator	***Weight***	***Case 1***	***Value***	***WV***	***Case 2***	***Value***	***WV***
General Vulnerabilities:							
Construction Year	0.063	No	0	0.000	No	0	0.000
Building Code/ Quality	0.063	Yes	1	0.063	No	0	0.000
Occupancy Type	0.063	No	0	0.000	No	0	0.000
Income Status	0.063	Yes	1	0.063	No	0	0.000
Location/Climate	0.063	Yes	1	0.063	Yes	1	0.063
Hazard Exposure	0.063	Yes	1	0.063	Yes	1	0.063
High-Performance Certifications/Features	0.063	Code	1	0.063	HPB	0	0.000
High-Performance Barriers	0.063	Yes	1	0.063	No	0	0.000
Failure Mode A.VI Vulnerabilities – Exterior Wall Water Damage:							
Flashing and sealants are present and show no signs of deterioration	0.125	False	1	0.125	True	0	0.000
Walls have a continuous WRB layer	0.125	True	0	0.000	True	0	0.000
Walls are highly resistant to moisture damage	0.125	False	1	0.125	False	1	0.125
Lower level walls are elevated (if located in a flood zone)	0.125	True	0	0.000	True	0	0.000
Failure Mode A.VI Vulnerability Totals:			**Case 1 VT =**	**0.625**		**Case 2 VT =**	**0.250**

6.2.4 Risk Assessment Results

The final results of the hurricane risk assessments performed for each demonstration case are listed in Table 31 and Table 32. Each hurricane risk (i.e. failure mode) is presented for each case home in terms of the vulnerability the home exhibits in relation to a specific failure mode, as well as the impact a specific failure mode could have on each case home. Figure 41 and Figure 42 then present the risks for each case home in a prioritized manner, where the failure modes that fall within the high impact and high vulnerability quadrant of the graphs are considered as high priority, and it is recommended that such risks be addressed first with mitigation strategies. This quadrant is highlighted in red.

As shown in the risk priority graphs, Case 1 is clearly more vulnerable to the impacts of hurricane hazards. Case 1 has three risks (C.V, B.VI, and C.I) that are considered high priority, while Case 2 does not have any high priority risks. However, Case 2 has considerably more vulnerability to failure mode B.I than any other failure modes, and can still consider mitigating the risk of this failure mode occurring.

Table 31 Case 1 hurricane risk assessment results

Risks	***Vulnerability***	***Impact***
Exterior Walls Failure Modes:		
A.I	0.63	0.50
A.II	0.71	0.33
A.III	0.50	0.11
A.VI	0.63	0.02
Roof Failure Modes:		
B.I	0.88	0.33
B.III	0.63	0.43
B.IV	0.71	0.67
B.VI	0.63	0.30
Windows/Doors Failure Modes:		
C.I	0.63	1.00
C.V	0.71	0.67
C.VI	0.88	0.04
Foundation Failure Modes:		
D.VII	0.45	0.17
D.VIII	0.50	0.33

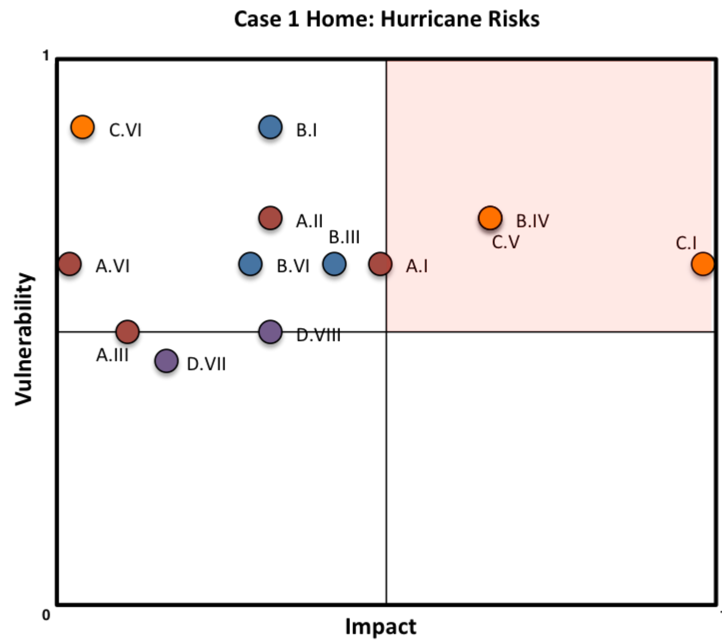


Figure 41 Case 1 hurricane risk priority graph

Table 32 Case 2 hurricane risk assessment results

Risks	***Vulnerability***	***Impact***
Exterior Walls Failure Modes:		
A.I	0.13	0.50
A.II	0.29	0.33
A.III	0.13	0.11
A.VI	0.25	0.02
Roof Failure Modes:		
B.I	0.63	0.33
B.III	0.25	0.43
B.IV	0.13	0.67
B.VI	0.13	0.30
Windows/Doors Failure Modes:		
C.I	.38	1.00
C.V	.13	0.67
C.VI	0.13	0.04
Foundation Failure Modes:		
D.VII	0.13	0.17
D.VIII	0.13	0.33

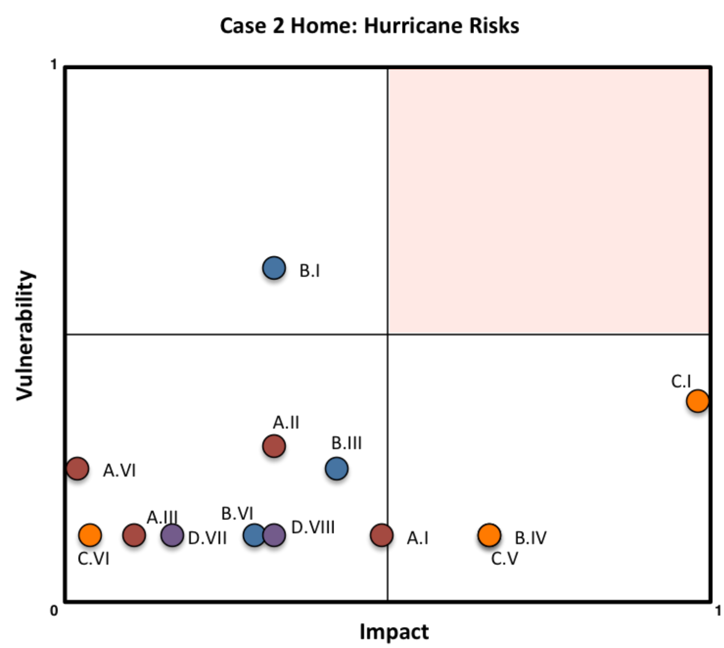


Figure 42 Case 2 hurricane risk priority graph

6.3 DEMONSTRATION CASES – HPRB TECHNOLOGY PRIORITIZATION

Following the risk assessment for the demonstration case homes, HPRB technologies were prioritized for hurricane failure mode risks that were considered high-priority for each case home. In order to perform this assessment, each case home was first evaluated for baseline building enclosure performance using the attributes and metrics previously defined to quantify residential building enclosure performance. Similarly, each home was also evaluated for baseline disaster resilience with regard to the specific risk being assessed (e.g. a high-priority risk). The attributes and metrics previously defined for disaster resilient residential buildings were used for this evaluation. The baseline levels of performance and disaster resilience were compared to benchmark levels in each aspect as an evaluation of how they fair prior to the implementation of recommended HPRB technologies to mitigate their risks. The cases were then re-evaluated for enclosure performance and disaster resilience with each applicable combination of HPRB technologies to mitigate their risks, prioritized according to how much of an improvement they can offer from the baseline assessment performed. This process is presented in the following sections.

6.3.1 Baseline Enclosure Performance

Evaluating the residential enclosure performance of a building involved an MCDM, weighted sum assessment of the identified high-performance residential building enclosure attribute values and weights. The possible values that can be achieved for each attribute have been previously defined. At this point the weights of each value were equally distributed among each attribute as a default, however, the weights can later be adjusted to give higher or lower consideration to one or more attributes over another. The formula used to represent the MCDM evaluation for enclosure performance is as follows:

$$P = (wv_{pa1} + wv_{pa2} + wv_{pa3} \ldots)/wv_{pht}$$

In this formula, the enclosure performance score (P) is determined by taking the sum of all of the individual performance attribute scores (wv_{pa}), which is the product of each performance attribute's value, v, and weight, w, then dividing that sum by the highest possible attribute weighted sum total (wv_{pht}), which in the demonstration cases performed here, was equal to 4.56.

Using the current set of high-performance building enclosure attribute values and equal weight distributions, the highest achievable score in an MCDM evaluation for a building enclosure is 1.00, while the lowest achievable score is 0.22. A score of 0 is not possible in the assessments because the lowest attribute metric values are set to 1, and not 0, to not exclude technology options if there were to be multiplied with 0.

Performance Benchmark Levels

Using the high-performance building enclosure attributes and metrics, a baseline enclosure performance score was determined for the demonstration case homes. Several benchmarks performance levels were defined to serve as points of reference to compare with the evaluated case homes. These performance levels (Figure 43) are discussed as follows in order of lowest achievable performance level to the highest achievable performance level rounded to the closest tenth decimal place.

As described in Chapter 5, the values used to quantify each attribute correspond to a certain level below or above standard new residential construction (e.g. IRC 2009), where generally, a value of 2 represents building code compliance, otherwise referred to as standard new residential construction.

Figure 43 Enclosure performance benchmark levels

A *Poor* enclosure performance score begins at 0.20. To achieve a score within this level, a building enclosure would have to score values consisting primarily of 1s (the lowest value achievable out all the attribute metrics). This score indicates the building enclosure is performing below the standard new building and energy code compliant residential buildings specific to a home's location.

To achieve a *Fair* performance score, the majority of the values obtained for each attribute would be 2s. This performance level indicates that the building enclosure represents the standard performance of a new code compliant residential building for a home's location.

A *Good* level of performance indicates that a home's building enclosure performs somewhat above the standard new residential building for the location. In an evaluation, it would primarily score values of 3.

Scoring within the range of 0.80 and 0.90 indicates that the building enclosure has a *Very Good* level of performance. A building enclosure in this category would need to primarily score values of 4 to achieve this level of performance. This performance level indicates that the enclosure is much more superior than a standard new residential building for the particular location.

Finally, scoring between 0.90 and 1.00 indicates that the building enclosure is *Excellent*, and is therefore considered to represent the highest attainable level of performance in this particular assessment when compared to the lower performance levels. Achieving this level would require scoring primarily values of 5, which makes it the most aggressive designation to obtain.

Baseline Enclosure Performance

The baseline enclosure performances of the demonstration case homes were evaluated using the high-performance building enclosure attributes and metrics. The baseline performance level that Case 1 achieved was within the *Poor Performance* range, with an enclosure performance score of 0.31. Case 2 achieved a score within the *Very Good Performance* range, with an enclosure performance score of 0.85.

Table 33 and Table 34 provide details for the enclosure evaluations performed for both Case 1 and Case 2 respectively. In order to support the evaluation and assumptions made for the demonstration cases, energy modeling, life cycle assessments (LCA), and a literature review of building and energy codes, construction reference tables, and case studies were performed. Such details are discussed in the Notes column of the tables. Where there was not enough detail available for the demonstration cases given the current assumptions and limitations of a conceptual analysis of a building enclosure (refer to Table 24 Demonstration case home characteristics summary) to assess certain attributes, a default value was selected to represent standard new construction, which was generally a value of 2 or 3 depending on the attribute being assessed.

Table 33 Demonstration Case 1 building enclosure performance evaluation

Attribute	*Metric*	*Weight*	*Value*	*WV*	*Notes*
High Levels of Insulation	Total UA	0.111	1	0.111	Total UA of the enclosure (581.24 UA) was calculated to be greater than IECC 2009 Total UA (538.58 UA) using the given values in the code and the same assembly areas. The higher fenestration U-Values in Case 1 compared to current IECC 2009 fenestration requirements contributed to substandard levels in this category.
Minimal Air Leakage	ACH50	0.111	2	0.222	Meets the optional verified ACH50 level for IECC 2009 of 7 ACH50.
Enhanced Occupant Comfort and Health	Resident Satisfaction	0.037	3	0.111	Residents surveyed as having a neutral satisfaction with thermal comfort.
	STC Rating	0.037	2	0.074	Meets baseline 2006 IRC enclosure STC requirement of STC 45. This requirement has not changed in the currently implemented 2012 IRC.
	IAQ	0.037	2	0.074	Enclosure condition report indicates no signs of material deterioration contributing to poor IAQ. The enclosure is compliant with radon pollution mitigation for the EPA zone (zone 3). The raised, open pier foundation system already mitigates the potential for radon exposure.
Energy Efficiency	EUI	0.111	1	0.111	The EUI 12.16 kWh/ft^2/year, which is above the current average SC home's EUI as a benchmark comparison, which is estimated to be 8.43 kWh/ft^2/year using monthly residential energy consumption data for SC (EIA 2014)
Resource Efficiency	CO_2e/ft^2	0.111	2	0.222	According to an LCA performed using Athena Sustainable Materials Institute (ASMI) software, Case 1's roof and wall systems have the same global warming potential compared to an equivalent IECC 2009, standard 2x4, wood framed wall and roof systems also using fiberglass batt insulation and vinyl siding.
Minimized Life-Cycle Cost	LCC/ft^2	0.111	1	0.111	When considering operation cost only in LCC, Case 1 spends $\$1.69/ft^2$ annually on energy consumption in comparison to the SC baseline of $\$1.18/ ft^2$ annually, using Charleston, SC utility rates.
Verified Quality Assurance	Cx	0.111	1	0.111	No Cx activities were performed for this home when it was constructed, and no RCx has been planned.
Enhanced Durability	Design Loads/ Limit States	0.037	1	0.037	According to a review and comparison of IRC 2006 to IRC 2012, the following design loads are below minimum requirements: 1) There are new requirements for wall sheathing to resist wind pressures (fastening size and penetration, panel thickness, span, stud spacing) which are not included in IRC 2006; 2) There are new performance requirements for wind resistance for exterior coverings in that are not in IRC 2006; 3) Roof uplift resistant (truss or rafter connection strength) has been updated in IRC 2012. Considering these code differences, Case 1 is assumed to be below current design requirements, as the home has not been updated.
	Water Control & Drying Capacity	0.037	1	0.037	Based upon the condition report: the floors and walls are sufficiently elevated for the BFE; adequate flashing and WRB is installed, although there are some signs of minor deterioration; walls have the capability of drying out if wet

					due to vented cladding and the drainage plane. The following IRC code changes impact water control: 1) Roof flashing - turnout is now required at end of roof/wall intersections; 2) There are new requirements for installing underlayment in high-wind areas. Considering the condition report assumptions and code differences, Case 1 is assumed to withstand minimal amounts of wetting.
	EUL or RUL	0.037	2	0.074	Case 1 is an existing home, so RUL (6 years elapsed) was evaluated for the exterior wall cladding, roof cladding, and window system used (the foundation and structural framing are considered to last the duration of the building's lifetime). Various EUL reference tables were consulted to support the evaluations (Fannie Mae 2014; HUD 2012; Lstiburek 2006; NAHB 2007). The following RULs were determined in order to estimate the average RUL for the enclosure components considered: exterior wall vinyl cladding RUL, 19 years; roof asphalt shingles RUL, 14 years; and standard double glazing and window frame RUL, 24 years.
Climate Zone Appropriate	IECC Climate Zone	0.111	1	0.111	The enclosure is no longer considered climate appropriate due to 2006 IECC enclosure requirements that have since changed for the climate zone in the 2009 IECC.
Case 1 Enclosure Performance Score =				**0.309**	**Poor Performance**

Table 34 Demonstration Case 2 building enclosure performance evaluation

Attribute	***Metric***	***Weight***	***Value***	***WV***	***Notes***
High Levels of Insulation	Total UA	0.111	5	0.556	Total UA of the enclosure (231.14 UA) was calculated to be approximately 57% less than IECC 2009 Total UA (538.58 UA) using the given values in the code and the same assembly areas.
Minimal Air Leakage	ACH50	0.111	5	0.556	The air leakage rate is < 1 ACH50, which is over 75% less than the optionally verified IECC 2009 air leakage maximum of 7 ACH50.
Enhanced Occupant Comfort and Health	Resident Satisfaction	0.037	4	0.148	Residents surveyed as satisfied with thermal comfort.
	STC Rating	0.037	5	0.185	The estimated STC for the enclosure based upon the exterior wall materials and layers is 66 STC. The additional insulation space for cellulose provided by a 2x6, 24" O.C. framed wall, and the use of a stucco clad exterior contributed to this estimated increase (HUD 2009; National Fiber 2008).
	IAQ	0.037	2	0.074	The enclosure was designed to comply with EPA Indoor airPlus (obtained the certification). The condition report also revealed no signs of high moisture content in materials or any deteriorated materials.
Energy Efficiency	EUI	0.111	5	0.556	The EUI 4.76 kWh/ft^2/year is over 40% below the current average SC home's EUI as a benchmark comparison, which is estimated to be 8.43 kWh/ft^2/year using average monthly residential energy consumption data for SC (EIA 2014).
Resource Efficiency	CO_2e/ft^2	0.111	1	0.111	According to an LCA performed using ASMI software, Case 2's roof and wall systems have over 40% more global warming potential compared to an IECC 2009, standard 2x4, wood framed wall and roof systems using fiberglass batt insulation and vinyl siding. The significant increase in Case 2 is highly due to the extensive use of exterior rigid insulation.
Minimized Life-Cycle Cost	LCC/ft^2	0.111	5	0.556	When considering operation cost only in LCC, Case 1 spends \$0.66/ft^2 annually on energy consumption in comparison to the SC baseline of \$1.18/ ft^2 annually, using Charleston, SC utility rates, which is over 40% less.
Verified Quality Assurance	Cx	0.111	5	0.556	Cx was performed during and after construction, and RCx is planned at a later date.
Enhanced Durability	Design Loads/ Limit States	0.037	4	0.148	Case 2 meets the IRC 2012 with additional improvements made to 1) increase resistance to wind and debris with the framing through hurricane strapping, fastener spacing, and stronger sheathing attachment; and 2) stronger enclosure surfaces, except for the roof, by using high-strength EIFS which can withstand 155mph winds, which is 41% more than the minimum speed of 110mph; and high-impact glazing which passed the missile D ASTM test, a missile double the weight and moving faster than standard missile C. Considering these improvements to the structural framing, exterior walls, and windows, it is assumed that Case 2's enclosure is 21-30% above minimum design load requirements.
	Water Control & Drying Capacity	0.037	3	0.111	Based upon the condition report: the floors and walls are sufficiently elevated for the BFE; adequate flashing and WRB is installed and in new condition; walls have the capability of drying out if wet due to vented cladding and drainage plane; the

					enclosure meets 2012 IRC requirements Considering the condition report assumptions and current code compliance, Case 2 is assumed to withstand moderate amounts of wetting.
	EUL or RUL	0.037	3	0.111	Case 2 is a new home, so EUL was evaluated for the exterior wall cladding, roof cladding, and window system used (the foundation and structural framing are considered to last the duration of the building's lifetime). As with Case 1, various EUL reference tables were consulted to support the evaluations (Fannie Mae 2014; HUD 2012; Lstiburek 2006; NAHB 2007). The following EULs were determined in order to estimate the average EUL for the enclosure components considered: exterior wall high strength EIFS/stucco, 50+ years; roof asphalt shingles EUL, 20 years; and triple glazed, high-impact windows EUL, 30+ years.
Climate Zone Appropriate	IECC Climate Zone	0.111	2	0.222	The enclosure meets IECC 2009 climate zone requirements, and is considered climate appropriate. Hygrothermal analyses were also performed to verify durability for the climate.
Case 2 Enclosure Performance Score =				**0.853**	**Very Good Performance**

6.3.2 Baseline Disaster Resilience

Evaluating the disaster resilience of the case homes involved a similar MCDM, weight sum method assessment to the one performed for enclosure performance; however, specific disaster risks were considered here when evaluating the various attributes. The possible values that can be achieved for each disaster resilient housing attribute have been defined previously. The weights of each value were equally distributed among each attribute as a default, which can be adjusted to give higher or lower importance to one or more attributes over another. The formula used to represent the MCDM evaluation for disaster resilience is as follows:

$$R = (wv_{ra1} + wv_{a2} + wv_{ra3} \ldots)/wv_{rht}$$

This formula follows the same logic used for evaluating enclosure performance. The disaster resilience score (*R*) is determined by taking the sum of all of the individual resilience attribute scores (wv_{ra}), which is the product of each disaster resilient attribute value, *v,* and its weight, *w*, then dividing that sum by the highest possible weighted sum total achievable (wv_{rht}), which in the demonstration cases performed here, was equal to 4.67. Using the current set of disaster resilience attribute values and weight distributions, the highest achievable score in an MCDM evaluation of disaster resilience is 1, while the lowest achievable score is 0.21.

Disaster Resilience Benchmark Levels

Using the disaster resilient housing attributes and metrics, baseline disaster resilience was quantified for the demonstration case homes when considering specific risks. Several benchmark disaster resilience levels were defined to serve as points of reference to compare with the case homes evaluated. These benchmark levels (Figure 44) are described as follows in order of the lowest achievable level of disaster resilience, to the highest level of disaster resilience.

As mentioned before in Chapter 5, the values used to quantify each attribute correspond to a certain level below or above standard new residential construction (e.g. IRC 2009), where generally, a value of 2 represents building code compliance otherwise referred to as standard new residential construction.

Figure 44 Disaster resilent housing benchmark levels

The score range to achieve a *Poor* resilience classification is between 0.20 and 0.40. A home that is classified as having poor resilience according to this evaluation would achieve values that consist primarily of 1s for the attributes assessed. This score indicates the home is not resilient in regards to the risk being evaluated. In addition to this, the home is characterized as performing below the standard new building and energy code compliant residential buildings in the local area.

The *Fair* resilience level is again used to represent the baseline for standard new homes. The majority of the values obtained for each disaster resilience attribute would equal 2.

A *Good* level of disaster resilience indicates that a home exhibits some resilient qualities that exceed that of a standard new residential building in regards to certain hazard risks.

Achieving the *Very Good* resilience score indicates that the home exhibits a much better level of disaster resilience in regards to certain risks, in comparison to standard new residential buildings.

The final level of resilience falls within the score range of 0.90 and 1.00 and is classified as *Excellent* resilience. This level of resilience indicates that the home exhibits the highest level of disaster resilience that can be obtained for certain risks.

Baseline Disaster Resilience

Baseline disaster resilience of the demonstration case homes was evaluated. A high-priority risk previously identified in the risk assessments performed was considered in each case being evaluated. For Case 1, risk C.I (Debris Penetration/Crack to Windows/Doors) was used in the disaster resilience evaluation, and for Case 2, risk B.I (Debris Penetration/Crack to Roof) was used in the evaluation. The results produced for baseline disaster resilience indicated that Case 1 is considered to have a *Fair* level of resilience to risk C.I, achieving a baseline score of 0.49. Case 2 is also considered to have a *Fair* level of resilience to risk B.I, achieving a baseline disaster resilience score of 0.56.

Table 35 and Table 36 provide details for the disaster resilience evaluations performed for both Case 1 and Case 2 respectively. Similar to the enclosure performance evaluations, to support the evaluation and assumptions made for the demonstration cases, energy modeling, life cycle assessments (LCA), and a literature review of building and energy codes, construction reference tables, and case studies were performed. Such details are again discussed in the notes column of the tables. Where there was not enough detail available for the demonstration cases given the current assumptions and limitations of a conceptual analysis of a home (refer to Table 24 Demonstration case home characteristics summary) to assess certain attributes, a default value was selected to represents code compliant construction, which was generally a value of 2 or 3 depending on the attribute being assessed.

Table 35 Demonstration Case 1 disaster resilience evaluation for risk C.I (Debris Penetration/Crack to Windows/Doors)

Attribute	*Metric*	*Weight*	*Value*	*WV*	*Notes*
Adaptivity	Reflective Learning Behaviors	0.111	5	0.556	Case 1 has protective shutters installed around windows and exterior doors that can be temporarily put in place to reduce the severity of potential debris impacts. This is considered to be a physically adaptable building component that specifically addresses the risk of debris impacts. A study showed that window protection on residential buildings in high wind speed zones during a hurricane reduced the likelihood of damage by 65% (Gurley et al. 2006).
Recovery	Recovery/Repair Time	0.111	4	0.444	With a reduced likelihood of damage to window and door openings as a result of the shutters adapting performance to reduce the severity of the risk, recovery time is assumed to be reduced. Repair of any damage will not however, exceed typical performance after the fact (i.e.it is repaired to pre-impact functionality).
Robustness	Design Loads/ Limit States	0.037	2	0.074	Window and door openings have protective shutters installed that abide by current code (IRC 2012) requirements for debris resistance.
	Water Control & Drying Capacity	0.037	1	0.037	Unchanged – Assumed to be the same as the enclosure performance evaluation. Refer to Table 33.
	EUL or RUL	0.037	2	0.074	Case 1 is an existing home, so RUL (6 years elapsed) was evaluated. The window and door systems used are of main concern for risk C.I. The RUL for the exterior doors, and standard double glazed windows and frame is 24 years.
Resourcefulness	Mobilization Time (Pre-Recovery)	0.111	2	0.222	Default code value assumed. There are no additional pre-event preparedness strategies in place (other than mobilizing opening protection, installed as required by code) that can further reduce pre-recovery downtime after a debris event.
Redundancy	Backups	0.111	2	0.222	Default code value assumed. Window and door openings are assumed to be temporarily covered after a hurricane event if they become damaged, which will restore and maintain partial functionality while waiting for repair.
Energy Efficiency	EUI	0.111	1	0.111	Unchanged – Assumed to be the same as the enclosure performance evaluation. Refer to Table 11 Demonstration Case 1 building enclosure performance evaluation
Resource Efficiency	CO_2e/ft^2	0.111	2	0.222	Unchanged – Assumed to be the same as the enclosure performance evaluation. Refer to Table 11 Demonstration Case 1 building enclosure performance evaluation
Simple	Complexity	0.111	2	0.222	Default code value assumed. Windows and doors repair/installation is assumed to be typical for local contractors. No specialty technologies are used.
Complementary	Interaction	0.111	1	0.111	The condition report revealed that there are signs of deficient sealing and flashing around windows, which make exterior walls more vulnerable to wetting hazards.
Case 1 Enclosure Performance Score =				**0.492**	**Fair Resilience**

Table 36 Demonstration Case 2 disaster resilience evaluation for risk B.I (Debris Penetration/Crack to Roof)

Attribute	*Metric*	*Weight*	*Value*	*WV*	*Notes*
Adaptivity	Reflective Learning Behaviors	0.111	3	0.333	Case 2 has no physically adaptable features on the roof that can reduce debris impact severity, however, RCx is planned at a later date should the roof need to be strengthened beyond the current design load to resist wind hazards. It is assumed that any RCx performed will reduce the risk of this failure by a minimum of 10-20%.
Recovery	Recovery/Repair Time	0.111	2	0.222	Default code value assumed. Repair time is assumed to be typical for debris damage to a roof.
Robustness	Design Loads/ Limit States	0.037	2	0.074	The roof meets current code (IRC 2012) requirements. It is not currently designed to withstand higher loads of debris, unlike the windows and exterior wall surfaces, which have been.
	Water Control & Drying Capacity	0.037	3	0.111	Unchanged – Assumed to be the same as the enclosure performance evaluation. Refer to Table 34.
	EUL or RUL	0.037	2	0.074	Case 2 is a new home, so EUL was evaluated. The roof system was of primary concern for risk B.I, more specifically the non-structural materials, as the roof structure lasts the lifetime of a building. The EUL for non-structural roof materials are considered to by typical for a code compliant roof.
Resourcefulness	Mobilization Time (Pre-Recovery)	0.111	2	0.222	Default code value assumed. There are no additional pre-event preparedness strategies in place that can reduce pre-recovery downtime after a debris event.
Redundancy	Backups	0.111	2	0.222	Default code value assumed. The roof is assumed to be temporarily covered after a hurricane event if it is damaged by debris, which will restore and maintain partial functionality while waiting for repair.
Energy Efficiency	EUI	0.111	5	0.556	Unchanged – Assumed to be the same as the enclosure performance evaluation. Refer to Table 12 Demonstration Case 2 building enclosure performance evaluation
Resource Efficiency	CO_2e/ft^2	0.111	2	0.222	When considering only the roof for Case 2, it meets baseline LCA values when compared to a standard residential roof constructed according to the same building and energy codes.
Simple	Complexity	0.111	2	0.222	Default code value assumed. A roof repair/installation is assumed to be typical for local contractors. No specialty technologies are used.
Complementary	Interaction	0.111	3	0.333	The condition report revealed that the roof is in new condition, and does not negatively or positively influence other building systems/components in regards to resilience to other hazards.
	Case 2 Enclosure Performance Score =			**0.555**	**Fair Resilience**

The final results from the baseline performance and disaster resilience assessments are presented in the following graphs (Figure 45 and Figure 46.) As depicted in the graphs, the bottom left quadrant represents lower levels of resilience and enclosure performance, which should be avoided. The top right green quadrant represents higher levels of resilience and performance, which is desired. Case 1's baseline resilience and performance to risk C.I. falls close to the low levels of resilience and performance quadrant, while Case 2's baseline resilience and performance fairs better, and falls within the more desired green quadrant. The performance of Case 2's enclosure is very high, although, in regards to resilience to risk B.I., there is still some room for improvement to further mitigate the risk of the failure occurring.

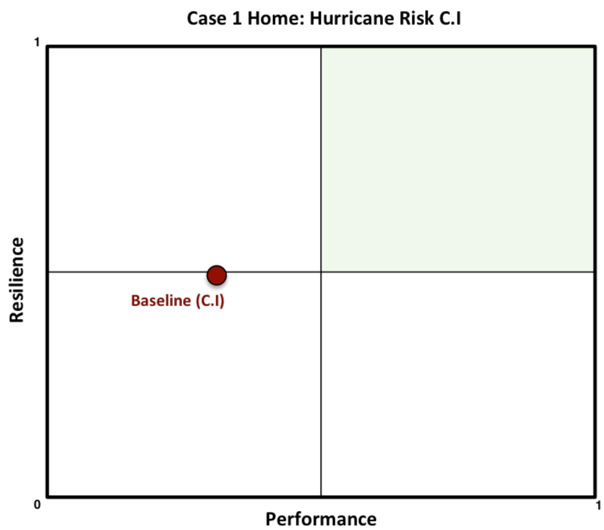


Figure 45 Case 1 baseline performance and disaster resilience for risk C.I.

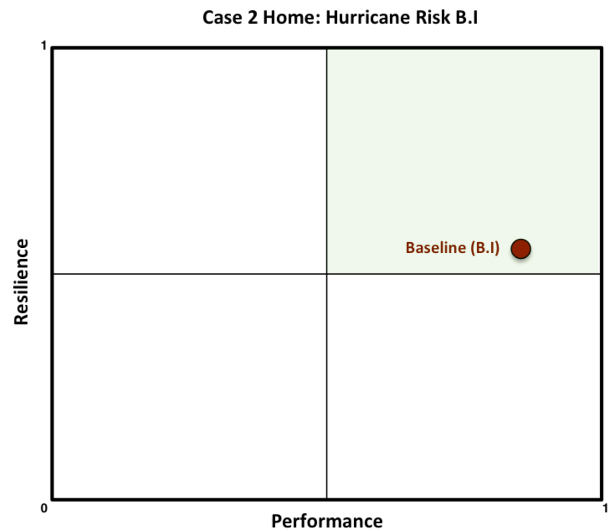


Figure 46 Case 2 baseline performance and disaster resilience for risk B.I.

6.3.3 HPRB Technology Prioritization Results

A re-evaluation of performance and disaster resilience was carried out for the case homes with a selection of HPRB technologies specific to each risk evaluated in the baseline assessments performed. HPRB technologies were prioritized for each risk in the re-evaluations.

Case 1 Re-Evaluation: Baseline vs. HPRB Technologies

When re-evaluating performance and disaster resilience for Case 1, the HPRB technologies that were considered included: **HPRB 1** – building commissioning, to simply evaluate the enclosure for deficiencies (this option is more appropriate for new construction to verify quality, however it is still considered as an option here); **HPRB 2** – replacing existing openings with low-U, high-impact and pressure rated openings; and **HPRB 1 & 2** – a combination of both, retro-commissioning to bring any enclosure deficiencies up to current code requirements, and replacing existing openings with low-u, high-impact and pressure rated openings.

When considering these three options, the following enclosure performance and disaster resilience scores for risk C.I were re-evaluated from baseline scores as presented in Table 37 and Table 38.

Table 37 Case 1 enclosure performance re-evaluation for risk C.I with HPRB technology options

Attribute	Metric	Weight	Baseline		HPRB 1		HPRB 2		HPRB 1 & 2	
			Value	WV	Value	WV	Value	WV	Value	WV
High Levels of Insulation	Total UA	0.111	**1**	**0.111**	1	0.111	3[a]	0.333	3[a]	0.333
Minimal Air Leakage	ACH50	0.111	**2**	**0.222**	2	0.222	2	0.222	2	0.222
Enhanced Occupant Comfort and Health	Resident Satisfaction	0.037	**3**	**0.111**	3	0.111	3	0.111	3	0.111
	STC Rating	0.037	**2**	**0.074**	2	0.074	2	0.074	2	0.074
	IAQ	0.037	**2**	**0.074**	2	0.074	2	0.074	2	0.074
Energy Efficiency	EUI	0.111	**1**	**0.111**	1	0.111	2[b]	0.222	2[b]	0.222
Resource Efficiency	CO_2e/ft^2	0.111	**2**	**0.222**	2	0.222	2	0.222	2	0.222
Minimized Life-Cycle Cost	LCC/ft^2	0.111	**1**	**0.111**	1	0.111	2[c]	0.222	2[c]	0.222
Verified Quality Assurance	Cx/RCx	0.111	**1**	**0.111**	3[d]	0.333	1	0.111	5[e]	0.556
Enhanced Durability	Design Loads/ Limit States	0.037	**1**	**0.037**	1	0.037	1	0.037	2[e]	0.074
	Water Control & Drying Capacity	0.037	**1**	**0.037**	1	0.037	1	0.037	3[e]	0.111
	EUL or RUL	0.037	**2**	**0.074**	2	0.074	3	0.111	3[f]	0.111
Climate Zone Appropriate	IECC Climate Zone	0.111	**1**	**0.111**	1	0.111	2	0.222	2[e]	0.222
Case 1 Performance Scores =			**Poor**	**0.309**	**Poor**	**0.357**	**Fair**	**0.439**	**Fair**	**0.560**
		% Improvement from baseline performance:				+16%		+42%		+82%

[a] Window openings upgraded to more energy efficient technologies: U-30 windows, with a 0.32 solar heat gain coefficient, and reduced air leakage, as well as high-impact and pressure ratings to increase resistance to debris. The Total UA is now calculated to be 19% less than IECC 2009 requirements.
[b] Increased thermal performance reduces the energy consumption to meet the average EUI for the local area.
[c] Increased thermal performance similarly reduces operation cost to meet the local average.
[d] Only Cx is performed in this scenario to identify areas in need to retrofit to improve enclosure performance (not recommended for existing homes)
[e] RCx is performed to retrofit and upgrade enclosure performance to meet IRC 2012 and IECC 2009 requirements. And deficiencies, which include material deterioration, insufficient design loads, flashing, and sealants, are also remedied.
[f] New openings installed increases the EUL, which is now estimated to be 30 years

Table 38 Case 1 disaster resilience re-evaluation for risk C.I with HPRB technology options

Attribute	Metric	Weight	Baseline		HPRB 1		HPRB 2		HPRB 1 & 2	
			Value	WV	Value	WV	Value	WV	Value	WV
Adaptivity	Reflective Learning Behaviors	0.111	**5**	**0.556**	5	0.556	5	0.556	5	0.556
Recovery	Recovery/ Repair Time	0.111	**4**	**0.444**	4	0.444	4	0.444	4	0.444
Robustness	Design Loads/ Limit States	0.037	**2**	**0.074**	2	0.074	5[a]	0.185	5[a]	0.185
	Water Control & Drying Capacity	0.037	**1**	**0.037**	1	0.037	1	0.037	3[b]	0.111
	EUL or RUL	0.037	**2**	**0.074**	2	0.074	3[c]	0.111	3[c]	0.111
Resourcefulness	Mobilization Time	0.111	**2**	**0.222**	2	0.222	2	0.222	2	0.222
Redundancy	Backups	0.111	**2**	**0.222**	2	0.222	5[d]	0.556	5[d]	0.556
Energy Efficiency	EUI	0.111	**1**	**0.111**	1	0.111	2[e]	0.222	2[e]	0.222
Resource Efficiency	CO_2e/ft^2	0.111	**2**	**0.222**	2	0.222	2	0.222	2	0.222
Simple	Complexity	0.111	**2**	**0.222**	2	0.222	2	0.222	2	0.222
Complementary	Interaction	0.111	**1**	**0.111**	1	0.111	1	0.111	3[f]	0.333
Case 1 Disaster Resilience Scores =			**Fair**	**0.492**	**Fair**	**0.492**	**Good**	**0.619**	**Good**	**0.682**
% Improvement from baseline disaster resilience:						+0%		+26%		+39%

[a] Window impact-resistance is doubled with high-impact glazing (passes the enhanced missile D ASTM test, a missile double the weight and moving faster than the standard missile C test)
[b] Flashing deficiencies and deterioration at window/door openings are brought up to code with RCx
[c] New openings installed increases the EUL, which is now estimated to be 30 years
[d] Redundancy is improved by having protective shutters and high-impact windows in place should the protective shutters fail (immediate mobilization and full functionality)
[e] Window openings upgraded to more energy efficient technologies: U-30 windows, with a 0.32 solar heat gain coefficient, and reduced air leakage, as well as high-impact and pressure ratings to increase resistance to debris. The Total UA is now calculated to be 19% less than IECC 2009 requirements
[f] New window openings installed and RCx performed remedies deterioration and deficiencies at window-wall connections, which includes restoring flashing up to current code requirements.

Case 2 Re-Evaluation: Baseline vs. HPRB Technologies

When re-evaluating performance and disaster resilience for Case 2, the HPRB technologies that were considered included: **HPRB 1** – insulated concrete forms (ICF) in place of wood frame construction (considering this case a new construction, and there is the possibility of altering the structural design), which alters the roof and wall construction to R-25 walls and an additional 4" of rigid insulation attached to the ICFs to maintain a high total R-value of R-45; and **HPRB 2** – attaching 4" of continuous rigid insulation to the roof sheathing. When considering these two HPRB options, the following enclosure performance and disaster resilience scores for risk B.I were re-evaluated from baseline scores as presented in Table 39 and Table 40.

Table 39 Case 2 performance and disaster resilience re-evaluation for risk B.I with HPRB technology options

Attribute	***Metric***	***Weight***	***Baseline***		***HPRB 1***		***HPRB 2***	
			Value	***WV***	***Value***	***WV***	***Value***	***WV***
High Levels of Insulation	Total UA	0.111	**5**	**0.556**	5	0.556	5	0.556
Minimal Air Leakage	ACH50	0.111	**5**	**0.556**	5	0.556	5	0.556
Enhanced Occupant Comfort and Health	Resident Satisfaction	0.037	**4**	**0.148**	4	0.148	4	0.148
	STC Rating	0.037	**5**	**0.185**	5	0.185	5	0.185
	IAQ	0.037	**2**	**0.074**	2	0.074	2	0.074
Energy Efficiency	EUI	0.111	**5**	**0.556**	5	0.556	5	0.556
Resource Efficiency	CO_2e/ft^2	0.111	**1**	**0.111**	1	0.111	1	0.111
Minimized Life-Cycle Cost	LCC/ft^2	0.111	**5**	**0.556**	5	0.556	5	0.556
Verified Quality Assurance	Cx/RCx	0.111	**5**	**0.556**	5	0.556	5	0.556
Enhanced Durability	Design Loads/ Limit States	0.037	**4**	**0.148**	5[a]	0.185	5[a]	0.185
	Water Control & Drying Capacity	0.037	**3**	**0.111**	5[b]	0.185	5[c]	0.185
	EUL or RUL	0.037	**3**	**0.111**	3	0.111	3	0.111
Climate Zone Appropriate	IECC Climate Zone	0.111	**2**	**0.222**	2	0.222	2	0.222
Case 1 Performance Scores =			**VG**	**0.853**	**VG**	**0.877**	**VG**	**0.877**
	% Improvement from baseline performance:					+3%		+3%

[a] The roof now has an improved impact resistance. This makes the window openings, and exterior wall surfaces all resistant to large impacts beyond code requirements.
[b] ICF have a high resistant to moisture damage
[c] Improved moisture resistance at roof with insulating sheathing (further prevents water leakage risks at the roof, and risk of condensation at roof surfaces is reduced)

Table 40 Case 2 disaster resilience re-evaluation for risk B.I with HPRB technology options

Attribute	*Metric*	*Weight*	*Baseline*		*HPRB 1*		*HPRB 2*	
			Value	*WV*	*Value*	*WV*	*Value*	*WV*
Adaptivity	Reflective Learning Behaviors	0.111	**3**	**0.333**	3	0.333	3	0.333
Recovery	Recovery/ Repair Time	0.111	**2**	**0.222**	4[a]	0.444	5[b]	0.556
Robustness	Design Loads/ Limit States	0.037	**2**	**0.074**	5[c]	0.185	3[c]	0.111
	Water Control & Drying Capacity	0.037	**3**	**0.111**	5[d]	0.185	5[d]	0.185
	EUL or RUL	0.037	**2**	**0.074**	2	0.074	2	0.074
Resourcefulness	Mobilization Time	0.111	**2**	**0.222**	2	0.222	2	0.222
Redundancy	Backups	0.111	**2**	**0.222**	2	0.222	2	0.222
Energy Efficiency	EUI	0.111	**5**	**0.556**	5	0.556	5	0.556
Resource Efficiency	CO_2e/ft^2	0.111	**2**	**0.222**	1[e]	0.111	1[e]	0.111
Simple	Complexity	0.111	**2**	**0.222**	2	0.222	2	0.222
Complementary	Interaction	0.111	**3**	**0.333**	5[f]	0.556	3	0.333
Case 1 Disaster Resilience Scores =			**Fair**	**0.555**	**Good**	**0.666**	**Good**	**0.627**
% Improvement from baseline disaster resilience:						+20%		+13%

HPRB Technologies Prioritized for Demonstration Case Hurricane Risks

The final results from the re-evaluation of performance and disaster resilience of the demonstration cases while considering HPRB technology options to mitigate specific risks are presented in the following graphs (Figure 47 and Figure 48). For Case 1, the combination of HPRB technology 1 and 2 is the best option to mitigate risk C.I. For Case 2, HPRB technology 1 increases the home's disaster resilience to risk B.I the most, however, HPRB technology 2 can also be considered as a viable option, as well as a much more feasible technology that can be achieved without requiring significant re-design and construction.

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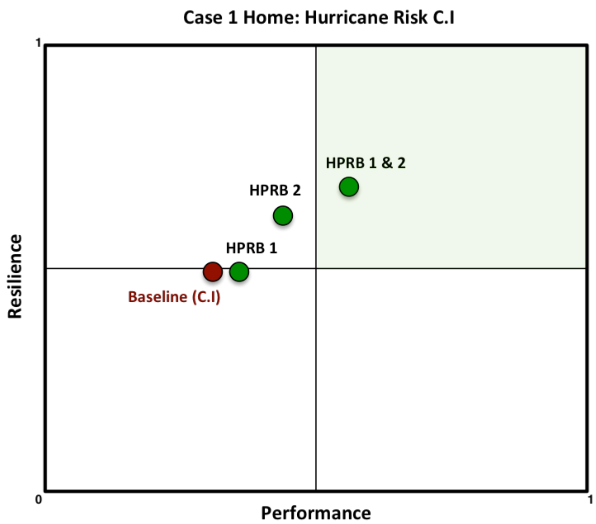
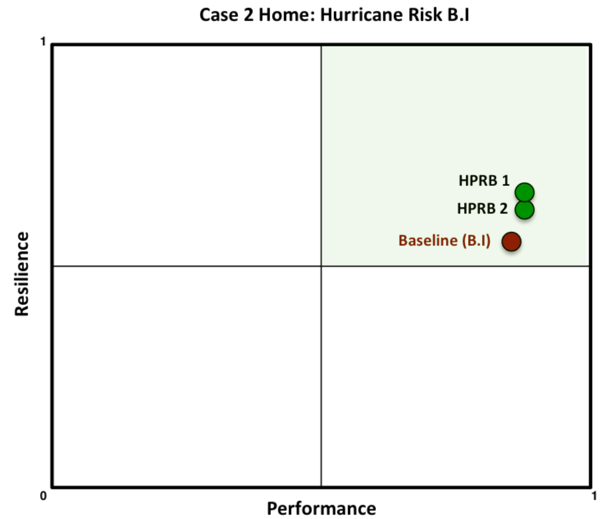
[a] A stronger roof surface is assumed to reduce the severity of debris impacts, and thus reduce the repair and recovery time needed should a debris event take place.
[b] Should the now stronger roof surface become damaged by debris, RCx, which has been planned, will repair the roof beyond pre-impact conditions with additional layers of protection as needed to increase robustness.
[c] The roof has an enhanced resistance to debris, which is assumed to be true even more so for ICF construction.
[d] Improved moisture resistance at roof with insulating sheathing (further prevents water leakage risks at the roof, and risk of condensation at roof surfaces is reduced)
[e] Resource efficiency is reduced due to the addition of several layers of rigid insulation, and ICFs similarly reduce resource efficiency due to the material content (i.e. concrete and rigid insulation).
[f] An ICF enclosure not only increases the strength of the roof, but it also will increase the strength of walls resistance to hurricane loads





Risk C.I	Baseline	HPRB 1	HPRB 2	**HPRB 1+2**	**Risk B.I**	Baseline	**HPRB 1**	HPRB 2
Performance	**0.31**	0.36	0.44	**0.56**	Performance	**0.85**	**0.88**	0.88
Resilience	**0.49**	0.49	0.62	**0.68**	Resilience	**0.56**	**0.67**	0.63

Figure 47 Case 1 prioritized HPRB technologies for risk C.I. compared to it's baseline

Figure 48 Case 2 prioritized HPRB technologies for risk B.I. compared to it's baseline

6.4 Summary of Results and Reflection

A process to prioritize climate induced natural disaster risks, and selective HPRB technologies to address these risks, was developed and demonstrated using hurricane hazards and conceptual case study homes. For both case homes that were used to demonstrate this process, it was revealed that HPRB technologies specifically addressing hurricane risks of high concern for each specific housing context are able to increase both, enclosure performance and disaster resilience beyond baseline levels using the metrics developed in this research. The process was also able to demonstrate how this can be done in a quantifiable and prioritized way for decision-makers. Figure 49 shows a diagram summarizing the work and results of this chapter, which corresponds to research Objective C.

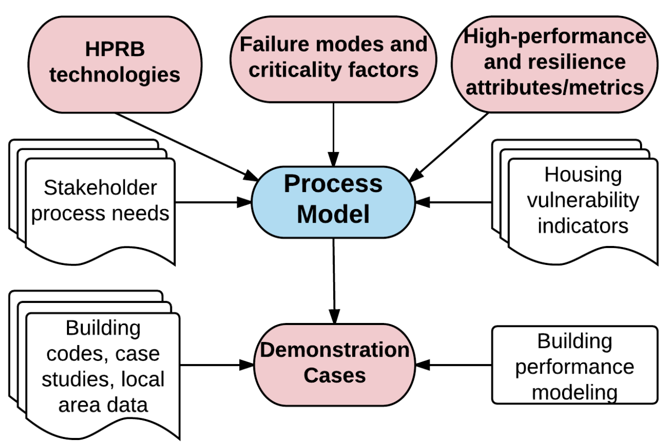


Figure 49 Summary diagram of Objective C work and results

While the developed process in this research used conceptual scenarios for demonstration, in the future, the process can be tested for validity and viability with users by having them perform assessments on actual homes and comparing their results with the theoretical outcomes of this research. Further testing and validation of the metrics, values, and weights used for the MCDM assessments should be performed with more case homes to refine the performed assessments. The incorporation of more hazards into this process will expand the processes applicability to more climate zones, which requires more hazard impact analyses to be performed in order to increase the database size of the process.

Developing this process further into a software program or web-based tool should be explored. Such a tool should allow for easy-use, and wide accessibility for the stakeholders who desire a process to assess both housing performance and disaster resilience as a combined goal for a variety of natural hazards and building systems.

7 Discussion of Results and Validation

In the residential building industry, homeowners are seeking ways to improve the performance of their homes in regards to cost, comfort, operation, and maintenance. Additionally, they are increasingly concerned with the risks of climate change and natural disaster destruction. Home designers, builders, and community planners are similarly seeking ways to support homeowners by addressing these concerns and achieving their goals of improving performance and mitigating natural disaster risks, however, they lack the resources to do so.

The original research question posed in response to this problem was:

How can we identify and prioritize high-performance building technologies that can effectively provide residential buildings resilience towards local level climate induced natural disaster risks currently experienced and anticipated throughout the diverse U.S. climate regions?

The research that has been performed to answer this question aimed to develop a process that can prioritize technologies for residential buildings that incorporate both high-performance and disaster resilient qualities for natural disaster risks applicable to specific housing contexts.

A framework for a process to perform the aforementioned prioritization was developed in this research. This process can assist decision-makers in the housing industry that try to efficiently make homes higher performing and disaster resilient in response to the challenges they face in terms of climate and building performance.

The following sub-sections discuss the obtained results and the different validation tasks that were performed for these results. The validation discussion also includes an audit trail of the collected data toward the produced results, as well as subject matter expert surveys that were conducted for various aspects of the research results.

7.1 VALIDATION OF FINDINGS

Validation of the research carried out using the previously stated validation methods (refer back to the Research Validation section) is explained here.

7.1.1 Validation of the Research Tasks and Results

Dependability and confirmability were considered continuously as the research was undertaken and as data was being collected. As previously stated, the entire research process was documented thoroughly, and all personal assumptions and preliminary theories were admitted and communicated prior to data collection. Additionally, all sources of data have been documented and aligned with the produced results as an audit trail, which is summarized in Figure 50. The audit trail illustrates the entire research process that was conducted. The purpose of the audit trail is to confirm the objectivity in the results that have been produced. In addition to what has been previously disclosed prior to data collection and analysis (i.e. the research design, assumptions, and preliminary theories), this audit trail depicts all of the data and processes that were performed, which ultimately lead to the final results and major findings of the research.

For Objective A, Tasks A1 and A2 required the literature research method. The sources of data used to produce the results drew upon data presented in the National Climate Assessment reports developed by over 300 experts and advisory member committees, which was extensively reviewed by additional experts and panels before dissemination, increasing the validity of the data. Older versions of this source of data have previously been used in prior studies investigating climate impacts on buildings (Larsen et al. 2011). Task A2 involved the examination of widely accepted and implemented high-performance building standards, as well as case studies detailing the use of various high-performance building technologies to increase the credibility of the technologies being identified for the inventory of solutions.

Task A3 involved the data collected from Tasks A1 and A2, as well as data from case studies and damage assessments performed for historic events of natural disaster occurrences and their impacts on residential buildings. An example of one of the credible sources of literature included for this task were FEMA Mitigation Assessment Team and Building Performance Assessment Team Reports, which included national expert contributions in fields such as engineering and architecture, and their observations of the successes and failures of buildings after natural disaster events. Using sources of data such as these ensured that the produced results were representative of the reality, and thus further increased the validity of this research. This is a method/type of data source that has been used in other research studies to validate FMECAs and FTAs by identifying failures and events that have occurred and that have been recorded in databases and/or reports in order to check for completeness (Stamatelatos et al. 2002; ten Veldhuis et al. 2009). FMECAs can also be used to validate FTAs to ensure completeness (Stamatelatos et al. 2002). Additionally, a triangulation was implemented by surveying a group of subject matter experts about the collected information to produce the different FMECAs and FTAs.

To ensure the transferability or generalizability of the tasks in Objective A, demonstrations showed how the data can be collected and analyzed to represent different types of climates and locations where natural hazards will vary. This was achieved by focusing on one specific region and one natural hazard throughout the research, in this instance focusing on hurricanes, which demonstrated how the same approach can be used for additional climates and other natural hazards of concern.

Tasks B1 and B2 required the selection of two samples of literature on the topics of high-performance building and disaster resilience for the residential building context, and then the subsequent thematic analysis of these literature resources to define a set of attributes and metrics that were used for decision-making. To increase the validity of the produced results from these tasks, credibility was sought after from the literature resources included in the samples by using a purposive sampling technique. This ensured that the sampled texts were specific to the subject matter and were able to effectively inform the research being conducted by meeting a set of qualifying criteria. In addition to this, due to the interpretative nature of thematic analysis and coding, a triangulation, in the form of another subject matter expert survey, was used to strengthen the credibility of the produced results. This validation method has been extensively advocated for improving the validity of thematic analysis coding (Guest et al. 2012). Additionally it has been discussed that having external members of the research team review the data produced from thematic analyses, is another acceptable method to increase the external reliability of data (Guest et al. 2012).

Finally, for Objective C, similar methods for credibility and transferability were used for validation. Task C1 required that the necessary steps were first defined for the process developed. This included consultation of literature that details current processes and/or needs of stakeholders to undertake disaster mitigation and building performance assessments. Reviewing these sources also ensured that the process was consistent with current capabilities, and that it aligns with the needs of stakeholders that can potentially use this process.

Task C2 involved the extraction of local area characteristics and housing stock data found in building and energy codes, and public databases provided by government census' to evaluate baseline performance and resilience levels for the demonstration case home and residential buildings located in the designated area of the cases. Census data, FEMA reports, and city and county level databases have been used in prior studies in which disaster resilience variables, or composite indicators, were constructed to measure baseline performance in regards to resilience and vulnerability (Cutter et al. 2010). Justification of the selection of such indicators was based upon their relevance (or agreeability) to resilience literature, and the availability of consistent and quality data in national databases (Cutter et al. 2010). For triangulation of the collected data, and to support various assumption made for the demonstration case homes in regards to building performance and disaster resilience, some building performance modeling, specifically for energy, thermal, and resource consumption, was performed.

Task C3 required additional modeling and supporting literature to justify the indicators, weights, and values used in the MCDM process. Results/data from Objectives A and B, which already include a substantially amount of credibility, were also integrated into Tasks C2 and C3. Transferability was also demonstrated in Task C2 with the demonstration cases, which tested the wide applicability potential of the MCDM process by using variables selected to represent diverse contexts for residential building assessments.

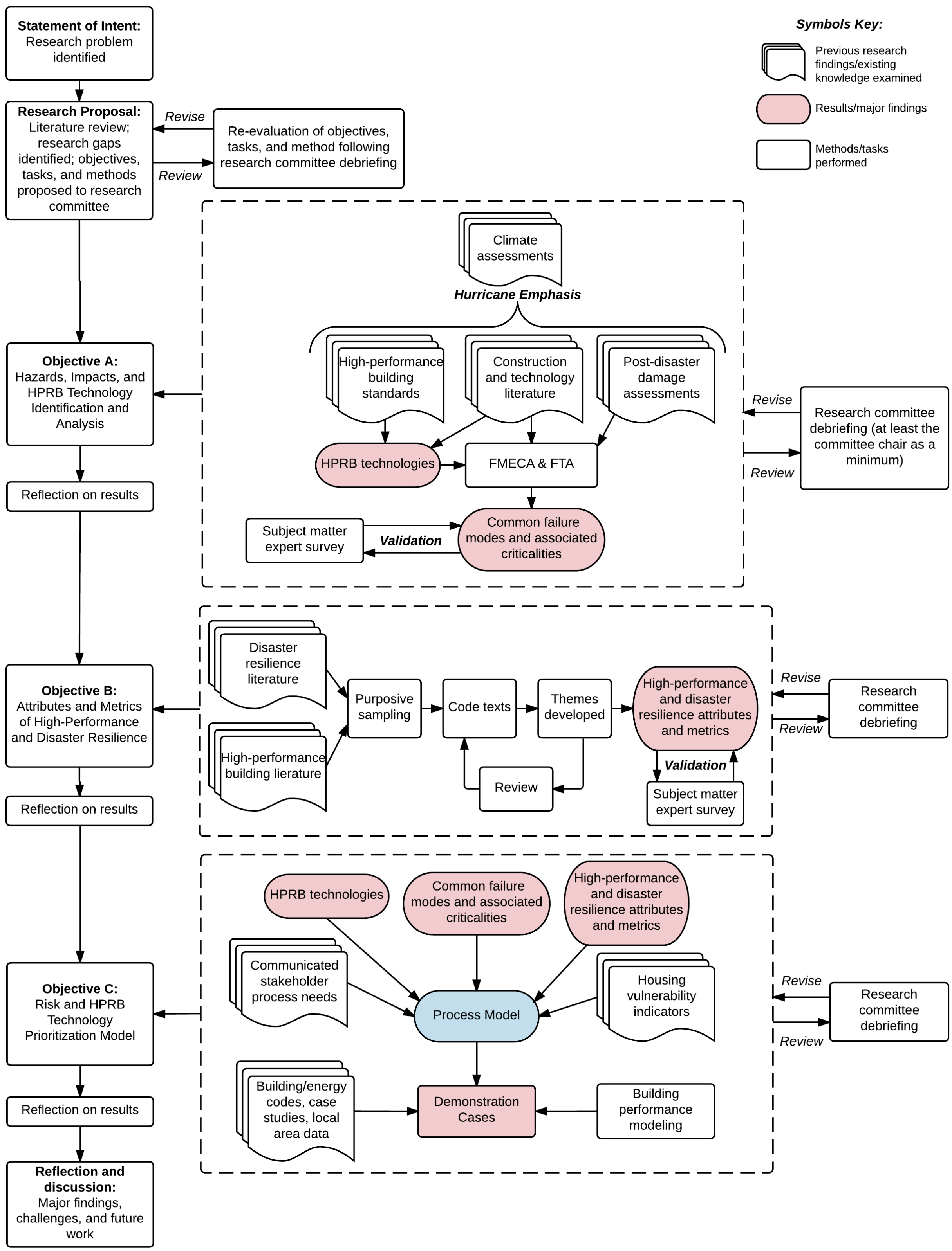


Figure 50 Audit trail of the research performed

7.1.2 Subject Matter Expert Surveys

Two validation studies were performed, which involved surveying a sample of participants who were identified as subject matter experts for either hurricane damage to residential buildings, and/or high-performance buildings and disaster resilience. The validation studies were administered in the form of an online survey. Specific questions were asked in relation to the research findings, which were determined through the use of other sources of data as detailed in the previous results section. The characteristics of the subject matter experts and the results from the validation studies are discussed in the following subsections.

Validation Study 1: Hurricane Damage Survey

A total of 10 subject matter experts were initially identified as eligible candidates to participate in Validation Study 1, with a final total of responses obtained from 6 of the experts. This survey was used to validate findings from Objective A. More specifically, the goal was to verify common failure modes that are encountered by residential building enclosures in the event of a hurricane, and compare the understanding of criticality of these failure modes. The questions posed to the participants for this survey were limited primarily to exterior walls for brevity during this phase of the research. Only a minimal set of key questions were asked in regards to other enclosure components.

Subject Matter Expert Characteristics: Several questions were asked to the experts prior to taking the survey. The intent of these questions was to gain a better understanding of the expert's background with regard to the conducted research. This included gathering information about the industries they currently work/have experience in, the number of years they have in their specified work areas, and the U.S. region or regions that they primarily work in. The results from these questions revealed the following about the 6 experts who participated in Validation Study 1.

Industry area(s) currently working in or have experience in:

Of the experts who participated in this survey, all have extensive experience in residential construction, which was an important factor specific to the scope of this research. Additional areas of experience varied with almost all of the experts having experience in building design and construction, conducting damage assessments of buildings, and working in natural hazard mitigation roles. Experts in the fields of natural disaster and homeowners insurance were also a part of the sample of participants, which were fields of expertise specifically sought after due to challenges with obtaining quantitative damage statistics from insurance agencies. Figure 51 summarized the work experiences of the experts.

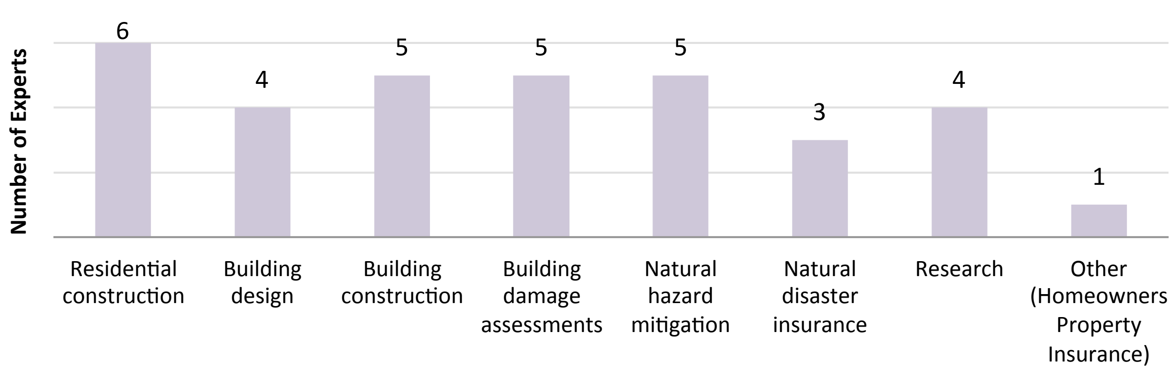


Figure 51 Work expererinece of the experts for Validation Study 1

Years of experience in specified work field(s):

The experts hold leadership positions in the industry and consequently have considerable amount of experience in their specified fields of work. No participant had less than 20 years of experience in their industries, which ensured that they were indeed qualified to provide sound insight into the questions they were asked as experts. The years of experience of the experts are summarized as follows:

- The experts have a **total average of 29 years of experience** in their specified industries
- The minimum amount experience indicated was 20 years
- The maximum amount of experience indicated was 40 years

U.S. region(s) primarily working in:

As the primary focus of this research was the Southeast region of the U.S. and the climate of that region, it was important that the experts also represented this area. As summarized in Figure 52, all of the experts work in the Southeast region of the U.S. as well as other regions throughout the country.

Figure 52 U.S. regions the experts primarily work in for Validation Study 1

Expert responses: The first series of questions asked to each participate was related to the initial damages, or failure modes, experienced by exterior walls during a hurricane, and the indirect effects, or consequential damages, of each failure mode if left unrepaired. In addition to this, the participants were also asked to identify common hazard loadings of a hurricane that contribute to each failure mode. The structure of this survey, and this particular series of questions, was setup up so that the participants could select answers from given options with which they agree with according to their own experiences/knowledge. In the event that an option that they felt answered the question was not available for them to select from, they could bring attention to this by selecting an option that indicated that such an answer or answers were not listed (i.e. "other not listed"). However, it was stressed that this only be selected if it was for a significant occurrence, and not for rare events. Summaries of the responses from Validation Study 1 are discussed as follows.

Hurricane hazard loadings:

As presented in Figure 53, all of the experts agreed that pressure from wind or floodwater, wetting from rain or floodwater, and wind- or water-borne debris are common hurricane hazard loadings for exterior walls. 1 expert also believed that there was a hazard load or loadings not represented in addition to pressure, wetting, and debris.

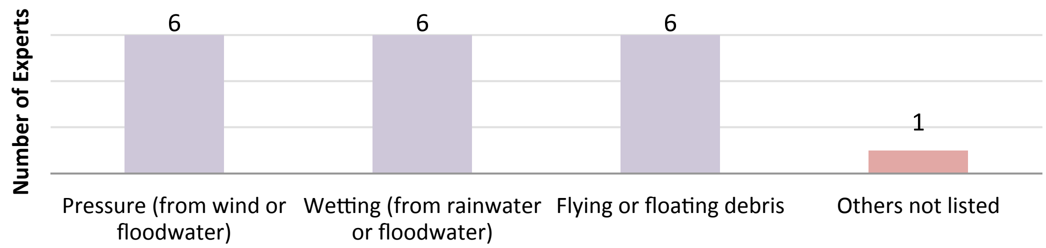


Figure 53 Expert responses for common hurricane hazard loadings

Pressure loading failure modes and effects:

As shown in Figure 54, all 6 of the experts agreed that common failure modes for exterior walls as a result of pressure are exterior wall structural failures, and detached non-structural components. 2 of the experts also believed that there was a failure mode or modes not represented.

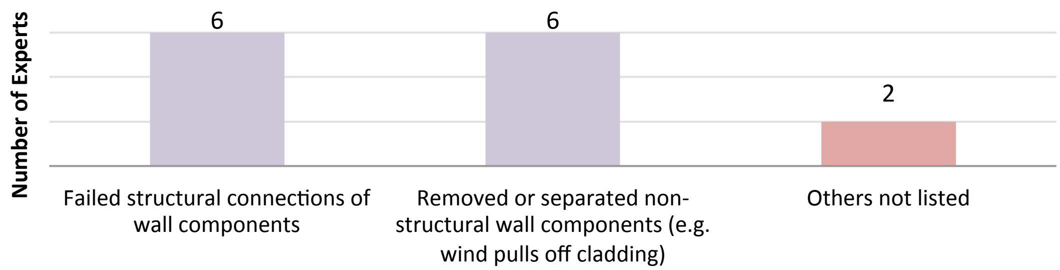


Figure 54 Expert responses for common pressure loading failure modes

Figure 55 shows that all of the experts agreed that common failure mode effects for the pressure induced failure modes were water damage and/or accumulation. 4 experts agreed that a building could completely collapse, and 3 of the experts agreed that a roof could experience structural damage. 2 experts also believed that there was a failure mode effect or effects not represented.

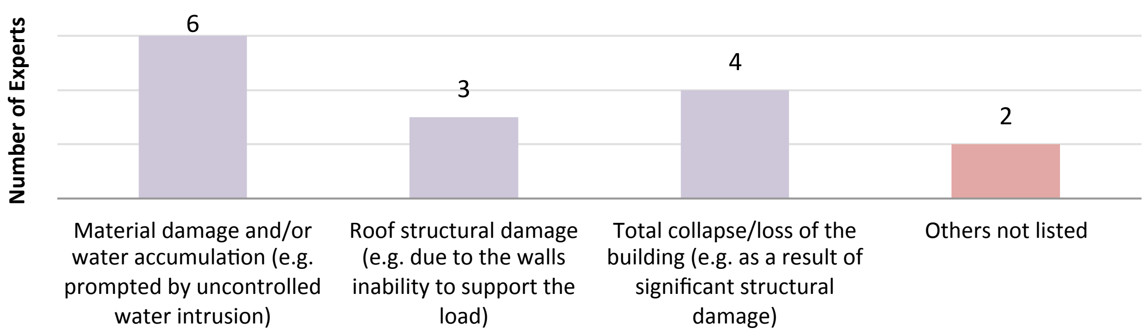


Figure 55 Expert responses for common pressure loading failure mode effects

Wetting loading failure modes and effects:

As shown in Figure 56, 5 of the experts agreed that common failure modes for exterior walls as a result of wetting are material damage and water accumulation within walls, while 1 expert believed that there was a failure mode or modes not represented in this category.

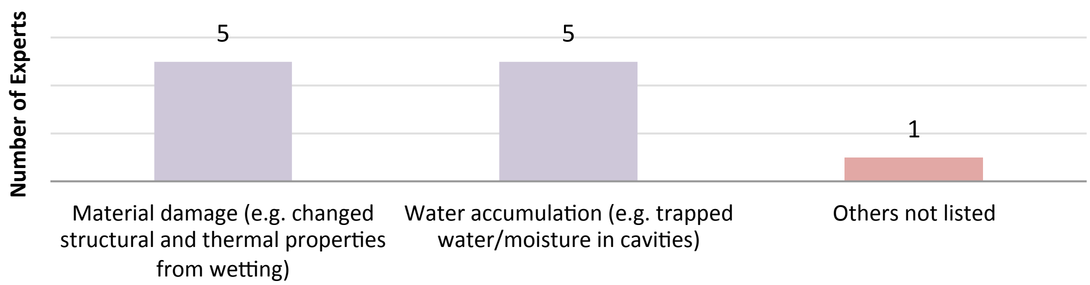


Figure 56 Expert responses for common wetting loading failure modes

As presented in Figure 57, all of the experts agreed that common failure mode effects as a result of wetting induced failures were unusable components due to water damage. 5 experts agreed that non-structural components could detach, and 4 agreed that a wall could experience structural failures**.** 2 experts also believed that there was a failure mode effect or effects not represented

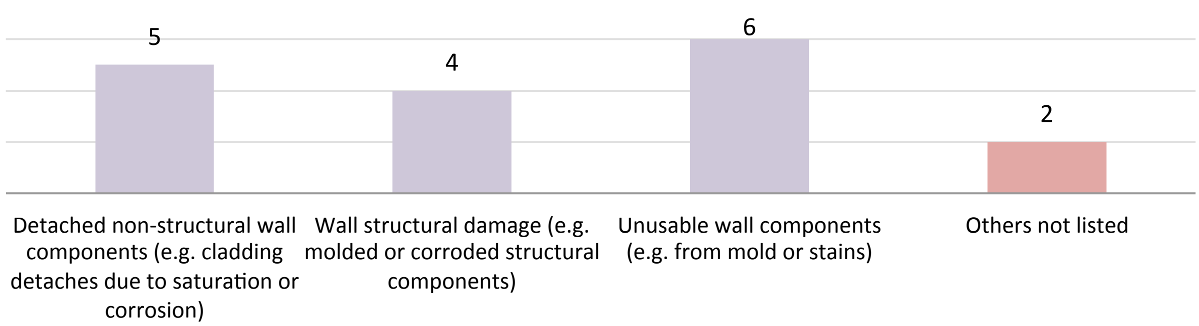


Figure 57 Expert responses for common wetting loading failure mode effects

Debris loading failure modes and effects:

Figure 58 shows that 5 of the experts agreed that common failure modes for exterior walls as a result of wind- or water-borne debris are penetrations and cracks, and 4 agree that permanent deformations (e.g. dents) could also occur from debris impacts. 2 experts believed that there was a failure mode or modes not represented.

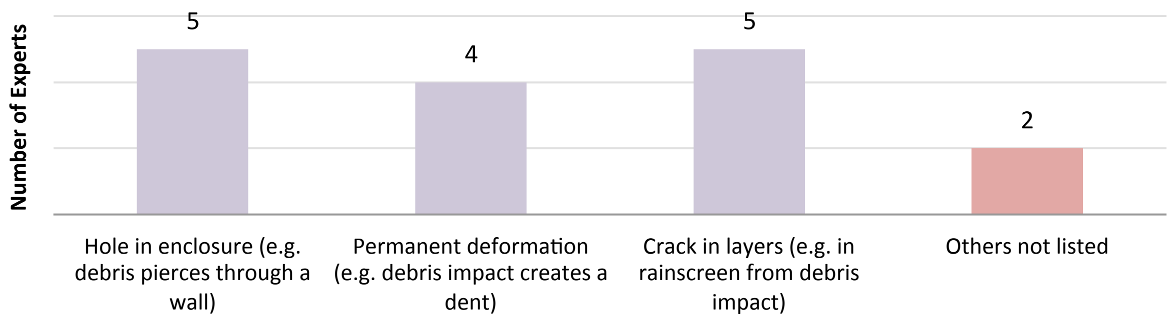


Figure 58 Expert responses for common debris loading failure modes

As presented in Figure 59, all of the experts agreed that common failure mode effects as a result of debris induced failure modes were unusable components due to water damage. 4 experts agreed that windows and door openings could be blown-out from internal pressurization, and that walls and roofs could experience structural failures also due to excessive internal pressure build-up or displacement from debris impacts. 3 experts agreed that a building could completely collapse. 1 expert also believed that there was a failure mode effect or effects not represented

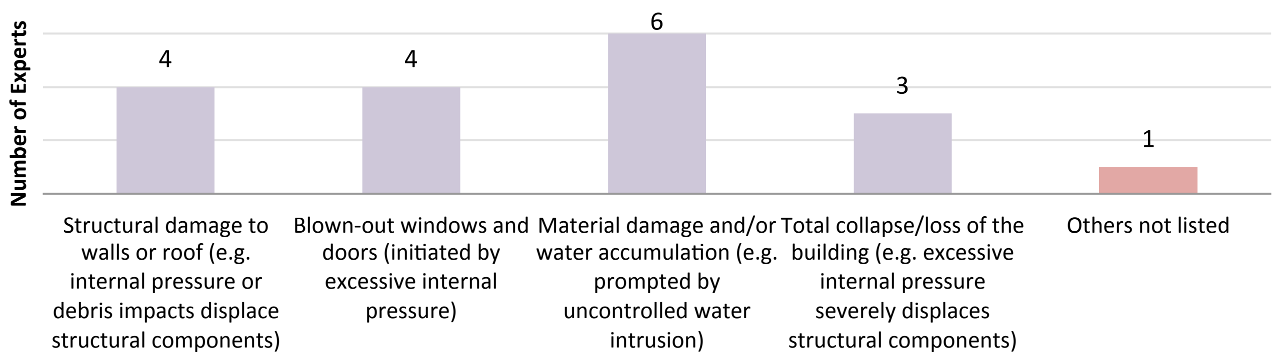


Figure 59 Expert responses for common debris loading failure mode effects

In another series of questions, the experts were asked the rank the likelihood of occurrence for the common failure modes identified for exterior walls, as well as the likelihood of different enclosure components experiencing any kind of damage during a hurricane. Summaries of the responses given by the experts are discussed as follows.

Likelihood of enclosure components experiencing damage:

According to the expert responses received as depicted in Figure 60, the results show that a roof is believed to be most likely to experience damage during a hurricane, while the foundation is considered to be the least likely to experience damage. Exterior walls and windows/doors were more evenly ranked between the two categories as either likely or unlikely. However, there was slightly more favorability that windows/doors are more likely to experience damage than exterior walls.

The expert responses agreed well with the results produced from the damage assessment data, where enclosure components ranked from most likely to experience damage during a hurricane to least likely, was also in the same order as follows: roof, windows/doors, exterior walls, and foundations.

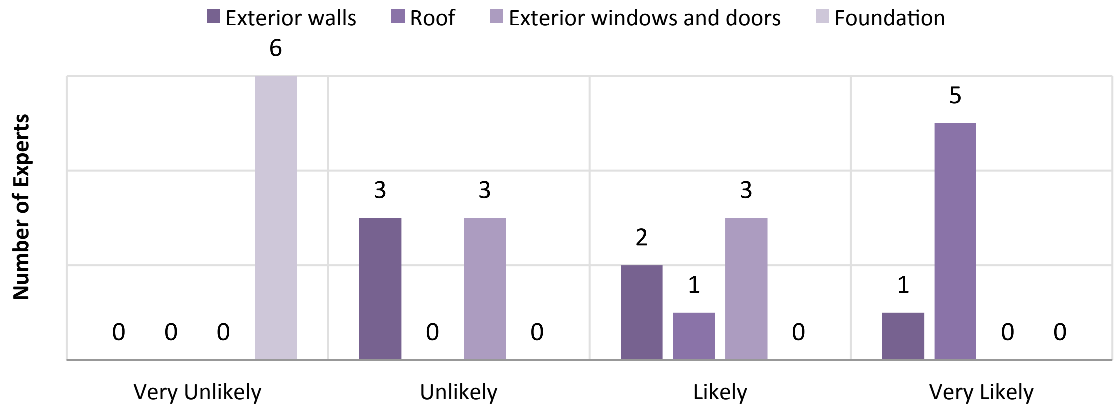


Figure 60 Expert responses for the liklihood of enclosure components expereincing damage during a hurricane

Likelihood of exterior wall failure modes occurring:

As presented in Figure 61, according to the experts, a detachment of non-structural wall components is believed to be the most likely failure mode to occur for exterior walls, while an exterior wall structural failure is believed to be the least likely failure mode to occur. Water damage and penetrations/cracks to exterior walls are closely ranked between each other in regards to their likelihood of occurrence. However, slightly more favor was shown towards penetrations/cracks as being more unlikely than water damage.

In comparison to the likelihood of occurrence determined from damage assessment data, the results agree well with the experts in regards to detached non-structural wall components being the most likely failure mode to occur, however, the remaining failure mode ranking differs from the general perception of the experts.

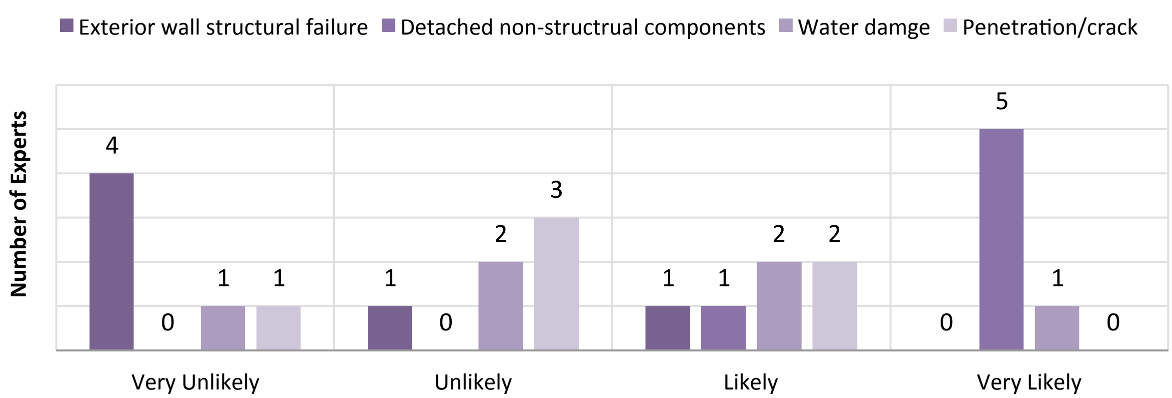


Figure 61 Expert responses for the liklihood of common exterior wall failure modes occuring

In a final series of questions, the experts were asked to estimate maximum repair costs for exterior wall failure modes as a percentage of the total cost of a residential building enclosure. The estimates provided by the experts are presented in Figure 62.

Exterior wall repair cost estimates:

The experts estimated that the average repair cost for exterior wall water damage is approximately 40% of a total enclosure cost in comparison to 17% estimated with an enclosure takeoff. The experts estimated the repair cost for detached non-structural wall components to equal approximately 22% of a total enclosure cost in comparison to 6% estimated with an enclosure takeoff. Finally, the experts estimated the average repair cost for exterior wall structural failure to be approximately 39% of a total enclosure cost in comparison to 11% estimated with an enclosure takeoff.

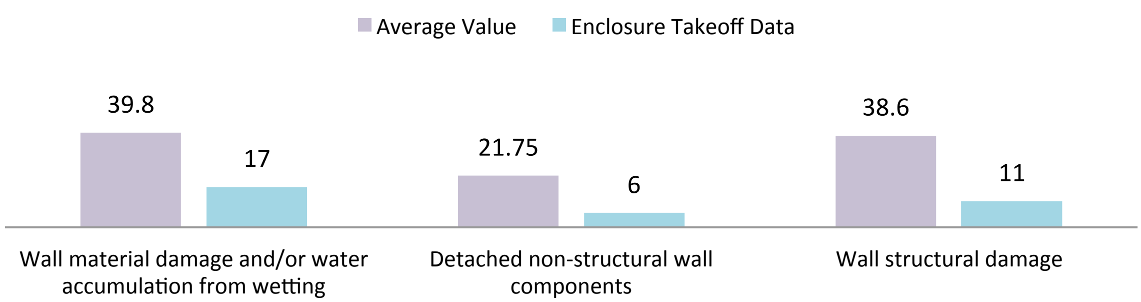


Figure 62 Expert estimates for exterior wall repair costs vs. enclosure takeoff estimates

Validation Study 1 Conclusions:

This validation study was performed to confirm that the research findings of this study were consistent with the experiences and perceptions of experts in industry. When comparing the subject matter expert survey responses and the data gathered and analyzed from literature, the validation study revealed several consistencies as well as some inconsistencies. In general, at least half or more the experts agreed with the FMECA results regarding hazard loadings, failure modes, and failure mode effects. The main areas for further investigation and refinement include the probability of certain failure modes occurring, as well as the repair costs of failure modes when evaluating severity. Additionally, it is also worthwhile to conduct further investigations into the common failures modes, effects, and hazard loadings that may have been overlooked or perhaps misrepresented as noted by the experts who indicated missing findings. The main conclusions from Validation Study 1 are summarized as follows:

- There was overall agreement between the experts and all of the identified hazard loadings of hurricanes that can lead to failure modes.
- All of the identified common failure modes and effects experienced during a hurricane event received agreement from at least half or more of the experts.
- 1-2 experts believed that there were some additional common hazard loadings, failure modes, and effects not represented in the data.

- The experts' probability ranking of enclosure components (i.e. roof, windows/doors, exterior walls, and foundation) experiencing damage during a hurricane generally agreed with the results determined from literature sources.
- The difference between the probability of damage experienced by exterior walls and windows/doors needs additional investigation to better define the probability factors that they should be given.
- There was poor consistency between expert responses and literature in regards to the probability of certain failure modes occurring, which will require further investigation to better understand the differences revealed in this initial investigation.
- Average repair cost estimates significantly differed from that was estimated from literature and from an enclosure takeoff. Due to the high variability that can be encountered with repair costs, this indicates that there is a great need to further refine what is considered in repair cost factors and how it can be better represented in the prioritization process.

Validation Study 2: High-Performance and Disaster Resilience Attributes

A total of 9 subject matter experts were identified as eligible candidates to participate in Validation Study 2, with a final total of responses obtained from 5 of the experts. This survey was used to validate the results of Objective B in which common attributes used to characterize a high-performance residential building enclosure and disaster resilient homes were identified.

Subject Matter Expert Characteristics: Similar to Validation Study 1, for the Validation Study 2 survey, several questions were asked to the experts prior to them taking the survey in order to gain a better understanding of their background with regard to the research conducted. Information was gathered about their work experience and the U.S. region or regions that they primarily work in. The results from these questions revealed the following about the experts who participated in this survey.

Industry area(s) currently working in or have experience in:

Of the experts who participated in this survey, all have experience in high-performance buildings, and the majority of them also indicated having experience in residential construction. Some of the experts also have experience with resilience. A summary of the experts work experiences is as follows in Figure 63.

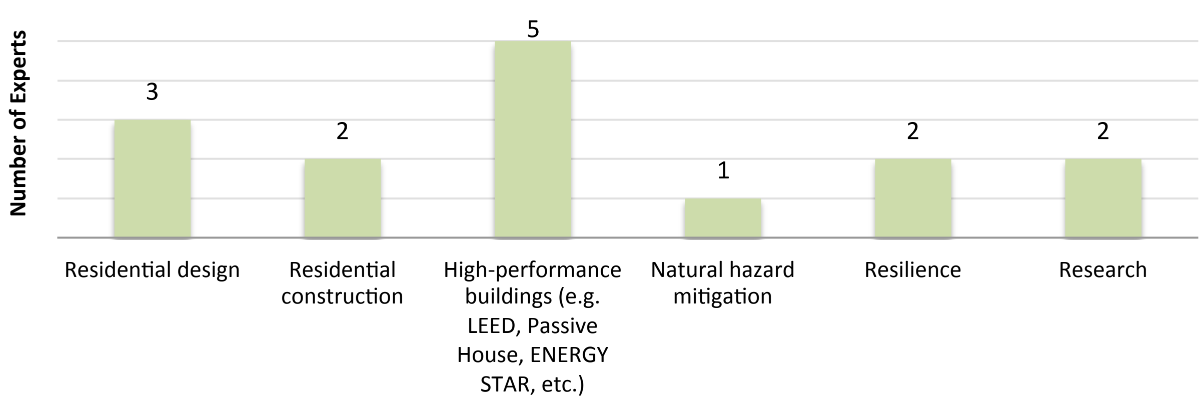


Figure 63 Work expererinece of the experts for Validation Study 2

Years of experience in specified work field(s):

The experts of this survey also had a substantial amount of experience in their specified fields of work. Four of the five experts had no less than 18 years of experience in his or her industries. One expert indicated having 6 years of experience. The years of experience of the experts are summarized as follows:

- The experts have a **total average of 23 years of experience** in their specified industries
- The minimum amount of experience indicated was 6 years
- The maximum amount of experience indicated was 35 years

U.S. region(s) primarily working in:

While the climate and region of the U.S. was not as pertinent to this validation survey as it was for Validation Study 1, it was nonetheless still asked for. As shown in Figure 64, all regions within the U.S. were represented by at least one expert.

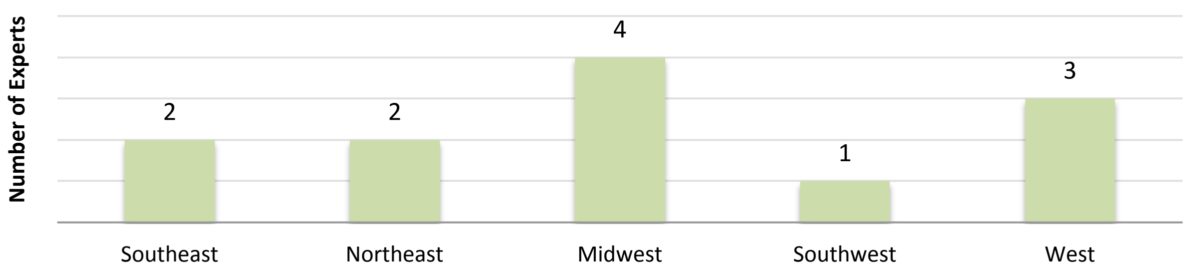


Figure 64 U.S. regions the experts primarily work in for Validation Study 2

Expert responses: The questions posed to the experts of this survey were first focused on gaining their unbiased views (from the standpoint of what this research had already identified in the thematic analyses) of what they believe characterizes a high-performance building enclosure for a residential building, and a disaster resilient home. Following this, they were then presented with the common attributes for high-performance residential building enclosures and disaster resilient housing, which were identified in the thematic analyses performed in this research. At this point, the experts were restricted from editing their initial responses given prior to viewing the attributes identified in the thematic analyses. The structure of this survey was then similar to what was used in Validation Study 1. The participants could select answers from given options with which they agree with according to their own experiences/knowledge. In the event that an option that they felt answered the question was not available for them to select from, they could bring attention to this by selecting the "other not listed" option. However, it was stressed here again that this only be selected if it was for a significant attribute missing, and not for rare cases. Summaries of the responses from Validation Study 1 are discussed as follows.

High-Performance Building Enclosure Attributes:

The experts used the following terms listed in the grey boxes to characterize the attributes of high-performance residential building enclosures. The experts also provided explanations for what they believe makes certain attributes more important to consider over one another, or what should be considered in the process of assigning weights to various attributes. This was provided as either a written response, or by assigning each listed attribute a numerical weight out a total sum of 100. Following each expert response, it is briefly discussed how their identified attributes align or differ from the attributes identified in the thematic analysis for high-performance residential building enclosures. Attributes in bold signify similarities between the expert responses and thematic analysis results.

Expert 1 response:

- Highly durable under normal interior and exterior conditions (25)
- Robust to typical construction delivery and operation activities and errors (20)
- A very high level of energy efficiency (15)
- Not harmful to indoor environmental quality (15)
- Resilient to extreme events (10)
- Provides superior comfort to the occupants (10)
- Resources are used in an efficient manner (5)

Thematic Analysis Attributes:

- High Levels of Insulation
- Minimal Air Leakage
- **Enhanced Occupant Comfort and Health**
- **Energy Efficiency**
- **Resource Efficiency**
- Minimized Life-Cycle Cost
- Quality Control
- **Enhance Durability**
- Climate Appropriate

The first expert provided several statements that matched closely with some of the attributes identified in the thematic analysis. This expert also indicated how they believe each attribute should be weighted among one another. The attributes that align with Expert 1's response include *Enhanced Durability, Energy Efficiency, Resource Efficiency*, and *Enhanced Occupant Comfort and Health*. This expert additionally included resilience as an attribute of a high-performance building enclosure instead of considering it as a separate category altogether. According to the numeric weights provided by this expert, *Enhanced Durability* should carry the greatest weight of importance, followed by *Energy Efficiency, Enhanced Occupant Comfort and Health, Resilience,* and *Resource Efficiency*.

Expert 2 response:

- Ventilation
- Window/Skylight Glazing and High Performance Coatings
- Window/Skylight Frames
- Roof Insulation
- Wall Insulation
- Floor Insulation
- Thermal Bridging
- Infiltration Control
- Vapor Control
- Moisture Control
- Thermal Mass

"The weight of importance for each attribute will depend on the individual house design, climate, and program. The weight of each attribute also depends on the baseline from which you're starting - for instance, 1" of insulation is much more important than none, but 12" is not that much more important than 11"".

Thematic Analysis Attributes:

- **High Levels of Insulation**
- **Minimal Air Leakage**
- Enhanced Occupant Comfort and Health
- Energy Efficiency
- Resource Efficiency
- Minimized Life-Cycle Cost
- Quality Control
- **Enhance Durability**
- Climate Appropriate

Of the attributes listed by Expert 2, they align with *High Levels of Insulation*, *Minimal Air Leakage, and Enhanced Durability*. This expert also provided insight into what should be considered when deciding how to weigh different attributes, which included considering the type of home, the climate in which it is located, the standard to which the home is constructed to, and the existing conditions of the home which provide baseline levels of performance.

Expert 3 response:	*Thematic Analysis Attributes:*
• Low U-Value/High R-Value (30) • Low infiltration rate (20) • Appropriate window/wall ratio (20) • Shading of glazing (20) • Rain screen Technology/system (10)	• **High Levels of Insulation** • **Minimal Air Leakage** • Enhanced Occupant Comfort and Health • Energy Efficiency • Resource Efficiency • Minimized Life-Cycle Cost • Quality Control • **Enhance Durability** • Climate Appropriate

The third expert's listed attributes coincided with *High Levels of Insulation, Minimal Air Leakage*, and *Enhanced Durability*. According to the weights indicated by this expert*, High levels of Insulation* should carry the greatest weight, followed by *Minimal Air leakage*, and *Enhanced Durability*.

Expert 4 response:	*Thematic Analysis Attributes:*
• Cost effective • Climate appropriate in response to forces of nature • Appropriate to indoor conditions (e.g. humidity) • Proper integration of fenestration	• High Levels of Insulation • Minimal Air Leakage • Enhanced Occupant Comfort and Health • Energy Efficiency • Resource Efficiency • **Minimized Life-Cycle Cost** • Quality Control • **Enhance Durability** • **Climate Appropriate**

The attributes identified by Expert 4 also share similarities to those identified from the thematic analysis. "Cost effective" and "Climate appropriate in response to forces of nature" align with the *Minimized Life-Cycle Cost* and *Climate Appropriate* attributes. "Proper integration of fenestration" could be closely matched to *Enhanced Durability* in terms of integrating control layers such as a WRB. "Appropriate to indoor conditions" could possible align with *Enhanced Occupant Comfort and Health* in regards to interior comfort levels, however, additional explanation is needed from this response in regards to the purpose behind the "indoor conditions".

Expert 5 response:	*Thematic Analysis Attributes:*
• Safe • Comfortable • Healthy • Low utility bills • Works as a system	• High Levels of Insulation • Minimal Air Leakage • **Enhanced Occupant Comfort and Health** • Energy Efficiency • Resource Efficiency • **Minimized Life-Cycle Cost** • Quality Control • Enhance Durability • Climate Appropriate

Expert 5 listed attributes that most closely aligned with *Enhanced Occupant Comfort and Health,* and *Minimized Life-Cycle Cost.* This expert also indicated that each attribute be given the same weight of importance.

In the next series of questions in this survey, the experts were then presented with the list of attributes and sub-attributes identified in the thematic analysis. They were asked to indicate the attributes and sub-attributes with which they agree with, and also provide weights of importance for each attribute and sub-attribute out a total sum of 100.

As depicted in Figure 65, of the attributes identified in the thematic analysis, when presented to the experts, almost all agreed that they represent a high-performance residential building enclosure. This consensus was quite a significant contrast to the individual responses given by each expert. Only one expert indicated that an attribute was missing from this list. Following this, in Figure 66, the experts provided values for how each attribute should be weighed against one another, which are presented as averages of all the responses. This provides data towards potential default weight values for the attributes used to assess enclosure performance.

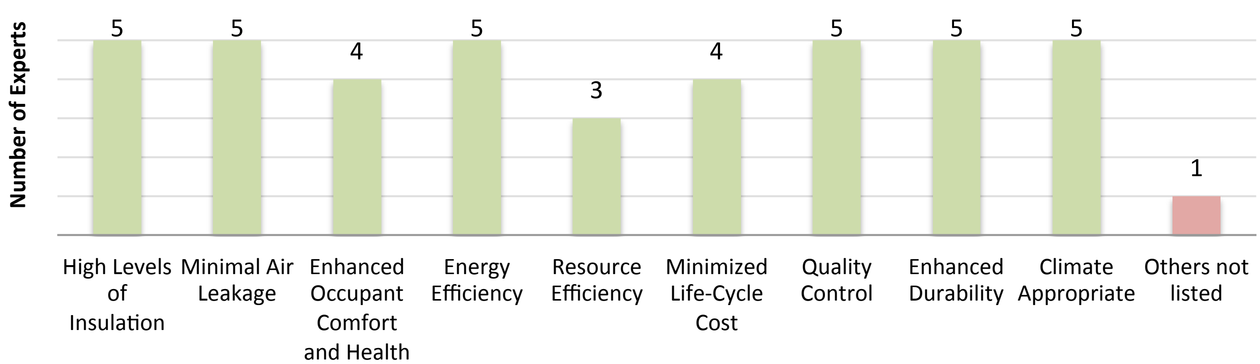


Figure 65 Expert responses for high-performance residential building enclosure attributes

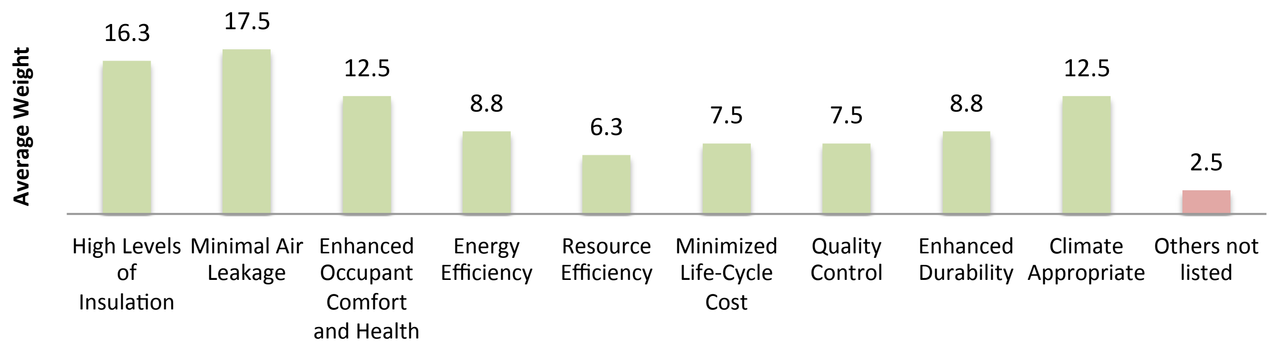


Figure 66 Expert responses for high-performance residential building enclosure attribute weights

Figure 67 to Figure 70 present the results of the sub-attribute evaluations performed by the experts for *Enhanced Occupant Comfort and Health*, and *Enhanced Durability*. In regards to the sub-attributes of *Enhanced Occupant Comfort and Health*, almost all of the experts agreed with those identified in the thematic analysis, with one expert indicating an un-represented sub-attribute. For the *Enhanced Durability* sub-attributes, again, almost all of the experts agreed with those listed, with one expert indicating a missing sub-attribute out of those presented.

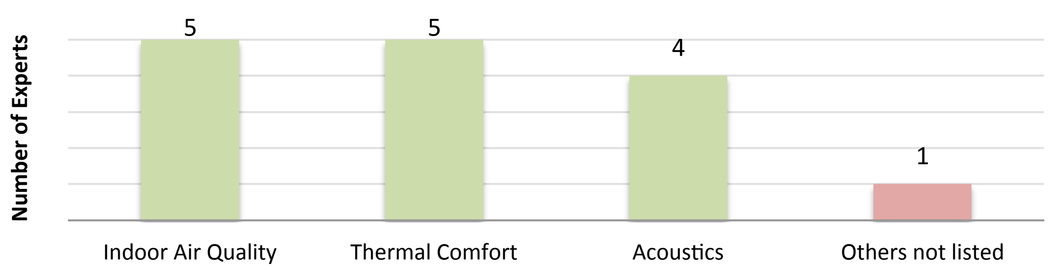


Figure 67 Expert responses for Enhanced Occupant Comfort and Health sub-attributes

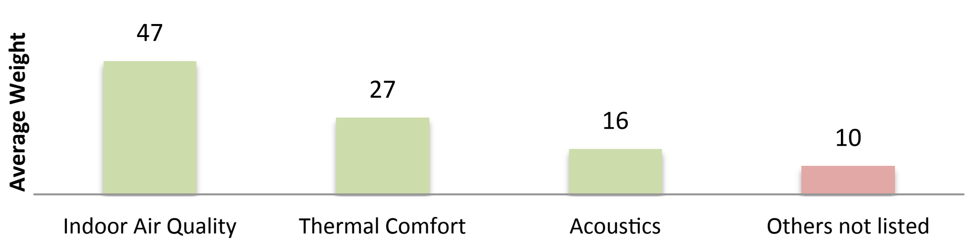


Figure 68 Expert responses for Enhanced Occupant Comfort and Health sub-attribute weights

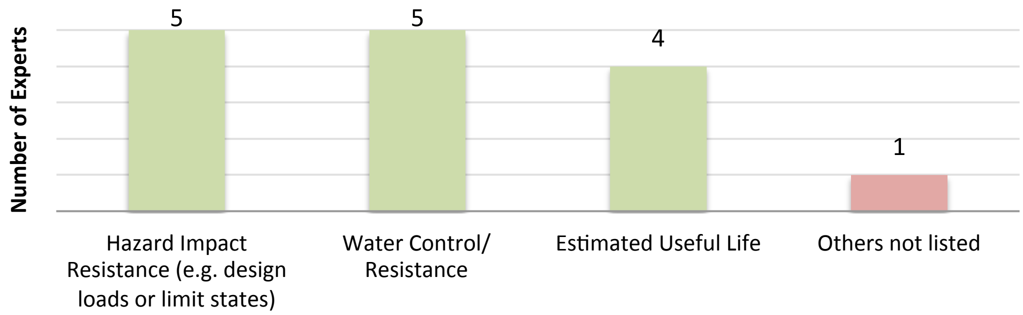


Figure 69 Expert responses for Enhanced Durability sub-attributes

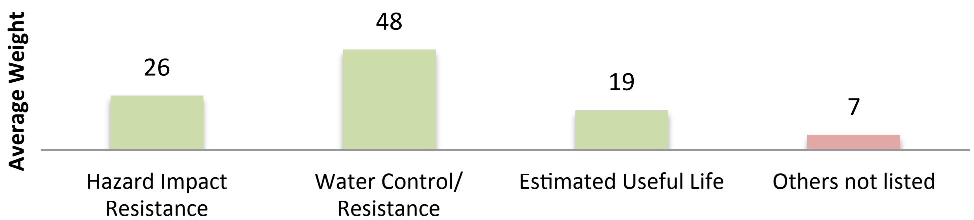


Figure 70 Expert responses for Enhanced Durability sub-attribute weights

Disaster Resilient Housing Attributes:

For the disaster resilient portion of this survey, only two of the previous five experts participated. These two experts were those who indicated they have experience with resilience. The same process used for the previous high-performance portion of the survey was followed here.

According the experts, the following terms listed in the grey boxes were used by them to characterize the attributes of a disaster resilient house.

Expert 1 response:

- Can be functional when public utilities are off-line
- Can sustain functionality after unusual natural events

Thematic Analysis Attributes:

- Adaptivity
- Recovery
- **Robustness**
- Resourcefulness
- **Redundancy**
- Complimentary
- Energy Efficiency
- Resource Efficiency
- Simple

The first expert provided responses that most closely align with the attributes of Robustness and Redundancy, according to how they were defined in this research.

Expert 2 response:

- High level of structural integrity
- Robust material, methods, and systems; able to withstand certain failure modes
- Survivability or ability to weather and provide safe shelter during the event
- Components that won't fail or can be easy to fix/replace if they do fail

Thematic Analysis Attributes:

- Adaptivity
- Recovery
- **Robustness**
- Resourcefulness
- Redundancy
- Complimentary
- Energy Efficiency
- Resource Efficiency
- **Simple**

The majority of Expert 2's responses fell within the Robustness attribute. In addition to this, the attribute Simple also aligns with a response given in regards to the ability to easily repair damaged building components.

In the next series of questions in this portion of the survey, the experts were then presented with the list of attributes and sub-attributes identified in the thematic analysis for disaster resilient housing. They were asked to indicate the attributes and sub-attributes with which they agree with, and also provide weights of importance for each attribute and sub-attribute out a total sum of 100.

As presented in Figure 71, the only attributes that did not receive any agreement from an expert were Energy Efficiency and Simple. However, an expert previously described disaster resilient housing as encompassing characteristics that coincide with the Simple attribute. Figure 72 then shows how each attribute was weighed according to the experts.

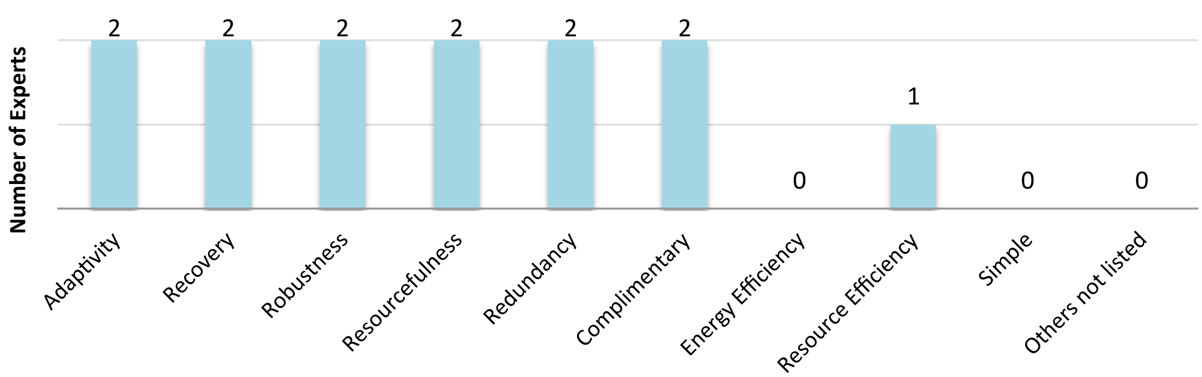


Figure 71 Expert responses for disaster resilient housing attributes

Figure 72 Expert responses for high-performance residential building enclosure attribute weights

Finally, Figure 73 and Figure 74 present the results of the sub-attribute evaluation performed by the experts for the Robustness attribute. In regards to the sub-attributes of Robustness, all of the experts agreed with those identified in the thematic analysis, with one expert indicating an un-represented sub-attribute.

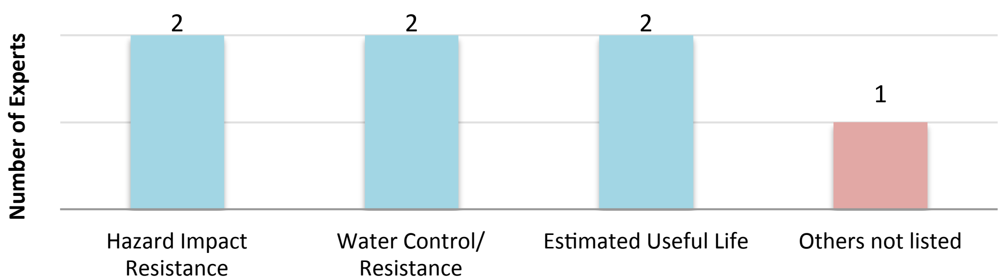


Figure 73 Expert responses for Robustness sub-attributes

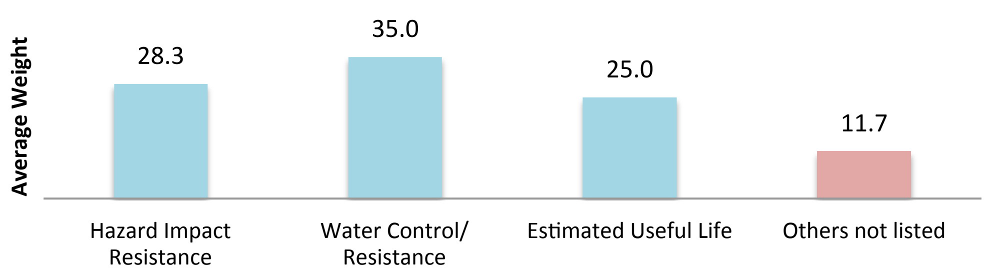


Figure 74 Expert responses for Robustness sub-attribute weights

Validation Study 2 Conclusions:

Validation study 2 confirms that the research findings of this study were consistent with the experiences and perceptions of experts in the high-performance building and resilience domain. When comparing subject matter expert survey responses to data gathered and analyzed from literature, it was revealed that the majority of the experts agreed with the identified attributes and sub-attributes. However, according to responses given by the experts to identify these attributes prior to being exposed to those produced from the thematic analyses, it is clear that there is a disconnect between industry terminology and what is communicated in literature. The experts' initial responses significantly differed from the list of attributes identified from literature, even though the experts later agreed with those same attributes, which were identified in literature. This further stressed the need for succinct definitions and attributes (as identified in this research) that can be easily referred to in order to reduce the various interpretations used by professionals in these industries, which can lead to a lack of consensus in how to define high-performance buildings and disaster resilience. Other areas for further investigation and refinement as identified from Validation Study 2 include reconsidering how *Energy Efficiency* and *Simple* are considered as attributes of disaster resilient housing, gaining more input from a larger sample of experts, and conducting further investigations into the attributes and sub-attributes that may have been overlooked or perhaps misrepresented as noted by the expert who indicated missing findings. The main conclusions from Validation Study 2 are summarized as follows:

- The was an overall good agreement between experts and identified attributes and sub-attributes for high-performance residential building enclosures and disaster resilient housing, except for *Energy Efficiency* and *Simple* in regards to disaster resilience.
- While the language used by the experts when characterizing high-performance residential building enclosures and disaster resilient housing had significant differences from the attributes defined from thematic analyses, there was still a wide consensus for the majority of the attributes identified from literature. This also confirmed the need for common definitions and attributes as overarching references, which have been identified in this research.
- The experts have identified weights, which can be applied to each attribute. These weights could be used a default settings or suggestions when assessing performance and resilience for a residential building using the process developed in this research.
- The inclusion of *Energy Efficiency* and *Simple* as attributes of disaster resilience will need to be reconsidered. Gaining more feedback from experts in regards to these attributes will help to better understand if and how they should be included.

8 Conclusions

8.1 Major Contributions

The initial goal of this research was to develop a decision-making process that can be used to evaluate residential buildings for climate induced natural disaster risks, and prioritize mitigation solutions that integrate high-performance and disaster resilient qualities. In addition to this, the research aimed to benefit and provide support for the stakeholders who have expressed the need for new tools, guidance, and knowledge in residential construction risk mitigation in the face of climate change. These goals were achieved, and as a result of this and the discovered findings during this research, several key contributions emerged. The major contributions, in no particular order, can be summarized as follows:

Development of a process framework for natural disaster risk-based prioritization of HPRB technologies

This research has developed a framework for a process that can prioritize natural disaster risks and identify specific HPRB technologies as associated risk mitigation solutions specifically for residential buildings. It has demonstrated how various types of data, metrics, and analyses can be integrated to assess residential buildings with the goal of improving building performance and disaster resilience in various housing scenarios. Once expanded to more hazards and technologies, this framework can strengthen the capabilities of stakeholders who plan, assess, and build homes with enhanced performance and natural disaster risk mitigation as main objectives, and can also help to improve the building performance and natural disaster resilience of new and existing housing stocks around the country.

The major research gaps that were initially identified included a lack of a local, residential building focus towards climate change and associated extreme weather risks in resilience assessment research, as well as a scarcity in resilience metrics and decision-making tools with respect to natural hazards other than earthquakes. The process developed here has addressed these gaps, which now allows resilience to be quantified for residential buildings. The process allows for consideration of climate induced natural hazards and local vulnerabilities of homes, while also incorporating high-performance technologies as an overlapping theme that can be simultaneously quantified towards selecting solutions that can enhance both building performance and disaster resilience.

Compilation of common terminologies for high-performance buildings and disaster resilience, including a prioritization process to derive metrics and benchmarks for comparative quantification

The prioritization process developed in this research required that attributes and metrics of high-performance technologies must be defined for residential building enclosures so that they can be used to assess levels of performance across various building standards, codes, and qualities of construction. This emerged as a major contribution not only for the process, but also for the residential construction industry in general. It reduces the lack of consensus that exists across multiple, existing high-performance building standards, while also integrating existing at- or below-code built home performance. These attributes and metrics allow for residential buildings to be evaluated and compared across common benchmarks within a community, county, or region, depending on the scale desired and the availability of data. Similarly, attributes and metrics to assess residential buildings for disaster resilience have also been defined in this research that can be used in the same manner.

Development of a ranking for common hurricane failure modes for residential building enclosures according to criticality factors demonstrating the developed process for hazard mitigation assessment

Hurricane hazards were the focus of this research to demonstrate the mitigation assessment process. As a result of this, the common failure modes that residential building enclosures can experience during a hurricane were identified from a review of several damage assessments performed on homes impacted by hurricanes. The critically of each failure mode was evaluated, quantified, and subsequently ranked in an order of most critical to least critical. This criticality ranking incorporates an analysis of the probability of the occurring failure mode, as well as an analysis of the severity of the worst-case effect of each failure mode if it were to occur. Enclosure component cost data was used to estimate initial values for severity, which represents repair cost only at this stage of the research; probabilities of occurrence were determined from literature, which included some statistical analysis performed in prior research as supporting data.

This evaluation and ranking provides guidance towards understanding what enclosure components are most at risk of damage during a hurricane, as well as the types of damage that can carry the greatest impact when considering the currently analyzed variables (i.e. worst case scenario consequences, potential repair costs, and the likelihood of damage occurring).

Compilation of an inventory of HPRB technologies that can be used to mitigate hurricane risks to building enclosures demonstrating the developed process for technology to hazard-mitigation mapping

Several high-performance building standards were analyzed in order to extract residential building enclosure technologies that have been classified as being able to mitigate various impacts and vulnerabilities associated with hurricane hazards. This evaluation produced an inventory of residential building enclosure HPRB technologies for hurricane hazards, which also included an analysis of which high-performance building standards address hurricanes in the most comprehensive way according to their prescribed mandatory and recommended strategies. The use of each identified HPRB technology for hurricane hazard mitigation purposes is supported by literature, which includes case studies and available testing data.

8.2 Research Challenges

Several challenges were encountered during the research process, which necessitated adjustments in the research plan and added some difficulty to certain aspects of the data collection process. One challenge occurred while analyzing the severity and probability of the various identified failure modes. The type of data that was initially sought after, which was residential damage insurance statistical data, was unavailable. This data pool was to be used as a way to assess the likelihood of certain enclosure components becoming damaged during a hurricane, and the type of damage that occurred to each component. This type of quantitative data is strictly proprietary information, however, qualitative data could be provided by some subject matter experts in this industry as a way to increase the validity of the initial conclusions made regarding criticality. Furthermore, repair cost data was the variable decided upon to assess the severity of failure modes. However, it was found to be a challenge to obtain this data, considering the variation in the type and amount of damage, types of construction, and geographic locations, which all impact recovery cost. Broad estimates of enclosure component costs based upon a comparison between a residential building enclosure takeoff with national cost estimates were finally used as initial estimates in this research. Nevertheless, it is the plan to gain more refined repair cost values by surveying experts such as repair contractors in various locations. This additional research task could not fit into the original timeframe of the research that was undertaken, and as a result was excluded for future work.

Another challenge that was encountered during this research occurred during the process of defining disaster resilience metrics for identified attributes. It became a much more difficult process than anticipated to generalize some of the metrics into value ranges due to the lack of existing references in regards to measuring resilience for residential buildings, unlike that of the much more documented building enclosure performance domain. While metrics were ultimately defined for each attribute to allow for the quantification of disaster resilience for residential buildings, it became apparent that more refinement and evaluations need to take place in order to further verify and develop the metrics currently defined.

When conducting the validation studies with subject matter experts, difficulties were experienced when attempting to gain feedback from the identified survey candidates, who were identified as high-level subject matter experts and subsequently contacted to be part of the validation process. Since no monetary support was available for experts to contribute their time, the number of desired participants to take each survey was less than initially anticipated. Nevertheless, the objective of the validation studies was to gain insight from individuals classified as high-level experts, and not general, industry-wide perceptions. With this being the case, expert participation was successfully achieved even though participation numbers were lower than desirable.

8.3 Future Work

This research concluded with the development of a risk and HPRB technology prioritization process framework. However, there are additional tasks that can extend from the work completed in order to further refine and develop the research. Several initial future work pathways were noted during data analysis phases, while consulting with the research committee, gathering feedback from subject matter experts, and after reflecting upon results produced. The areas for future work are discussed as follows:

Evaluation of additional hazards and building systems for inclusion in the process database

In order to increase the applicability of the process to a larger scope and to create a complete picture of climate induced natural disaster risks that exist for a specific residential building, more climate regions and associated natural hazards must be analyzed with respect to their current and future outlook for various locations, as well as the potential impacts they can have on residential buildings. In the southeast region of the U.S. alone, in addition to hurricanes, extreme heat events are a growing concern, as are wildfires in the southwestern regions of the U.S. While winter storms and extreme cold events are projected to decline in the southern regions, they should still be included in this process in addition to the other prevalent hazards, although potentially considered with less criticality when compared to other growing climate trends.

The same methods and types of data sources used in this research study can be used again to perform additional hazard analysis tasks. However, if the data sought after to perform these tasks are not available for certain hazards (e.g. damage assessments and reconnaissance reports from snowstorm events), other methods will need to be identified. This could include going directly to areas located with individuals and organizations that survey residential buildings following severe weather events to gather information regarding the impacts of hazards through interviews. Alternatively, modeling the damage that could occur to residential buildings with physical experimentation or simulation tools could provide data on the potential impacts of various hazards.

When considering additional hazards, the remaining systems that make up a residential building (e.g. mechanical, electrical and plumbing systems) will need to be evaluated as well. In doing so, high-performance attributes and metrics will need be defined to coincide with each building sub-system. Additional HPRB technologies will also need to be identified and evaluated in conjunction with this and included in the inventory of existing technologies already identified. This will reveal a need for, or prevalence of existing technologies to address additional hazards and considered building systems.

Overlapping and/or conflicting HPRB technologies for different hazards (e.g. hurricane and heat wave) may emerge from this process. Due to this, analyzing the interaction between different building systems and technologies in regards to basic functions, multiple hazards, and how they will influence each other will need to be considered in the decision-making process.

Refinement of metrics and values for disaster resilience and high-performance

The metrics and values defined to quantify both high-performance and disaster resilience will require further refinement in order to increase the reliability and accuracy of evaluations that may need to be performed. More knowledge and references are needed, especially in regards to quantifying disaster resilience, beyond "engineering judgment" to match the given values (e.g. typical recovery time for certain impacts should have pre-determined time ranges). This will require external analysis of the various attributes in order to provide a more accurate depiction of the values that can be achieved with respect the to the location, building systems, and hazards of concern. This task could entail reviewing additional case studies, interviewing subject matter experts, and/or performing experimental tests and modeling studies to develop more accurate and representative "resilience curves" for each attribute as presented in the current descriptions.

Upon refining the metrics, they could be used to evaluate existing stocks of homes, high-performance standards, or building code levels of new construction in various locations, and create benchmarks to represent the various levels of performance and resilience across the country as quick reference guides for homes.

Performing additional validation studies utilizing the developed process

Additional cases, both conceptual and actual, should be performed utilizing the process and to further compare the validity of the produced data and results. Furthermore, having potential users test the process by carrying out their own assessments on homes can test for usability, and identify potential areas in need of further improvement from the feedback received.

Refinement of evaluations of impact and vulnerability and inclusion of additional variables

There are other variables that can be explored and subsequently included in the assessment of vulnerability and impact that were not included in the research performed here. This includes additional housing vulnerability indicators as well as potentially including various levels of vulnerability within each indicator, where currently they only include two levels (i.e. high and low). In addition to including repair costs when assessing for the level of impact severity, other factors such as safety can be investigated for inclusion.

Validation Study 1 revealed the need for further analyses regarding variables that can be used to evaluate the impact of failure modes and their accuracy in representing data, specifically in regards to severity and probability. This should be further investigated in order to refine the risk assessment process.

Including post-assessment decision variables

Variables that help to further prioritize HRPB technology options following an assessment are also important for informed decision-making. For example, the cost of the various HPRB technologies when prioritizing mitigation options for various risks can be incorporated in the future. Should a decision come down to two or more very similar technologies that can provide the same benefits in regards to enhancing building performance and/or disaster resilience, the cost to purchase, install, or operate a technology becomes even more pertinent to a decision-maker. The possibility of integrating this type of data into the process should be addressed.

Expanding the scale from individual buildings to community-wide housing developments

Moving the research focus from an individual residential building scale to a community wide scale has always been an intention of this research going forward. In regards to achieving higher levels of resilience to natural disasters, there are many technologies, strategies, and benefits behind the idea of a community developed with high-performance homes. By accomplishing the goals and tasks that were set forth for this research, it has provided important groundwork for crossing scales, and realizing how an entire community's performance and disaster resilience could be assessed using a similar process in the future.

The connectivity and sharing of systems, resources, social responsibilities, and the burden of various impacts from natural hazards become essential aspects that should be considered when evaluating communities. Homes and their occupants as individual systems are no longer the primary concern. However, while technologies at the building scale that are used to enhance building performance and disaster resilience are still essential towards also achieving this at a community level, landscapes, systems, and strategies that exist and operate on larger scales now emerge as additional HPRB technologies for consideration and analysis. This can include dedicated community resource production and distribution services, improving the economic well-being of an area, protecting and adapting landscapes, and enabling community self-sufficiency. A diagram of a community that exhibits high levels of performance and resilience, at least with respect to its buildings and infrastructure, is exemplified in Figure 75, where it is composed of high-performance homes (denoted by the green square outlines, which represents high-performance building enclosures, and blue rectangles, which represent PV arrays) and has also implemented community based technologies that share and store resources and energy. In addition to individual capabilities that may exist with the HPRB technologies implemented on/within the individual homes, the community based technologies (combined heat and power (CHP) and stored heat and hot water produced by onsite renewable energy) further influence the energy demand and costs for the households within the community by reducing consumption and expenditure during normal conditions; operating efficiently as immediate redundant and backup systems during emergency scenarios; and also increases the ability for the community to sustain operation as an independent system separated from the grid, which can additionally alleviate larger scale strains (e.g. recovery/repair efforts and aging infrastructure). Compared to a community developed with predominantly code level performance homes (Figure 76), a high-performance community and the homes within it could fair even better before, during, and after certain natural hazard events.

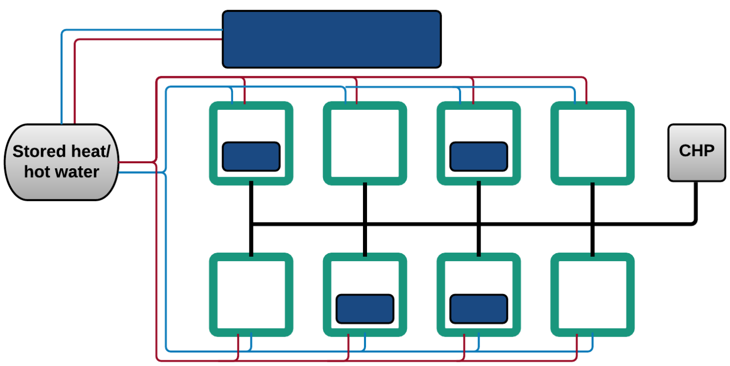


Figure 75 Example of a community with high levels of performance and disaster resilience

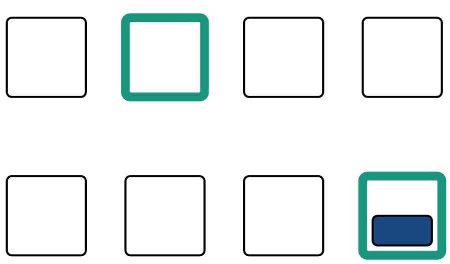


Figure 76 Example of a community with low levels of performance and disaster resilience

Policies and codes that move beyond building specifications and additionally include provisions that effect urban planning, become factors that must now be evaluated in regards to barriers and facilitators of various levels of resilience. Natural hazard impacts, vulnerabilities, and attributes of high-performance and disaster resilience, which are specific to community developments will need to be identified and evaluated to coincide with these considerations, especially if prioritization of risks and mitigation strategies are similarly desired as to what was developed here for residential buildings as single entities.

To address this future research agenda, a partner tool as an extension from the building scale process could be developed. This could entail inputting housing characteristics in the form of current performance and resilience levels identified from initial building assessments performed to prioritize risks and HPRB technologies. Inputting this information could produce a profile of the buildings within a community, which would then coincide with evaluating other variables to complete a risk assessment for a community (e.g. buildings, social and economic factors, infrastructure, policies, planning). A community risk assessment could be performed with respect to various natural hazards, much like that of what was demonstrated for the process developed in this research using demonstration cases. The final results would provide an evaluation of the vulnerability of a community to various hazard impacts, which takes into account the multi-faceted nature of what forms a community. Additionally, following the definition of appropriate attributes for quantifying community resilience, various mitigation strategies could be presented for selection to enhance communities in response to the risks they face. Such a process would benefit policy makers, disaster planners, and local code officials who would need to appropriately modify current standards and practices to encourage, and possibly incentivize, the implementation of high-performance and disaster resilience community technologies. To perform this research, the tasks involved become much greater and will require collaboration and input from various fields and locations. Seeking funding from organizations that can promote the use of this research can help to assemble a dedicated multidisciplinary research team and a consortium of experts to tackle the research efficiently.

Moving beyond residential buildings and communities, thinking even further forward is important. It will require making connections to even higher scales, such as towns, cities, and counties, and crossing back and forth between each at key points of influence that can spur positive development towards increasing the performance of systems, as well as achieving greater levels of resilience for climate challenges. High-performance homes can fit into the scheme of communities striving for greater disaster resilience, but what other aspects of a community will similarly contribute to this, and how are they currently being evaluated? Cohesiveness should be sought after among the various methods and needs of stakeholders at the different scales who assess their systems for ways to improve. This will involve making sure that common terminology used in assessments is reconciled within and across industries. Doing so makes the problem increasingly interdisciplinary, and it will require collaboration across disciplines to reach the potential goals and benefits that exist.

8.4 Final Reflections

The framework for the prioritization process that has been developed and demonstrated in this research is beneficial towards performing its intended purpose of assessing homes for natural disaster risks, and selecting appropriate high-performance and resilient hazard mitigation technologies. However, it is important to stand-back and consider the bigger picture in regards to how this process can integrate into current industry practices; what organizations/individuals are most likely to readily accept this process; and what are the additional costs, benefits, and barriers to future implementation. All of which were reflected on upon completing this research.

Existing building performance assessment programs and high-performance building standards are some of the initial targets that this process can be marketed to. This is due to the process' ability to address their growing need to incorporate resilience and natural hazard mitigation as features and goals, which are areas they currently fall short in, but are nonetheless piloting solutions to do so. All or part of the findings of this research can be utilized and integrated in their current assessments and scoring systems to evaluate building profiles for resilience and building performance with the metrics developed here. Some high-performance building standards, such as EarthCraft, ENERGY STAR, and LEED, which received already relative wide acceptance and application, may be utilized as platforms as they are perhaps the most ready to incorporate aspects of this research as complimentary processes in the evaluations they provide for residential buildings. For example, during the design phase for a building where perspective performance paths are decided upon, complete building profile options which implement selected credits and technology alternatives can be comparatively assessed for natural disaster risk, resilience, and performance using the framework developed in this research. This approach can further aid the design process if natural hazard risk mitigation is a priority for building owners and/or designers when deciding upon building technology alternatives.

For a wider application of this research in the residential building industry, a stand-alone performance and resilience scoring tool could be developed to evaluate new and existing building stocks constructed to various codes and standards on a single scale. This scale could be similar to the use of the Home Energy Rating System (HERS) Index Score for assessing a home's energy efficiency. However, it would combine the performance and resilience scores developed in this research into a singular *HPRB Score,* and thus include and assess many more attributes currently not incorporated into a HERS Index Score. HPRB scores would extend from the benchmarks developed using the defined attributes, values, and weights for high-performance and resilience in this research. For this application, a *Risk Score* that combines impact and vulnerability, as well as an *HPRB Score* could be generated from different residential building profiles and plotted on a consistent scale of representative residential construction standard benchmarks for natural hazard risk, performance, and resilience. Furthermore, to streamline design processes, standard building profiles for various locations, building codes, resilience and high-performance standards could be embedded into the tool and subsequently aligned with benchmarks on each scale to aid in decisions towards either abiding by or augmenting the profiles to meet specific risk and HPRB goals. In doing so, this would of course first require the inclusion of more natural hazards and building systems to be evaluated and incorporated into the process, as well as the refinement of the metric values to ensure they are representative of various qualities and standards of residential construction for various locations.

When developing such a scoring tool, it would require a separate assessment process and even a potential coinciding certification to verify scores achieved for both risk and HPRB evaluations. This could entail creating a building assessment software application that is easy to use by building auditors or designers in the field or in the office post-assessments. Similar to the tools building auditors currently use to assess homes for performance that aids them in identifying retrofit opportunities, this process could extend their line of services into the hazard mitigation field to similarly identify and prioritize both high-performance and resilience opportunities for homeowners or building developers.

Integrating this tool into existing industry practices and building assessment processes is not a simple task, and in addition to packaging the findings of this research into a more user-friendly and streamlined tool, it will also require partnerships and backing from organizations that can provide incentives for performing risk assessments and implementing HPRB technologies. A large barrier for increasing the performance and resilience of the nations building stock is cost and motivation in regards to designing and building with natural disaster mitigation in mind. The process developed in this research can aid decision-makers in assessments needed to improve building performance and resilience; however, they lack incentives to use such resources to implement resilient strategies. With this in mind, to bare some of the associated costs for implementation, support can be sought after from large and vocal advocates for climate change resilience such as the U.S. Department of Housing and Urban Development (HUD), the U.S. Department of Energy (DOE), the Insurance Institute for Business and Home Safety (IBHS), and FEMA. However, before taking such large strides in search of backing, a more practical and manageable pathway would be to first approach other smaller, municipal or community based agencies that can encourage local participation and implementation of risk-based housing assessments, and improving the performance and resilience of their buildings. Such organizations can develop policies for rebates, subsidies, and/or tax incentives, or alternatively at little to no cost, prestigiously recognize those who incorporate this process into planning, retrofitting, and rebuilding efforts. They could then benefit from these efforts through better disaster preparedness and emergency management within their communities and towns, experience less disruptions to business operations, and reduce occupant displacement, which are all motivations for striving for more resilient infrastructure and buildings. Insurance agencies could similarly be approached to provide support and motivation for the use of this process and the investment in HPRB technologies by offering reduced rates if certain risk and HPRB scores are obtained and/or certified. The insurance providers could then benefit from the increased resilience and reduced risk to their clients while still earning money, which is shared between their own profits and their clients through reduced premiums.

In summary, while increasing the performance and resilience of homes in response to natural disaster risks is a clear application and benefit of this research, the costs and acceptance in the residential building industry is less defined towards eventually putting this research into practice. Nonetheless, the next steps identified in the larger scheme of this research is to make efforts to integrate this process as seamlessly as possible into current building standards and assessment practices. An additional step is to seek supporting industry partnerships from organizations who benefit from higher performing and resilient buildings, and can promote this research while taking on some of the costs to realize this potential.

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10 Appendices

10.1 Appendix A – FMECA Tables and FTA Diagrams

Roof hurricane FMECA table

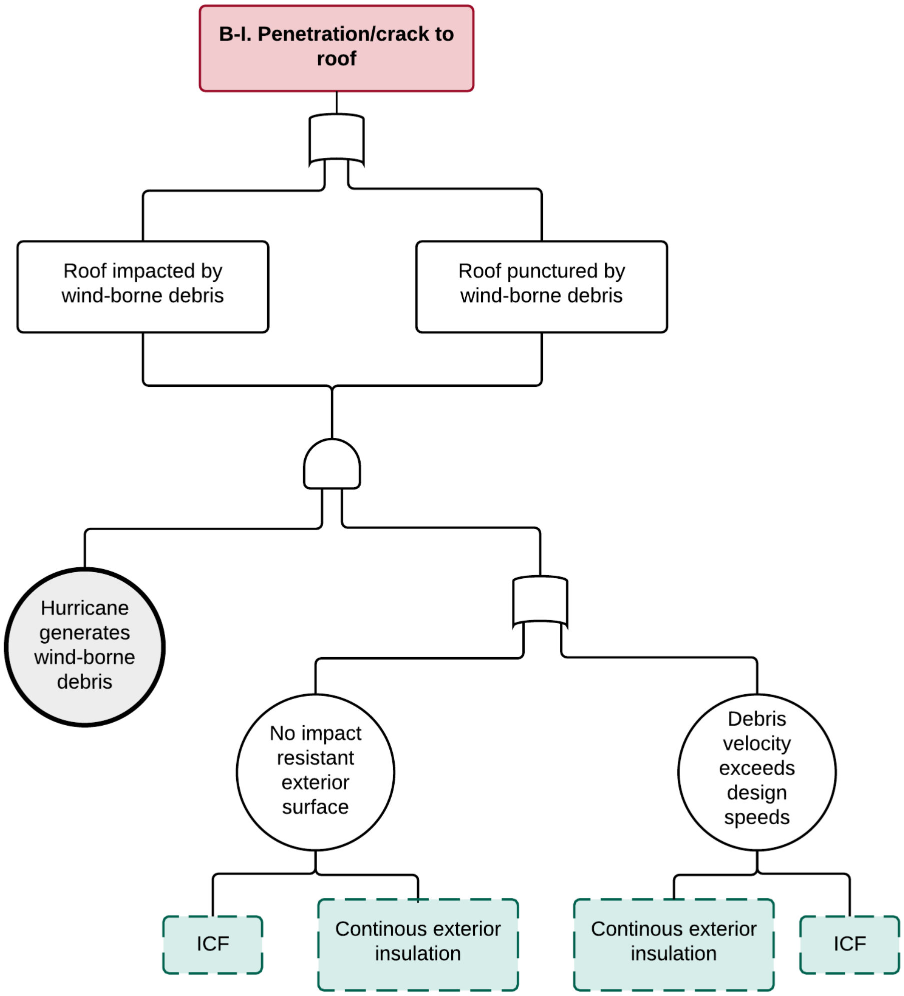
Component	Hazard Loading(s)	Failure Mode	Causes of Failure Mode	Potetnial Effects of Failure Mode	Severity of Consequence (SF)	Probability of Occurrence (PF)	Criticality (SFxPF)	Needs to Prevent/Reduce Risk of Failures
B. Roof	Wind-borne debris	I. Pentration/ crack	Roof punctured by wind-borne debris, or roof impacted by wind-borne debris	Internal pressurization; Roof structural failure; Exterior wall structural failure; Water damage; Blown-out windows/doors; Total building collapse/loss	1.00	0.25	0.25	Materials with high impact resistance properties
	Wind pressure	III. Detachaed non-structural components	Wind pressure removes non-structural roof materials, or uplift at overhangs removes non-structural roof materials	Water damage	0.32	1.00	0.32	Non-structural material properties and attachement methods that can withstand high pressures
		IV. Roof structural failure	Wind pressure and uplift forces separate structural roof connections, or wind pressure and uplift forces remove roof substrate panels	Roof collapse; Water damage; Exterior wall structural failure; Total building collapse/loss	1.00	0.50	0.50	Stronger superstructure connections at roof for high wind pressures; stronger substrate panel and attachment
	Wetting	VI. Water Damage	Rainwater infiltration to roof substrate damages materials	Roof structural failure	0.30	0.75	0.23	Enhanced water control methods to mitigate water exposure risks

Windows/doors hurricane FMECA table

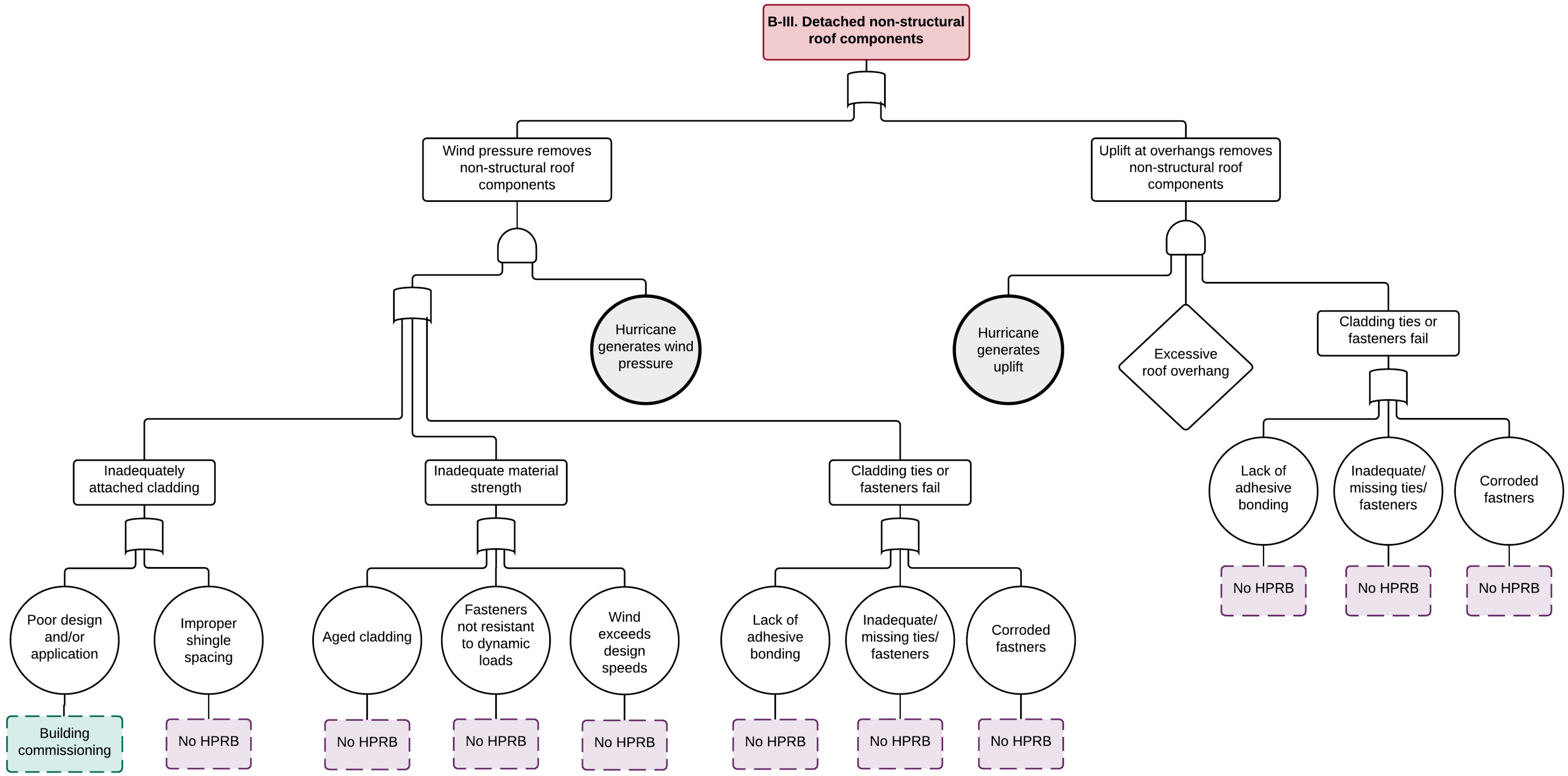
Component	Hazard Loading(s)	Failure Mode	Causes of Failure Mode	Potetnial Effects of Failure Mode	Severity of Consequence (SF)	Probability of Occurrence (PF)	Criticality (SFxPF)	Needs to Prevent/Reduce Risk of Failures
C. Exterior Doors and Windows	Wind/water-borne debris	I. Penetration/ crack	Windows/doors punctured by water-borne debris and/or wind-borne debris, or windows/doors impacted by water-borne debris and/or wind-borne debris	Internal pressurization; Exterior wall structural failure; Water damage; Blown-out windows/doors; Total building collapse/loss	1.00	0.75	0.75	Materials with high impact resistance properties
	Wind/water pressure	V. Blown-in window/door	Wind pressure overloads window/door surface (i.e. over-pressurization), or flood water overloads window/door surface	Internal pressurization; Exterior wall structural failure; Water damage; Blown-out windows/doors; Total building collapse/loss	1.00	0.49	0.49	Material properties and attachement methods that can withstand high pressures
	Wetting	VI. Water Damage	Wind-driven rain enters at window/door-wall intersections and damages materials	Water damage; Exterior wall structural failure	0.11	0.25	0.03	Enhanced water control methods to mitigate water exposure risks

Foundation/floor hurricane FMECA table

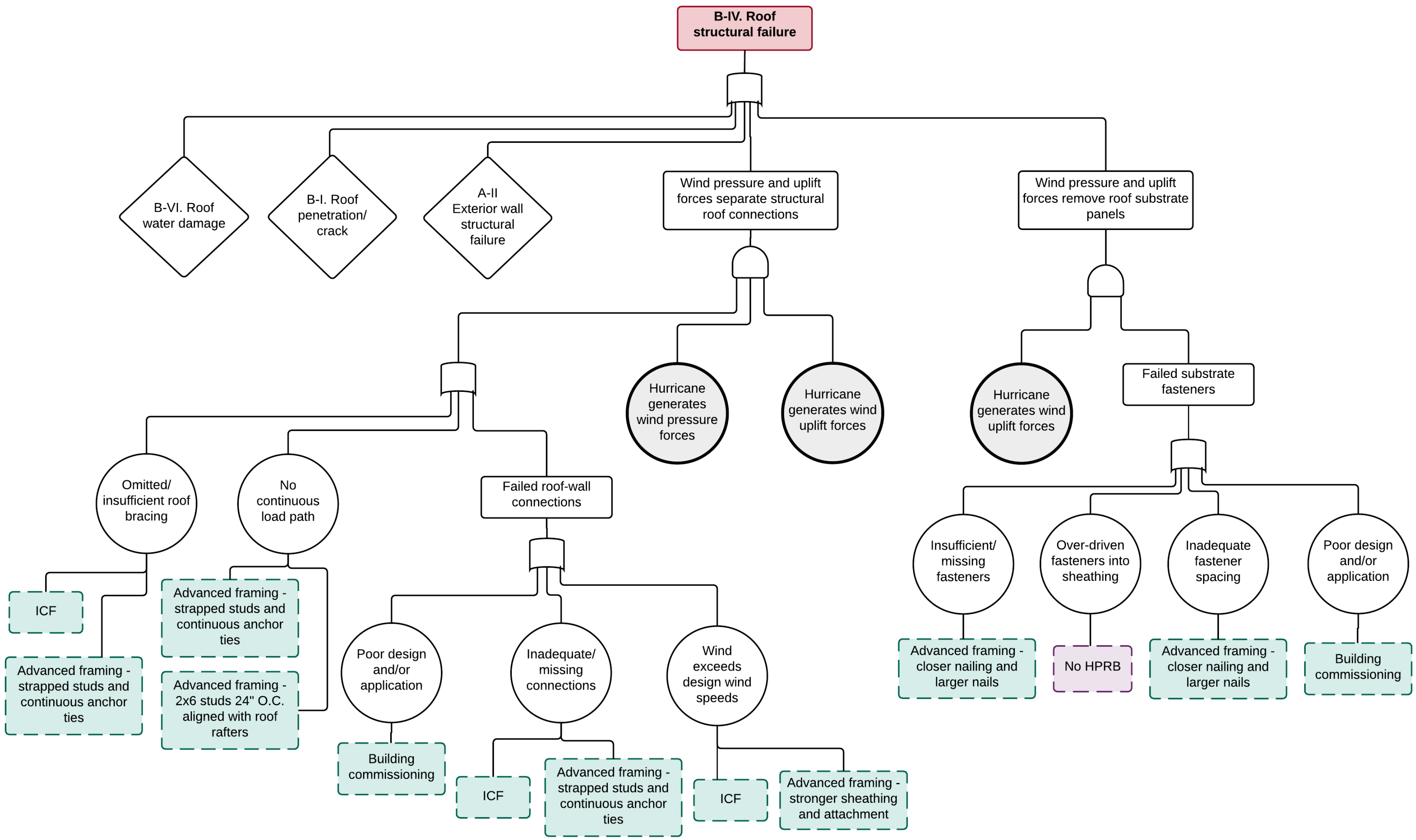
Component	Hazard Loading(s)	Failure Mode	Causes of Failure Mode	Potetnial Effects of Failure Mode	Severity of Consequence (SF)	Probability of Occurrence (PF)	Criticality (SFxPF)	Needs to Prevent/Reduce Risk of Failures
D. Foundation/ Floor	Wave erosion/ scour, water-borne debris, wind/water pressure	VII. Foundation structural failure	Flood and wave erosion/scour loosens the foundation elements, or wind pressure forces separate structural foundation connections, or water-borne debris impacts exposed foundation elements	Exterior wall structural failure; Total building collapse/loss; Water damage	1.00	0.13	0.13	Stronger superstructure connections at foundation for high wind/water pressures; elevated floor and deeper foundation elements; stronger foundation element material properties
	Wave erosion/ scour	VIII. Flotation	Flood water and wave erosion/scour undermines foundation	Total building collapse/loss	1.00	0.25	0.25	Elevated floor and deeper foundation elements; enhanced water control at foundation



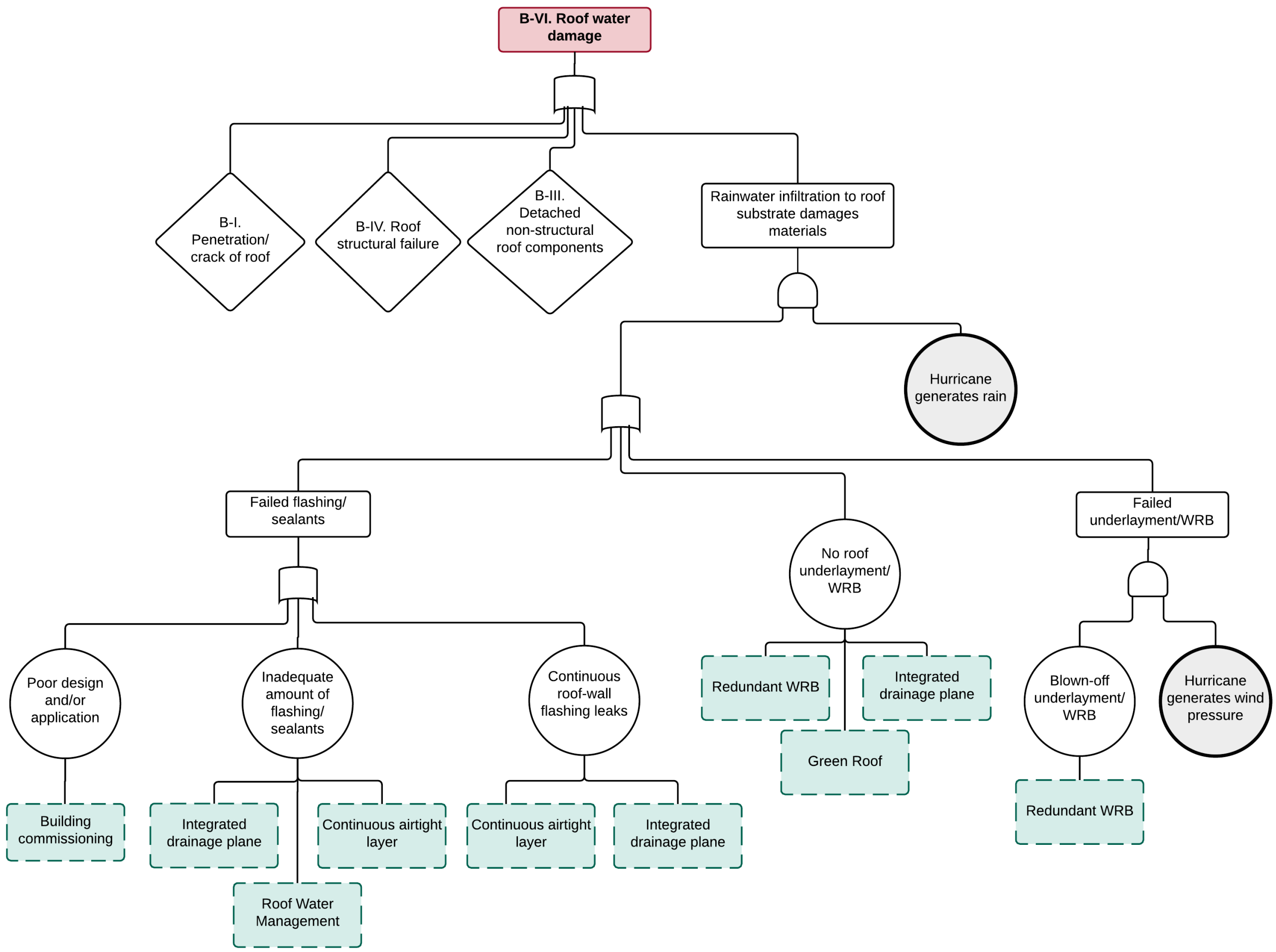
B.I. Penetration/Crack to Roof FTA diagram



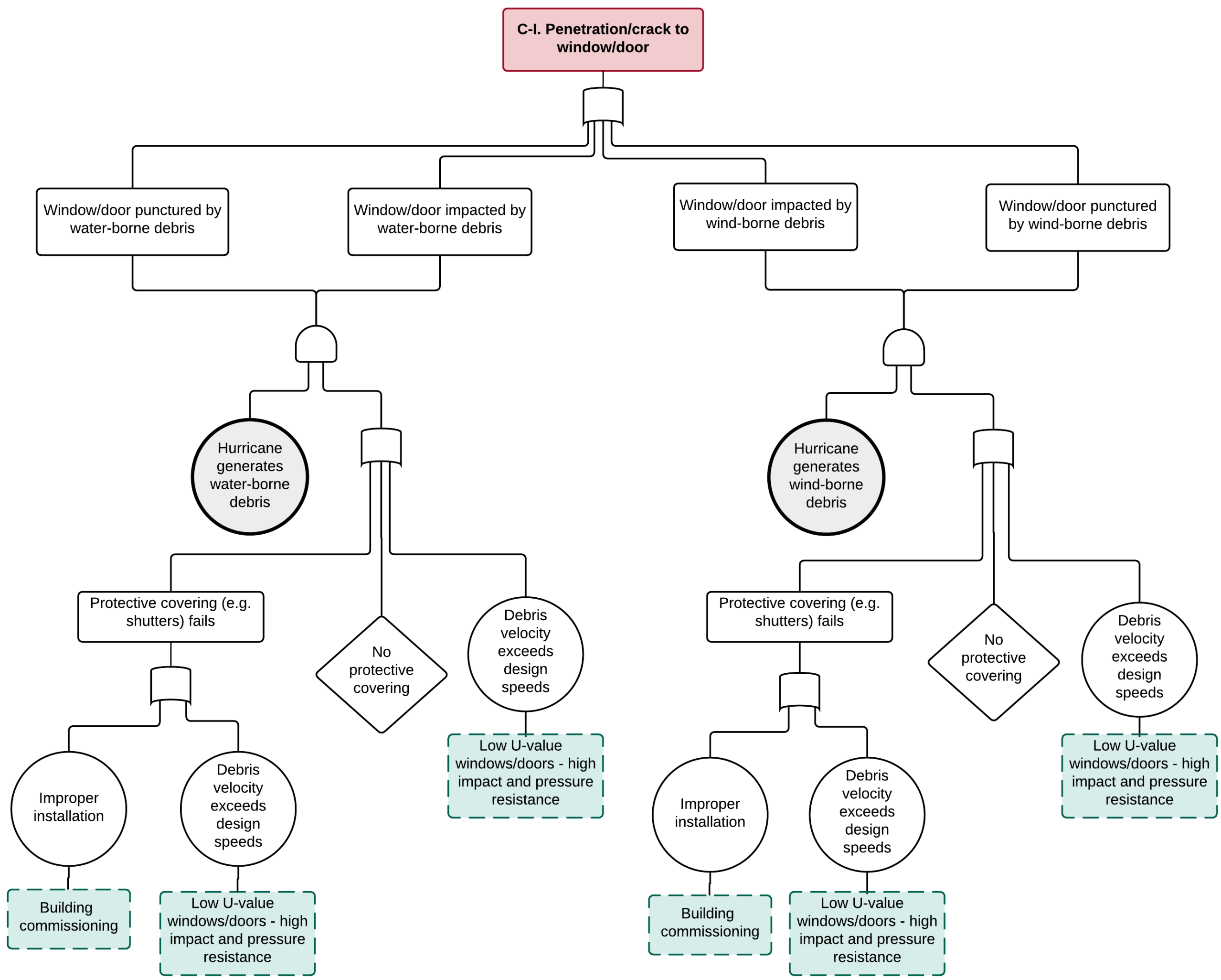
B.III. Detached Non-Structural Roof Components FTA diagram



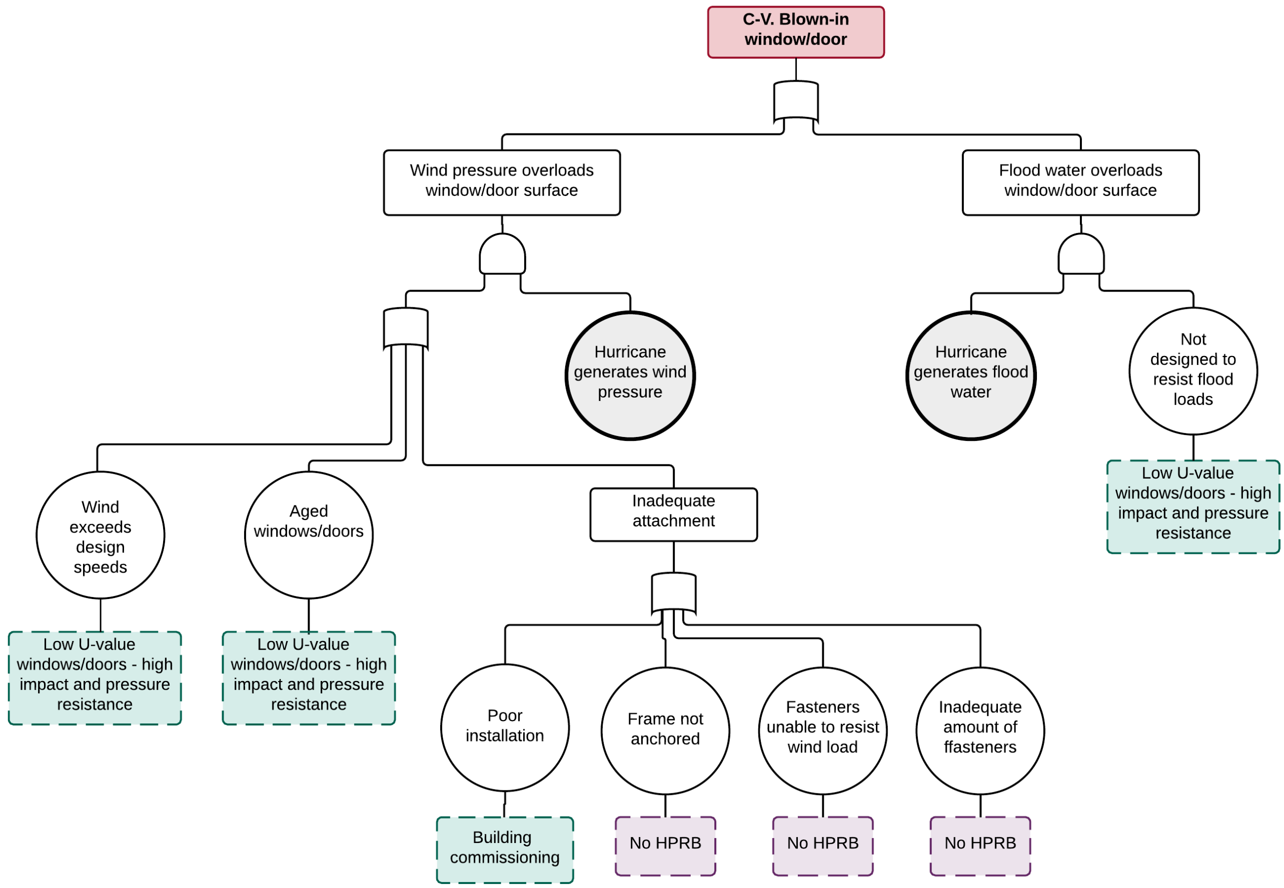
B.IV. Roof Structural Failure FTA diagram



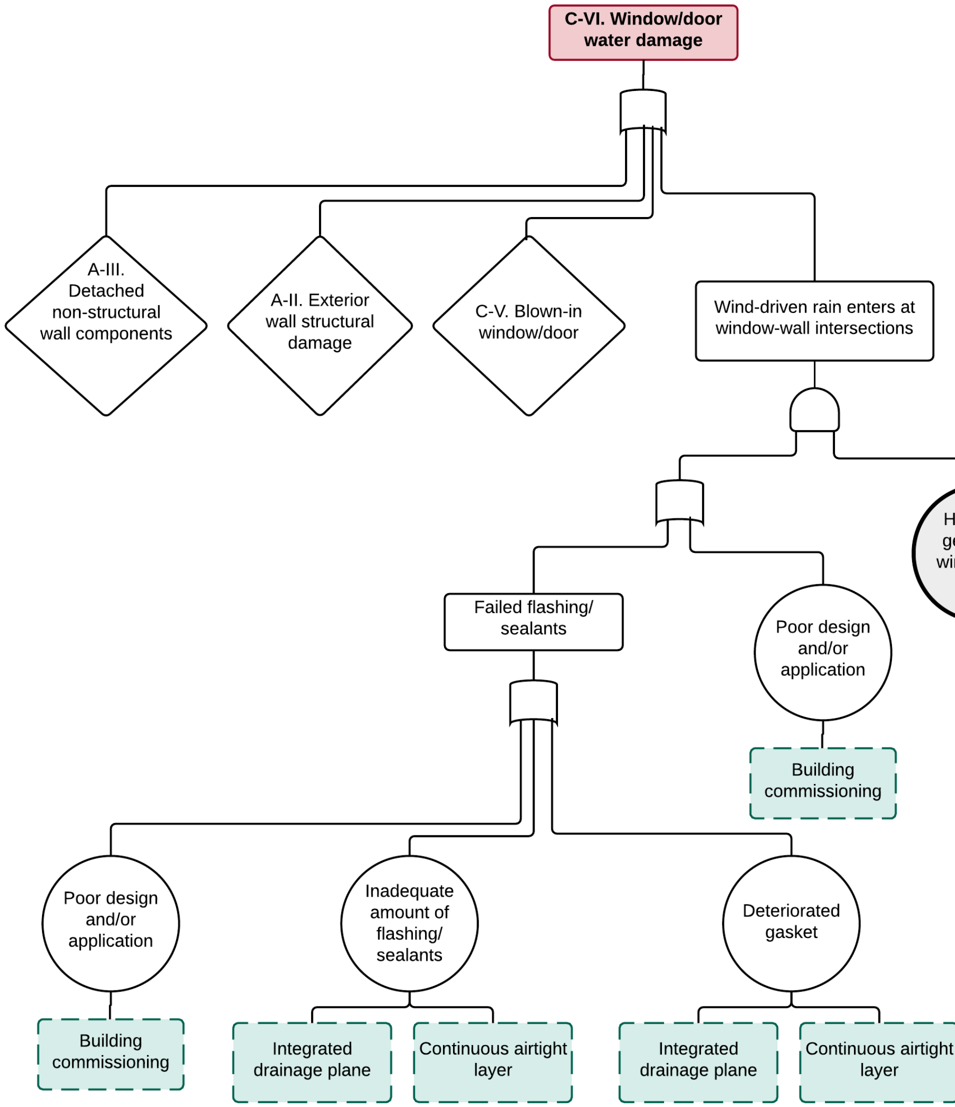
B.VI. Roof Water Damage FTA diagram



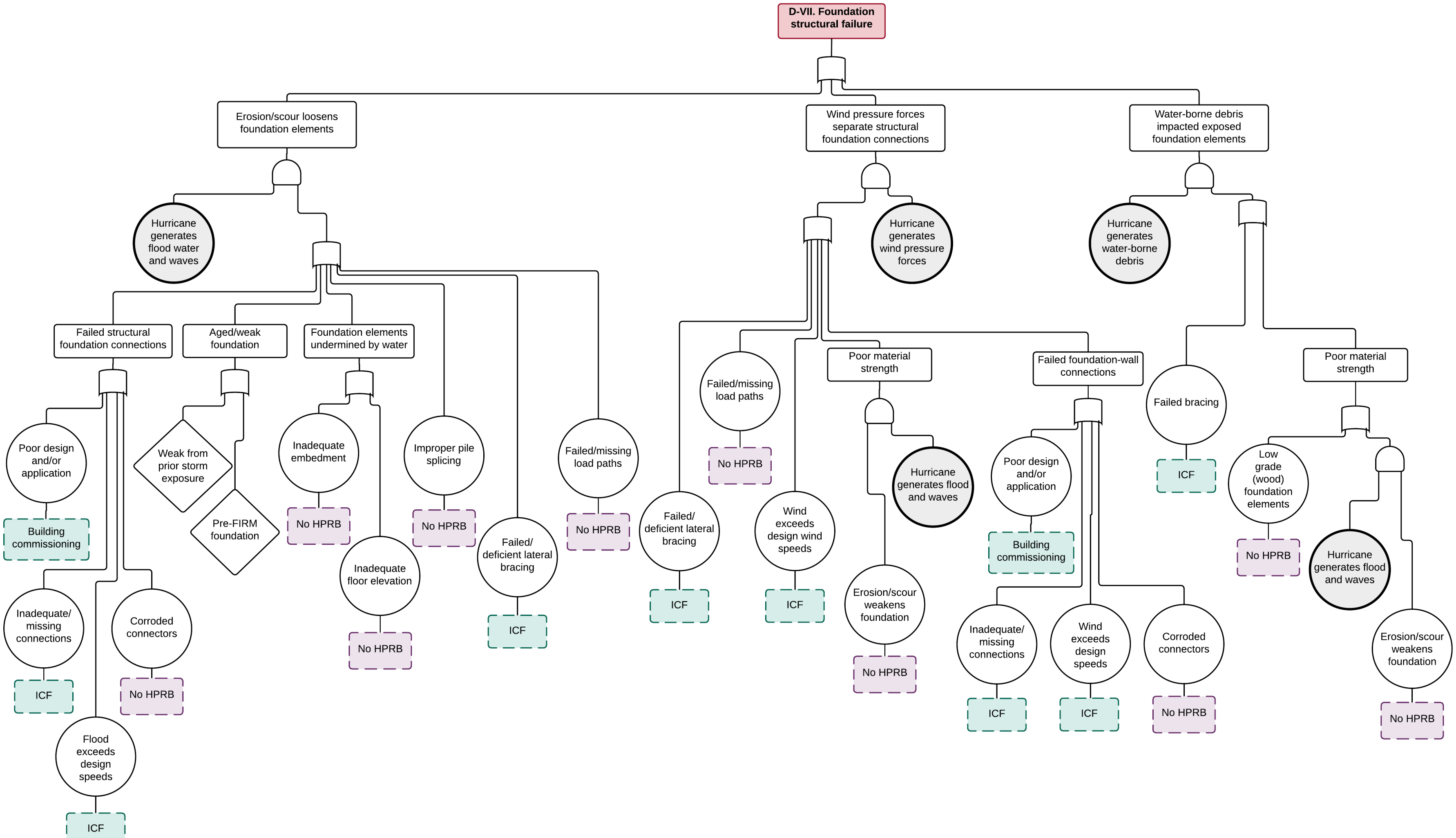
C.I. Penetration/Crack to Window/Door FTA Diagram



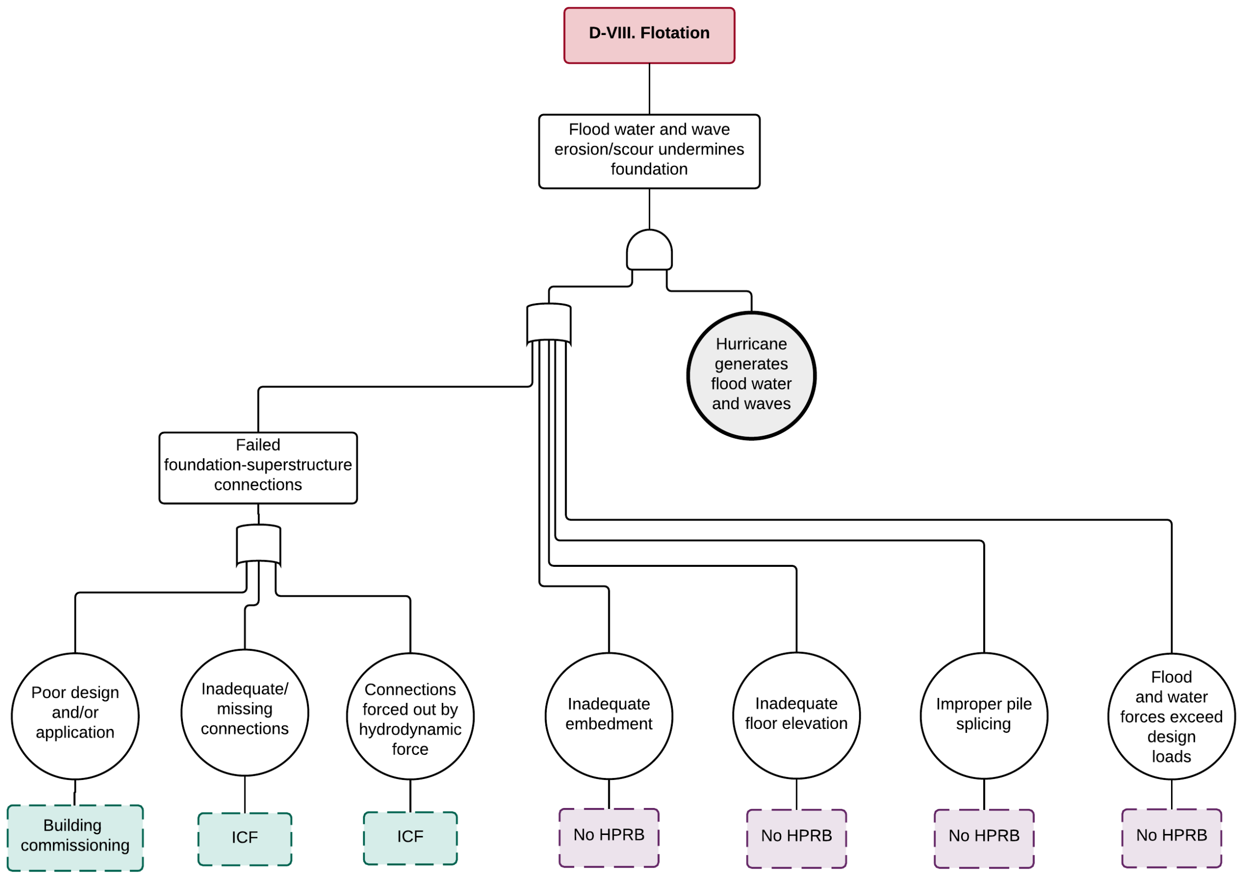
C.V. Blown-In Window/Door



C.VI. Window/Door Water Damage



D.VII. Foundation Structural Failure FTA diagram



D.VIII. Flotation FTA diagram

10.2 Appendix B – Vulnerability Assessments For The Demonstration Case Homes

Failure mode B.I vulnerability assessment

Vulnerability Indicator	*Weight*	*Case 1*	*Value*	*WV*	*Case 2*	*Value*	*WV*
General Vulnerabilities:							
Construction Year	0.063	No	0	0.000	No	0	0.000
Building Code/ Quality	0.063	Yes	1	0.063	No	0	0.000
Occupancy Type	0.063	No	0	0.000	No	0	0.000
Income Status	0.063	Yes	1	0.063	No	0	0.000
Location/Climate	0.063	Yes	1	0.063	Yes	1	0.063
Hazard Exposure	0.063	Yes	1	0.063	Yes	1	0.063
High-Performance Certifications/Features	0.063	Code	1	0.063	HPB	0	0.000
High-Performance Barriers	0.063	Yes	1	0.063	No	0	0.000
Failure Mode B.I Vulnerabilities – Debris Penetration/Crack to Roof:							
The roof is rated as high-impact resistant	0.500	False	1	0.500	False	1	0.500
Failure Mode B.I Vulnerability Totals:			**Case 1 V_T =**	**0.875**		**Case 2 V_T =**	**0.625**

Failure mode B.III vulnerability assessment

Vulnerability Indicator	*Weight*	*Case 1*	*Value*	*WV*	*Case 2*	*Value*	*WV*
General Vulnerabilities:							
Construction Year	0.063	No	0	0.000	No	0	0.000
Building Code/ Quality	0.063	Yes	1	0.063	No	0	0.000
Occupancy Type	0.063	No	0	0.000	No	0	0.000
Income Status	0.063	Yes	1	0.063	No	0	0.000
Location/Climate	0.063	Yes	1	0.063	Yes	1	0.063
Hazard Exposure	0.063	Yes	1	0.063	Yes	1	0.063
High-Performance Certifications/Features	0.063	Code	1	0.063	HPB	0	0.000
High-Performance Barriers	0.063	Yes	1	0.063	No	0	0.000
Failure Mode B.III Vulnerabilities – Detached Non-Structural Roof Components:							
Roof cladding can withstand large amounts of wind/water pressure	0.125	False	1	0.125	False	1	0.125
All roof cladding is securely fastened	0.125	False	1	0.125	True	0	0.000
No signs of corroded cladding fasteners	0.125	True	0	0.000	True	0	0.000
The roof does not have excessive overhangs	0.125	True	0	0.000	True	0	0.000
Failure Mode B.III Vulnerability Totals:			**Case 1 VT =**	**0.625**		**Case 2 VT =**	**0.250**

Failure mode B.IV vulnerability assessment

Vulnerability Indicator	*Weight*	*Case 1*	*Value*	*WV*	*Case 2*	*Value*	*WV*
General Vulnerabilities:							
Construction Year	0.063	No	0	0.000	No	0	0.000
Building Code/ Quality	0.063	Yes	1	0.063	No	0	0.000
Occupancy Type	0.063	No	0	0.000	No	0	0.000
Income Status	0.063	Yes	1	0.063	No	0	0.000
Location/Climate	0.063	Yes	1	0.063	Yes	1	0.063
Hazard Exposure	0.063	Yes	1	0.063	Yes	1	0.063
High-Performance Certifications/Features	0.063	Code	1	0.063	HPB	0	0.000
High-Performance Barriers	0.063	Yes	1	0.063	No	0	0.000
Failure Mode B.IV Vulnerabilities – Roof Structural Failure:							
The enclosure has continuous load paths	0.167	False	1	0.167	True	0	0.000
The roof substrate is securely fastened	0.167	True	0	0.000	True	0	0.000
The roof is adequately braced	0.167	False	1	0.167	True	0	0.000
Failure Mode B.IV Vulnerability Totals:			**Case 1 V_T =**	**0.708**		**Case 2 V_T =**	**0.125**

Failure mode B.VI vulnerability assessment

Vulnerability Indicator	*Weight*	*Case 1*	*Value*	*WV*	*Case 2*	*Value*	*WV*
General Vulnerabilities:							
Construction Year	0.063	No	0	0.000	No	0	0.000
Building Code/ Quality	0.063	Yes	1	0.063	No	0	0.000
Occupancy Type	0.063	No	0	0.000	No	0	0.000
Income Status	0.063	Yes	1	0.063	No	0	0.000
Location/Climate	0.063	Yes	1	0.063	Yes	1	0.063
Hazard Exposure	0.063	Yes	1	0.063	Yes	1	0.063
High-Performance Certifications/Features	0.063	Code	1	0.063	HPB	0	0.000
High-Performance Barriers	0.063	Yes	1	0.063	No	0	0.000
Failure Mode B.VI Vulnerabilities – Roof Water Damage:							
Flashing and sealants are present and show no signs of deterioration	0.250	False	1	0.250	True	0	0.000
The roof has a continuous WRB layer	0.250	True	0	0.000	True	0	0.000
Failure Mode B.VI Vulnerability Totals:			**Case 1 V_T =**	**0.625**		**Case 2 V_T =**	**0.125**

Failure mode C.I vulnerability assessment

Vulnerability Indicator	***Weight***	***Case 1***	***Value***	***WV***	***Case 2***	***Value***	***WV***
General Vulnerabilities:							
Construction Year	0.063	No	0	0.000	No	0	0.000
Building Code/ Quality	0.063	Yes	1	0.063	No	0	0.000
Occupancy Type	0.063	No	0	0.000	No	0	0.000
Income Status	0.063	Yes	1	0.063	No	0	0.000
Location/Climate	0.063	Yes	1	0.063	Yes	1	0.063
Hazard Exposure	0.063	Yes	1	0.063	Yes	1	0.063
High-Performance Certifications/Features	0.063	Code	1	0.063	HPB	0	0.000
High-Performance Barriers	0.063	Yes	1	0.063	No	0	0.000
Failure Mode C.I Vulnerabilities – Debris Penetration/Crack to Windows/Doors:							
The windows/doors are rated as high-impact resistant	0.250	False	1	0.250	True	0	0.000
Protective coverings (e.g. shutters) are installed	0.250	True	0	0.000	False	1	0.250
Failure Mode C.I Vulnerability Totals:			**Case 1 V_T =**	**0.625**		**Case 2 V_T =**	**0.375**

Failure mode C.V vulnerability assessment

Vulnerability Indicator	***Weight***	***Case 1***	***Value***	***WV***	***Case 2***	***Value***	***WV***
General Vulnerabilities:							
Construction Year	0.063	No	0	0.000	No	0	0.000
Building Code/ Quality	0.063	Yes	1	0.063	No	0	0.000
Occupancy Type	0.063	No	0	0.000	No	0	0.000
Income Status	0.063	Yes	1	0.063	No	0	0.000
Location/Climate	0.063	Yes	1	0.063	Yes	1	0.063
Hazard Exposure	0.063	Yes	1	0.063	Yes	1	0.063
High-Performance Certifications/Features	0.063	Code	1	0.063	HPB	0	0.000
High-Performance Barriers	0.063	Yes	1	0.063	No	0	0.000
Failure Mode C.V Vulnerabilities – Blown-In Windows/Doors:							
The windows/doors are rated as high-velocity/pressure resistant	0.167	False	1	0.167	True	0	0.000
Windows/doors do not show signs of wear and tear	0.167	False	1	0.167	True	0	0.00
Window/door frames are adequately attached/anchored	0.167	True	0	0.000	True	0	0.000
Failure Mode C.V Vulnerability Totals:			**Case 1 V_T =**	**0.708**		**Case 2 V_T =**	**0.125**

Failure mode C.VI vulnerability assessment

Vulnerability Indicator	*Weight*	*Case 1*	*Value*	*WV*	*Case 2*	*Value*	*WV*
General Vulnerabilities:							
Construction Year	0.063	No	0	0.000	No	0	0.000
Building Code/ Quality	0.063	Yes	1	0.063	No	0	0.000
Occupancy Type	0.063	No	0	0.000	No	0	0.000
Income Status	0.063	Yes	1	0.063	No	0	0.000
Location/Climate	0.063	Yes	1	0.063	Yes	1	0.063
Hazard Exposure	0.063	Yes	1	0.063	Yes	1	0.063
High-Performance Certifications/Features	0.063	Code	1	0.063	HPB	0	0.000
High-Performance Barriers	0.063	Yes	1	0.063	No	0	0.000
Failure Mode C.VI Vulnerabilities – Windows/Doors Water Damage:							
Flashing and sealants are present and show no signs of deterioration	0.250	False	1	0.250	True	0	0.000
Gaskets does not show signs of deterioration	0.250	False	1	0.250	True	0	0.000
Failure Mode C.VI Vulnerability Totals:		**Case 1 V_T =**		**0.875**	**Case 2 V_T =**		**0.125**

Failure mode D.VII vulnerability assessment

Vulnerability Indicator	*Weight*	*Case 1*	*Value*	*WV*	*Case 2*	*Value*	*WV*
General Vulnerabilities:							
Construction Year	0.063	No	0	0.000	No	0	0.000
Building Code/ Quality	0.063	Yes	1	0.063	No	0	0.000
Occupancy Type	0.063	No	0	0.000	No	0	0.000
Income Status	0.063	Yes	1	0.063	No	0	0.000
Location/Climate	0.063	Yes	1	0.063	Yes	1	0.063
Hazard Exposure	0.063	Yes	1	0.063	Yes	1	0.063
High-Performance Certifications/Features	0.063	Code	1	0.063	HPB	0	0.000
High-Performance Barriers	0.063	Yes	1	0.063	No	0	0.000
Failure Mode D.VII Vulnerabilities – Foundation Structural Failure:							
The enclosure has continuous load paths	0.071	False	1	0.071	True	0	0.000
The foundation does not show signs of deterioration	0.071	True	0	0.000	True	0	0.000
The foundation is Post-FIRM (if within 100-year flood boundary)	0.071	True	0	0.000	True	0	0.000
Foundation elements are sufficiently embedded (if it is a deep foundation)	0.071	True	0	0.000	True	0	0.000
The foundation/floor is adequately elevated	0.071	True	0	0.000	True	0	0.000
The foundation is adequately braced (if applicable)	0.071	True	0	0.000	True	0	0.000
Exposed foundation elements can withstand large debris impacts	0.071	True	0	0.000	True	0	0.000
Failure Mode D.VII Vulnerability Totals:		**Case 1 V_T =**		**0.446**	**Case 2 V_T =**		**0.125**

Failure mode D.VIII vulnerability assessment

Vulnerability Indicator	***Weight***	***Case 1***	***Value***	***WV***	***Case 2***	***Value***	***WV***
General Vulnerabilities:							
Construction Year	0.063	No	0	0.000	No	0	0.000
Building Code/ Quality	0.063	Yes	1	0.063	No	0	0.000
Occupancy Type	0.063	No	0	0.000	No	0	0.000
Income Status	0.063	Yes	1	0.063	No	0	0.000
Location/Climate	0.063	Yes	1	0.063	Yes	1	0.063
Hazard Exposure	0.063	Yes	1	0.063	Yes	1	0.063
High-Performance Certifications/Features	0.063	Code	1	0.063	HPB	0	0.000
High-Performance Barriers	0.063	Yes	1	0.063	No	0	0.000
Failure Mode D.VIII Vulnerabilities – Foundation Structural Failure:							
The enclosure has continuous load paths	0.125	False	1	0.125	True	0	0.000
Foundation-superstructure connections are securely attached	0.125	True	0	0.000	True	0	0.000
The foundation is adequately elevated	0.125	True	0	0.000	True	0	0.000
Foundation elements are sufficiently embedded (if it is a deep foundation)	0.125	True	0	0.000	True	0	0.000
Failure Mode D.VIII Vulnerability Totals:			**Case 1 V_T =**	**0.500**		**Case 2 V_T =**	**0.125**