Journal of Building Engineering 21 (2019) 446–454

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Attributes and metrics for comparative quantification of disaster resilience across diverse performance mandates and standards of building

Oluwateniola Ladipo[a,*], Georg Reichard[a], Andrew McCoy[a], Annie Pearce[a], Paul Knox[b], Madeleine Flint[c]

[a] Department of Building Construction, Virginia Polytechnic Institute and State University, Blacksburg, VA 24060, USA
[b] Global Forum on Urban and Regional Resilience, Virginia Polytechnic Institute and State University, Blacksburg, VA 204060, USA
[c] Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24060, USA

ARTICLE INFO

Keywords:
Disaster resilience
Buildings
High performance
Natural disasters
Risk assessments

ABSTRACT

With the growing concern of climate change and more frequent and severe natural disaster events affecting the built environment, enhancing the performance and resilience of buildings has become increasingly vital. Stakeholders are seeking guidance towards improving both the individual performance of buildings and systems as well as their overall disaster resilience. Thus, they require tools that can comparatively evaluate technologies across multiple standards and qualities of construction in a consistent way. Such tools would be used as a means to make effective decisions based upon different performance metrics as they apply to a particular situation or context. However, neither common, succinct definitions nor metrics for evaluating both resilience and building performance across various construction standards exists, which makes conducting such assessments a considerably difficult task. Evaluating and comparing the performance and resilience levels of buildings and their systems in response to various natural disaster risks necessitates metrics that distinguish the contributing attributes for each aspect of performance and resilience. Consequently, such metrics then allow for benchmarking and comparisons between buildings and systems, and permit the quantification of potential improvements, or lack thereof, when implementing various building technologies in an effort to simultaneously increase performance and resilience. This paper addressed this need by demonstrating that attributes and corresponding metrics of disaster resilience for buildings can be consistently quantified by a function of Functionality and Time and subsequently used for disaster resilience assessments. A thematic analysis of a sample of relevant texts was conducted to validate the hypothesis theorized for measuring resilience.

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 harsher climates and more frequent extreme weather events [17]. 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 infrastructure. In the built environment, the consequences of climate change are already taking a toll on builders, owners, and occupants in various ways. For example, The U.S. energy sector, in particular the aging electric grid [5], 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 [6]. Additionally, the majority of the grid exists above ground and is thus exposed directly to harsh weather conditions, leaving it vulnerable to increased deterioration and destruction. This was recently exemplified in 2017 in Puerto Rico, in which Hurricane Maria caused unprecedented damage to Puerto Rico's electrical grid leaving millions of people without power for weeks. These events and circumstances contribute to billions of dollars in annual economic fluctuation and inflation as a result of costs incurred for repairs and maintenance, where in 2012, the year of “Superstorm” Hurricane Sandy, costs to repair damages were estimated to be $52 billion [5]. Following recent hurricane events in 2017, repair estimates are expected to far exceed this number.

The health and safety of people are similarly becoming more

---

[*] Corresponding author.

E-mail addresses: teni@eocengineers.com (O. Ladipo), reichard@vt.edu (G. Reichard), apmccoy@vt.edu (A. McCoy), apearce@vt.edu (A. Pearce), knox@vt.edu (P. Knox), mflint@vt.edu (M. Flint).

https://doi.org/10.1016/j.jobe.2018.11.007
Received 1 September 2018; Received in revised form 11 November 2018; Accepted 14 November 2018

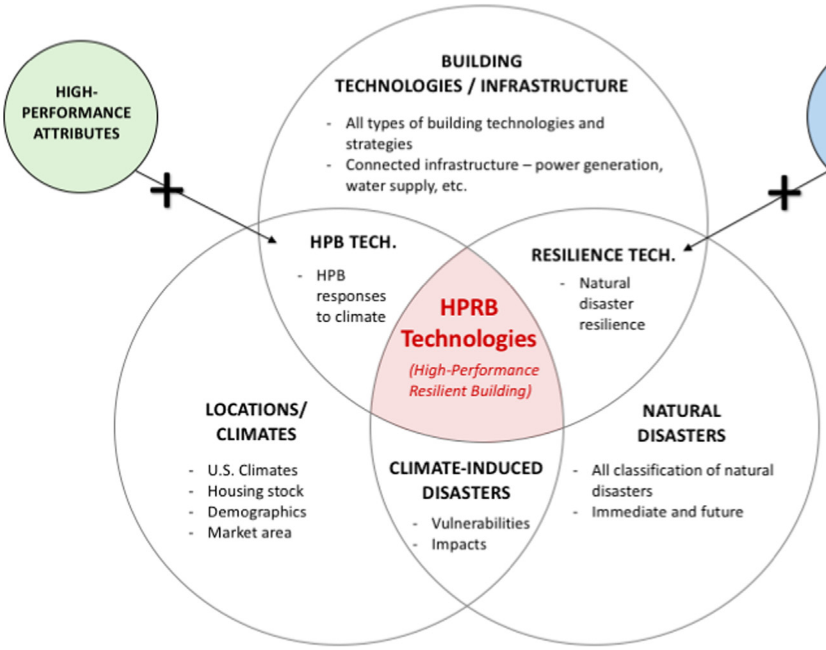

Fig. 1. Research goal overview diagram (HPB = high-performance building).

vulnerable to the adverse consequences of climate change and severe weather events. Older homes, poor construction, and substandard building enclosure performance lack the ability to provide adequate protection for occupants susceptible to adverse and extreme weather conditions, either heat waves or periods of extreme cold temperatures.

There is no doubt that in the wake of climate change, natural disasters can and will strike, taking a toll on the built environment and many lives. *Disaster Resilience*, as an integrated approach across the various building systems, 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.

In building construction, there is a great potential for specific high-performance building technologies (e.g., technologies with enhanced energy performance and durability features) to play a vital role in creating and increasing the resilience of the built environment through the application of such technologies on a local building 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.

1.1. Motivation

Research efforts linking high-performance building technologies, resilience strategies, and climate adaptation preparedness into concerted efforts have been made to some extent in the past. For example, Larsen et al. identified LEED credits that can potentially provide disaster resilience resulting from climate change impacts on a regional level [13]. FEMA provided an assessment of natural disaster impacts on high-performance building ratings strategies that can be implemented to improve resilience [7]. And the National Institute of Building Science (NIBS) developed tools to assist with reaching high-performance building goals and to achieve multi-hazard resilience [16]. However, there are still gaps in these efforts, which includes the following:

- Local level, **natural disaster risk assessments, specifically for the housing sector are in need** for all U.S. climate regions
- Definition/**attributes of "high-performance" lack consensus** for buildings, which is needed for identifying metrics for comparative evaluations
- Defining and **measuring "resilience" for buildings** and technologies towards 'climate induced' natural hazards require more research efforts
- According to a literature review**, no risk-based decision-making tools exist to improve both building performance and resilience** by means of context specific prioritization of technologies

Some work has been done to assess the resilience of residential buildings, for example, the hazard specific standard FORTIFED Home. This standard works to make residential buildings more disaster resilient through methods and strategies designed to surpass key minimum building code requirements specific to hazard property protection. Additionally, it offers three designation certificates of Bronze, Silver and Gold. However, FORTIFED Home does not specifically apply to high-performance building technologies as an objective in concert with resilience. Nor does it assess and quantify resilience in regards to specific attributes that represent resilience as well as high-performance metrics, and therefore inadvertently excludes strategies and qualities that make assessments all-encompassing risk-based evaluations. FORTIFIED Home focuses first and foremost on the fabric of the building (more specifically the protection of the roof) above strategies such as the resilient and efficient use/supply of energy and resources over a building's life cycle that are also key to the function and durability of a building.

Therefore, a research agenda was formulated to address these gaps. More specifically, this research aims to develop a decision-making process model that can be used to identify, evaluate, and prioritize building technologies that provide attributes of both high-performance and disaster resilience in response to natural disaster risks for a variety of contexts at a local level. Fig. 1 provides an overview of the different facets of this research agenda that will be integrated to identify and evaluate an inventory of high-performance resilient building "HPRB" technologies prioritized for a variety of natural disaster risks.

As a part of this larger research agenda, the first stage required the investigation of how one can quantify resilience as a performance metric for buildings, which is the focus of this paper. The subsequent approach for quantifying and assessing other high-performance metrics for buildings will be demonstrated in a separate paper.

2. Parameter modeling framework

Comparing and contrasting buildings and technologies require attributes and assessment metrics that are consistently defined so that various levels of resilience can be quantified. Doing so will strengthen decision-making process in regards to allowing for a more convenient comparison of building technologies across several construction standards while taking multiple criteria into consideration.

Literature can reveal that the *Functionality* of a building/system prior to, before, and after a natural hazard event, as well as the *Time* it takes to recover functionality, can both be considered important variables of the many aspects used to define disaster resilience. Both variables can be useful for measuring resilience and reconciling the differing attributes that exist for it. Therefore, the objective of this research study was to prove this hypothesis by identifying a set of common attributes defining disaster resilience, then deriving and validating a function from the attribute definitions that can be used to measure disaster resilience in regards to Functionality and Time.

The stakeholders for this research include building auditors, retrofitters, and disaster mitigation officials who assess building performance with regard to natural disaster risk, and the insurance industry. These professionals are most familiar with the attributes and metrics identified here. They can utilize the taxonomy derived in this research to evaluate and ultimately quantify a building's current resilience to various hazards, and subsequently communicate results and strategies for improving resilience to owners, government agencies (e.g., FEMA or HUD), builders, and community planners.

The outcome of this study is a set of metrics and attributes that define and evaluate, in this stage specifically, residential disaster resilience across various qualities and standards of construction based upon a function of Time and Functionality. To accomplish the research goal of this study, disaster resilience literature (listed in Table 1) was drawn upon for an inductive *Thematic Analysis,* to develop a function for measuring resilience based upon attributes identified from the analysis as summarized in Fig. 2.

Thematic Analysis is a type of textual content analysis and falls into the group of qualitative research methods. Similar to the more quantitative based text analysis method of content analysis [12], thematic analysis is a “content-driven” approach that involves rigorously searching for key implicit and explicit themes in textual data [9]. Themes are identified through codes developed by interpreting meaning from relevant excerpts of text, the unit of analysis. This method is also a preceding task to the grounded theory method [3]. For this research, the sampled literature was thoroughly reviewed and coded in order to identify common themes for disaster resilient homes. These themes then built the basis to formulate a comprehensive list of attributes and metrics, which were used to characterize and later quantify disaster resilience applicable to various dimensions of residential buildings.

To ensure credibility and trustworthiness could be gained for the results produced in this thematic analysis, *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 [4]. The type of purposive sampling used for this research was *Criterion Sampling*, which ensured that all the texts selected meet specific 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 [4]. The criteria set for the sampling for this research 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, initially limited to residential buildings.
   a. This entailed a vetting process of identifying texts and reviewing them to ensure they included authors/contributors with pertinent research and industry experience in the following areas (all of which are represented in the final sample):
      i. Residential environmental design, construction, and/or planning
      ii. Governmental or non-profit organizations relating to community development
      iii. Sustainable building and construction
      iv. Natural disaster response and rebuilding in communities
      v. Climate resiliency in communities
      This information is typically disclosed in author/contributor biographies, their publication lists (if applicable), work and organizational history, as well as accompanying mission statements.
2. Texts are related to the built environment, with specific mentions/focus given to residential buildings or communities to reduce sample size.
   a. Once potentially eligible texts were found, a screening process was carried out to ensure that all texts eventually included in the final sample relate specifically to residential building and community systems.
3. Texts are either building standards, community plans, construction and design principles, or case studies related to implementing natural disaster resilience technologies.
   a. This was also an essential screening criterion because they include and describe strategies implemented and needed for creating resilient buildings. This was specifically sought after for analysis and coding purposes to ensure key ideas and terms were identified which may or may not necessarily be explicitly stated.

Sample sizes for qualitative research to demonstrate saturation of a topic can vary widely with no strict guidelines or consensus on a sufficient number [14]. However, Guest et al. [8] provide some insight and basis for when to stop sampling. In Guest et al.’s study, sixty interview

Table 1
Disaster resilient housing thematic analysis literature sample.

Texts	*Description*
FORTIFIED Home™ [10,11]	Describes the standard that is used to design and strengthen new and existing homes to reduce potential damage from natural hazards such as hurricanes.
A Stronger, More Resilient New York [18]	A comprehensive plan of actionable recommendations created by the city of New York to combat climate change and increase the city's resilience and sustainability.
Resilient Design Institute (RDI) Principles and Resilient Design Strategies [19]	Principles of resilience and design strategies to achieve resilient buildings and communities in the built environment.
The City Resilience Framework [2]	A literature review, case study, and fieldwork based framework developed to understand the drivers of resilience in cities [1]
Building Resiliency Task Force [20]	Proposals and strategies for increasing the resilience of buildings impacted by Hurricane Sandy.
Housing in America: Integrating Housing, Health, and Resilience in a Changing Environment [15]	Explores how housing responds to extreme weather events, and the need for greater resilience to such events.

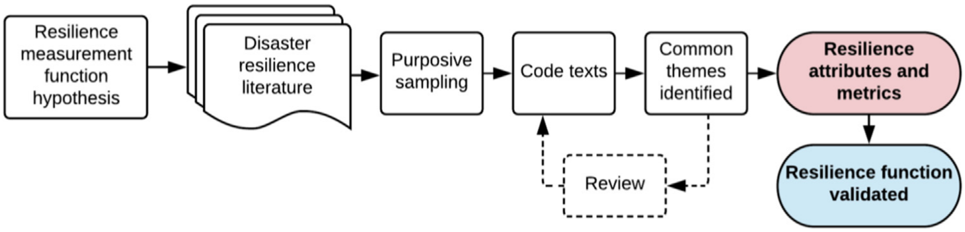

Fig. 2. Summary of the disaster resilience literature analysis and resilience function development process.

transcripts were coded and no new themes emerged after coding twelve of the interview transcripts. This was in part due to the homogeneity of the study's sample, as well as the narrow focus of the study. They concluded that the presence of overarching themes in a data set can likely result in saturation occurring in the earlier stages of analysis, and that meaningful, common overarching themes could be developed from a sample size of six.

The final sample of texts for this study was narrowed down based upon the vetting and screening process described above. While this resulted in a small sample size, the texts selected are saturated with relevant experience, real-world strategies and objectives, and natural disaster responses related to the focus and objective of this study to identify common attributes.

As discussed earlier, the focus of this study was to quantify resilience for residential buildings, which necessitates the emphasis on resilience themed texts. Other texts focusing on the theme of high-performance buildings will be explored in a separate study as a part of the larger research agenda.

Due to the interpretative nature of thematic analysis and coding, a triangulation, in the form of a 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 results produced from thematic analysis coding [9].

Table 2
Disaster resilient housing thematic analysis attributes and sub-attribute descriptions.

Attributes	*Sub-Attributes*
Recovery	Returns to normalcy or better quality following a shock/stress
	Quicker recovery time
Robustness	Enhanced durability and resistance to shocks/stress
	Maintenance of functionality during shocks/stresses
	Habitable conditions during shocks/stresses
	Enhanced protection and/or sheltered away from the exposure to shocks/stresses
	Reduced severity of impacts (e.g. damage, cost)
Redundancy	Backup or failsafe resources or technologies/strategies
	Does not rely solely on the grid, non-renewable and/or non-local resources to function
Resourcefulness	Resourcefulness in times of need
Adaptivity	Adapt to sudden shocks/stresses and short- or long-term changes
	Learn from previous experiences to improve
Energy Efficiency	Efficient use and distribution of energy
Environmental Impact	Level of impact in terms of harm to the environment
Simplicity	Simple operation, control, and repair
Complementarity	Encompasses and is associated with comprehensive, integrative, and/or collaborative strategies to reduce vulnerabilities

3. Results: attributes and metrics for disaster resilience

3.1. Disaster resilient housing attributes

A total of 134 thematic codes were identified from all of the reviewed texts in the sample. Each code was then grouped into one or more common themes (later re-named sub-attributes) based upon the meaning interpreted from the code as a part of the thematic analysis process. 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 2 lists each identified attribute and their sub-attributes from the coding process.

Each identified attribute from the Thematic Analysis were defined as follows:

> **Recovery**: 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 the rate at which this process occurs.
>
> **Robustness:** The ability to withstand an impact that effects the overall severity of an event.
>
> **Redundancy**: Having backup or failsafe technologies/strategies in place as an alternative means of maintaining functionality and/or accessing critical resources.
>
> **Resourcefulness:** Having resources readily available in times of need, and the ability to prepare for and anticipate an event by re-organizing and implementing resources as needed.
>
> **Adaptivity:** 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.
>
> **Energy Efficiency:** A reduction in energy consumption needs (specifically under times of stress) by means of efficient use, production, and/or distribution.
>
> **Environmental Impact:** The level of environmental impact of technologies, such as impact on greenhouse gas (GHG) emissions associated with construction materials and processes.
>
> **Simplicity:** Technologies are simple to operate with the ability to be manually overridden if necessary, and repair is not complex.
>
> **Complementarity:** Technologies/strategies are connected supportive, and/or comprehensive in reducing vulnerability and increasing resilience.

It should be noted that some of the resilience attributes identified will also contribute to high-performance as an HPRB Technology (refer to Fig. 1), such as *Energy Efficiency*. The development of applicable High-performance attributes and metrics for an integrated decision-making process will be discussed in a forthcoming paper.

The following discusses the attribute definitions that were defined from this study. Each attribute definition is based upon specific codes that were extracted from the texts to identify each attribute.

Recovery has been defined in this research as follows: *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 in comparison to the rate of recovery that is typically expected.*

This definition describes several aspects that can occur with a

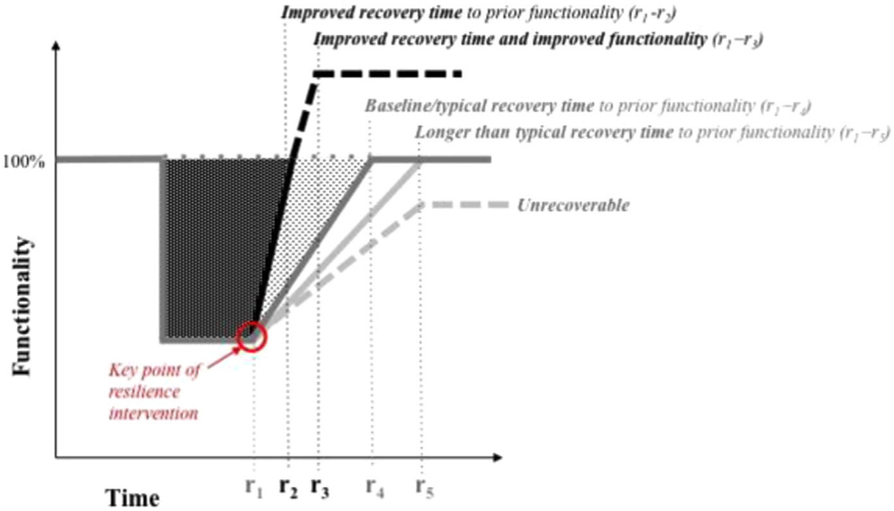

Fig. 3. Resilience and recovery.

recovery. The first, and perhaps most apparent aspect, is a reduction in the typical recovery time to pre-event functionality. Fig. 3 depicts this characteristic of a recovery. This figure and additional figures to follow, are based upon the codes and themes identified in this study, and as a result of this, they exemplify how the attribute can be measured based upon Functionality and Time. A circle is used to highlight key points 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 recovery path of a typical or baseline performing home if it was impacted by a sudden shock or stress is illustrated. This baseline/typical recovery track returns to prior functionality, however, it is also a possibility that a complete recovery is not attainable, which is represented by the lighter colored dashed line that does not return to 100% functionality. In comparison to this, the dark shaded area represents a highly resilient recovery, where a home bounces back to pre-impact functionality at a faster rate of recovery. Fig. 3 also illustrates some additional aspects of a resilient recovery that can occur. In comparison to the baseline recovery, a more resilient recovery may not only improve at a quicker rate, but also it can additionally improve to a better state than the pre-impact functionality as shown by the darker colored dashed line. This is essentially the ability to “bounce-forward” rather than “bounce-back” by improving a system's *robustness*.

When considering building enclosures, one example of a resilient recovery would be using a high-performance resilient building (HPRB) technology (which are technologies that can be found in various high-performance building standards as recommended or mandatory strategies) that uses 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 a hurricane in which heavy wind-driven rain occurred. 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 beyond pre-impact functionality.

Robustness has been defined as follows*: The ability to withstand an impact that affects the overall severity of an event.*

The key aspect of robustness as depicted in Fig. 4 is the measure of severity of an impact (i.e. how detrimental the impact is to functionality). Higher robustness is indicated by an increase in maintained functionality following an impact compared to typical, baseline expectations. This coincides with a reduction in the necessary time and effort associated with repair/recovery to restore pre-impact performance. The key point of resilience intervention for robustness occurs at the point of impact, where steps have been taken (e.g. during design) prior to a disruptive event to prepare for potentially harmful effects as a means of mitigating the severity of the impact. The shaded area (indicated by a black line) is less in comparison to the total area for baseline robustness (grey line), as well as the robustness that is below baseline levels (indicated by a grey dashed line). This illustrates how the ability of a building or system to better withstand or resist impacts can reduce damage, recovery time, and associated costs, among other disruptions for homeowners.

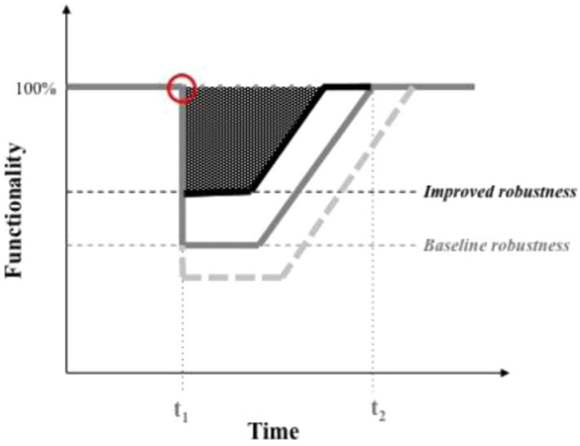

Fig. 4. Resilience and robustness.

An HPRB technology that represents resilient robustness is the use of 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 superior water resistance qualities that reduce the likelihood of damage that can occur from the exposure to moisture.

Redundancy has been defined as follows: *Having backup or failsafe technologies/strategies in place as an alternative means of maintaining functionality and/or accessing critical resources.*

Redundant technologies that are put in place to prevent the complete loss of functionality can increase the resilience of a system. Redundancy can be implemented in various ways with differing levels of effectiveness. This specifically refers to influences on the level of resilience that can be achieved as a result of mobilizing a redundant technology, and what level of functionality can be maintained by this technology. This provides context for different scenarios. For example, a redundant technology that mobilizes soon after an initial impact but can only restore partial functionality may provide less resilience than a redundant technology that similarly mobilizes with a delay, but is able to restore full functionality until a complete recovery has occurred. Alternatively, if a technology were to restore and maintain only partial functionality immediately after impact, the level of resilience that can be achieved may surpass that of a technology that takes much longer to mobilize even though it then could provide complete functionality. The highest resilience could be achieved through redundant technologies that can mobilize immediately and restore complete functionality until a complete recovery occurs. However, these options are typically cost-prohibitive.

The important takeaway from this is that the level of resilience that can be obtained in each of the redundancy scenarios discussed above will vary. The key aspects of comparison to consider for redundancy 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 in regards to the resilience of a system following an impact, but not necessarily in regards to the cost investment in the strategy.

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.

Resourcefulness has been defined as follows: *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 and influences on *Resourcefulness*. 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 Fig. 5, anticipating and thus preparing for an impact (which has ties to robustness), contributes to a reduction in the severity of an impact that reduces loss of functionality by mobilizing resources more quickly (e.g. even before the disaster strikes as part of a preparedness 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 an exterior wall 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 specialty resources being unavailable locally.

Adaptivity has been defined as follows: *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.*

Adaptivity involves the ability to learn from experience in order to improve performance. This ability is termed hereafter as “reflective learning”. As represented in Fig. 6, 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.

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 that no longer meet current building 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 an existing building to current requirements, but it can additionally be a chance to exceed standard code levels by implementing other HPRB technologies.

Energy Efficiency has been defined as follows: *A reduction in energy consumption needs by means of efficient use, production, and/or distribution.*

Energy Efficiency can be 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

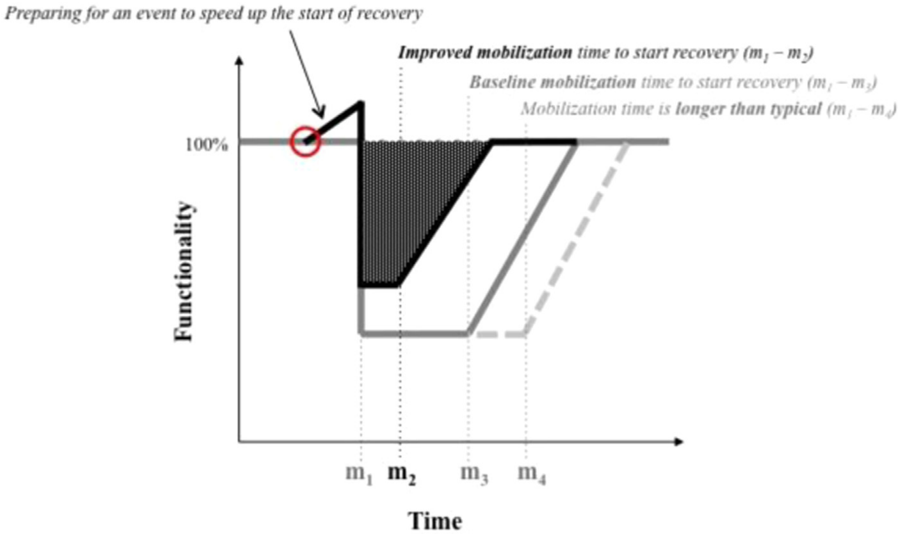

Fig. 5. Resilience and resourcefulness.

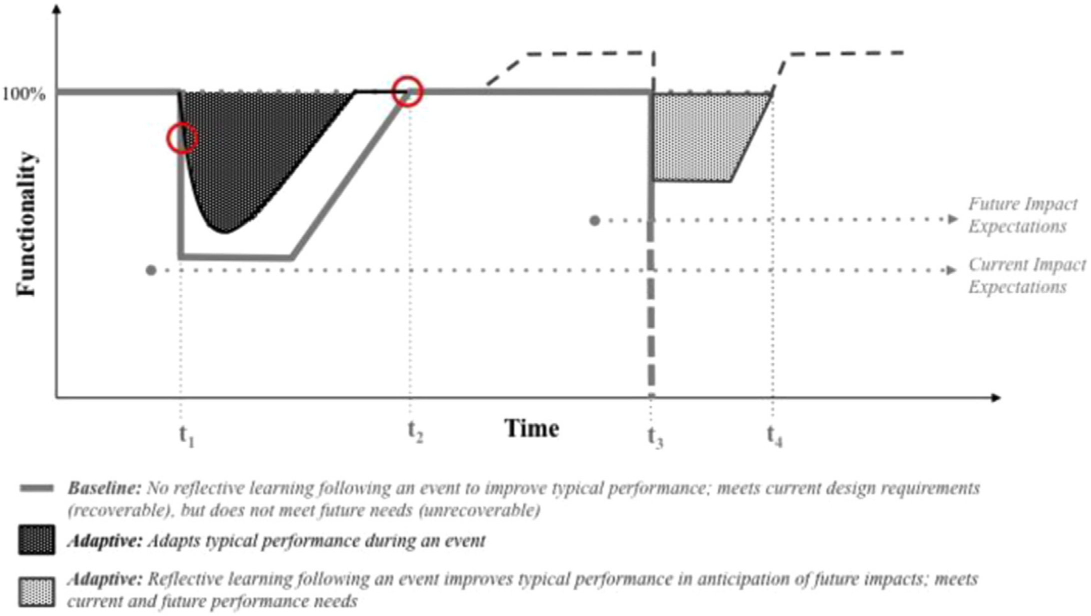

Fig. 6. Resilience and adaptivity.

or stress. A resilient home should have lower annual energy consumption per unit area when compared to non-resilient or standard new constructed homes. The energy consumption comparison can take into account the energy demand, as well as any energy that may be produced on site in an effort 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 helps to keep 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 an enclosure not only reduces the annual energy consumption of a home, but also reduces the need for large energy intensive heating and cooling equipment in times of stress to provide sufficient occupant comfort. For example, a home built to the PassivHaus Standard can maintain habitable temperatures for several days in case of power outages.

Environmental Impact has been defined as follows: *The level of environmental impact of technologies, such as impact on greenhouse gas (GHG) emissions associated with construction materials and processes.*

Similar to energy efficiency, the way in which resources are used (e.g. material quantities, recycled and/or local resources) can increase or decrease the potential for homes to be self-sustaining. A reduction in the use of resources tends to be more material and cost efficient to reconstruct in the case of disaster strikes. *Environmental Impact* can involve requiring increased or fewer materials and/or processes to manufacture, construct, and operate a building, and similarly the amount of 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 environmental impact, or carbon footprint, is more resilient than homes with larger carbon footprints.

Advanced framing is an example of an HPRB technology with a reduced *Environmental Impact* in comparison to standard, code construction framing. This HPRB 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.

Simplicity has been defined here as follows: *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 improved 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* can include strategies such as overriding mechanical controls when necessary with passive systems. Examples would be 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 as well as in the event of a severe weather.

Complementarity, the final attribute of disaster resilient housing, has been defined as follows: *Technologies/strategies are connected, integrated, and/or comprehensive in reducing vulnerability and increasing resilience.*

Complementarity of 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.

3.2. Resilience measurement function

For analysis and comparison in the decision-making process of different design alternatives, or for an assessment of an overall resilience factor for existing buildings, the following equation could be formulated:

$$TRR(t) = \int_{te}^{ts} \frac{1}{\sum w_a} \bullet \sum_{a=1}^{n} f_a \bullet w_a \bullet dt$$

where

Table 3
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
Environmental Impact	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

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

TRR	the total resilience rating over a building's life cycle
ts	the start time of the building's life cycle
te	the end time of the building's life cycle
a	the individual resilience attributes
n	the total number of resilience attribute considered
f	the functionality state (of an individual resilience attribute) at a given time
w	A possible weighting factor (of an individual resilience attribute) to prioritize specific needs in a given context

This Total Resilience Rating (TRR) could become a similar metric as the HERS rating became for Net-Zero Energy performance, comparing designs or existing buildings to a baseline building in a given context.

3.3. Disaster resilient housing metrics

In order to be able to evaluate homes for disaster resilience using the identified attributes, it required the definition of metrics to coincide with each attribute. Each attribute's metric was also assigned a range of values 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. For example, for the metric *Recovery/Repair Time,* since 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 for recovery were set in between the range of a) being unrecoverable, or recovering at a rate below what is typically expected, b) at an expected rate, or c) recovering at a rate that is 10–25% faster or even more 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.

Where existing metrics do not commonly exist to measure the identified resilience attributes, alternative qualitative metrics have been defined based on references found in the literature that follow the definitions devised in this research. For quantitative assessment of these qualitative measures (i.e. levels 1–5), background literature and/or expert judgment has been provided where possible at this stage of the research in support of the proposed values and ranges. The initial set of metrics and values determined for each attribute are listed in Table 3.

A comparison of subject matter expert survey responses to the data gathered and analyzed from literature, showed that a significant majority of the experts agreed with the identified attributes and sub-attributes, and thus contributed to validating the results obtained in this study.

4. Conclusion

A thematic analysis was performed for texts purposively sampled as relevant to a qualifying set of criteria for natural disaster resilient housing. As a result of this analysis, a total of nine common attributes were identified and defined to characterize different construction technologies that represent disaster resilient housing. Additionally, the thematic analysis was used to validate the hypothesis and function derived to measure resilience by the variables Functionality and Time. For each identified attribute, this research further specified initial metrics and values that now can be further developed and used to quantify different levels of resilience based on a set of building technologies, hazard characteristics, and local contexts.

The produced results can now further be used to simultaneously evaluate performance and disaster resilience of residential buildings across differing qualities of construction and high performance building standards for new and existing homes. The identified 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 of homes based on different options of building systems when exposed to diverse natural disaster risks. These attributes and metrics can also be used to evaluate technology alternatives in efforts to simultaneously improve resilience in multiple attributes. The findings of this research can further be used in integrated building performance assessment and scoring systems to evaluate building profiles for resilience. The development of such tools will then aid the design process if natural hazard risk mitigation is a priority for building owners and/or designers when deciding upon building technology alternatives.

4.1. Future work

Future research will focus on assessing the disaster resilience of a home and its systems using multi-criteria decision-making based on the developed attributes and values from this study. This resilience evaluation method will be integrated into a forthcoming risk assessment process, which will also include a High-Performance evaluation process in conjunction with a Resilience evaluation to develop a *High-Performance Resilient Building (HPRB) Score*. This HPRB Scoring method will be a stand-alone performance and resilience-scoring tool used to evaluate new and existing building stocks that are constructed to various codes and standards on a single scale. This proposed assessment tool is similar to the use of the Home Energy Rating System (HERS) Index Score for assessing a home's energy efficiency, however, it will have a broader application in regards to the technologies, systems, and attributes that can be evaluated.

The metrics and values defined in this research to quantify disaster resilience will require further refinement in order to increase the reliability and accuracy of evaluations that can be performed. 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 to a location, building systems, and individual hazards of concern. This analysis will aid the development of more accurate and representative "resilience curves" for each attribute. Furthermore, to allow for priorities to be given to various attributes over others when evaluating the disaster resilience of homes, varying weights of importance for each attribute can be integrated into the decision-making model so that it is possible to prioritize specific attributes within the overall disaster resilience of a home.

References

[1] ARUP, City resilience framework, City Resilience Index, ARUP International Development and The Rockefeller Foundation, 2014.

[2] ARUP, City Resilience Framework, ARUP and the Rockefeller Foundation, 2015.

[3] J. Corbin, A. Strauss, Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory, (2008).

[4] J.W. Creswell, Qualitative Inquiry and Research Design: Choosing Among Five Approaches, Sage Publications, 2007.

[5] DOE, Economic Benefits of Increasing Electric Grid Resilience to Weather Outages, in: W.H.C.O.E. Advisers, U.D.O. Energy, (Eds.), Washington DC.

[6] EIA, Observed Outages to the Bulk Electric System, 1992–2012, U.S. Energy Information Administration, 2013.

[7] D.S. Gromala, O. Kapur, V. Kochkin, P. Line, S. Passman, A. Reeder, W. Trusty, Natural Hazards and Sustainability for Residential Buildings, FEMA, 2010.

[8] G. Guest, A. Bunce, L. Johnson, How many interviews are enough?: an experiment with data saturation and variability, Field Methods 18 (1) (2006) 59–82.

[9] G. Guest, K.M. MacQueen, E.E. Namey, Applied Thematic Analysis, (2012).

[10] IBHS, What is FORTIFIED? New Home, Insurance Institute for Business & Home Safety, 2014.

[11] IBHS, What is FORTIFIED? Existing Home, Insurance Institute for Business & Home Safety, 2014.

[12] K. Krippendorff, Content Analysis: An Introduction to its Methodology, Sage Publications, 1980.

[13] L. Larsen, N. Rajkovich, C. Leighton, K. McCoy, K. Calhoun, K. Mallen, K. Bush, J. Enriquez, C. Pyke, S. McMahon, A. Kwok, U.S.G.B. Council (Ed.), Green Building and Climate Resilience: Understanding Impacts and Preparing for Changing Conditions, University of Michigan, 2011.

[14] M. Mason, Sample size and saturation in PhD studies using qualitative interviews, Forum Qual. Soz. 11 (3) (2010) (Art. 8).

[15] J. McIlwain, M. Simpson, S. Hammerschmidt, Housing in America: Integrating Housing, Health, and Resilience in a Changing Environment, Urban Land Institute, Washington, D.C., 2014.

[16] NIBS, High performance based design for the building enclosure: a Resilience Application Project Report, in: U.S.D.O.H. Security (Ed.), Buildings and Infrastructure Protection Series, National Institute of BuildingSciences, 2011.

[17] NRC, Climate change: evidence, impacts, and choices, Natl. Acad. Sci. (2012) 40.

[18] ORR, A Stronger, More Resilient New York, *PlaNYC*, New York City Mayor's Office of Recovery and Resilience (ORR), 2013.

[19] RDI, The Resilient Design Institute, The Resilient Design Principles, Resilient Design Strategies, 2015, 〈http://www.resilientdesign.org/%3E〉, (20 October 2015).

[20] Urban Green Council, Building Resiliency Task Force, Urban Green Council, U.S. Green Building Council, New York, NY, 2013.