Disaster Resilience and Sustainability

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EXECUTIVE SUMMARY

The importance of sustainability within structural engineering has become more widely accepted in recent decades. When structural engineers think of sustainability, they often limit their scope to material selection and recycling. Few structural engineers recognize the relationship between sustainability and disaster resilience, an area in which they can make significant contributions. Consequently, the aims of this report are to

- Raise awareness of the relationship between disaster resilience and sustainability by discussing how a holistic view of sustainability must recognize the need for disaster resilience, and to
- Provide a critical review of resilience-related efforts and resources available to practicing structural engineers and related professionals.

Sustainability encompasses three spheres: economic, environmental, and social. Within each of these spheres, sustainability requires providing for the needs of the present while allowing future generations to meet their own needs. Disaster resilience pertains to the ability to suffer less damage and recover more quickly from adverse events such as hurricanes and earthquakes. A resilient structure provides socially valuable services such as shelter and safety, even in the face of disaster, and it should do so while minimizing economic and environmental costs. Ignoring resilience during design can lead to structures that may seem green but that cannot reliably provide the services that we expect from them. Sustainability and disaster resilience are related in complex ways. Often times striving for one will help achieve the other as when a more robust structure reduces the environmental and economic cost of repairing extensive damage. Sometimes the two are at cross-purposes. For example, striving for material efficiency may render a structure less redundant, and hence less safe in a disaster.

The main section of this report discusses a variety of efforts to promote resilience and resources for resilient design. Some of these are prescriptive, offering a set of design rules more stringent than existing building codes. Others are performance-based, offering performance criteria and methods for predicting the performance. Prescriptive criteria are simpler, but do not explicitly assure better performance. Performance-based approaches allow the designer to provide specified improvements in performance, but this requires much more effort to achieve. Some of the efforts are voluntary and others are intended to become model codes. Voluntary efforts depend on the desire of the owner or developer to enforce the guidelines. Model codes aim to become law that all designers and builders must follow. Voluntary initiatives may become accepted more quickly and be more adaptable to changing times, but efforts to change model codes have the potential to effect change more broadly.

The report also discusses current efforts to quantify the connection between disaster resilience and sustainability through life cycle methods. There is no current agreement as to the best way of achieving this, nor are there standard tools for the structural engineer to use in everyday practice. However, it is important to remain aware of developments in this area, as it will likely become a common consideration in structural design. The structural engineer who stays abreast of developments – and even better, who contributes to them – will be at an advantage when these methods mature.

In the interest of encouraging positive and meaningful action, the report provides the following suggestions for structural engineers who are interested in supporting disaster resilience and sustainability:

1. **Becoming better informed** by using the references and links in this document.
2. **Participating in the code adoption process** to encourage resilient design standards.
3. **Supporting legislation** that requires or provides incentives for resilient construction.
4. **Educating owners** regarding the importance and value of resilient construction.

5. **Advocating with insurance companies and portfolio managers** to offer decreased costs for better performing facilities.
6. **Advocate with ASCE, SEI and other professional organizations** to raise the profile of structural engineers.

Concluding the report is a thoughtful afterword on resilience and sustainability in developing countries. The afterword suggests considerations for those interested in projects in these countries and provides potential solutions to common challenges, some of which can inform design practices in developed countries such as the United States.

INTRODUCTION

The importance of sustainability within structural engineering has become more widely accepted in recent decades. Structural engineers most often think of sustainability as pertaining to material selection and recycling. Many professionals also consider issues such as durability, obsolescence, and the impact of structure on operational efficiency (Kestner et al. 2010). While the link between disaster resilience and sustainability has been recognized for some time (e.g., FEMA 2000; NIBS 2012), the structural engineering community has not yet embraced this relationship (some notable exceptions are Kneer and Maclise 2008 and Bocchini et al. 2013). In light of this, the aims of this report are to:

- Raise awareness of the relationship between disaster resilience and sustainability by discussing how a holistic view of sustainability must recognize the need for disaster resilience, and to
- Provide a critical review of resilience-related efforts and resources available to practicing structural engineers and related professionals (guidance for other sustainability-related topics is provided by Kestner et al. 2010).

This introduction reviews sustainability, resilience, and natural disasters. Following the introduction, the report presents important considerations for resilient design and summaries of current efforts and available resources. Funding and policy initiatives are then discussed briefly, followed by a section on life cycle assessment, which presents the status of current approaches for incorporating resilience and sustainability metrics. The report concludes with recommendations for effective actions practitioners can take to promote resilience of their projects and communities. A short piece on resilience and sustainability in developing countries is included in an afterword. The afterword suggests considerations for those interested in projects in these countries and provides potential solutions to common challenges, some of which can inform design practices in developed countries such as the United States.

Sustainability

Within the civil engineering profession, two definitions are commonly offered for sustainability. These are the Brundtland Definition which is stated as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987) and the Triple Bottom Line (Figure 1), which views sustainability as satisfying three objectives: not only economic but social and environmental as well (Elkington 2004). This is also sometimes referred to as “People-Planet-Profit” or the “Three Pillars of Sustainability”. In current practice, this entails designing in a cost-effective manner while reducing environmental impacts. The social aspect, while less clearly defined, includes considerations such as safe and healthy work environments, reduced traffic delays, and quality of life in the community. The following references are available for additional information on definitions of sustainability. Kestner et al. (2009) provide more details from the structural engineering point of view. Tapia and Padgett (2012) summarize sustainability with an emphasis on life cycle methods and natural hazard risk mitigation. Rodriguez-Nikl (2011) proposes a more formal treatment of the concept of sustainability. Brandon and Lombardi (2011) provide a comprehensive understanding of sustainability.

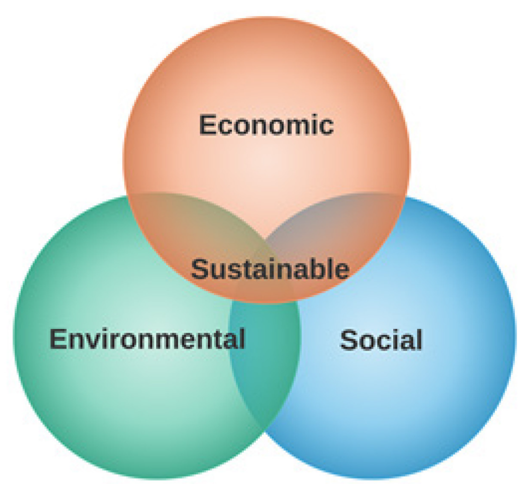

Figure 1: Triple Bottom Line

To date, most efforts to promote sustainability have resulted in green[1] certifications, codes and standards, whose focus is primarily on the direct impacts of the project on its surrounding environment. Leadership in Energy and Environmental Design (LEED n.d.) is arguably the most well-known of the currently available building sustainability rating systems in the United States. The Institute for Sustainable Infrastructure (ISI) has released Envision, a similar rating system for infrastructure (ISI n.d.). These rating systems have different but similar sets of criteria that encourage the designer to consider issues such as site selection, energy efficiency, material use, water use and pollution, indoor environmental air quality, and quality of life. Envision also provides five credits related to resilience. When analyzing impacts of construction materials, considerations include greenhouse gas emissions, energy use, and amounts of materials used. These are influenced by the extraction of raw materials, manufacture of construction materials, delivery to the site, construction practices, and total quantities of material used. Some building designers also consider the effect of the structure on the operational performance. For example, use of the high thermal mass of concrete or reduction of thermal bridging in steel buildings can reduce HVAC (heating, ventilation, and air conditioning) loads. These important considerations are discussed in depth by Kestner et al. (2010).

Less often considered but no less important is enhancing service life. The following are the three main considerations for enhancing service life:

- **Durability** against environmental attack (preventing deterioration)
- **Design for adaptability and deconstruction** (preventing obsolescence)
- **Disaster resilience** (protecting against disasters)

Each of these topics merits in-depth consideration. Kestner et al. (2010) address durability (related to environmental exposure) and design for adaptability and deconstruction (related to obsolescence and changes in usage). Disaster resilience is the topic of this paper. All of these considerations should influence decisions about the designed service life of a facility.

Disaster Resilience

Various organizations and individuals define disaster resilience differently. The concept of resilience pertains to the response of systems to disruptive events. The National Academy of Sciences (NAS) defines resilience as:

> the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events (NAS 2012).

The Department of Homeland Security defines infrastructure resilience as:

> the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event (NIAC 2009).

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[1] As used in this document, "green" will refer to efforts to reduce environmental impacts in some way. It is not used as a carefully defined technical term.

A recent presidential policy directive (PPD 2013) 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.

Bocchini et al. (2013) concluded there are two constants in most definitions of resilience: "(i) resistance to an unusual external shock (often referred as 'robustness') and (ii) ability to recover quickly (often called 'rapidity')".

Important aspects of resilience can be seen in the resilience triangle suggested by Bruneau et al. (2003) and adapted in Figure 2. This figure represents the "quality of infrastructure", where 100 is the pre-disaster level. A disaster occurs at time t_o, causing an immediate loss of quality from 100 to Q_o. Mitigation efforts try to reduce the magnitude of this loss. After the event, recovery efforts aim to restore (or even improve) pre-disaster quality. The time at which this is accomplished is at time t_f. Resilience is affected by both the magnitude of the loss of quality at t_o and the speed of recovery between t_o and t_f. The ratio of the area under the curve to the total area between t_o and t_f can be viewed as a metric of resilience. The structural engineer's main contribution is to mitigation (limiting the losses at t_o). Through intelligent design – e.g., designing easily repairable structural elements such as fuses in seismic force resisting systems – the structural engineer can also contribute to recovery efforts (reducing time to t_f).

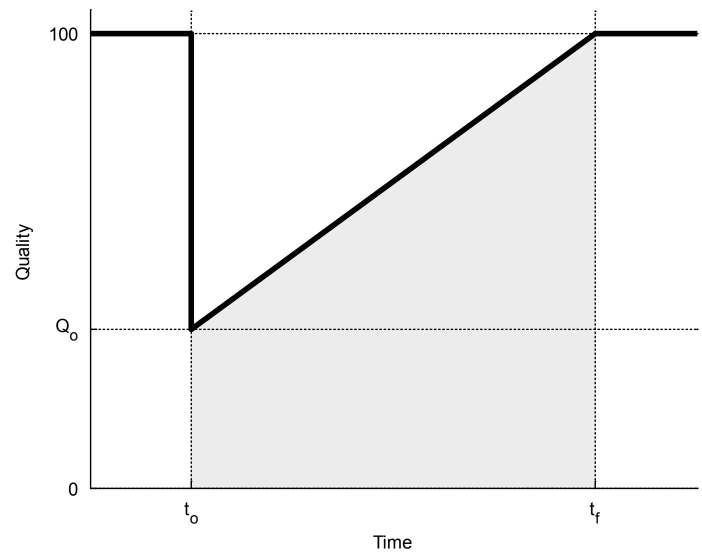

Figure 2: Resilience Triangle (adapted from Bruneau et al. 2003)

The concept of resilience applies to systems of different scales. At a broad scale is the resilience of a community. At this scale, system level considerations are paramount, and there are many complex interactions to consider, including non-technical considerations such as policies, procedures, and a variety of stakeholders. At this scale, we are concerned with the resilience of engineering systems such as power grids, transportation networks, water distribution systems, and the building stock as a whole. With adequate infrastructure design and emergency response plans, a community can be resilient even if some of the structures within the community fail. This is related to the risk categories in ASCE 7 (ASCE 2010) that attempt to capture the relative importance of different building types. Within this context, in their day-to-day practice, structural engineers focus on the resilience of a single structure. The focus is mitigating the losses due to the disaster, but it is also important to design in such a way that the losses incurred help a speedy recovery.

McAllister (2013), who reviews the history and present state of resilience concepts and summarizes research needs, provides a good source for additional information on resilience. The document identifies the following research needs (copied verbatim here):

- Identify technical gaps and research needs from reviews of past disaster events and existing model codes and standards
- Define resilience terminology for the built environment to help communicate new concepts
- Develop guidance for community resilience planning
- Develop risk-based performance goals for resilient communities
- Develop tools and metrics to support quantitative technical assessment, policy development, and decision making
- Develop guidelines on risk-based performance goals and criteria for inclusion in standards for voluntary reference.

Relation between Disaster Resilience and other Aspects of Sustainability

Sustainability is a complex concept that touches on many aspects of the built environment. Resilience is just one consideration to achieve sustainability; many other traditional design considerations are also necessary (e.g., those presented by Kestner et al. 2010). For example, if a new LEED certified building with all the latest green features is rendered useless after a disaster, many resources will be wasted in reconstruction; this building cannot be considered sustainable. On the other hand, if a building is made robust with no consideration of its environmental and social impacts, then it cannot be considered sustainable either. However, a more robust structure may cause greater environmental impacts initially, but if it requires few repairs after subsequent disasters, its impacts over its service life may be lower than a less robust building that requires demolition and reconstruction. Both traditional sustainable design considerations and disaster resilience are necessary for sustainability. This is shown in Figure 3.

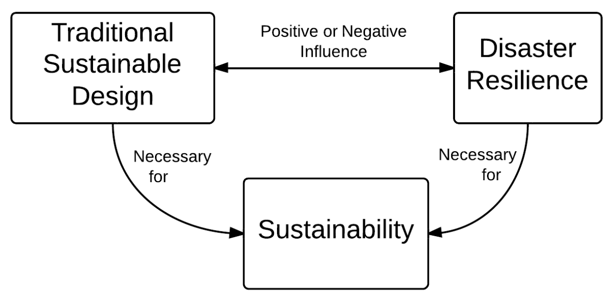

Figure 3: Relation between traditional sustainable design, disaster resilience, and sustainability

Figure 3 also shows that these two different areas can be related to each other in positive or negative ways. The wide range of different requirements can create situations where resilience and other aspects of sustainability are not compatible. This can occur, for example, in the following cases.

- A recycled material may not be as reliable as a traditional material
- An innovative design may not be as reliable as a traditional design
- A design that strives for minimum material use may be less redundant
- The added weight of a green roof may be detrimental to the seismic performance of a building

The Federal Emergency Management Agency (FEMA) has outlined other ways in which sustainable design features may affect the disaster resilience of residential structures (FEMA 2010b). Table 1 summarizes some of the connections between sustainable design and resilience. Many other connections between traditional sustainable design and disaster resilience could and should be explored. The design team should bear in mind the concepts summarized in Figure 3. Traditional sustainable design and disaster resilience can both influence each other in both positive and negative ways. Such considerations greatly increase the complexity of a design project.

An effective design process that considers both resilience and sustainability requires cooperation among many professionals, e.g., architects, structural engineers, mechanical engineers, contractors, and suppliers. The owner also plays a crucial role in decision-making. To bring these issues to the table, SEs must be included in the design process from the early design stage. Accomplishing this will likely require a marketing effort supported by professional societies such as SEI to highlight the value that structural engineers bring to an integrated design team during all stages of the design process.

Table 1: Some links between resilience and sustainability. The importances were determined from an informal poll conducted for this report of SEI Sustainability Committee members.

Design Consideration	**Importance** (H = High, M = Medium, L = Low)				
	For Sustainability	For Hazard Resistance			
		Fire	Seismic	Wind	Flood
Building geometry and orientation	H	L	H	H	M
Construction material type (steel, concrete, masonry, wood, etc.)	M	H	H	M	H
Design for adaptability and deconstructability	H	L	H	M	M
Flood-resistant design	M	L	L	L	H
Green roof	M	L	M	L	L
HVAC system	H	M	L	L	L
Operable windows (natural ventilation)	H	M	L	M	L
Reuse of structural components	H	M	M	M	M
Risk assessment	M	H	H	M	M
Safe room	L	M	M	M	L
Site and perimeter design	H	M	L	L	M
Structural durability	H	L	H	M	M
Structural system	M	M	H	H	M
Urban wildland interface (fire protection)	M	H	L	L	L
Use of recycled materials	H	L	M	L	L
Use of regional materials	M	L	L	L	L
Water (runoff) management	H	L	L	L	M
Window system	H	M	L	L	L

Natural Disasters and their Consequences

In 2011, the U.S. experienced 14 separate disasters, each with an economic loss of $1 billion or more, totaling $55 billion and surpassing the record set in 2008 (NOAA 2012). According to reinsurer Swiss Re, insurers lost at least $108 billion on disasters globally in 2011, the second-worst year in the industry's history. Only 2005, with Hurricane Katrina and other major storms, was more costly (AFP 2011). In 2012, there were 11 natural disasters costing $1 billion or more in damage, making 2012 the second highest year with billion-dollar disasters. Figure 4 shows the historical trend in billion dollar weather disasters.

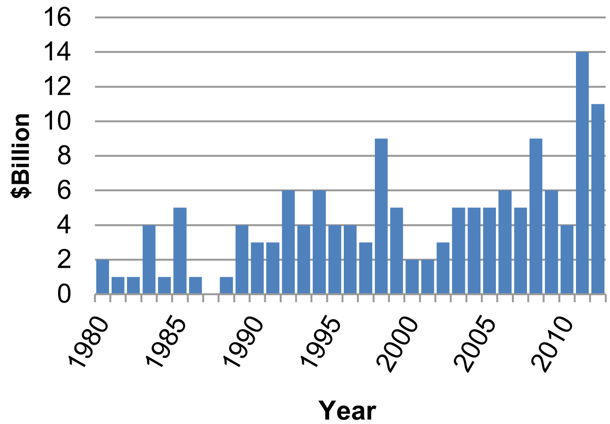

Figure 4: Billion Dollar U.S. Weather/Climate Disasters 1980-2012 (2012 Dollars)

Figure 5 shows the number of hurricanes in each decade and the corresponding increase in losses (similar trends exist for other types of disasters). The increase in losses can be attributed mostly population migration and increase in wealth. In the last several decades, population in the United States has migrated toward the coasts, concentrating along the earthquake-prone Pacific coast and the hurricane-prone Atlantic and Gulf coasts (CRS 1997). In addition, the economic value of possessions has increased substantially. While the high concentration of people in coastal regions has produced many economic benefits, this has also increased the consequences of natural hazards. Moreover, many elements of the aging infrastructure in these areas are highly vulnerable to breakdowns that can be triggered by relatively minor events.

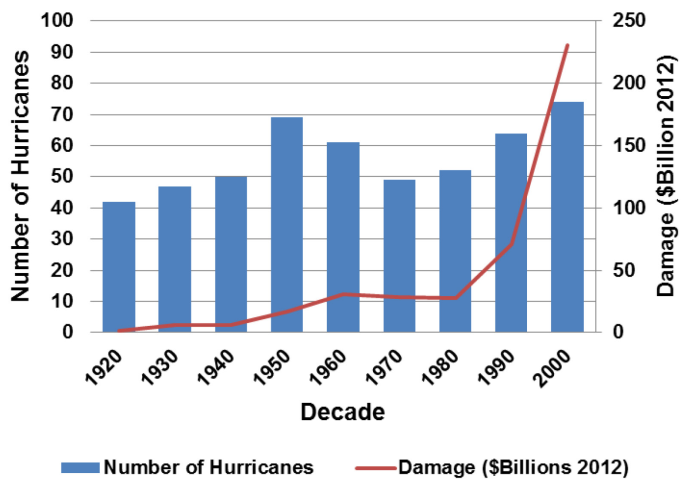

Figure 5: Number of hurricanes and damage by decade (Wunderground n.d.)

Climate change is also implicated in the rise in storm-related losses. The National Academy of Sciences (NAS 2012) states, "Impacts of climate change and degradation of natural defenses such as coastal wetlands make the nation more vulnerable." Larsen et al. (2011), writing on green buildings and climate resistance, conclude that climate change is already increasing storm intensity, raising sea levels, and accelerating coastal erosion, among other effects. They state, "The effects of climate change will likely be more extreme than what we have observed so far. With each additional increase in the global mean annual temperature, the severity of the effects is likely to worsen".

Despite the increased risk, there is strong evidence that hazard mitigation can be implemented successfully and with significant benefit. The Multihazard Mitigation Council (MMC) of the National Institute of

Building Sciences conducted an independent study on the effectiveness of government sponsored disaster mitigation activities (MMC 2005). The council quantified the future savings, in terms of losses avoided, for programs between 1993 and 2003. Savings included reduced property damage; business disruption; non-market damage (environmental damage to wetlands, parks, wildlife and historic structures); deaths, injuries and homelessness; and cost of emergency response (ambulance and fire service). The study found that the natural hazard mitigation grant programs funded by FEMA were cost-effective and did in fact reduce future losses from earthquakes, wind, and floods. The mitigation programs resulted in significant net benefit to society and potential savings to the federal treasury in terms of future increased tax revenue and reduced hazard related expenditures. The FEMA grant programs cost the federal government $3.5 billion from 1993 to 2003 but yielded a societal benefit of $14 billion. In other words, every dollar spent on hazard mitigation provided four dollars in future benefits.

Spending time and money up front to reduce the likelihood of loss during a natural disaster can bring significant benefits to owners and communities. These benefits are many and include lowering insurance costs, raising property values, providing security to residents, maintaining a consistent tax base, and minimizing the cost of disaster response and recovery. No community can ever be completely safe from all hazards, but resiliency planning gives communities the knowledge and abilities to protect themselves before and mend themselves after a disaster. Structural engineers play a vital role in resilient communities. To assist them in the effort, the following sections provide a critical review of resilience-related efforts and resources available to practicing structural engineers and related professionals.

GENERAL CONSIDERATIONS FOR RESILIENT DESIGN

Strategies for achieving resilient designs vary from prescriptive approaches to detailed analyses that include probabilistic assessments of the hazard and the resulting damage. The simplest approach is prescriptive. In a prescriptive approach, rules specify what the engineer must achieve and avoid in the design. These rules are similar to traditional code regulations, but with stricter requirements. For example, the rules may state an increased design load or additional detailing requirements. Prescriptive guidelines are built upon many assumptions about the nature of the hazard, the structural response, and the design objectives. When using a prescriptive approach the design professional must evaluate these assumptions against the objectives of the project. If the two are not consistent, a more detailed analysis should be conducted.

Kneer and Maclise (2008) highlight the importance of thinking beyond prescriptive requirements and provide examples of projects in which performance was an explicit consideration that led to improvements of code-base designs. Some of these examples are deterministic in nature. Other examples use probabilistic calculations that consider the likelihood of a disaster occurring, the likely costs of mitigation, and the expected benefits resulting from the mitigation efforts. In probabilistic approaches, design loads depend on probabilities of occurrence for events of varying magnitudes. Considering a range of possible event yields a hazard curve that describes the probability occurrence for different hazard levels. Structural performance can be assessed probabilistically to obtain fragility functions, which describe the likelihood of suffering a defined level of damage given an intensity measure for a hazard (e.g., wind speed or peak ground acceleration). An established methodology to estimate losses due to seismic events is available from FEMA (2012) as is a broader loss estimation methodology for a range of hazards (FEMA 2003a). The fragility functions can be paired with hazard curves to determine the probable losses during the lifespan of a facility (see, e.g., Comber et al. 2012). This approach takes into consideration a range of possible disasters of varying magnitudes and their respective probabilities of occurrence to gain a holistic understanding of the expected damage the facility might suffer to during its lifetime.

The design team must conduct a thorough cost-benefit analysis to balance increased costs[2] with improved performance resulting from structures that are more resilient. For instance, designing a structure to withstand the anticipated forces induced by a category V hurricane will generally require more materials and resources than a design that only considers a category III hurricane. Appropriate resilient design will consider the differences in materials and resources required for structures that are more robust and weigh them against the potential benefit gained in terms of added resilience. The probabilistic process discussed above can be repeated for varying levels of robustness in design to determine the optimum balance between additional materials required for construction and probable savings in damage during the facility's life.

As an example of a holistic design approach that takes into account the performance of all aspects of the facility, consider a hypothetical building intended for use as a manufacturing facility in a high seismic zone. This building contains partitions, many mechanical, electrical, and plumbing (M/E/P) components, and large amounts of equipment. These components are damaged by different phenomena. The M/E/P components and equipment are damaged when the structure they are attached to accelerates too quickly. The partitions, on the other hand, are attached to two adjacent levels in the structure and will be damaged

[2] A higher-performing structure is not always synonymous with additional materials and construction expenses. In many cases, a more resilient structure can be realized for the same or even a reduced cost than a less resilient structure through appropriate performance-based design and careful attention to detailing in both the structure and the connections to nonstructural elements.

by relative displacements between those two levels (interstory drift). One might be tempted to focus on lateral strength & stiffness and use a stiff steel braced frame system because it uses less material than a more flexible moment frame. One should however consider the possibility that the stiffer braced frame system will generate lower drifts and higher structure accelerations during a given seismic event than the comparable moment frame system. Given the sensitivity of a majority of the nonstructural components and contents to damage induced by floor accelerations as opposed to interstory drifts, the braced frame system will likely cause a much higher level of overall damage to the building in a major event. Although the moment frame system may require a larger initial investment in materials and resources, consideration of the potential savings due to reduced damage to building components may reveal that this initial investment will lead to lower expected lifetime impacts. To achieve overall benefits through resilience strategies it is important to considerer these tradeoffs holistically to find a solution that protects the whole system efficiently and effectively.

TECHNICAL GUIDANCE FOR RESILIENT DESIGN AND DISASTER MITIGATION

The National Institute of Building Sciences (NIBS 2013) reminds us that

> Unsustainable development is one of the major factors in the rising costs of natural disasters. Given that hazard mitigation is at the core of disaster resistance, then, many design strategies and technologies serve double duty, by not only preventing or reducing disaster losses but serving the broader goal of long-term community sustainability.

This section summarizes and evaluates some of the existing programs that can aid structural engineers in reducing disaster losses and thereby promoting sustainability. Depending on location, many disasters can threaten a facility. These include natural disasters such as earthquake, wind, flood, and wildfire as well as deliberate attacks on structures. This section begins by describing general, multi-hazard programs and then describes programs that are limited to one or a few hazards.[3]

From a policy point of view, disaster mitigation programs are divided into voluntary or mandatory. In voluntary programs, communities or owners choose to implement programs to reduce their risk from natural disaster. Alternately, mandatory programs seek to enforce standards through law. In the same way that governments adopt model codes as law (e.g., International Building Code), mandatory mitigation programs provide language for governments to adopt as law with the objective of reducing losses from natural hazards. One program discussed below, High Performance Building Requirements for Sustainability, aims to enhance model codes. The rest of the programs are voluntary. From a technical point of view, disaster mitigation programs are divided into performance-based or prescriptive, as discussed in the previous section. Despite the superiority of a performance-based approach, many of the programs discussed are prescriptive. This is due to the relative simplicity of prescriptive approaches, as well as their likelihood of being adopted by owners or governments.

Comprehensive, Multi-Hazard Programs

FORTIFIED for Safer Living and Safer Business

The Insurance Institute for Business and Home Safety (IBHS) has created a voluntary program called FORTIFIED for Safer Living and Safer Business (IBHS n.d.). The goal is to incorporate improved techniques into construction to provide a greater level of protection against a variety of natural hazards. IBHS is a not-for-profit applied research and communications organization supported by the insurance industry. Their focus is to reduce residential and commercial property losses due to wind, water, fire, hail, earthquake, ice, and snow. The programs also address other business continuity issues such as interior fire, burglary, lightning protection, and electrical surge.

IBHS promotes the need for strong, well-enforced building codes but also realizes that building codes offer minimum life safety standards and often do not have the necessary provisions to provide disaster resilience. For that reason, IBHS developed its FORTIFIED programs. The programs provide specific design criteria and the necessary construction and inspection oversight to ensure resilient structures that are designed to standards beyond the code.

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[3] Due to space limitations some programs are not discussed in this report. A comprehensive list of programs and publications is provided by the National Institute of Building Sciences (NIBS 2013).

Over 250 homes have been designated as FORTIFIED since 2001. The program was tested by Hurricane Ike on the Bolivar Peninsula in Texas, in September 2008. Ten of the thirteen FORTIFIED homes survived a direct hit from Hurricane Ike, which included a 20 ft. storm surge. The FORITIFED homes were the only structures left standing for miles around because they were specifically designed and built to withstand extreme wind and water damage (IBHS 2009).

High Performance Building Requirements for Sustainability

The Portland Cement Association (PCA) is leading an effort to modify model codes in the interest of increased resilience. As described by PCA, "detailed criteria that combine functional resilience with the other key aspects related to the design and construction of green buildings are presented as a compilation of modifications to the International Code Council International Building Code … as High-Performance Building Requirements for Sustainability (HPBRS)" (PCA n.d.). HPBRS provides design recommendations in five main topic areas: service life, structural components, fire-protection components, interior components, and exterior components (see PCA 2010 for proposed code amendments). The following list provides a brief summary of the recommendations in HPBRS for buildings (excluding low-rise residential buildings). Some of these criteria are directly influenced by the structural engineer, some will influence the structural engineer's design, and some are less relevant to the structural engineer, but are presented for a full overview of the PCA functional resilience design recommendations. The term functional resilience is related to all three causes of reduced service life: deterioration, obsolescence, and disasters.

HPBRS required that buildings be designed to a minimum service life of 50 years. Although some components may have a lower design life, the 50-year requirement applies to structural components and any other components that are difficult or cost-prohibitive to replace during the design service life. A service-life plan provides the owner with decision-making information on what the overall maintenance cost will be based on the materials selected. Information on determining service life can be found in the Canadian Standards Association (CSA) standard for durability in buildings (CSA 2007).

For structural components, provisions are made for fire, flood, earthquake, snow, and wind loads as follows:

- For fire resistance, all structural load-bearing elements should have a minimum fire rating of 1 hour.
- For flood damage resistance, structural components should comply with ASCE 24 (ASCE 2005) as well as state building codes. Foundations located in Coastal Zone A should be designed to the same criteria as those located in Coastal Zone V. Levees and flood walls should not be considered flood protection when renovating or designing new buildings for resistance to flood damage. There are additional requirements, including compliance with Appendix G of the International Building Code (International Code Council 2012a).
- For seismic, in locations where the 0.2 second spectral response acceleration is 0.4 *g* or higher, HPBRS requires seismic loads that are 20% greater than that currently required by code. In the opinion of the working group, this requirement is inadequate, as it could lead to stiffer buildings and consequently, more non-structural damage and slower post-disaster recovery.
- For snow, buildings should be designed for 20% greater snow load than required by code.
- For wind, buildings should be designed for an increased basic design wind speed by 20 mph. Additionally, roof coverings, their attachments, and gutter attachments should comply with UL and FM standards. Storm shelters should be provided for all building occupants when design wind speed is 160 mph or greater (in hurricane- and tornado-prone areas). Storm shelters should be designed according to ICC 500 (International Code Council 2008).

Other requirements that can interest structural engineers are as follows:

- For fire protection, all buildings should have sprinkler systems, unless the occupancy category is low-hazard manufacturing (Type F) or storage (Type S). Fire separations should be rated at 2 hours and concealed spaces should have fire stopping and draft stopping. Areas of collection of recyclables should have enhanced fire protection.
- For moisture protection, HPBRS requires use of hard, smooth, non-absorbent surfaces where water is likely to be present during the use phase of the building as well as protection of any moisture-sensitive materials during construction.
- HPBRS also provides requirements for exterior components. For exterior fire damage resistance, when structures are located close to one another, such as in dense, urban areas, openings should be limited in size. In addition, combustible materials should not be used in exterior walls that are located close to other structures. For wildfire damage resistance, buildings should meet the requirements of the International Wildland-Urban Interface Code (International Code Council 2012b). For wind damage resistance, if located in hurricane- or tornado-prone areas, use of exterior cladding that is susceptible to wind damage is limited. Finally, for hail damage resistance, if located in moderate-to-severe hail exposure areas, use of exterior cladding that is susceptible to hail damage is limited.

Other Resources

High Performance and Integrated Design Resilience (multi-hazard, focus on security)

In 2009, the U.S. Department of Homeland Security (DHS) Science & Technology Directorate (S&T) created the High Performance and Integrated Design Resilience Program (DHS n.d.). The goal of the program is "to better prepare buildings and infrastructure to recover from human-caused and natural disaster events such as explosive blasts; chemical, biological, and radiological agents; floods; hurricanes; earthquakes, and fires". The program consists in publications and software for use by engineers and other building professionals. It pays close attention to blast and security issues, but addresses all hazards to some extent.

The program fosters an integrative approach to the design, construction, and operation of buildings and infrastructure. This approach incorporates resilience as one of the primary goals during design. Achieving such integration requires active collaboration, starting at the initiation of the project, among all of the team members involved in the design process. When the integrative approach is done well, the resulting facilities are more likely to be resilient, cost effective, resource efficient, durable, and high-performing.

The Science and Technology Directorate has developed a series of software tools and publications, called the Building and Infrastructure Protection Series (BIPS), to provide guidance on risk assessment and mitigation against various hazards. These tools emphasize strengthening and protecting critical infrastructure from the impacts of a terrorist attack. Objectives are to reduce physical damage to structural and nonstructural components of buildings and critical infrastructure, and reduce resultant casualties from impact events that include human-caused hazards (including explosive blast, and chemical biological, or radiological agents) and natural hazards (including floods, hurricanes, and earthquakes).

Some of the BIPS publications and tools (DHS n.d.) are:

- **BIPS 06/FEMA 426**, *Reference Manual to Mitigate Potential Terrorist Attacks against Buildings, 2nd Edition*–provides architects and engineers with an updated version of risk assessment techniques, a new concept on infrastructure resiliency, and identifies new protective measures and emerging technologies to protect the buildings, related infrastructure, and people.
- **BIPS 07,** *Primer to Design Safe School Projects in Case of Terrorist Attacks and School Shootings*, 2nd Edition–provides the design community and school administrators with the basic principles and techniques to design a school that is safe from potential physical attacks and, at the same time, offers an aesthetically pleasing design that is functional and meets the needs of the students, staff, administration, and general public.
- **BIPS 09,** *Urban Blast Tool*–quantifies the effects of blast in urban environments, including the influence of buildings on blast pressures propagating from explosions located in urban settings. The tool also quantifies the potential for these blast pressures to damage primary structural members and accounts for the sensitivity of several common building types to progressive collapse due to damage of key support members. The tool also evaluates the likelihood that blast pressures may damage equipment needed for Emergency Evacuation, Rescue and Recovery (EERR) operations.
- **BIPS 10**, *High Performance Based Design for the Building Enclosure*–provides owners, developers, and designers with a methodology to evaluate the benefits of increasing performance of key building attributes to help them plan buildings that are resilient as well as energy efficient, durable, and sustainable. The Owners Performance Requirements (OPR) software tool has been made available to assist with this process (NIBS n.d.).

BuildingGreen (multi-hazard, focus on storm and energy interruption)

Alex Wilson, the founder of BuildingGreen, writes a blog with regular entries on the topics of green and resilient design. Wilson argues that consideration of climate change should influence structural designs. Wilson pays particular interest to energy interruptions and increased severity and frequency of storms. BuildingGreen and Environmental Building News have a library of references on resilient design and green design. The following are Wilson's suggestions on designing for greater resilience:

To improve storm resistance Wilson (2011a) suggests that buildings should be designed to more-stringent provisions, such as those listed in the Miami-Dade County Building Code. This code requires, for example, tie-down strapping or clips between roof trusses and wall framing. Wilson also suggests including safe rooms, or shelters, in hurricane- and tornado-prone areas. Wilson emphasizes the need to keep rain away from structures. Gutters, basement drainage, rain screens, adequate overhangs, damp-proofing, and downspouts are mentioned as solutions. With greater frequency of storms and more hardscape added during development, there is a greater need to manage stormwater. By increasing pervious surfaces and minimizing erosion, among other strategies, both localized flooding and the burden on our streams and rivers can be reduced.

Wilson also advocates for common-sense smarter design (2011b). If possible, buildings should not be built in areas prone to flooding, fires, and other disasters. For flood damage resistance Wilson suggests elevating living spaces above potential flood elevation (this working group has concerns with this suggestion in seismic areas). For moisture protection in flood-prone areas, Wilson suggests avoiding materials that are damaged by or trap moisture. Wilson also suggests optimizing square footage. Smaller structures typically use fewer resources in their operation, but are also easier to keep warm in the winter if the power happens to go out.

Wilson has also written on strategies to minimize consequences of energy interruptions (2012abc):

- Increasing insulation and thermal mass in envelope elements.

- Using triple-glazed windows, which, although expensive, can reduce energy consumption significantly.
- Keeping building envelopes tight to minimize energy loss.
- Using the sun to a building's advantage—through use of direct-gain, indirect-gain, or isolated-gain solar systems—reduces their dependence on energy.
- Orienting buildings with their long axis in the east-west direction maximizes solar gains in the winter and minimizes solar gains in the summer. Minimizing fenestration on the east and west faces of the building minimizes cooling loads in the case of a power outage in the summer months.
- **S**hading windows from direct sun in the summer months, when the sun is highest in the sky, minimizes cooling loads on a building.
- Lighter colored roof and wall coverings reflect more of the sun's heat, minimizing cooling loads.
- Operable windows can allow for natural ventilation in the cool evenings during summer months in the event of a power outage.

ATC-58 / FEMA P-58 (seismic)

Present-generation performance-based seismic engineering, e.g., ASCE 41 (ASCE 2006), expresses performance "in terms of a series of discrete performance levels identified as Operational, Immediate Occupancy, Life Safety, and Collapse Prevention. These performance levels are applied to both structural and nonstructural components, and are assessed at a specified seismic hazard level. Although they established a vocabulary and provided a means by which engineers could quantify and communicate seismic performance to clients and other stakeholders, implementation of present-generation procedures in practice uncovered certain limitations and identified enhancements that were needed" (FEMA 2012). FEMA-P58 (FEMA 2012) proposes a new seismic performance assessment methodology based on:

- the probability of experiencing an earthquake of specified intensity,
- the probability, given an earthquake intensity, of experiencing a specified response (e.g., accelerations or drifts),
- the probability, given a response, of experiencing a specified damage state, and
- the probability, given a damage state, of incurring specified consequences. The consequences of interest are repair costs, repair time, casualties, and unsafe placarding.

The total probability of different consequences is calculated by considering a range of possible earthquakes, responses, damage states, and consequences. This calculation is impractical to perform in a closed form or by hand. A computer software program, the Performance Assessment Calculation Tool (PACT), is provided as part of ATC-58, the precursor project to FEMA P-58, to assist with the calculations. The tool has an extensive database of structural and non-structural elements but allows significant user-specified input if necessary. The user needs to perform a seismic analysis independently and import the response parameters into PACT. The analysis can be a simplified linear analysis with dispersion factors applied to the response parameters. The most updated version of PACT is available from the ATC-58 website (ATC n.d.). A methodology to add environmental impact assessments to the seismic performance assessment procedures has been developed and may be implemented in a future project (Court et al. 2012).

U.S. Resiliency Council / CoRE Rating (seismic)

The US Resiliency Council (USRC n.d.) is a non-profit organization that has developed a rating system for evaluating the resilience of individual buildings and for communicating the results to decision-makers (Reis et al. 2012). The Certification of Resilient Engineering (CoRE) Rating uses the ATC-58 methodology and a rating system similar to the Earthquake Performance Rating System (EPRS) developed by the Structural Engineers Association of Northern California (Mayes et al. 2011). The CoRE rating system is reproduced in Table 2. It offers two tiers of ratings. One is a star based rating that considers safety, reparability, and functionality. The second is a simple certification that considers only safety. The US Resiliency Council hopes that their rating system will "become a standard for due diligence in real estate transactions and for quantifying the value of improved disaster resilience." This would help owners and developers recover investments made toward resilient design in the same way that LEED has allowed them to recover costs for sustainability-related improvements. The focus of the USRC is currently on earthquakes, but they plan to expand their efforts for wind and flood events.

Table 2: CoRE Rating

USRC CoRE Rating	Safety	Reparability	Functionality
*****	Safe	Loss <5%	Occupiable Immediately Functional < 72 hours
****	Safe	Loss <10%	Occupiable Immediately Functional < 1 month
***	Safe	Loss <20%	Occupiable < 1 month Functional < 6 months
Certified	Safe	Not estimated	Not estimated
Not Certified	Safety Hazard	Not estimated	Not estimated

REDi Rating System (seismic)

The Resilience-based Earthquake Design Initiative (REDi) Rating System is a framework for owners, architects, and engineers to implement a holistic beyond-code design, planning and assessment approach to facility resilience (Almufti and Willford 2013). The REDi ratings (Platinum, Gold, and Silver) establish objectives in the following categories:

- **Building Resilience**: Minimize expected damage to structural, architectural and MEP components through enhanced design
- **Organizational Resilience**: Contingency planning for utility disruption and business continuity
- **Ambient Resilience**: Reduce risks that external earthquake-induced hazards damage building or restrict site access
- **Loss Assessment**: Evaluate financial losses and downtime to meet resilience objectives (based on the FEMA P-58 methodology)

By establishing categories that are based on FEMA P-58 and that are easy to communicate to decision-makers, REDi is similar in many ways to the CoRE Rating. Table 3 illustrates the requirements in the loss assessment that must be met at the various levels. However, REDi is broader in scope, involving prescriptive design requirements that address different components of resilience to help owners and operators achieve their specific resilience goals. The most novel of these are the requirements for organizational resilience (Table 4). With this breadth in scope, REDi has the potential to engage owners and all building professionals in a coordinated effort to provide resilience.

Table 3: Requirements of the loss assessment component of the REDi rating system

Rating	Re-Occupancy	Functional Recovery	Financial Loss	Occupant Safety
Platinum	Immediate	< 72 hours	< 2.5%	Injuries Unlikely
Gold	Immediate	< 1 month	< 5%	Injuries Unlikely
Silver	< 6 months	< 6 months	< 10%	Injuries Unlikely

Table 4: Requirements of the organizational resilience component of the REDi rating system

Requirement	Platinum	Gold	Silver
Establish a resilience plan to identify risk drivers and mitigation options	Required	Required	Required
Provide continued operations of primary functions when utilities are disrupted	Required	Recommended	Recommended
Provide back-up of communications systems	Required	Required	Recommended
Contingency planning to reduce downtime due to 'impeding factors'	Required	Required	Required
Business continuity planning including supply chain risk	Required	Recommended	Recommended
Provide supply of food and water	Required	Required	Recommended

Storm shelters

Including a safe room built in a home, business, or community building can help provide excellent protection from injury or death caused by the dangerous forces of extreme winds and debris. Safe rooms can be designed to function as regular rooms so that they do not waste space; windowless rooms such as closets, gymnasiums, and storage areas are ideal for safe rooms. FEMA provides two guidelines to help designers assess risk of tornado and hurricane force winds and design storm shelters: FEMA P-320 (FEMA 2008b) and FEMA P-361(FEMA 2008a). Recently, the International Construction Code developed standards for the design and construction of storm shelters (ICC 2008). Although the building codes do not require storm shelters, these standards can be followed if an owner decides to build one.

Wind and Flood

There is significant guidance on flood resistant construction. Those interested in details can consult the following documents.

- ASCE 24-05, *Flood Resistant Design and Construction* (ASCE 2005) is referenced in the International Building Code.
- FEMA P-55 (FEMA 2011) is a two-volume publication primarily for design professionals that provides a comprehensive approach to planning, siting, designing, constructing, & maintaining homes in the coastal environment.

- FEMA P-499 (FEMA 2010a) consists of 37 fact sheets illustrating the National Flood Insurance Program (NFIP) regulatory requirements, the proper siting of coastal buildings, and recommended design and construction practices for building components, including structural connections, the building envelope, and utilities.
- FEMA 543 (FEMA 2007) is a design guide for improving critical facility safety from flooding and high winds.

FUNDING AND POLICY INITIATIVES FOR RESILIENCE

Funding and policy initiatives at the federal, state and local level could help provide incentives for communities and owners to build to disaster resilient standards. For example, reductions in insurance premiums can encourage communities to develop fortified structures and to enforce building codes and land-use management measures. Such reductions can be provided to all policyholders in the area based on the stringency of land-use regulations, building code standards, and inspection. The Federal Insurance Administration created such a community rating system in 1990 as a way to recognize and encourage community flood plain management activities. This model could be applied to other hazards as well. Government grants and legislation can also be effective in encouraging change. Legislation providing tax incentives (similar to energy efficiency incentives) for owners who build to a disaster resilient standard might be another way to encourage resilience. Structural engineers can help shape these policy programs by getting involved in political action through their local and national professional associations. Some examples of policy and legislation designed to encourage disaster mitigation are:

- The Housing and Community Development Act of 1974 authorized communities to use community development block grants to construct tornado-safe shelters in manufactured home parks.
- FEMA’s Hazard Mitigation Grant Program (FEMA n.d.a) provides grants to state and local governments to fund projects that provide protection to both public as well as private properties. Projects that are eligible under the program include acquiring and demolishing or relocating structures from hazard-prone areas; retrofitting structures to protect them from floods, high winds, earthquakes, or other natural hazards; and constructing residential and community shelters in tornado-prone areas.
- FEMA's Pre-Disaster Mitigation Program (FEMA n.d.c) provides funding for communities that have an approved hazard mitigation plan. Priority is placed on projects that address repetitive loss properties due to flooding but other projects such as safe rooms can be funded. Funding grant request for FEMA projects must come from state agencies tied directly to FEMA.
- FEMA manages the National Flood Insurance Program (FEMA n.d.b). Nearly 20,000 communities across the United States and its territories participate in the program by adopting and enforcing floodplain management ordinances to reduce future flood damage including building flood resistant homes and buildings. In exchange, the program makes federally backed flood insurance available to homeowners, renters, and business owners in these communities. Community participation in the program is voluntary. Flood insurance is designed to provide an alternative to disaster assistance to reduce the escalating costs of repairing damage to buildings and their contents caused by floods. Flood damage is reduced by nearly $1 billion a year through communities implementing sound floodplain management requirements and property owners purchasing flood insurance (FEMA 2003b).
- The Disaster Savings and Resilient Construction Act of 2013 (Congress 2013) would provide a tax credit when a structure receives a designation as FORTIFIED for Safer Living/Business. Building owners would be eligible for a tax credit if they built disaster resilient homes or buildings within a federally declared disaster zone up to three years following the occurrence of the disaster (up to $3,000 for residential property and up to $25,000 for commercial property). In addition, homeowners could reduce insurance costs because insurance companies would be able to improve the accuracy of their risk assessment. According to the Alabama Press-Register, an Alabama couple who retrofitted their home to meet resilient standards saw their annual insurance premiums reduced from $3,488 to $1,800 – a $1,688 yearly savings to the homeowner (Jumper, 2011).

- In 2013, the city of San Francisco signed into law the Mandatory Seismic Retrofit Program for Soft Story Wood Frame Buildings (City and County of San Francisco 2013a), which will lead to seismic strengthening of vulnerable soft story buildings[4]. Over 55,000 people live in these buildings, which also house 7,000 businesses and employ 2,000 people (City and County of San Francisco 2013b). The new law will be implemented over seven years, starting with a mandatory notice and evaluation period beginning in late fall, 2013. Buildings shown to have a soft story will be classified into four tiers with phased requirements for completing the work to meet current seismic standards (City and County of San Francisco n.d.).

[4] Wood frame, soft story buildings built before 1978 having five or more units and at least two floors over a weak story.

INCORPORATING DISASTER RESILIENCE WITH LIFE CYCLE ASSESSMENT

It was argued in the introduction that disaster resilience is an important component of sustainability. The National Institute of Building Science (NIBS 2012) concurs, "given that hazard mitigation is at the core of disaster resistance, then, many design strategies and technologies serve double duty, by not only preventing or reducing disaster losses but serving the broader goal of long-term community sustainability." However, just making the argument is not good enough. The connection between disaster resilience and sustainability has to be quantifiable. There is an ongoing effort among practitioners and researchers to develop methods and tools to do just this. It is important to remain aware of developments in this area, as it will likely become a more common consideration in structural design.

Life Cycle Assessment

The Life Cycle Assessment (LCA) methodology is a well-established framework that can be adapted for this task, although traditional LCAs are not conducted with disaster resilience in mind. The Life Cycle Assessment (LCA) methodology, as defined by the ISO 14040 standard (ISO 2006), is used to quantify and assess many possible environmental impacts, e.g., greenhouse gas emissions, energy used, water pollution, and many more. These impacts are considered from cradle to grave, e.g., from procurement of the basic construction materials, through the service life of the facility, to decommissioning. Different practitioners and researchers use the term LCA differently, some taking the term to mean "Life Cycle Analysis". While ISO 14040 limits LCA to environmental impacts, LCAs can be extended to include social impacts and economic impacts as well. The latter is usually referred to as life cycle costing. Tapia and Padgett (2012) review the life cycle costing literature as it relates to sustainability.

LCA is a mature and robust methodology. Numerous LCA studies have been performed for buildings and for infrastructure (Cole and Kernan 1996; Guggemos and Horvath 2005; Horvath and Hendrickson 1998; Junilla and Horvath 2003; Junilla et al. 2006). These studies provided insight to the environmental footprint of different structural and non-structural materials and systems. Various software programs are available for conducting LCAs and there are many professionals qualified to perform LCAs for the built environment.

One methodological distinction in LCA pertains to the way of accounting for environmental impacts. To determine impacts by the bill of materials (or process-based) method, one starts with a bill of materials, consults a database (called a life cycle inventory or LCI), performs an impact assessment for each material or product, and sums the impacts. Although precise, this method requires comprehensive databases that may be proprietary or simply do not exist. It is also not well suited to the conceptual design stage during which member sizes and arrangements are not known. A second method, called Economic Input/Output LCA (EIO-LCA, Carnegie Mellon University Green Design Institute n.d.), draws from national databases that quantify environmental impacts in various economic sectors as functions of dollars spent. While this method is less exact, it is not as sensitive to missing data and can provide estimates of impacts at the conceptual design level. Hybrid methods combining both approaches have also been proposed.

Incorporating Disaster Resilience

Although the LCA methodology is mature for buildings and infrastructure, it is not common practice to consider disaster resilience in such studies. None of the major commercial software programs do so, and the profession has only recently begun to discuss the subject. Nonetheless, all of the studies discussed next have found that consideration of disaster resilience can make a significant difference in the LCA results.

The most common approach is to introduce impact estimation into existing methods for seismic loss assessments. The goal of these methods is to provide decision makers with a range of metrics for each design option being considered. These metrics include casualties, damage, and business downtime as well as environmental impacts. While this approach does not fall strictly within the LCA methodology as defined by ISO 14040, it seems like the most appropriate for decision making in the context of buildings and infrastructure. There is also potential for these approaches to be used for durability threats and multi-hazard scenarios.

There is significant uncertainty in conducting LCAs that include disaster resilience in the calculations. In addition to uncertainty in the impact data used for any LCA, there is additional uncertainty in the characteristics of the disasters, the damage that may result from the disasters, and in the consequences of the damage. These sources of uncertainty must be acknowledged when conducting an analysis of this type. Despite the uncertainty, useful results can be obtained, especially when comparing options instead of seeking exact results for any one option. Even during the early design stage, several design options can be compared with a goal of selecting the structural systems (and related architectural and mechanical, electrical, and plumbing systems) that minimize the impacts relevant to the project.

Details of Research and Development Efforts

Details are provided next for specific efforts to combine LCA and disaster resilience. These are divided into efforts from FEMA& ATC, private practice, and academic researchers. Approaches by private practice and FEMA & ATC have focused on a common set of tools that are familiar to practioners in earthquake engineering. In contrast, academic research has focused on frameworks applicable to any damage type and customized use of fundamental statistical methods.

FEMA and ATC

The Federal Emergency Management Agency (FEMA) contracted with the Applied Technology Council (ATC) to initiate the ATC-86 project in the spring of 2011 to make recommendations for including environmental impacts in the FEMA P-58 seismic performance assessment methodology. The ultimate project objective is to add environmental impact assessment capability to the FEMA P-58 methodology so that environmental impacts can be calculated in parallel with costs and other consequences of earthquakes on individual buildings at specific sites (Court et al. 2012).

The resulting report outlines a two stage developmental effort consisting of a preliminary EIO-LCA based procedure then a detailed process-based LCA procedure to be incorporated into the FEMA P-58 Performance Assessment Calculation Tool (PACT) so that probability distributions of environmental impacts of earthquakes on buildings can be assessed and reported.

The FEMA P-58 methodology uses sophisticated probabilistic seismic performance assessment procedures to calculate consequences of earthquakes. The first step in the methodology is to assemble a detailed building model to represent both the structural and non-structural systems and their fragility functions (defined on page 8). The next step is to consider a range of seismic hazards or specific scenario earthquakes and integrate the predicted seismic responses with the building fragility model to generate probabilistic estimates of damage, repair, and cost consequences. The modification to FEMA P-58 is to use these estimates to assess the probable range of environmental impacts. These are reported in terms of multiple impact metrics that include global warming potential. The methodology is planned to provide detailed environmental impact assessments of probable earthquake damage that can then be integrated into full-building life cycle assessments. Whereas the existing EIO-LCA procedures are typically envisioned as providing tools for preliminary planning and comparisons, the FEMA P-58 methodology promises a tool for assessments that are more detailed and are thus useful for comparison of specific design alternatives later in the design process.

Private Practice

Degenkolb has developed an analysis methodology called Environmental Impact Seismic Assessment (EnvISA; Comber et al. 2012). EnvISA pairs a seismic loss assessment with LCA data to determine the expected environmental impacts of repairing a seismically damaged building. Impacts are calculated from single event scenarios (a deterministic approach) or from a wide range of hazards that may occur over the life of the building (a probabilistic approach). Seismic losses are estimated using a customized procedure based on HazUS, a software program produced by FEMA to estimate losses due to natural hazards (FEMA 2003a). Degenkolb has extended the methodology used in the HazUS single-building seismic module to enable analysis of unique building systems such as base isolation and viscous damping or of unique characteristics of existing buildings when assessing seismic retrofit strategies. Environmental impacts, measured in terms of global warming potential greenhouse gasses, are estimated using a hybrid EIO-LCA database that Degenkolb developed in conjunction with a specialized LCA consulting firm.

The EnvISA approach is approximate due to its use of the HazUS-based seismic assessment procedure and the national average EIO-LCA data. This approach is not suited for assessing the potential impacts of detailed changes in a design. It is however well suited for a comparative analysis of general building system types and seismic design strategies during the early phases of a project before any details are developed. An analysis can be easily run during these early phases to provide information on which general approach might be best suited to the project's lifetime impact objectives. EnvISA is proprietary, not being developed further, and there are no plans for releasing it to the public.

Skidmore, Owings & Merrill (SOM) has developed a similar methodology and software called the Environmental Analysis Tool (EA Tool) to calculate the embodied carbon of structural systems (Sarkisian et al. 2012). The Environmental Analysis Tool considers probable seismic loss through assessments of traditional and non-traditional seismic force resisting systems. Embodied carbon data are obtained from several public databases. In preliminary design stages, the Environmental Analysis Tool can produce results with just five user inputs: number of stories, average area per floor, structural system, expected design life, and site conditions that determine wind and seismic loads. For use during more advanced stages of design, the Environmental Analysis Tool allows the user to modify all parameters for detailed carbon accounting, e.g., travel distance of aggregate. The algorithms of the Environmental Analysis Tool are described in its user manual (SOM n.d.). The EA Tool has been used on hundreds projects at SOM. Since its public release, it has also been employed by numerous practitioners and researchers outside of SOM. Although both EnvISA and the Environmental Analysis Tool are applied to buildings, the same methodologies could be applied to infrastructure.

Academic Researchers

Several academic studies have also focused on merging environmental accounting with seismic loss assessments. Many of these efforts are similar to those already discussed in their overall methodology. The various efforts involve detailed structural models and probabilistic modeling of a hazard such as an earthquake to obtain probabilities of different levels of damage. These different damage levels can then be tied to any of a number of economic, social, or environmental impacts. Using this approach, Itoh et al. (2006) considered CO_2 emissions for a steel bridge and Russell-Smith and Lepech (2009) studied primary energy and global warming potential of fiber reinforced polymer (FRP) and steel jacket bridge retrofits. In addition to presenting a particular methodology, these studies also yield concrete results on specific types of structures. For instance, Itoh et al. found that CO_2 emissions due to lifetime seismic risk were 26% of construction costs. Russell-Smith and Lepech examined several different earthquake magnitudes and damage states and found that in all cases the impacts due to the FRP retrofits were lower.

All of the efforts discussed so far are limited to seismic hazard. It is of interest to extend the concept to include durability, other single hazards (such as hurricane), and to multiple hazards (such as hurricane with flood or corrosion with earthquake). Flint and Billington (2011) approached durability problems with a proposed framework called Performance-Based Durability Engineering (PBDE). In its overall structure, this is the same as performance-based earthquake engineering. Flint and Billington describe in broad strokes a series of four linked analyses for a concrete structure exposed to chloride. The first analysis stage, exposure analysis, determines the characteristics of chloride exposure from the environment. Deterioration analysis follows, in which the rate and manner of deterioration are calculated. The repair analysis stage determines the necessary remediation efforts and the materials expended to make the repairs. Using the results of this analysis, any of a number of impacts (including economic, environmental, and social) can be determined during the impact analysis stage.

Few researchers have addressed multi-hazard scenarios. Tapia et al. (2011) examined a multi-span bridge under seismic impact with potential corrosion due to marine exposure. Tapia et al. introduced a family of fragility functions that depend on time-dependent deterioration. Using this approach, they were able to issue recommendations on the best repair procedures taking cost, energy, and CO_2 emissions into consideration. Rodriguez-Nikl et al. (2012) proposed a framework for comparing the environmental impacts of a structure under any multi-hazard scenario (including durability concerns such as corrosion). The method focused on the idea of "functional equivalence", which is defined within the ISO 14040 LCA methodology and which refers to comparing options that have equivalent function. Using safety as the measure of functional equivalence, structural reliability methods were used to develop design options with the same probability of failure. Having established options with the same probability of failure, a standard LCA was conducted to determine environmental impacts. Rodriguez-Nikl et al. applied the method to a concrete bridge exposed to earthquakes and chloride due to marine spray. They measured energy use, greenhouse gas emissions, and virgin aggregate use in a bridge using various concrete mixtures: with ordinary cement, high volumes of fly ash, and recycled aggregate. Considering disaster resilience had a significant influence on the LCA results in all cases. In some cases the influence was detrimental and in others beneficial.

All studies demonstrate that disaster resilience must be considered to obtain an accurate estimate of environmental, social, and economic impacts of structures on the environment. The academic studies are more general and make use of fundamental concepts more directly. The efforts from private practice and professional committees use tools more common to practioners and are well suited for drawing rough conclusions for structures early in the design process. While the Environmental Analysis Tool is available to the public, its results are only starting to be validated by the structural engineering community. It should be considered a work in progress. The ATC-86 project is defined but not completed. For everyday practice, the structural engineer currently has no fully vetted options for quantifying the influence that disaster resilient design has on lifetime impacts. However, over the next decade it will likely be ever easier to perform these calculations. Given the rising prominence of sustainability as a design consideration, engineers able to address these concerns will be increasingly in demand.

RECOMMENDATIONS

If you are interested in doing more to support disaster resilience and sustainability, consider taking action in the following ways:

1. **Become better informed**. Reading this report is an important first step. Use the reference list and links provided to research initiatives that are important to your areas of practice.
2. **Participate in the code adoption process** in your state and/or community. Many cities adopt amendments to state codes. Engineers can look to PCA's High Performance Building Standards for Sustainability for model language. Encourage your local building authority to add their requirements even if your state does not. Look beyond just building codes. Participate in all aspects of urban planning that limit your ability to provide resilient and sustainable designs.
3. **Support legislation** that requires or provides incentives for resilient construction. Write your representatives to support legislation. Encourage your structural engineers association to advocate for legislation.
4. **Educate owners** regarding the importance and value of resilient construction. Be committed to the importance of resilience when setting project objectives. Be in the discussions as early as possible.
    a. Many owners are willing to spend money and resources on obtaining LEED certification. When working on a LEED project, suggest an innovation in design credit or pilot credit for resilient design. Remind owners that resilient design safeguards the investment they made in obtaining LEED certification.
    b. Programs such as FORTIFIED, CoRE, and REDi offer a similar concept to LEED: a certification for leading edge design. As these rating systems become fully developed, they will become standard practice that owners and occupants expect. Encourage owners to seek certification.
    c. Discuss performance-based design (PBD) directly with owners. Frame PBD as a methodology for achieving a level of performance defined by the owner to meet their specific needs. Bring case studies to show the owner how they can benefit from resilient design.
5. **Advocate with insurance companies and portfolio managers**. If insurance companies can provide decreased costs to owners with better performing buildings, this may help sway owners to invest in higher performance. Portfolio managers may decide to take out less insurance if they invest in making the buildings more resilient.
6. **Advocate with ASCE, SEI and other professional organizations** to raise the profile of structural engineers. It is difficult for individual structural engineers to effect change. Professional organizations can market the value that structural engineers bring to all stages of an integrated design process.

AFTERWORD: RESILIENCE AND SUSTAINABILITY IN DEVELOPING COUNTRIES

The rest of the report has considered sustainability and disaster resilience with emphasis on the United States and other developed countries. In this afterword, we discuss the topic through the lens of developing countries. The main goals of this section are to share important considerations for getting involved in and lessons learned from projects in developing countries. Some of these lessons are also relevant to projects in developed countries. These are drawn from the direct experience of working group members with involvement in developing countries. Concluding this section are short descriptions of organizations involved in such work for those interested in getting further involved.

In developing countries, several major issues restrict the ability to build for sustainability and resilience. These include lack of capital, lack of natural resources and raw materials, lack of manufacturing infrastructure, inadequate education, non-existent or ineffective building standards, and lack of modern construction experience. Often times, solutions that work in developed countries will not work and may even be detrimental when attempted in developing countries. When designing for resilience and sustainability in developing countries, one must think creatively, outside the bounds of regular practices in developed countries. Often, technological advances cannot be used because there is little infrastructure to support their implementation. One must use local knowledge and resources. The concept of the triple bottom line is useful here. Social responsibility and economic viability are equally important to environmental stewardship; without knowledge of local economies and communities, striving for environmental stewardship can cause damage to the other two. Because of these differences, the following considerations are relevant to those who are becoming involved in projects in developing countries:

- How can new or modern engineering practices contribute to (or harm) the local economy?
- How can the design support and reinforce existing cultures of local communities?
- Can we learn from and expand on vernacular construction techniques, thereby lowering the technical and economic barriers?
- Does existing local labor support the construction typology, or is a new construction industry needed?
- What local resources are available and adaptable?
- Can materials be introduced to create new local economies or drive existing economies?
- How can construction processes minimize environmental impact and affect communities positively?

While all countries, communities, and projects differ in important ways, the following solutions may likely be relevant to new projects in developing countries. Some of these ideas can be used beneficially for projects in the United States and other developed countries.

- **Identify regional weather patterns and research the local history of natural disasters** as a means to understand prevalent impacts or future events that may help guide the building design and construction process.
- **Use locally available materials** to enhance the economical, viable, and replicable aspect of new construction rather than imposing the use of commercial, imported, or advanced materials that may not be available in the region.
- **Understand the local code policies and procedures**. Are standards not being successfully followed or mandated? What are the intentions of this code and how can the codes support the design of the building? Be mindful and respectful of existing practice and policies that may or may not apply to the country's existing codes or the familiar codes such as the International Building Code.

- **Build upon local construction techniques**, skillsets, and economies to build a stronger, fiscally sound building industry for the future. Avoid making assumptions about the means and methods by which the structure will be built.
- **Identify materials of appropriate strength** that are locally available and can be procured regularly at an expected quality.
- **Consider performance-based design**. The structure's level of importance should dictate the required level of performance for a given design event.
- **Tailor building geometries to simple forms**, avoiding significant vertical or horizontal irregularities that create vulnerabilities in the building structural system during disasters.
- **Create redundancy** in the design of the structural system, allowing for alternate load paths down to the foundation to avoid a progressive collapse if a structural element is compromised during a disaster or if construction techniques have not met a high standard.
- **Consider using locally prefabricated structures** or components, e.g., wall assemblies that can resulting in higher quality construction because of controlled fabrication matched with quick on-site assembly.
- **Provide for quality assurance** in design and construction by employing trained, third-party inspectors.

Gryc (2012) addresses many of these issues in her description of a *pro bono* project by Arup to design a kindergarten in Ghana. Arup used a systematic approach called ASPIRE (A Sustainability Poverty and Infrastructure Routine for Evaluation). As Gryc describes it:

> The key to this development design approach is to have sustainability and resilience at its heart. In developing nations sustainability should focus on affordability, buildability, replicability, durability and structural integrity and safety. The success of this project also relied on effective project management, liaison with the Government departments, and building relationships with district authorities and communities.

Haiti suffered a devastating earthquake in 2010 with over 300,000 deaths in large part due to inadequate construction methods. Kijewski-Correa et al. (2012ab) made several post-disaster trips to Haiti. Their experience led them to similar conclusions. They argue strongly that importing practices from developed countries without regard to local needs and abilities will result in permanent dependence on foreign aid. They developed a paradigm for guiding reconstruction in Haiti. Called the "empowerment model" this paradigm emphasizes resilience, use of existing local capacity, use of local and affordable materials, and cultural acceptance of any proposed solution.

Individuals can get involved in volunteer efforts in developing countries through organizations such as Architecture for Humanity (AFH n.d.), RedR (n.d.), and Engineers without Borders (EWB n.d.). Cameron Sinclair and Kate Stohr founded Architecture for Humanity in 1999. Their goal was to bring design services to deserving communities while also attempting to find compelling architectural solutions to our world's most pressing humanitarian crises. Since its inception, AFH has led the way in promoting socially conscious architecture. The organization has teams deployed around the world. Current locations include Haiti, India, Brazil, Gaza, Iran, Thailand, China, Afghanistan, and the United States. Each team's effort is part of a long-term reconstruction plan that includes design and construction services, training in sustainable building techniques, providing consumer awareness and construction bid opportunities. Through educational forums, community design-build workshops and local partnerships, they hope to promote better building techniques with the support of local economies in mind. Topics addressed include Disaster Reconstruction, Housing Development, Community Growth & Development, Basic Services & Materials, Politics, Policy & Planning including peace & security. RedR (Register of Engineers for Disaster Relief) is an international charity that coordinates the deployment of skilled engineers and other professionals to locations where they can have most impact in emergencies. Current locations include Australia, India, Lanka, Malaysia, New Zealand, and the UK. With over 12,000 volunteers of various professions, the US chapter of Engineers without Borders has worked on over 350 small-scale infrastructure projects in over 45 developing countries. Their main goal is to help provide the fundamental human needs (clean potable water, sanitation systems, energy, agricultural development, etc.) to various communities through practical and sustainable engineering methods while considering the local socio-economic conditions and long-term viability of these projects.

Other opportunities for action can be found through firms and professional organizations through *pro bono* projects. For example, the U.S. Green Building Council (USGBC) collaborated with the Clinton Global Initiative (CGI) to spearhead an effort to design a LEED certified orphanage in Haiti as part of the rebuilding effort following the earthquake in 2010. The architectural firm HOK designed the orphanage (USGBC n.d.). Not open to individual membership, the goal of the Clinton Global Initiative is "turning ideas into action" by bringing together global leaders to create solutions to the world's pressing issues. The group's main themes are divided into "tracks," three of which are relevant to resilience and sustainability in the built environment: built environment, environmental stewardship, and response & resilience (CGI 2014).

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