Role of Materials Selection in the Resilience of the Built Environment

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Abstract

The resilience of U.S. communities, defined as the "ability to withstand and recover rapidly from disruptive events," is directly dependent upon the ability of the built environment to maintain and support the functions upon which modern society relies. The built environment includes both buildings and infrastructure systems. Buildings are important to the extent that they provide critical services (e.g., hospitals, police stations, and mercantile/office buildings). Infrastructure systems include the physical networks, systems, and structures that make up transportation, energy, communications, water, wastewater, and other systems that support the functionality of community social institutions. As local decision makers consider resilience, choices often involve cost-benefit decisions among materials with differing initial and lifetime costs, as well as differing performance characteristics. This paper will describe the important role that materials science plays in enabling informed local decisions for resilience, as well as identify knowledge gaps, such as the service life of the materials designed for new construction or system repair.

Keywords: Materials, community resilience, material selection, durability of materials, infrastructure

Introduction

Resilience has emerged as increasingly important consideration in community preparedness. Community resilience is defined as the ability of a community to prepare for anticipated hazards, adapt to changing conditions, and withstand and recover rapidly from disruptions (PPD21, 2013). While resilience is a national goal, the U.S. also has a critical need to invest in buildings and infrastructure systems (ASCE, 2013) (NSTC, 2005). As shown in Figure 1 (NIST, 2015), a community cannot be fully resilient without considering the highly interdependent elements of buildings and infrastructure, along with the critical role they play in supporting the social functions. The left circle in Figure 1 shows the functionalities and services needed by a community (such as health care, public safety, and economic activity), while the right circle shows how they are supported by the built environment. Social functionalities are generally expected to operate fully under normal conditions, despite the constant challenge of deterioration and aging of building elements and infrastructure systems exposed to routine weathering conditions. Social functions are also expected to be at least partially functioning and restored quickly after major acute hazards such as earthquakes, floods, hurricanes, or tornados. These expectations define community resilience goals.

According to Francis (Francis, 2014), the resilience of a system is composed of three capacity components: 1) absorptive, 2) adaptive and 3) restorative. This is similar to the PPD 21 definition. Obviously, the community cannot recover unless the infrastructure is viable and operational. This would imply that buildings, roads and bridges are still standing and operational.

Buildings comprise a major segment of the built environment, and include private assets such as residences, stores, and office buildings, but also public buildings such as hospitals, government buildings, and schools. In order to support the corresponding social functions (shelter, commerce, or healthcare, e.g.), buildings need to do more than simply remain standing – they should be constructed in a way that the envelope protects occupants from wind, rain and projectiles. Buildings, however, are also dependent upon other segments of the built environment. A building without water, electricity or gas, sewage, or communications (e.g. telephone, internet) would not be able to provide full support to the intended social functions.

Fig. 1. *The social functions of a community define the functional requirements of a community's buildings and infrastructure systems. (NIST, 2015)*

Operationalizing the goals of community resilience typically involves decisions of two primary types: policy decisions and design/material decisions. Policy decisions may include, but are not limited to, community land use regulations to prohibit construction in highly vulnerable areas or corporate policies to establish alternative site operational capabilities. Design and material choices, the focus of this chapter, can include decisions to resist design level events (e.g., selecting between reinforced concrete and steel for structural framing or considering ground motions in the specifications for underground water pipes).

Key to the design/material decision is a science-based understanding of the performance of various construction materials and engineered systems subject to a range of acute loads (e.g., winds, earthquakes, fires, or water intrusion), as well as their long-term performance subject to the routine, yet relentless forces of weathering (e.g., ultraviolet (UV) radiation, freeze-thaw, relative humidity, deicer salts, or cyclic thermal expansion and contraction). A helpful analogy might be the difference between catastrophic fracture of a steel bar under sudden tensile loading vs. failure under many sub-critical fatigue cycles. The ability to predict the service life of different materials and systems with reasonable certainty enables decision makers in a community to capture the benefits of various alternatives, and compare those benefits to differences in cost.

Calculating service life is not only a function of specifying the material and assessing the service environment (both weathering and acute loads); the service life of a material or system also depends on the degree of maintenance and repair committed to the system. Life-cycle analysis considers the full lifetime costs and benefits, from initial capital costs, to maintenance and repair costs, as well as externalities and indirect costs/benefits.[1] See Gilbert, et al. (Gilbert, 2015) for a comprehensive discussion of the economics of decision making in community resilience planning.

In addition to enabling the resilience of a community, many decision makers will also consider the sustainability of the materials. Sustainability is defined (Lounis, 2016) as a structure that is "meeting needs of the present without compromising the future," in other words, "sustainable or green systems consider environmental impacts for the initial design and subsequent rehabilitation choices." Sustainability has significant complementary characteristics to resilience; notably, both concepts require the ability to accurately assess the expected service life of a material or system, which will incorporate repair and maintenance during normal operations, as well as recovery from a disaster. However, sustainability adds additional considerations to the resilience-based concept of service life by assessing the environmental impact of raw material selections (before), impact on environment while in-service (during), and the recyclability of the products as the end of service life is reached (after).

Unfortunately, validated tools needed for science-based decision making to assess esiliennce are not available, hindering the ability of the community to develop a comprehensive plan for resilience.

Role of Materials Selection in the Resilience of Infrastructure

For a structure to be operational, sustainable, resilient, and possess a desired service life and life cycle cost, all of its essential components must have the required properties. The common denominator of any of the components is the materials selected to construct them. Civil

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[1] Externalities are costs or benefits that impact a third party that is not part of the direct decision to implement a given strategy and may be either positive or negative. For example, a more resilient bridge may also have a positive externality of reducing greenhouse gas emissions from improved traffic flow. Indirect costs/benefits are those costs or benefits that accrue during all phases of a hazard event and during business-as-usual circumstances. For example, an indirect benefit of more resilient electrical infrastructure may include a reduction in business interruption losses due to non-hazard-related power outages (Gilbert 2015).

engineers have been constructing infrastructure for a long time and they are very good at ensuring the structure is standing and operational the day of the grand opening. Often, the effect of material aging is too uncertain to allow an accurate service life prediction to be considered during the initial design. Further, structures do not come with a maintenance manual, rendering planned repair difficult.

An otherwise great design composed of poorly selected or constructed materials may lead to materials failing too soon, causing the structure to either be repaired or non-operational. In this case, both the service life and the resiliency (Schmeida, 2016) of the structure would be compromised. On the other hand, if material selection is adapted to the environment (normal exposure and episodic or acute hazard events) and the expected usage of the structure, then the whole structural element would be more resilient and sustainable.

Consider an existing hospital that has successfully provided healthcare to a community for years that is exposed to a severe storm event. Underground cables providing electricity to the building may short circuit due to damage to the outer insulation caused by chronic deterioration of the insulation coming into contact with groundwater; glass of the windows may be shattered due to winds which carry loose aggregate from a nearby roof; roads may be impassable due to undermining of the road base from storm runoff. With each of these failures, the hospital may be rendered inoperable until repairs are completed. With limited electricity from emergency power sources, life support and other safety systems likely would not be operational; broken windows allow rain and other debris to enter the building and compromise the hospital environment; impassable roads prevent doctors and nurses from reporting to work and ambulances from delivering patients. The materials selected for each component (insulation for electrical cables, glass for the windows, or road sub-surface materials) can contribute to the loss of one or more supporting systems, and, ultimately, loss of the function of the building. From the perspective of the building code, however, since the hospital structure remained standing, the building met the minimal criteria of life safety. This scenario occurred in 2005 after the Hurricane Katrina and Rita. The Medical Center of Southeast Texas in Port Arthur closed because wind-driven rain penetrated in through the waterproofing around the windows that remained intact. The structure of the hospital had no damage but all the interior walls needed to be replaced due to mold (Cauffman, 2006). Resilient structures go beyond the life safety objectives of the building code and consider the full interconnectedness of supporting systems in delivering the social function of the structure to the community.

Another example was falling pieces of concrete in the Washington, DC subway system that closed a station in 2016 (Washington Post, 2016). After two days of investigation, it was determined that there was no structural damage, but repair needed to be conducted, by replacing the fallen pieces and securing the rest of the concrete structure. In this case, the Metro station was not resilient due to loss of functionality of one station for at least two days due to a material failure, the concrete.

NIST Community Resilience Planning Guide and Performance of Materials

The NIST Community Resilience Planning Guide (NIST, 2015) describes a six-step planning process (Figure 2) that helps a community develop a customized resilience plan by including all relevant stakeholders, establishing community-level performance goals, and developing and implementing plans to improve overall resilience. Most importantly, this approach focuses on the roles that buildings and physical infrastructure systems play in assuring social functions resume after a hazard event (Figure 1). Ultimately, the performance of the built environment is directly related to the selection of materials. As discussed below, successful navigation of the six steps requires application of knowledge about various materials and their performance under service loads and acute loads:

- Step 1, *Form a Collaborative Planning Team.* Among many others, key planning team members may include experts with knowledge of material performance, including those representing local government (e.g., buildings, emergency management, or public works departments) or representing entities responsible for operating or managing infrastructure systems.
- Step 2, *Understand the Situation*. In addition to defining the social dimensions, the built environment is characterized and linked to the social dimensions. Characterization of the built environment typically involves determining the current condition of buildings and infrastructure systems. Nondestructive tests are ideal since they do not alter the performance of the underlying system and include such methods as seismic echo for deep concrete foundations (Olson, 1990) and acoustic emissions or ultrasonic for a variety of materials in infrastructure including polymer composites (GangaRao, 1995; Habermehl,

2009). Other tests may need to remove whole elements or parts of elements (e.g., drilling cores from concrete) in order to assess the current condition.

- Step 3, *Determine Goals and Objectives.* Once the current condition of the built environment is characterized, performance goals for the built environment must be specified relative to three (increasingly severe) hazard levels: routine, design, and extreme. The performance of the built environment subject to these hazard levels is assessed. During this process, knowledge of the current state of the materials and systems is essential for an accurate assessment of anticipated performance. This is where a validated materials service curve (Asset Insight.net, 2016) for all elements found in infrastructure would allow a prediction of the remaining service life of the infrastructure under chronic or typical aging conditions, subject to assumptions about the level of future maintenance and repair.
- Step 4, *Plan Development.* Once the expected performance of the built environment is estimated, any gaps between the desired performance (expressed in terms of the time needed to recover the function and role in the community) and the expected performance are identified and implementation strategies can be developed. While costs for most plans can be estimated using standard methods, calculating the benefits (expected performance levels) of various options is a function of the state of knowledge about the rate of aging (degradation due to long-term exposure to the environment), as well as the performance subject to exposure to routine, design, and extreme level events. These two phenomena are not independent (in other words, a system exposed to significant weathering conditions for 40 years with minimal maintenance and repair is likely to fail at a lower level of hazard than a brand new system).
- Step 5, *Plan Preparation, Review, and Approval,* involves documenting the plans followed by a thorough review on what needs to be done and a maintenance schedule, with prioritization of the necessary tasks.
- Step 6, *Plan Implementation and Maintenance*. Once the execution of approved solutions and evaluations is underway, the plan should be periodically reviewed and adapted. In this step, a validated estimate of the material properties as a function of time in the expected environment will be invaluable. Complementary to a validated materials service curve, continued assessment of the materials in infrastructure will be essential to

determine the appropriate maintenance routine, which in turn will help to decide if repair is needed.

SIX-STEP PROCESS TO PLANNING FOR COMMUNITY RESILIENCE

1. FORM A COLLABORATIVE PLANNING TEAM

- Identify leader
- Identify team members
- Identify key stakeholders

2. UNDERSTAND THE SITUATION

Social Dimensions

- Characterize social functions & dependencies
- Identify support by built environment
- Identify key contacts

Built Environment

- Identify and characterize built environment
- Identify key contacts
- Identify existing community plans

Link Social Functions & Built Environment

- Define clusters

3. DETERMINE GOALS & OBJECTIVES

- Establish long-term community goals
- Establish performance goals
- Define community hazards
- Determine anticipated performance
- Summarize results

4. PLAN DEVELOPMENT

- Evaluate gaps
- Identify solutions
- Develop implementation strategy

5. PLAN PREPARATION, REVIEW, AND APPROVAL

- Document plan and strategy
- Obtain feedback and approval
- Finalize and approve plan

6. PLAN IMPLEMENTATION AND MAINTENANCE

- Execute approved solutions
- Evaluate and update
- Modify strategy as needed

Fig. 2. *Six-step planning process for community resilience. (NIST, 2015)*

Issues with Material Selection for Community Resilience

Decisions about the most efficient infrastructure options can be greatly assisted with accurate and validated data about the performance of materials and systems as a function of time throughout their expected service life. These decisions should factor the expectations for maintenance and repair over time, which can vary significantly when considering solutions comprised of different materials. In addition, information on material repair or replacement procedures is required for episodic or acute events. The following examples highlight some of the challenges facing aspects of U.S. infrastructure.

Pipelines carry a variety of products to and from our communities. Many pipelines that carry natural gas and water in many of the nation’s cities are approaching 100 years of age and incidents of leaking or ruptured pipes are on the rise. Between 2006 and 2015, incidents of cracked or corroded natural gas line blasts killed an average of 13 people annually, in addition to millions of dollars of property damage (Marsh, 2016). Many communities are faced with difficult choices about how to repair or replace these pipelines and make them resilient. The Department of Energy (DOE, 2015) estimates that it will cost $270 billion to replace all aging pipelines.

In 2011, Congress mandated Pipeline and Hazardous Materials Safety, a division of the Department of Transportation (US Congress, 2011) to provide enhanced safety in pipeline transportation. One of the 42 requirements is the study of materials and corrosion prevention (Dominguez, 2016). Corrosion, leaks and breaks in older pipes are degrading our water delivery and sewage treatment systems, which are critical to public health and the environment. Today's corrosion crisis is due to materials used in America's underground pipe networks over the last 100 years. Cast iron and ductile iron were initially used. Both now suffer from the ravages of corrosion. In a 2010 report, the American Water Works Association (AWWA) showed that much of the nation’s drinking water infrastructure, which consists of more than one million miles of pipes, is nearing the end of its useful life and approaching the age at which it needs to be replaced (AWWA, 2010). In addition, shifting population trends are bringing significant growth to some areas of the country that require larger pipe networks to provide water service. The AWWA estimated that it will cost at least $ 1 trillion over the next 25 years, if only to maintain the current levels of water service. A key to the AWWA analysis for planning for infrastructure renewal was to understand the various materials from which pipes were made, and where and when the pipes of each material were likely to have been installed according to required sizes. The types of materials examined were cast iron cement-lined, ductile iron, asbestos cement, polyvinyl chloride (PVC) and pre-stressed concrete cylinder pipe. The AWWA averaged the estimated service life by pipe material, but they noted that the actual service lives of pipes may be very different in a given utility. This is because the service life of a pipe depends on many important local variables (e.g., the characteristics of the soil or local precipitation), as well as utility practices (e.g., inspection, maintenance, and repair). Non-corrosive materials, like PVC, have shown to be cost-effective and sustainable, but in some cases, newer materials have not completed certification and are therefore prohibited from being specified in procurement packages.

Railway transportation infrastructure is also showing its age (Marsh, 2016). In New Jersey, the Portal Bridge, constructed in 1910 and operating on a swing-span, is opened to allow for boat and barge traffic and then is switched back for rail use. However, after more than 100 years of service, the joints of the rails don’t always align correctly. This misalignment results in disruption to train traffic. Transportation tunnels are not faring much better. The over 100-year-old tunnel that connects Jersey City to Manhattan is cracked and crumbling. Some of this wear and tear is due to the 230,000+ daily commuters (service load), but after Superstorm Sandy in 2012, the tunnel (Marsh, 2016) has suffered periodic power failures. The flood from Sandy left salt that is further deteriorating the concrete structure, the iron rails, and the power cables. The materials used in the tunnel design were not meant to endure salt water penetration (episodic or acute event). Thus, a plan for rehabilitation needs to be developed to account for both chronic and episodic events.

Not all of the infrastructure failures are based on aging, but may involve material failures. In 2006, in the newly opened Boston, MA interstate 90 tunnel, a section of the tunnel’s suspended concrete ceiling detached and fell onto the road on a vehicle below. A total of about 26 tons of concrete and associated suspension hardware fell onto the road and a vehicle, killing a motorist (NTSB, 2007). The cause of the ceiling collapse was the inappropriate use of an epoxy anchor adhesive with poor creep resistance, such that the epoxy formulation was not capable of sustaining long-term loads. Over time, the epoxy deformed and fractured until several ceiling support anchors pulled free and allowed a portion of the ceiling to collapse (Chin, 2010).

The American Society of Civil Engineers (ASCE) has also assessed the state of U.S. infrastructure and generally reported poor findings, rating the overall state of U.S. infrastructure with a score of D^+ (ASCE, 2013). The score varies depending on the type of infrastructure, with a high score of C^+ for bridges and most of the rest of the infrastructure earning a D. Nearly 60,000 bridges across the country are in need of significant repairs. For example, in Pittsburgh, PA and Chicago, IL, netting was placed under bridges to protect drivers from falling concrete (Marsh, 2016). Beyond the funding issue to repair or replace the bridges, it is still not well understood how to make the bridges better. Academic researchers are studying novel materials that can react to changing circumstances (Herbert, 2013), such as cracks or additional weight stresses.

What is the Plan Moving Forward?

Materials Measurement Platform for the Resilience of Structures

The resilience of a community depends on the performance of many different aspects of its infrastructure due to the high degree of interdependencies inherent in modern life. For social functions to be delivered (e.g., healthcare, schooling, governance), all critical parts of the system need to be operational, from the integrity of the building structure and envelope, to the towers and cables for electricity and communication, to the pumps and pipes for water delivery. Functionality will be compromised if one critical element fails. The historical view holds that structures need only remain standing to protect lives during design-level hazard events. While life safety is certainly the critical starting point for a resilient community, it has experienced the economic and social consequences that such an important but limited view produces. Resilient communities prepare to recover quickly and “bounce forward” (rather than simply bounce back to the prior state) by ensuring that shelter, commerce, governance, healthcare, and education can be restored in a timely manner and with minimal disruption to the lives of the residents comprising the community. The community resilience goals are achievable through a holistic assessment of the community, which requires a sound understanding of the performance of all interdependent components comprising the community’s built environment subject to both the everyday effects of wear and weathering, as well as exposure to acute hazard events. The foundation for this understanding is materials science, without which resilience-oriented decision making is not possible.

To ensure that materials perform as needed for the expected service life of the infrastructure system, knowledge and prediction of the service life of the materials designed for new construction or system repair is necessary. Today, the selection of materials for new construction and the estimate of the remaining service life of materials already in place is primarily the domain of engineers and inspectors, respectively. Ideally, the full service curve (Figure 3) for any material or system should be known. This would enable projection of the expected service life of the selected material(s), taking into account the environment to which it is or will be exposed. Service curves for a number of common infrastructure materials or systems exist, though with varying degrees of certainty. However, novel or innovative materials, complex systems, or extreme environmental conditions often result in little or no data upon which to build a service curve.

In-service systems and their constituent materials present challenges due to their uncertain present condition and service history. For some materials, tools or standard test methods can estimate the condition of the material at the time of the measurement. Accurate knowledge about the current state of existing infrastructure is a critical step towards projecting the remaining service life and enables informed decision making for maintenance, repairs, and/or replacement. For other materials, new evaluation technologies and methods need to be developed to enable accurate condition assessment and support decision making.

Figure 3 shows a typical service curve, in this case with and without scheduled maintenance. The horizontal line shows the material’s functionality limit. This limit depends on where and how the material is used, what properties are required and at what level of material failure would the infrastructure still be functional. Most infrastructure materials no longer deliver their required properties (become non-resilient) prior to complete failure. In the example provided earlier of the Boston tunnel, the creep value of the epoxy determines the functionality limit for the tunnel because even if the epoxy itself was not destroyed, the ceiling was no longer viable.

Research has been conducted for decades to characterize materials traditionally used in construction, such as concrete, polymers, wood and steel or various metals. But the remaining service life of a structure is still hard to predict, as it is not yet possible to evaluate the materials in place in existing construction to determine the remaining service life and a plan of maintenance of the structure.

Some specific examples will help to illustrate the consequences of the lack of service life prediction capability. For instance, it is reported that a large portion of concrete repairs do not perform satisfactorily as soon as 5 years after the repair (Zewdu, 2013), implying that the structure will need to be repaired again to maintain functionality. This would imply that either the repair used the wrong materials (15% of the time) or that other interactions between the repair and the existing structure rendered the repair ineffective. A service life cost analysis should be done for proposed materials and repair methods.

If the service curve is known for each selected material in a structure, it is possible to estimate the performance of the system by combining material service curves. This requires an assessment of the constituent materials to determine parts that are critical for overall functionality. For instance, if a piece of concrete has deteriorated from a façade, is that a critical or just an aesthetic failure? Loss of insulation on an electrical cable may be critical depending on whether the cable provides the main power feed to the structure (critical) or a branch line for non-emergency lighting (secondary). Further, depending on where the cable is located, it might require days or weeks for cable replacement, rendering the structure non-functional for that period of time.

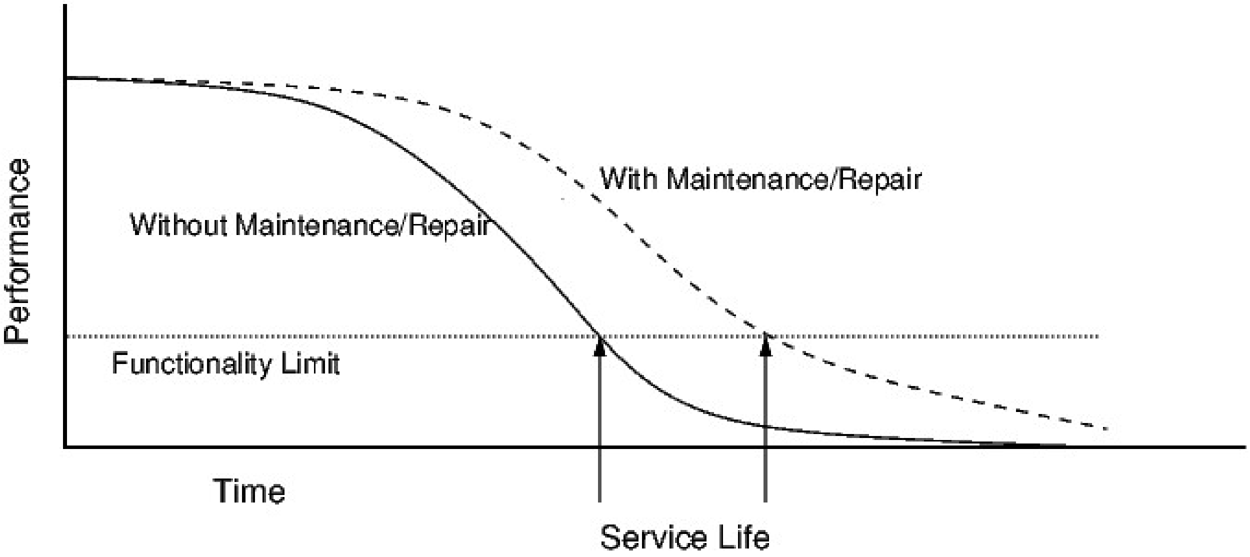

Fig. 3. *Material service curve with and without maintenance (adapted from Asset Insight.net, 2016). The horizontal line represents the functionality limit of the material.*

Figure 4 shows the effect of a hazard event on the performance of a system. The time and costs for recovery of system functionality depend on the condition of the system at the time of the hazard event and the degree of damage that is sustained. For less damage, the recovery trajectory is shorter and more certain (A). Significant damage often results in longer recovery times and costs, with increased uncertainty (B). However, an additional significant source of uncertainty for the performance of a systems exposed to an episodic or acute event (hurricane, earthquake, tornado) is the present state of the system, which may vary significantly from the original design and installed state due to the long-term effects of service loads and weathering. Thus, it is necessary to know where on the service life curve the constituent materials of the system reside. The current state of the materials is needed in order to properly assess whether the properties required to resist a catastrophic event for that structure are still sufficient (for instance above the horizontal functionality line in Figure 3) or whether a repair/replacement is needed to bring the service curve back above the functionality line.

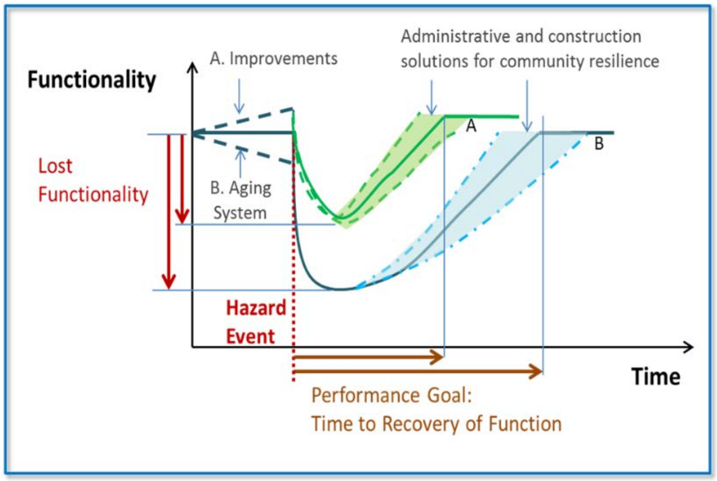

Fig. 4. *Material service curve subject to a significant hazard event, shown with and without resilience improvements (McAllister, 2013).*

Thus, materials should be selected at the time of construction with their service life in mind as well as the system functionality requirements. Two examples demonstrate this point more clearly. First, consider the important role of storm water management in determining the severity of flooding resulting from a severe storm. After the severe flooding that resulted from Hurricane Irene in 2011 in Vermont (Childs, 2016), many local communities were assessing the best options for replacing or restoring damaged culverts. Some of the culverts were made out of metal sheets, but it was observed that the culvert then corroded quickly due to the highly corrosive environment typical of high snowfall states. Thus, the decision was made to replace many culverts with concrete culverts to increase resilience as concrete should not deteriorate as rapidly in that environment and allow protection from floods or extended functionality. This decision was deemed to be cost effective in the long-run despite the higher initial cost of concrete culverts compared to metal.

As a second example, consider the role that private residences play in providing shelter for people in U.S. communities. Most residential construction in the U.S. is made of wood (Cheng, 2004), with 175 million cubic meters of lumber bought for construction in 2011 (Howard, 2013). The quality of the selected wood and the construction design determines the resilience of the structure. In addition, the design industry has been increasingly looking at timber as a building material for the construction of tall buildings, 10 to 30 stories in height (Barber, 2014). This interest is partly due to the development of new engineered timber products and the benefits of prefabricated timber elements and composite building systems, but also due to the importance of green and sustainable architecture (Barber, 2014). A common hazard event for a residential house and new tall timber buildings is a severe wind event. Design and construction practices focus on limiting the wind damage, especially protecting the roof from separating from the walls and framing. A secondary, though costly, effect of wind damage is often moisture intrusion (e.g., wind-driven rain soaking insulation, wood members, and interior finishes). Careful selection of fastenings, building envelope materials, and third-party ratings for wind-resistance of materials can significantly limit these primary and secondary effects. In addition, the life cycle cost of the material should be considered, which is dependent upon the environment and location of a house. It is understandable that including a lifecycle analysis would increase the project planning time and cost, but the benefit could outweigh the cost, as it may reduce maintenance costs and/or recovery time after a disaster. For example, a residence might be built using an alternative material such as insulating concrete form (ICF), instead of the traditional wood material. The initial cost might be higher for the innovative material but the life cycle cost of the structure might be lower due to improved wind resistance, moisture tolerance, and/or improved energy efficiency.

Finally, innovation in material science and products may represent an important opportunity to improve the resilience of a community. It is well-known that one of leading causes of deterioration of concrete or steel bridges is corrosion (FHWA, 2012). Corrosion in reinforced concrete construction is generally due to the penetration of salt (usually chloride ions from winter deicing salts) and water reaching the reinforcing bars embedded within the concrete. As the reinforcing bars corrode, they lose the ability to carry tensile loads within the concrete system, which is their primary function. A possible solution is to cover or encase the metal parts with paint or a polymer wrap (Kar, 2016), which would provide a protective barrier to keep the chlorides from contacting and corroding the reinforcing bars. This has been done using epoxy coated rebars or painting a metal bridge. The issue is then determining the service life and maintenance schedule for of the paint/epoxy. Again, the service life of all materials in all critical components needs to be known to inform sound resilience decision making.

New Research and the Role of Material Science in Community Resilience

Globally, community resilience programs and organizations are being developed. They range from non-profit organizations, such as the Rockefeller Foundation[2] , the 100RC (Hundred Resilient City[3]) or the Community and Regional Resilience Institute[4], and government backed institutes, such as the Community Resilience in Public Health Emergency[5] with the US Department of Health and Human Services, and independent entities such as National Academy of Sciences -Resilience Round Tables[6]. Other programs are being developed by academia, where efforts are made to add resilient classes to the curriculum. However, not all programs examine infrastructure down to the materials level.   One such program is the Center of Excellence for Risk-Based Community Resilience Planning at Colorado State University[7]. Funded by NIST, the Center is unique in merging the disciplines of engineering, social sciences, and economics to model community resilience comprehensively. Systems that are essential for the recovery and vitality of a community are being integrated in the model, creating a nexus between social and physical infrastructure networks that will narrow the gap between

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[2] https://www.rockefellerfoundation.org/

[3] http://www.100resilientcities.org

[4] http://www.resilientus.org/

[5] https://www.phe.gov/Preparedness/planning/abc/Pages/community-resilience.aspx

[6] http://sites.nationalacademies.org/PGA/ResilientAmerica

[7] http://resilience.colostate.edu/

engineering and social science aspects of resilience planning. Such models will facilitate risk and resilience communication among stakeholders and community resilience planners. The work products from the Center will provide a quantitative and science-based approach to community resilience assessment and, for the first time, will support a business case for enhancing disaster resilience at the community level. The research has three main thrusts:

1. Develop a multidisciplinary computational environment with fully integrated databases, entitled the Interconnected Networked-Community Resilience Modeling Environment, which will enable the factors and their inter-relationships that determine community resilience to be fully understood.
2. Produce a robust data architecture and effective data management tools to support the computational environment and to permit databases from stakeholders representing multiple domains of engineering and social sciences to be integrated seamlessly in the decision process.
3. Validate the resilience data architecture through a series of testbeds that stress the process of data collection, its integration into the computational modeling environment, and decision algorithms.

Materials science is critical to all three thrusts. Materials properties are necessary model inputs and validation parameters, including both aging mechanisms, as well as system response to hazard events.

In summary, it is necessary to promote more research on service life of materials traditionally used in construction and on development of new materials. Material functionality curves are needed to account for the role of various design materials in the infrastructure system performance and resilience.

Summary

This paper asserts that resilient communities are better enabled when the functionality of materials is incorporated into the design, maintenance, repair, and recovery of infrastructure systems. As in any complex system, the weakest link determines the functionality limit of the overall system. Operationalizing this concept will require a science-based foundation of material properties, including a thorough understanding of the performance of specific materials subject to both chronic loads (e.g., service loads and weathering) and the routine, design, and extreme levels for the hazard events possible during the service period (e.g., wind or earthquake events). This new perspective to construction may reduce overall costs during the lifetime of the infrastructure system.

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