Quantitative Assessment of Resilience and Sustainability

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Sustainability is a word that is ubiquitous, yet often vague. At the Massachusetts Institute of Technology Concrete Sustainability Hub (CSHub), we have a concise mantra: "We want our world to last." This saying helps us clarify what we mean by sustainability with regard to the structures we build, including bridges. Such structures will remain sustainable only if civil engineers are farsighted. Many aspects of a structure, including its future economic impact and the environmental conequences of construction, repairs, or replacement, affect its sustainability. Our research finds that quantitative assessment of these factors can lead to alternatives that improve a structure's sustainability (see http://cshub.mit.edu/news/lca-research-brief-quantifying-hazard-life-cycle-cost for more information).

Sustainability analyses are usually conducted by considering a structure's typical loading conditions throughout its life. An additional important consideration is the structure's response to atypical loading conditions, such as those caused by natural or human-made disasters. A structure's response to such conditions is a measure of resilience that is vital to understanding sustainability, particularly in regions where climate-related events are becoming increasingly frequent and destructive.

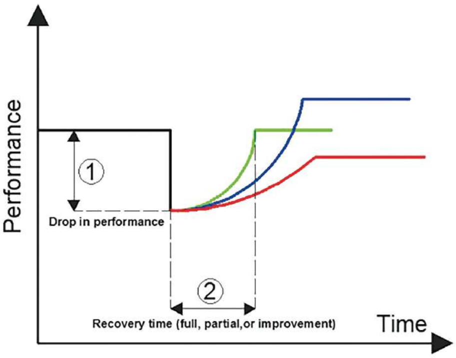

Figure 1. Resilience has two parts—initial response to a damaging event (the drop in performance) and recovery time. All Figures: Dr. Jeremy Gregory.

Resilience, an important element of sustainability, can be quantifiably measured in two stages, response and recovery (**Fig. 1**). First, we assess the system's immediate response to an event. For example, let's imagine that a city experiences a hurricane. Before the storm arrives, the city operates at peak performance, as indicated by parameters like economic productivity, transportation efficiency, and so on. As the storm ensues, the city's performance will drop because of economic inactivity, disabled infrastructure, and other damages. The extent of the drop in performance is the first measure of resilience—a smaller reduction in performance indicates greater resilience. The second measure of resilience is the time to recovery to a performance level that may be lower than, the same as, or higher than the performance level before the disaster. A rapid and strong recovery signifies effective resilience.

A recent example of resilience can be seen in the aftermath of Alaska's November 2018 7.0-magnitude earthquake. While the photos of crumbled highways were dramatic, the actual devastation was not extensive. Authorities reported no fatalities and no collapsed buildings, and seriously damaged roadways were repaired within days.[1,2] Pundits therefore declared the state's response to the disaster a success.

Alaska has not always enjoyed such resilience. In 1964, the state experienced the largest earthquake in U.S. history. This 9.2-magnitude quake shattered roads and bridges, destroyed neighborhoods, disrupted livelihoods, and killed an estimated 139 people.[3] In response to the earthquake, authorities established more rigorous building codes intended to protect buildings from future seismic activity. Alaska's successful response to the 2018 earthquake is due, in large part, to the changes implemented in building and bridge design codes.[1]

Alaska's rapid recovery demonstrates how efforts to improve resilience can deliver a return on investment (ROI). If stakeholders remain unaware of the ROI of resilience, success stories like that of Alaska in 2018 will occur less frequently. Calculating this ROI is therefore a key aspect of CSHub's work, and, to do it, a probabilistic hazard repair estimation model has been developed.

The crux of this model is the probability curve, which allows us to analyze the uncertainties of disaster and predict outcomes. Using government and other scientific data, we can generate a probability curve that estimates the likelihood of a hazard in a given location. We refer to this as a *hazard curve* (**Fig. 2**).

The hazard curve's counterpart in resilience analyses is the *fragility curve* (**Fig. 3**), which estimates the damage a hazard will inflict on a structure. To generate fragility curves, we employ a technique inspired by molecular dynamics. We model the integrity of a structure's components like we would the bonds of atoms. This methodology allows us to efficiently estimate the effects of hazard-induced loads on these components. What makes this technique unique is its versatility and precision. Whereas conventional models of building fragility approximate damage for a broad class of buildings, we can efficiently generate fragility curves of the damage to different elements of specific building designs. Fragility curves for specific building designs give stakeholders a more detailed and quantitative understanding of building damage for proposed mitigation solutions.

By integrating hazard and fragility curves, we can create a comprehensive damage model that assesses potential damage from hazards of different intensities. When we assign costs to these damages and add them to the normal lifetime maintenance and construction costs of a structure as part of a life-cycle cost analysis, we can determine whether investments in resilience will prove cost effective over a structure's life when compared to conventional designs.

Our research has shown that the value of hazard resistance can be quantified and that investments in hazard mitigation can pay off, particularly in locations where hazard repair costs approach the value of initial construction costs. Within expectation of sustainable infrastructure, such resilience analyses for structures, including bridges, are critical. It is essential that we create a culture of resilience by educating stakeholders that quantitative resilience assessments are possible and necessary for infrastructure. Bridge engineers are well positioned to carry this mantle.

References

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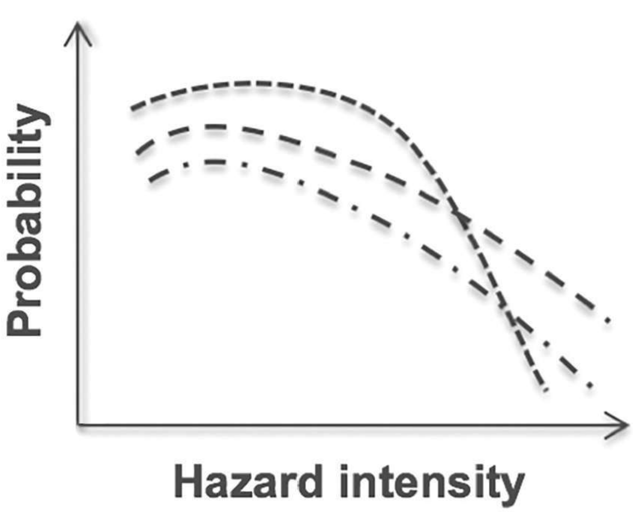

Figure 2. A generic hazard curve.

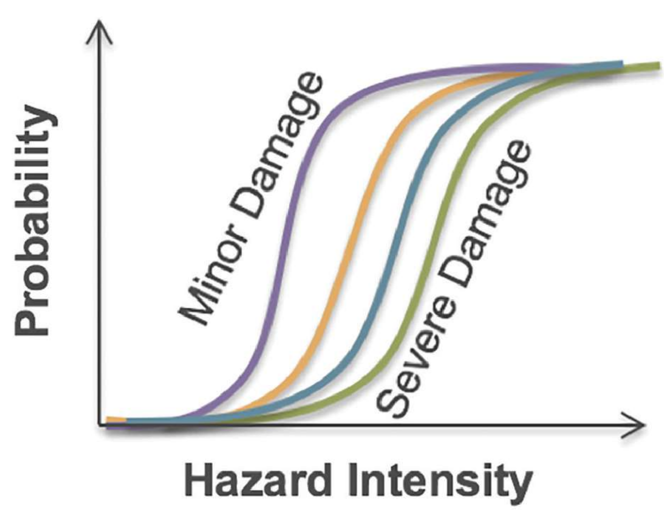

Figure 3. A generic fragility curve.