A NEW MODEL FOR SUSTAINABLE SOLUTIONS TO BRIDGE INFRASTRUCTURE SUBJECTED TO MULTIPLE THREATS (SSIMT)

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Abstract

Aging, increased traffic, and natural hazards all threaten bridge performance. These threats result in physical damage, and cascading social, environmental, and economic impacts that impair sustainability. A scientific approach is needed to mitigate risks to bridges posed by multiple threats while balancing broader objectives of sustainability. Therefore this research proposes a new model, "*Sustainable Solutions for Bridge Infrastructure Subjected to Multiple Threats*" (SSIMT), that evaluates the effects of multiple threats on bridge reliability while taking into account sustainability implications. In addition to describing the SSIMT concept, recent developments in multi-threat bridge fragility modeling are summarized, as key input to SSIMT.

Introduction

Bridge infrastructure is susceptible to damage from a large host of threats--aging and deterioration, natural hazards that may become more frequent with climate change, and demands that increase with population growth and urbanization (ASCE 2009; Perry and Mackun 2001; RPA 2005; USDOT 2007b). Though the USDOT and many state departments of transportation (DOTs) have embraced the goal of sustainable transportation infrastructure (Jeon and Amekudzi 2005; National_Research_Council 2009; USDOT 2007a), a scientific approach is needed to mitigate risks to bridges posed by multiple threats while balancing broader objectives of sustainability. While a range of definitions for sustainable engineering exists in the literature (Amekudzi et al. 2009; Daly 1996; Goncz et al. 2007; J. E. Padgett et al. 2009; Pearce and Vanegas 2002; Taylor and Fletcher 2006; USDOE 2003; Vanegas 2003; WCED 1987), in the context of this paper, sustainable built infrastructure (e.g., bridges) effectively serves public needs while limiting adverse environmental, social, and economic impacts. Such impacts might include waste generation, energy expenditure, or emissions associated with bridge construction, maintenance, or post-disaster repair and replacement. Current approaches to bridge engineering and management tend to focus on how a single threat causes failure, and to select design or upgrade strategies using metrics limited to initial cost or deterministic performance. Such existing approaches do not take into account the fundamentals of sustainable design (Adeli 2002; Black et al. 2002; Little 2005; National_Research_Council 2009), the recently recommended principles for infrastructure investment (ASCE 2008), the reality of multiple threat exposure (MCEER 2008; Simpson et al. 2005), or the uncertainty inherent in such an analysis (Biswas 1997; Li and Ellingwood 2006; J. Padgett and DesRoches 2007). Therefore, a new model for bridge infrastructure

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engineering is proposed in this paper, "*Sustainable Solutions for Bridge Infrastructure Subjected to Multiple Threats*" (SSIMT). This model evaluates the effects of multiple threats on bridge reliability, while taking into account the social, economic, and environmental consequences that are often neglected in designing, maintaining, and rehabilitating these systems.

In the forthcoming section of this paper the proposed SSIMT model is presented, elaborating its conceptual backbone and highlighting the critical input needed to make the model a reality to support bridge engineering and management. The paper then highlights recent advances in multi-threat and multi-hazard bridge fragility modeling. Such models of the conditional probability of damage to bridges subjected to individual hazards (e.g. earthquakes or hurricanes), combined hazards (e.g. earthquakes and scour), or combined threats (e.g. earthquakes and aging/deterioration) offer critical input to the SSIMT framework by uncovering the physical vulnerability that must be modeled in order to effectively quantify sustainable impacts. The paper concludes with an indication of how such reliability models may be integrated into a sustainable assessment and offers insights and suggestions for future research.

The SSIMT Model

Currently, no analysis or upgrade approach exists to mitigate risks posed by multiple threats to bridge infrastructure while balancing broader goals of sustainability. This critical gap is addressed by providing a model for bridge infrastructure enhancement where performance goals are driven by sustainability metrics, such as energy usage, life-cycle cost, and downtime. The proposed model, "Sustainable Solutions for Bridge Infrastructure Subjected to Multiple Threats" (SSIMT), identifies

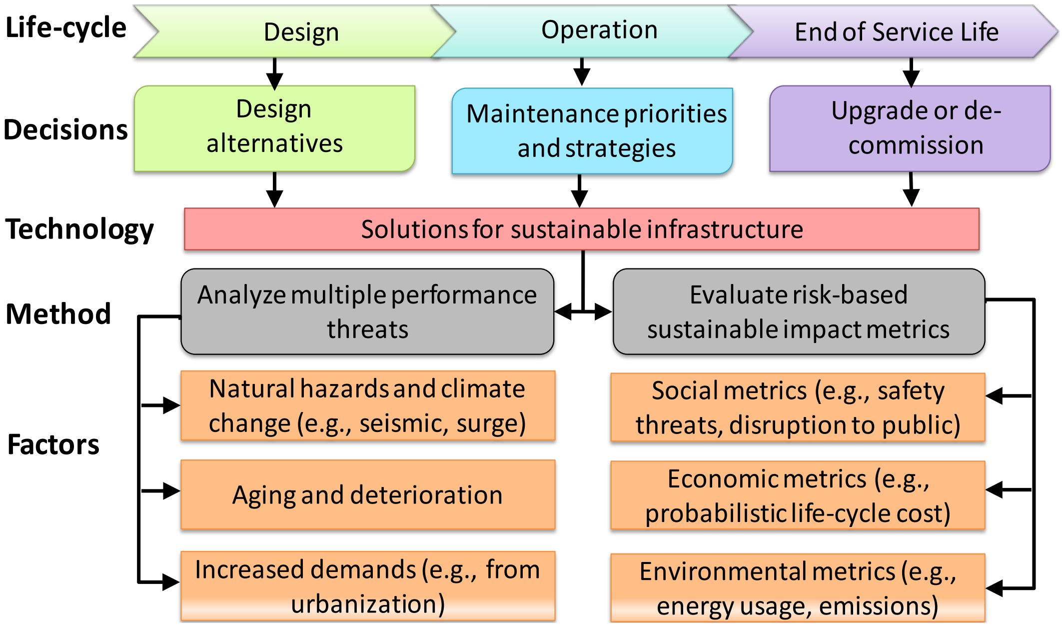

Figure 1. Concept Model for SSIMT, Demonstrating Key Decision Phases Throughout the Infrastructure Life-Cycle that can Benefit From Fusion of Multi-Threat Reliability and Sustainability Models.

methods for design and management using risk-based measures of sustainable performance that consider multiple threats over a bridge's life. Figure 1 illustrates the concept model for SSIMT. Casting multi-threat mitigation decisions within the contextual framework of sustainability provides distinct advantages over traditional approaches. For example, a typical approach for addressing a bridge deficiency to earthquake or hurricane hazards may suggest rebuilding the bridge to current design standards over costly retrofit. However, the increased energy use, waste generation, and disruption to the public may in fact indicate that this solution is misaligned with the objectives of sustainability. The proposed SSIMT model derives solutions where risks from multiple threats are mitigated, while simultaneously promoting system sustainability. Its application results in bridge infrastructure that is safer, due to considering failure probability from multiple threats; is more effective in meeting public needs, by mitigating loss of functionality; and is cost-effective, by accounting for life-cycle cost in the design and management. Detrimental environmental impacts are avoided by selecting strategies based on quantified metrics such as anticipated energy usage or waste generation.

To effectively realize SSIMT, advanced research tools are required that integrate multi-threat vulnerability assessment, life-cycle modeling of sustainability metrics, risk reduction and optimization strategies. This integrated framework can then aid in discerning cost-effective, socially-conscious, and environmentally-friendly solutions to bridge infrastructure deficiencies. Ongoing work in the Padgett Research Group at Rice University (http://www.owlnet.rice.edu/~jp7/) is helping to address input needs for SSIMT, including the following areas of emphasis which align directly with the SSIMT concept model presented in Figure 1:

(1) Probabilistic modeling of the vulnerability of bridges under multiple threats to understand the individual and coupled effects of threats on bridge performance required to assess sustainability.

(2) Life-cycle analysis to relate bridge infrastructure performance to quantifiable objectives for sustainability, including risk-based metrics such as life-cycle cost, energy consumption, waste generation, functionality loss, and safety threats, among others.

(3) Derivation of methods to select bridge retrofit or repair strategies that enhance lifetime sustainability through inverse problem solving or multi-objective optimization to jointly target multiple threats while balancing competing sustainable objectives.

The risk assessment tools for SSIMT are derived through an analytical and simulation based research approach supported by field or test data where viable. Ongoing research is developing multi-threat bridge vulnerability models to uncover the complex coupled effects of hurricane induced storm surge and waves, earthquakes, aging and deterioration, and increased service loads on bridge reliability. The next section of the paper highlights advances in this multi-threat bridge fragility modeling.

In SSIMT, this physical vulnerability is then related to metrics of sustainable performance for specific social, environmental, and economic impacts, ranging from safety to downtime, and from life-cycle cost to energy usage (Figure 1). Although not covered in this paper, examples of this life-cycle modeling of sustainability metrics can be found in Padgett and Tapia (2013) and Padgett (2010). Methods are then formulated to assess and enhance bridge sustainability. Potential tradeoffs and interactions between natural hazard risk mitigation and sustainable engineering are addressed by posing multi-threat upgrade selection in terms of sustainable objectives. While also not the focus of the current paper, early advances in this area include the pursuit of sing and multi-objective optimization frameworks using genetic algorithms to identify sustainable retrofit and repair combinations (Tapia and Padgett 2013).

Advances in Multi-Threat Vulnerability Modeling

As described in the previous section, vulnerability models that characterize the damage potential of bridges when subjected to multiple threats are a key input to the SSIMT framework. The SSIMT approach relies upon fragility models, which offer statements of the conditional probability of failure (or limit state exceedance) given level of threat intensity. In fact, such fragility models offer a building block of many risk assessment frameworks, such as the performance-based earthquake engineering paradigm often reference to support seismic design or upgrade decisions (Moehle et al. 2005). This section describes recent advances in multi-threat fragility modeling of bridges, breaking down the overview into cases that consider: 1) individual threats or natural hazards alone; 2) joint threats; 3) multiple simultaneous natural hazards. Examples of each case are described along with methodological advances relative to the state of the art, sample fragility models or insights from their applications.

Individual Hazards

Traditionally, fragility models for the performance of bridges subjected to natural hazards have been most widespread developed for bridges when subjected to earthquake loads. Although the details may vary on finite element modeling fidelity, level and treatment of uncertainties, and failure modes or bridge components considered in the reliability assessment, seismic fragility models for bridges have been developed by a number of researchers (Mackie 2004; Nielson and DesRoches 2007; Shinozuka et al. 2000). Typically the models condition failure probability on a single ground motion intensity measure (IM) such as the peak ground acceleration, or spectral acceleration, whose selection is guided by such principles as the ability to reduce uncertainty in the predictive model (so called “efficiency”) as well as the ready availability of probabilistic hazard models consistent with the IM (so called “hazard computability”). Recent advances in seismic fragility modeling by the author’s group, collaborators, and others include its application to a number of regional portfolios of structures (e.g., those typical of the state of California, or Central and Eastern Canada); or to the exploration of the influence of alternative design details and site conditions (e.g., the influence of vertical ground motions, seismic versus non-seismic detailing, soil structure interaction and liquefaction effects).

One advance in the seismic fragility modeling of bridges with particular relevance to supporting SSIMT is the recent development of parameterized fragility models for bridges subjected to earthquakes (Ghosh et al. 2013a). In this approach, the failure probability is conditioned not only on the ground motion intensity measure but also a set of structural parameters, x_1 through x_n as shown in Equation 1:

$$P_f = P\left[Demand > Capacity \mid im, x_1, x_2, \ldots, x_n\right] \tag{1}$$

Such parameterize fragility modeling typically takes advantage of the use of surrogate modeling, or metamodels, to enable efficient vulnerability assessment that covers the predictor parameter space. This formulation offers advantages in averting the need to redevelop the fragility model for each bridge within a portfolio of bridges (requiring often computationally expensive finite element simulations); enabling sensitivity studies; supporting the updating of parameters with additional field data; or enabling parameter optimization studies such as those proposed in SSIMT for identifying design or upgrade parameters that support sustainability objectives. As demonstrated in Rokneddin et al. (2013), such parameterized models can also offer advantages of reduced uncertainty (quantified by the dispersion in the fragility curve) relative to the traditional approach of using the IM as the sole predictor of the seismic demand and fragility (Figure 2).

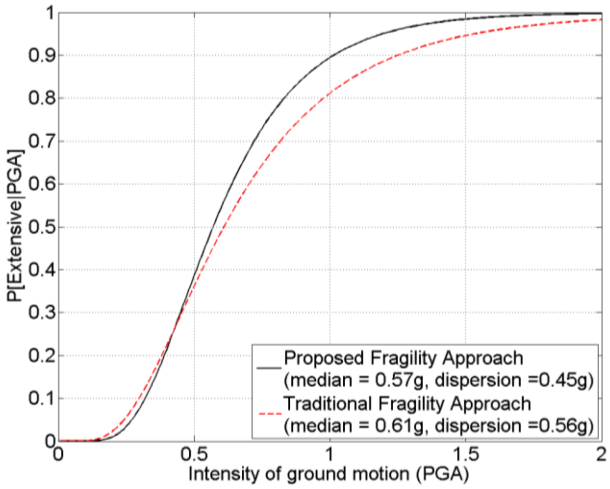

Figure 2. Example Seismic Fragility Curve for a Case Study Multi-Span Simply Supported Concrete Girder Bridge. This Plot Also Shows a Comparison of the Fragility Curve Obtained using the Parameterized Fragility Approach and Traditional Fragility Approach (Rokneddin et al. 2013).

Beyond seismic hazards, recent research has provided the first fragility models for coastal bridges susceptible to hurricane hazards. Past hurricanes, such as Hurricanes Katrina, Ivan, and Ike in the United States have demonstrated the severe consequences of such loads resulting in bridge damage and impairment of transportation network functionality. The predominant failure mode of interest for these bridges is deck unseating caused by hurricane induced wave and storm surge loading. Figure 3 shows an example of a hurricane fragility curve, developed using a simplified method based upon by Monte Carlo Simulation with static analysis (Ataei and Padgett 2013). The fragility indicates the failure probability for a range of levels of relative surge elevation (Z_c), or surge minus deck elevation, and maximum wave height (H_{max}). The plot reveals a relatively distinct transition zone between failed ad safe regions demarcated by the dashed line in Figure 3, which can be attributed in part to the lack of vertical connectivity between the deck and supports and relatively “brittle” failure mode. More advanced fragility analysis techniques have also been proposed for developing hurricane fragilities to accommodate dynamic analyses or fluid structure interaction, enable additional uncertainty treatment associated with such models, and utilize efficient sampling techniques and surrogate modeling. These fragility models enable for the first time risk assessments of coastal bridge infrastructure under severe storms, which were traditionally limited to inundation analyses, but now can offer predictions of bridge failure potential.

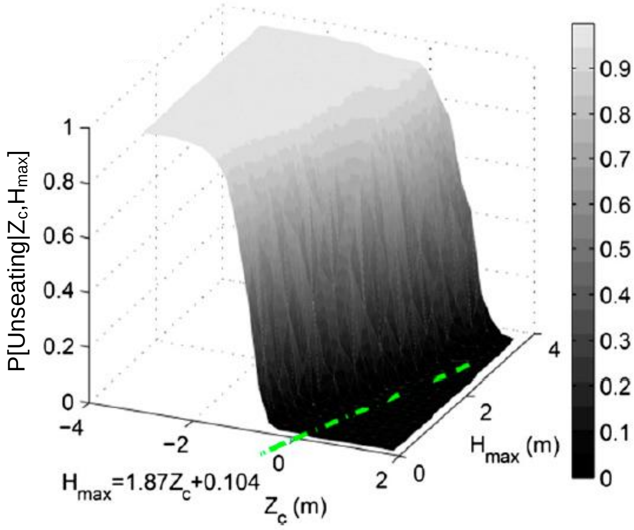

Figure 3. Example Hurricane Fragility Curve For A Case Study Multi-Span Simply Supported Concrete Girder Bridge. This Plot Shows the Failure Probability (y-axis) for Different Levels of Relative Surge Elevation (Z_c) and Maximum Wave Height (H_{max}) (Ataei and Padgett 2013).

Joint Threats

While fragility modeling of bridges has been evolving to consider the vulnerability of bridges against various natural hazards, such as earthquakes and hurricanes, the joint impact of multiple threats has received relatively less attention. In this paper the term “threats” is considered more broadly to encompass not only natural hazards but also other factors that threaten the performance of bridges such as aging and deterioration or service loads. Recent studies have investigated the joint impact of natural hazards (e.g. earthquakes) and simultaneous consideration of aging and deterioration (e.g. from corrosion) or service loads (e.g. truck traffic). The results suggest the importance of considering joint threat occurrence and the influence of these additional threats on natural hazard fragility. For example, several researchers have investigated the influence of corrosion on the seismic fragility of bridges (Do-Eun et al. 2008; Ghosh and Padgett 2010), albeit with different bridge types and exposure conditions, among other considerations. Ghosh and Padgett (2010) proposed the use of time-dependent fragility curves to reflect the increase in vulnerability throughout the life of a bridge. An illustration is shown in Figure 4 for a case study multi-span continuous steel girder bridge exposed to deicing salts, showing that the median value as well as the dispersion of the lognormally distributed fragility are affected by aging and deterioration. A comparison of different exposure conditions—marine environment, atmospheric condition, deicing salt exposure—revealed that bridges in seismic zones where deicing salts are typical are susceptible to the greatest increase in fragility. Across different bridge types common to the Central and Southeastern United States, multi-span continuous and simply supported bridges are among the most vulnerable types for which aging also has a significant impact on increasing the fragility. This can be attributed in part to the high type steel fixed and rocker bearings as well as the significant demands placed on corroding reinforced concrete columns with limited reinforcement.

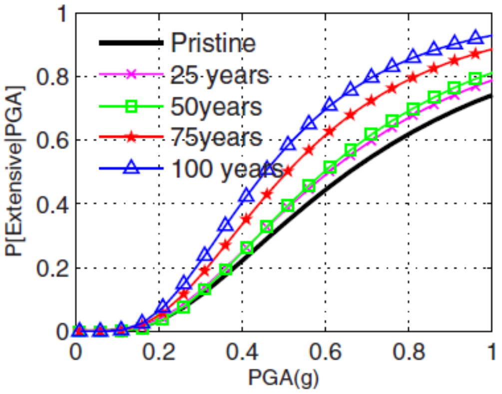

Figure 4. Example Time Dependent Fragility for a Case Study Multi-Span Continuous Steel Girder Bridge, Showing the Joint Consideration of Aging and Seismic Threats (Ghosh and Padgett 2010).

Ghosh et al. (2013b) proposed a framework for joint live load and seismic reliability analysis, to account for the realistic condition that vehicular loads may be present atop a bridge during seismic excitation. Figure 5 shows an illustration of the fragilities derived as statements of bridge failure probability conditioned upon peak ground acceleration as well as truck gross vehicle weight (GVW). This figure suggests that presence of a truck atop a bridge can have an impact on the seismic vulnerability and that this impact is sensitive to the vehicle weight (i.e. almost a linear increase in median value with increase in GVW). The method elaborated in Ghosh et al. further necessitates the integration of a truck gross vehicle weight histogram and truck flow rate and density, to consider the likelihood of truck presence and weight in seismic fragility estimation. The results revealed that for the case study multi-span continuous steel girder bridge (used in Figure 5) and regional weigh in motion data typical of the state of Alabama, that the increased fragility (reduced median PGA) can be small once the probabilities of occurrence of truck presences and GVWs are taken into account.

Never the less, this joint threat may be of interest for priority bridges on key trucking routes, such as access routes to ports.

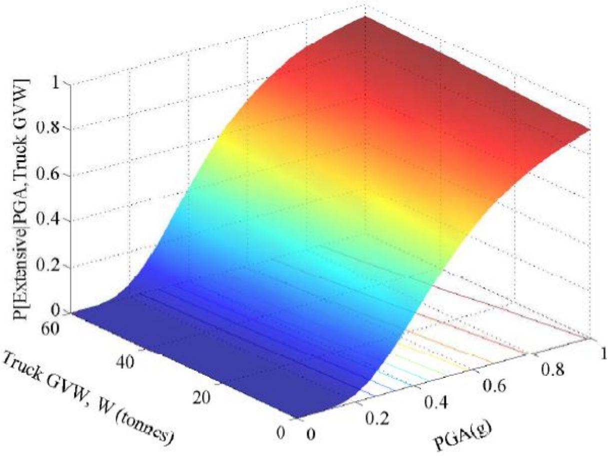

Figure 5. Example Joint Seismic and Live Load Fragility for a Case Study Multi-Span Continuous Steel Girder Bridge. Failure Probability is Conditioned on Earthquake Intensity as PGA and Truck Gross Vehicle Weight (GVW) (Ghosh et al. 2013b).

Multiple Simultaneous Hazards

The last class of fragility models required to enable SSIMT are those that consider the potential simultaneous occurrence of hazards. For many hazards, such as earthquakes and hurricanes presented above, the joint event occurrence potential is negligible. However, there are other cases that have been acknowledged in the literature as simultaneous hazards of practical interest. One such case for bridges is the joint consideration of scour and seismic hazards, which has been recently explored for its impact on seismic fragility as well as implications on load factor derivation (Wang et al. 2013). An example fragility surface is shown in Figure 6 for a case study two-span box girder bridge susceptible to scour and earthquakes. In this figure the failure probability (vertical axis) is a function of the ground motion intensity (IM) (taken here as $S_{a-05,}$ or the spectral acceleration at 0.5 second) and the scour depth (H). The derivation of this fragility surface is enable by developing multi-hazard probabilistic seismic demand models, in which the bridge response is considered as a function of both IM and H, before comparing with the capacity. The resulting Figure suggests the influence of scour depth on the failure probability of the bridge when an earthquake occurs. In general this case suggests an increase in fragility with H, but there are some cases where the fragility may also decrease slightly due to the elongation of period that accommodates the increase in scour (e.g. an equivalent base isolation effect). The multi-threat fragility models categorized into three subclasses in this paper provide key quantification of the failure probability of bridges for different exposure conditions. Subsequent risk assessment and life-cycle modeling in the SSIMT framework rely upon these fragility estimates to quantify the sustainable impacts of hazard damage and characterize the benefits of design details or upgrades.

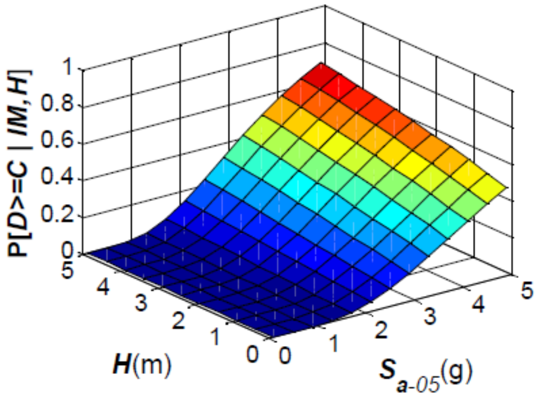

Figure 5. Example Multi-Hazard Scour and Earthquake Fragility Surface for a Case Study Two Span Integral Box Girder Bridge. Failure Probability is Conditioned on Earthquake Intensity Taken as $S_{a\text{-}05}$ and Scour Depth (H) (Wang et al. 2013).

Conclusions

This paper presents “Sustainable Solutions for Bridge Infrastructure Subjected to Multiple Threats” (SSIMT) as a model to identify methods for bridge upgrade and management using risk-based measures of sustainable performance that consider multiple threats over a bridge’s life. Overall SSIMT integrates multi-hazard reliability and risk assessment with life-cycle modeling of sustainability metrics, such as cost, energy usage, or fatalities, to support the identification of sustainable designs or retrofits. This approach offers a way to explore the relationship between protection from natural hazards and implications on social, environmental, and economic performance. Prior to quantifying metrics of life-cycle sustainability, SSIMT relies heavily upon the characterization of bridge vulnerability to multiple threats; hence this paper emphasizes recent advances in bridge fragility modeling deemed critical to enable SSIMT. Threats in the SSIMT model include the consideration of natural hazards, aging and deterioration, and potential increases in service loads. The three main categories of multi-threat bridge vulnerability models described in this paper include individual hazards (e.g. hurricane or earthquake fragility); joint threats (e.g. joint aging and seismic fragility); and multiple simultaneous hazards (e.g. scour and earthquake fragility surfaces).

Recent methodological advances in fragility modeling include the use of metamodeling to enable efficient, parameterized bridge fragilities amenable to SSIMT. The models offer flexibility for application across bridge portfolios, for integration of new information collected from the field, and for sensitivity or design parameter optimization to achieve sustainability objectives. Recognizing a key gap in the literature, new probabilistic models of hurricane fragility were developed focusing on the unseating failure mode associated with surge and wave loading. Additional opportunities exist to explore other failure modes, including those associated with hurricane induced scour and debris impact. These fragility models for independent hazards can be used to explore tradeoffs in the risk of damage and subsequent sustainability metrics for bridges in regions prone to earthquakes and hurricanes or typhoons (e.g. the state of South Carolina in the USA, Puerto Rico, Japan). The examination of joint threats revealed that both aging and deterioration as well as the presence of truck traffic can have an impact on bridge fragility to seismic hazards. However, the relative magnitude of these effects depends heavily on bridge type, exposure condition, and likelihood of the secondary threat. In general the consideration of time-dependent seismic fragility is recommended for life-cycle analysis of the sustainability of bridges to account for the impacts of aging on seismic performance; however, the joint consideration of truck and earthquake loads may not have a significant impact on the fragility unless the bridge is located on a heavily traveled route. It is acknowledged that further studies with a wide array of bridge types are required to confidently generalize these findings. Additionally, the joint impact of earthquakes, aging, and traffic has yet to be explored in the literature. However, the methods presented in this paper and its associated references can offer viable approaches to consider these joint threats. Finally, while the simultaneous occurrence of natural hazards may be impractical for some cases, others like the joint occurrence of scour and earthquake have received increasing attention in the literature. The derivation of multi-hazard demand models and fragility surfaces, such as that presented in this paper for scour and earthquake, offer a basis to conduct multi-hazard risk and life-cycle assessments in the SSIMT model. Future opportunities exist to extend this multi-hazard framework to other hazards, including triggered hazards such as fire following earthquake or tsunami. By integrating these multi-threat fragility models in a life-cycle framework, the impact of hazard exposure on bridge sustainability can be better understood and the potential synergies and tradeoffs in hazard protection and sustainable design revealed.

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