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Multi-hazard risk assessment of highway bridges subjected to earthquake and hurricane hazards

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ABSTRACT

This paper presents a Parameterized Fragility based Multi Hazard Risk Assessment (PF-MHRA) procedure risk for assessment of a portfolio of highway bridges subjected to earthquake and hurricane events. As a part of this approach, parametric bridge fragility functions are generated for the two hazards, which are an advance over conventional fragility curves as they can be used for bridges with different geometric and structural properties given exposure to different hazard types. The parametric bridge fragility functions are derived using metamodels and stepwise logistic regression with a non-linear logit function. The relative change in hurricane and earthquake fragilities of the bridges is captured by the parametric fragility functions given variation in design details or geometric parameters of the bridges. These fragility functions are combined with regional hazard data to evaluate annual risk, which is measured as the annual probability of damage. For this purpose, hazard input parameters are identified for earthquakes and hurricane events and a new risk assessment procedure for bridges subjected to hurricane wave and surge loading is also developed. Furthermore, coupling of the risk assessment procedure with parameterized fragilities enables a comparative assessment of the contributions of different hazards to the total risk as the bridge details differ in a portfolio. The proposed framework is applied to multi-span simply supported concrete girder bridges located in South Carolina. The application demonstrates the identification and derivation of input models for the multi-hazard risk assessment for earthquakes and hurricane induced storm surge and wave loading. By applying the proposed method, insights are gained on the influence of different bridge geometries and hazard exposure conditions to the risk of bridge damage. The potential of the proposed procedure to serve as an aid to risk based design of bridges is also highlighted.

1. Introduction

Bridges are often exposed to multiple hazards during their service life. Among these hazards earthquakes and hurricanes are the costliest natural disasters in history [1] and have been known to inflict severe damage to a portfolio of bridges across a region. Under such events, crucial bridges in the emergency response routes may suffer damage. Therefore, these events not only cause economic losses by damaging infrastructure and other facilities but also adversely affect post disaster response capability. Thus, identification of major sources of risk to bridges in a region subjected to multiple hazards is vital for pre- and post-event activities such as retrofit of deficient structures or selection of viable emergency response routes. Quantification of the risk of damage and subsequent consequences, along with the identification of factors that affect the risk, is important for informed decision making. For example, quantification of the risk of damage to each bridge considering multi-hazard exposure may help in prioritizing retrofit activities for bridges in a network. Also, new bridges must be designed to mitigate the risks from various hazards. Therefore, a risk based design should consider the potential competing or synergistic effect of design decisions on multi-hazard performance and their impact on the total risk. However current design codes such as the *AASHTO LRFD Bridge Design Specifications* [2] do not consider such interactions. In order to facilitate such advances toward multi-hazard risk based design of new bridges or management of existing structures, multi-hazard risk assessment approaches must be developed. This need for multi-hazard risk assessment procedures for infrastructure has also been highlighted by researchers such as Ettouney et al. [3] and Li et al. [4]. Such a risk assessment procedure may consider different types of hazards such as: independent hazards like blast and earthquake, hazards with correlated

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demand such as earthquake and snow loads on buildings, concurrent hazards such as wind and wave, and cascading hazards such as tsunami following an earthquake. However, the application presented herein considers earthquakes and hurricanes, a case of multiple independent and non-concurrent hazards.

Early work on multi-hazard analysis such as that by Pearce and Wen [5] and Rackwitz and Fiessler [6] focused on determining the probability of joint hazard occurrences and on evaluation of load cases for concurrent occurrence to facilitate reliability assessment. In addition to these aspects of multi-hazard analysis, recent research efforts also focus on risk assessment of structures when subjected to multiple hazards. In this regard, the aspect of load combination for design of bridges has been addressed by researchers such as Ghosn [7], wherein methods to determine load combination of extreme events on bridges have been developed in a multi-hazard perspective. In his study, several hazards such as earthquakes, live load and scour are considered for designing bridges, but the issue pertaining to competing demands (i.e. a remedial measure for one hazard worsening the response of the structure when subjected to other hazards) from these hazards still needs to be addressed. Liang and Lee [8,9] propose an analytical framework for multi-hazard reliability analysis of bridges. The framework models time dependent loads, their simultaneous occurrences and resulting load combinations with examples for simultaneous occurrences of live load and earthquakes. They point out the issue of contradictory demands during design. A time dependent multi-hazard risk assessment framework for bridges is proposed by Decò and Frangopol [10]. Pier scour, aging, earthquakes and flexural failure of aging superstructure due to live loads are considered and a structural redundancy index is used for risk assessment. Although this framework includes different modes of failure, the effect of variation in structural and geometrical properties on the risk from different modes is not studied. Moreover, the issue of competing demands from multiple hazards is not addressed.

Apart from the above mentioned multi-hazard studies on bridges, several studies on other structures have provided methods for risk and loss assessment. Although these methods may not be directly applicable to bridges, they have several advantageous features. A general framework outlining the steps for multi-hazard analysis of structures in coastal environments vulnerable to earthquakes, tsunamis, extreme winds and storm surges is proposed by McCullough and Kareem [11]. In their paper, minimizing the total risk to structures while maintaining a cost efficient design is emphasized. Asprone et al. [12] evaluate threats to buildings from earthquake and blast events to derive the annual risk of collapse. Their methodology separates risks due to each event and allows for a comparison of the contribution from individual hazards to the total risk. A multi-hazard loss assessment framework for residential wood buildings subjected to earthquakes and hurricane winds is presented in Li and Ellingwood [13] and Li and van de Lindt [14]. These comparative risk assessment frameworks evaluate and compare risks from earthquake and hurricane to residential buildings. In a study by Yin and Li [15] a multi-hazard risk assessment framework is proposed for light frame wood residential buildings subjected to earthquake, snow loads and the combined loading. This framework is object oriented, i.e. the framework is divided into self-sufficient modules, thereby providing flexibility to incorporate new information as it becomes available. Reliability of an offshore structure subjected to earthquake, wind and wave loads was studied by Kafali [16]. The different loads were simulated using appropriate power spectrums and were applied to a simplified single degree of freedom model of the structure. Though the method handles multiple hazards very well, the applicability to bridges is limited due to complexity of the structure.

While hurricanes have been considered among the multiple hazards in past risk assessments, these studies tend to focus on wind. Hurricane wind and surge may be the dominant contributors to the risk to coastal buildings or residential structures, but in the case of highway bridges, surge and wave loads cause the most damage and should be considered in a multi-hazard risk assessment. However, only a few studies have been conducted regarding the reliability assessment of bridges and their components under such hurricane loads [17–19] and a framework for risk analysis or comparison to other hazards has not been addressed. Furthermore, the approaches proposed in existing multi-hazard frameworks are mostly applicable to individual structures. Therefore, these models may not be used to study the effect of variation of design parameters on the risk to a portfolio of structures, like bridges across a region, without the need for reanalysis for each design permutation.

To address the aforementioned gaps, this paper presents a multi-hazard (hurricane surge, wave and earthquake) risk assessment method for a portfolio of bridges. The proposed framework allows quantification of the risk due to different hazards, while evaluating their relative contribution to the total risk. It uses parameterized fragility functions to capture the variation of risk due to changes in bridge parameters. This formulation enables an efficient assessment of the potential tradeoffs in performance under multiple hazards. The parameterized fragility functions are obtained by using metamodels, which offer approximating functions of the structural response and avert the need to rely solely upon finite element simulations to estimate the demand under hazard loads. Since metamodels provide computationally inexpensive alternative for time consuming simulations, they can be used for integration and optimization [20]. These advantages suggest that metamodels are well suited for reliability estimation. Recent studies on bridge fragility evaluation have used metamodels, especially response surface methods. Seo and Linzell [21] have used the response surface method to evaluate the seismic response of curved steel bridges and subsequently evaluate the fragilities of different bridge components in a Monte Carlo simulation. Another work on reliability estimation of track on steel plate girder bridges by Park and Towashiraporn [22] has also used response surface method for seismic fragility assessment. In their study, the mean and standard deviation of the seismic response of bridges were modeled using a response surface which was used to obtain fragilities via Monte Carlo simulations. Ghosh et al. [23] compared different metamodels for fragility assessment. Polynomial response surface, Multivariate Adaptive Regressive Splines (MARS), Radial Basis Function (RBF) and support vector machines were considered for fragility assessment. The fragility curves obtained were also compared with conventionally obtained fragility curves and a close match was observed. Though the initial computational costs for generating the metamodels are significant, the advantages of metamodels make them suitable for reliability and risk evaluation. However, different metamodels have different advantages and weakness; the performance of the metamodels is also dependent on the experimental design selected and the problem at hand [20,24]. In view of the advantages, metamodels are used in this study to develop the parameterized fragility functions used for risk assessment for different hazards. The proposed method is applied to multiple-span simply supported (MSSS) concrete girder bridges which are exposed to earthquakes and hurricanes. As a part of this study, a method to assess the risk for bridges subjected to hurricane induced surge and wave loads is also developed since an existing approach is lacking for this purpose.

The next section of the paper discusses the steps in PF-MHRA procedure. Section 3 elaborates the framework and methods for deriving inputs to the multi-hazard risk assessment for bridges. A case study is used to describe the procedures to obtain hazard