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Risk and resilience assessment of bridges under mainshock and aftershocks incorporating uncertainties

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ABSTRACT

The non-functionality of bridges after the occurrence of a sudden hazard can significantly impact highway transportation systems and affect the recovery process. Seismic risk assessment is particularly important for the rapid decision making process associated with structures under mainshock and aftershock sequences. In this paper, a framework for probabilistic seismic performance assessment of highway bridges subjected to mainshock and aftershocks is presented. The seismic ground motion intensity, seismic vulnerability analysis of bridges, and consequences evaluation under mainshock and aftershock sequences are considered herein along with their associated uncertainties. The recovery functions associated with different damage states are integrated within the proposed functionality assessment procedure. Additionally, the probabilistic direct loss, indirect loss, and resilience of bridges under seismic hazard are investigated. The assessment of probabilistic risk and resilience of highway bridges under mainshock and aftershock sequences can aid in implementing risk mitigation strategies and equip decision makers with a better understanding of structural performance under seismic hazard.

1. Introduction

Highway bridges are crucial infrastructures that impact both the economy and society, especially after a catastrophic event such as a strong earthquake. The non-functionality of bridges after the occurrence of an extreme event can significantly impact highway transportation systems and affect the recovery process. Mainshocks are typically followed by a few aftershocks. Usually, these aftershocks occur close in time to the mainshock. Therefore, repair or retrofit activities are often not possible to be applied within this time interval; this, in turn, may increase the risk associated with already damaged structures. Consequently, it is necessary to evaluate structural performance after a mainshock and during aftershocks in order to aid emergency management procedures and repair/retrofit decision processes. A quantitative forecasting framework regarding risk assessment of bridges considering mainshock and aftershock (MSAS) sequences should be established. This paper presents a generalized framework that includes the consideration of seismic ground motion hazard, seismic vulnerability associated with the bridge ability to resist aftershock hazard, and consequences evaluation under MSAS sequences.

Most previous studies associated with bridge seismic risk assessment have focused on the effects of a mainshock while neglecting aftershocks [50,21,55,23,24]. However, aftershocks may produce disastrous economic and societal consequences compared to a mainshock event [53]; therefore, the effects of aftershocks should be incorporated within the approach for probabilistic seismic risk assessment of highway bridges. The seismic performance of a bridge considering aftershocks is related to the seismic intensity of the ground motions and conditional damage state of a structure under mainshock [47]. This paper aims to compare the effect of mainshock alone with that associated with the mainshock followed by aftershocks, and to investigate the effects of aftershocks on seismic consequences and functionality associated with damaged bridges; ultimately, the presented framework can aid the decision making process. The uncertainties associated with the seismic hazard and consequences evaluation are also incorporated within the seismic performance assessment process to compute risk and resilience.

Various methods may be adopted for seismic demand assessment of structural systems. One method is the three dimensional (3D) nonlinear time-history analysis, which is complex and time consuming [32]. Another reliable approach is associated with static nonlinear pushover analysis and can also be used to determine seismic demand of structural systems [15]. Simplified force–displacement-based single degree of freedom (SDOF) models

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representative of complex structural systems can be generated using pushover analysis [45,29]. Generally, an idealized inelastic SDOF system can be adopted to evaluate the nonlinear response of a structure whose dynamic behavior is dominated by the fundamental vibration mode [30]. The approximate method using SDOF may only produce accurate results for specific periods of vibration. To account for aftershock effects, structural systems should be subjected to a series of mainshock and aftershock sequences [3,30,36,54]. Most of the previous studies regarding aftershock effects were focused on buildings. Overall, there has been limited research regarding bridge seismic performance under MSAS sequences [46,2]. Further research is necessary to investigate aftershock effects on seismic performance of bridges.

Generally, the uncertainties associated with the seismic performance assessment and consequences evaluation should be considered in the decision making process. Reliability-based structural performance indicators effectively reflect the probability of failure of structural systems under given seismic hazard. However, reliability-based methods do not account for outcome of a failure event in terms of economic losses. Risk-based performance measures combine the probability of system failure with the consequences associated with a particular event [27]. Since failures associated with bridge structures under seismic hazard can have significant impact on the economic, social, and environmental systems, risk-based methodologies are the most appropriate for bridge management under extreme events. An approach to compute the repair cost of bridges under seismic hazard that utilizes repair cost ratios associated with different damage states has been formulated [38]. Similar methodologies have been adopted in [21,23,50,52,55]. Research is required to handle risk-based decision making concerning highway bridges while incorporating MSAS seismic sequences.

In addition to risk, resilience is another indicator that accounts for structural functionality and recovery patterns after hazard occurrence. Based on the functionality of a bridge under extreme events, the probability of a bridge experiencing different performance and functionality levels (e.g., one lane closed, all lanes closed) can be obtained [56]. Generally, the criteria regarding the decision-making process to open traffic on bridges can be established on basis of functionality. Federal Highway Administration [26] investigated bridge functionality considering different seismic damage states; the functionality restoration process was modeled by a normal cumulative distribution function. Additionally, Mackie and Stojadinovic [37] quantified the functionality of a damaged bridge under seismic hazard in terms of lateral and vertical load-carrying capacity. Presidential Policy Directive [42] defines resilience as a structure's ability to prepare for and adapt to changing conditions while simultaneously being able to withstand and recover rapidly from functionality disruptions. The quantification of seismic resilience should be processed through a probabilistic framework because of the considerable amount of uncertainties in the seismic vulnerability and consequence assessments. An analytical model that has been widely implemented for resilience quantification of critical infrastructure systems after an extreme event was proposed by Bruneau et al. [9]. This analytical model was previously applied to bridge and transportation networks [8,22], healthcare facilities [17], and power networks [10]. To the best of the authors' knowledge, the effects of aftershocks on structural seismic resilience have not been studied yet. This paper aims to not only quantify the seismic vulnerability of bridges but also to integrate the resilience performance indicator within a seismic risk assessment process under MSAS sequences through a probabilistic framework.

In this paper, a framework for the seismic performance assessment of bridges subjected to mainshock and aftershocks is presented. An analytical model of a highway bridge subjected to MSAS seismic sequences, considering damage or collapse is developed. An equivalent SDOF structure is used to evaluate the structural damage caused by MSAS sequences. The evaluation of repair loss and functionality of bridges under seismic scenarios is based on a set of damage states, which are mutually exclusive and collectively exhaustive. The uncertainties associated with seismic scenarios, seismic vulnerability analysis of bridges, and consequences evaluation under mainshock and aftershocks are incorporated within this framework. Ultimately, the probabilistic risk and resilience of bridges under mainshock and aftershock sequences can provide decision makers with a better understanding of structural performance under seismic hazard and help them implement appropriate risk-informed mitigation strategies.

2. Seismic scenarios associated with mainshock and aftershock

The first step in seismic performance assessment of bridges is to identify representative seismic events that characterize the region under investigation. A flowchart summarizing the proposed methodology is shown in Fig. 1. A specific seismic scenario associated with a mainshock should be generated and applied to structural systems. The earthquake early warning system (EEWS) consists of a set of seismic stations that are located in potentially active seismic zones, which can provide real-time data regarding the mainshock magnitude within the first few seconds of an earthquake [35]. Based on P-wave signals received by the seismic stations, the seismic magnitude can be obtained. Then, using historical data and real time information, the earthquake magnitude and source-to-site distance can be updated using Bayes' theorem. In the Bayesian updating process, the data that is available

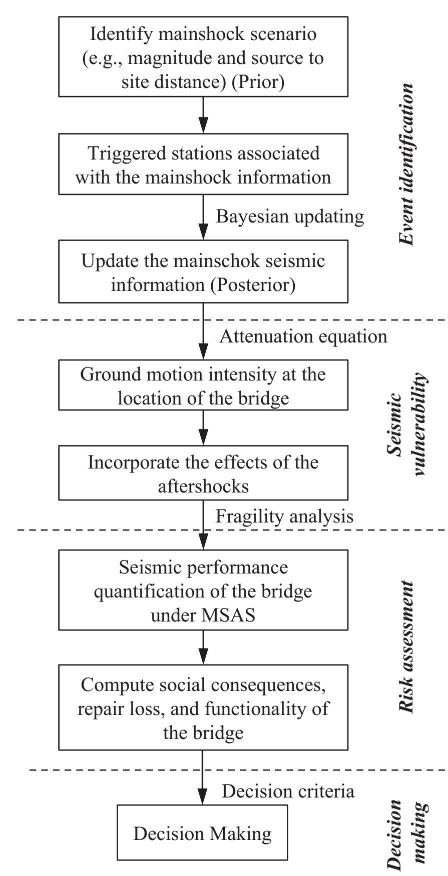

Fig. 1. Flowchart of the seismic risk-informed decision making.