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Force-based and displacement-based reliability assessment approaches for highway bridges under multiple hazard actions

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ABSTRACT

The strength limit state of American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications is developed based on the failure probabilities of the combination of non-extreme loads. The proposed design limit state equation (DLSE) has been fully calibrated for dead load and live load by using the reliability-based approach. On the other hand, most of DLSEs in other limit states, including the extreme events I and II, have not been developed and calibrated though taking certain probability-based concepts into account. This paper presents an assessment procedure of highway bridge reliabilities under the limit state of extreme event I, i. e., the combination of dead load, live load and earthquake load. A force-based approach and a displacement-based approach are proposed and implemented on a set of nine simplified bridge models. Results show that the displacement-based approach comes up with more convergent and accurate reliabilities for selected models, which can be applied to other hazards.

1. Introduction

Designing bridges to resist extreme hazard loads has been a major concern of American Association of State Highway and Transportation Officials (AASHTO) and the bridge engineering community for decades. In recent decades, a considerable amount of efforts were devoted to earthquake and wind effects and also extended to other hazards, such as scour, storm surge, vessel and vehicular collisions, etc. (Huang et al., 2014;

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Kameshwar and Pedgett, 2014a, 2014b; Lee et al., 2008, 2011, 2013a, 2013b, 2014; Li et al., 2012; Liang and Lee, 2012, 2013; Wang et al., 2014a, 2014b, 2014c; Zhu and Frangopol, 2013). Other hazards including fire and blasting were also taken into account in the multiple hazard framework (Fujikura and Bruneau, 2012; Petrini and Palmeri, 2012; Potra and Simiu, 2009; Rini and Lamont, 2008). Analysis and design for these hazard loads have been developed individually because each one requires different expertises and knowledges to formulate the "demand" or "capacity" for bridge design. However, a bridge may experience these multiple types of hazards at the same time or in a certain sequence. Examples include the bridge damage during 2011 Tohoku earthquake and the tsunami in Japan (Akiyama et al., 2013), and the combination of earthquake and mudflow after 2008 Wenchuan earthquake (Cui et al., 2008). The bridge capacity needs to be carefully designed by considering its resistance to these multiple extreme hazards in a fair platform to ensure the safety of the bridge structure and the transportation system.

The establishment and implementation of AASHTO Load and Resistance Factor Design (LRFD) Bridge Design Specifications (AASHTO, 2012) were considered as a milestone in the historical development of bridge design specifications. In AASHTO LRFD, both loads and resistance were treated as random variables to take the uncertainties introduced by various external or internal factors into account. For the first time, the safety of bridge was evaluated in a quantitative approach using the bridge reliabilities or the risks against various loads and/or load combinations.

AASHTO LRFD can be categorized to four types of design limit states: strength, service, extreme events and fatigue. The calibration of AASHTO LRFD consisted of trying out various combinations of load and resistance factors on a number of bridges and their components (AASHTO, 2012). Currently the strength design limit state in the AASHTO LRFD is formulated and fully calibrated using the reliability-based approach (Kulicki, 1998; Kulicki et al., 2007; Nowak, 1999). The extreme event design limit states, however, are constructed by combining the non-extreme load effects with the independently established extreme hazard load effects through professional judgment. Its margin of safety and adequacy has not been assessed quantitatively.

Lee et al. (2008, 2011) highlighted the problems related to the standards indications in order to obtain commeasurable criteria of multiple hazards for highway bridge design. To face these issues the Multidisciplinary Center for Earthquake Engineering Research (MCEER) in 2009 started a project for developing uniform risk design criteria for highway bridges under multiple hazards.

Lee et al. (2013a, 2013b) and Huang et al. (2014) presented several different approaches and theoretical backgrounds for the establishment of design limit state equations (DLSEs) with a comprehensive consideration of multiple hazards based on proper reliability measures. Sun et al. (2015) applied the proposed method on a typical bridge located at Southeast China to calibrate the risk of failure. A particular force-based approach was presented to combine two time-varying loads with the permanent load. In this paper, with limited data/resources, the application of this approach and a displacement-based approach are given to demonstrate the procedure for calibrating the bridge reliability under dead load, live load and earthquake. Furthermore, the results are compared to address the needs for obtaining a more accurate result from the standpoint of bridge engineering community.

2. General steps for evaluation of bridge reliability

Based on the previous research by Nowak (1999), the entire procedure to establish the current AASHTO LRFD limit states consists of six steps (Lee et al., 2013a, 2013b). A flow chart to demonstrate the general procedure to determine bridge reliability is given in Fig. 1.

The first four steps can be used to evaluate the bridge reliability, as following:

1) Selection of representative bridges. Bridges vary with many parameters, such as structural system, material, span, width, height, skew, etc. To obtain the reasonable result, representative bridges need to be selected to conduct further analysis. Since the considered loads are dead load, live load and earthquake, and the earthquake load effect is mainly applied on the substructure of a bridge, the research focus in this study is placed on the bridge columns with the assumption that other bridge components can be simplified.
2) Establishing the statistical database for load and resistance parameters. Load distributions can be obtained from recorded data and statistical analysis, which commonly reflect the probability of occurrence and related intensity for each hazard. Many researchers proposed reasonable assumptions for simplicity. These simplified assumptions can be used for calculation before more accurate data is obtained.
3) Development of load and resistance models. For each given bridge structure, we can calculate three items: the load effect distribution, the nominal value of load effect (Q_1, Q_2, Q_3, ...) and the resistance distribution. Note that the load effect distribution is different from the load distribution, and the failure probability can only be calculated through load effect distribution. For example, the load distribution for earthquake commonly referred to is the distribution of peak ground acceleration (PGA), but the failure probability must be calculated by using the internal force such as bending moment applied on the column.
4) Development of the reliability analysis procedure. Borges and Castanheta (1972), Wen (1977), Turkstra and Madsen (1980), Ghosn et al. (2003), Liang and Lee (2012) proposed different methods to calculate the failure probability of a structure using the load effect and structural information provided in Steps 2 and 3. This paper focuses on the exhaustive approach proposed by Lee et al. (2013a, 2013b), which consists of calculation of partial and total failure probabilities and normalization (i.e., converting the load effect distribution into a normal distribution). Lee et al. (2013a, 2013b) proposed that, for two different time-variant loads, the failure probability of a structure is the sum of three partial failure probabilities from three mutually exclusive events. In this case, the total failure probability is