DEVELOPMENT OF MULTIHAZARD BRIDGE DESIGN FRAMEWORK

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Abstract

The American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Specification for bridges has its strength design limit state formulated and fully calibrated using the reliability-based approach. 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 could not be assessed quantitatively. A research project sponsored by the Federal Highway Administration (FHWA) has been carried out to explore principles and approaches for establishing multiple-hazard (MH)-LRFD based on the established rationale and reliability-based methodology of the AASHTO LRFD. An analytical framework has been established to consider the non-extreme and extreme loads on a common reliability-based platform. This paper describes the formulation of specific extreme event design limit state (e.g. the limit state for non-extreme load with the earthquake load effects) by using the all-hazard, reliability-based approach. Future challenges towards the development of a comprehensive MH-LRFD will be described.

Introduction

Evolution of Bridge Design for Life Safety

Since the publication of the first AASHTO standard specification in 1931 (AASHTO 1931), bridges are designed by using a uniform factor of safety in the working stress design approach. The margin of design safety was modified to use load factors in the ultimate load carrying capacity approach. Since 1994, bridge design philosophy for life safety was modified with the margin of safety established using the reliability-based (or risk-based) approach (AASHTO 1994). This formulation considers various uncertainties included in different possible loads (both intensity and probability of occurrence) and in variation among factors affecting the bridge resistance. This is a milestone of bridge design history and leads to current AASHTO Load and Resistance Factor Design (LRFD) specification (AASHTO 2012). In the LRFD specifications, design limit states for other failure modes (extreme event, serviceability and fatigue) are established separately and linked with the regular, non-extreme load based on professional judgment.

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In recent decades, bridge design philosophy is being pursued in two separate fronts. The first is the reliability-based approach which is based on force effects. The other is the performance based approach which considers force effects as well as ductility, such as the earthquake effects. In the long run these two thrusts of development should merge into a unique set of bridge design limit states for all non-extreme loads and extreme hazard effects that are reliability-based as well as performance-based. For design of sustainable bridges, equal risk for all hazard effects should be considered during the expected service life of a bridge.

With the premise of an all-hazard, reliability-based and performance-based design limit states for bridge, it is reasonable to first-consider the upgrading of the AASHTO LRFD extreme event design limit state equations as their failure probabilities of all hazard effects (non-extreme and extreme) under consideration.

The Current AASHTO LRFD in Extreme Loads

The current LRFD (AASHTO 2012) provides four categories of design limit states equations: strength, extreme events, service and fatigue. The strength design limit state equations are formulated based on bridge component failure probability due to non-extreme loads. These equations are developed and fully calibrated in the reliability-based formulation (Nowak 1999, Kulicki 2007). The strength design limit state is written as

$$\sum \gamma_i Q_i \quad = \quad \phi \mathrm{R_n} \tag{1}$$

where γ_i are the load factors and Q_i are the loads (In this case the nominal dead and live loads). Φ is the resistance factor and $\mathrm{R_n}$ is the nominal resistance. The design limit state has a different philosophy from those of previous WSD and LFD limit state by considering the probability of occurrence in addition to load intensity. In this regard the margin of safety is established from the prescribed amount of risk when the overlapping portion between resistance and load is negative. This can be seen from Figure 1. This risk can be measured by a reliability index (β in Figure 1).

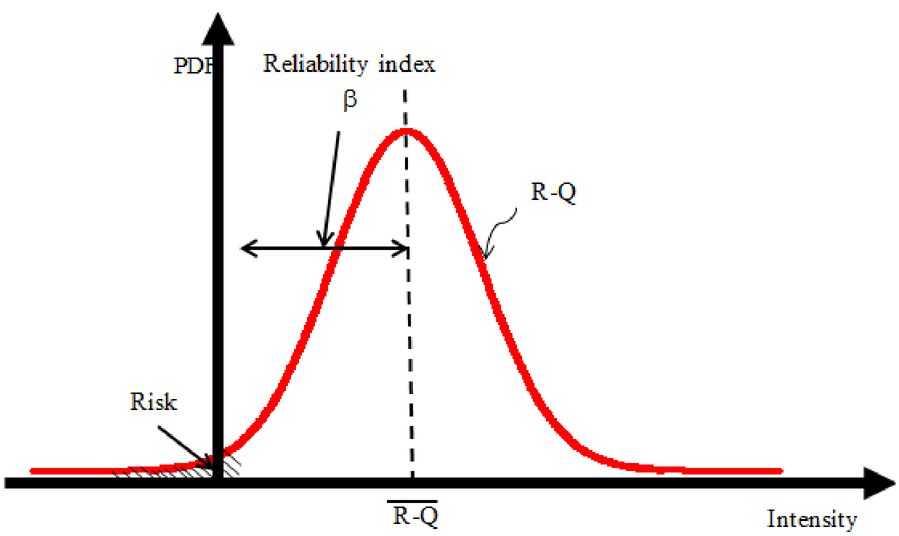

Figure 1. Relation between resistance, load and risk

The procedure of formulating the LRFD is briefly illustrated in Figure 2.

It is noted that the design limit state given by Eq. (1) is an important design philosophy from the viewpoint of bridge safety. Regarding to the reliability index, it has been fully calibrated to be 3.5 for the strength design limit state I (Nowak 1999, Kulicki 2007). For the design limit state equations on extreme events, service and fatigue, the reliability indices are not yet fully calibrated and certain failure modes are not established on the same reliability-based platform used for the non-extreme loads.

In view of the increased frequency of major natural disasters in recent decades, structural design against extreme events has been a research focus of considerable interests. Seeking the possibility to improve the extreme event design limit state equations is the initial motivation to explore possible approaches in targeting the development of multiple-hazard (MH) LRFD by the Federal Highway Administration.

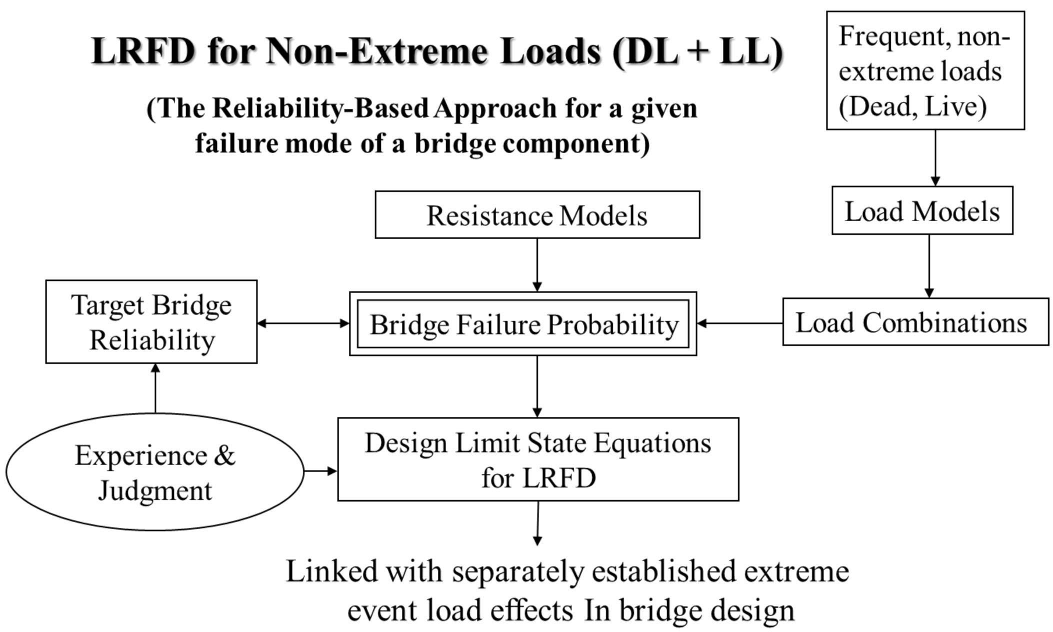

Figure 2. The process of formulating the LRFD specification

<u>Major Tasks in this Development and Challenges</u>

The development of MH-LRFD consists of four major components:

- Review of available information on extreme hazards and their damaging effects on the bridge structure. The objective of this task is to gather quantitative information for the purpose to establish load models and damage models for bridges and/or bridge components to facilitate the formulation of failure probabilities and relevant design limit states.
- Develop an analytical framework and necessary methodology to obtain design limit states due to combined non-extreme and extreme hazard load effects from information obtained on hazards and structural damages of bridges of the first task.

- The third task is to carry out a few case studies and selected extreme event design limit states to illustrate the application of established theoretical framework and to assess its limitation and accuracy.
- The final task is to identify short term and long term research opportunities for the continued establishment of MH-LRFD and their deployment for future practical applications.

Development of Analytical Framework for MH-LRFD

The analytical framework established contains several significant challenges that must be overcome before design limit states can be established. This analytical frame, by expanding the same framework used to develop the AASHTO LRFD, is given in Figure 3.

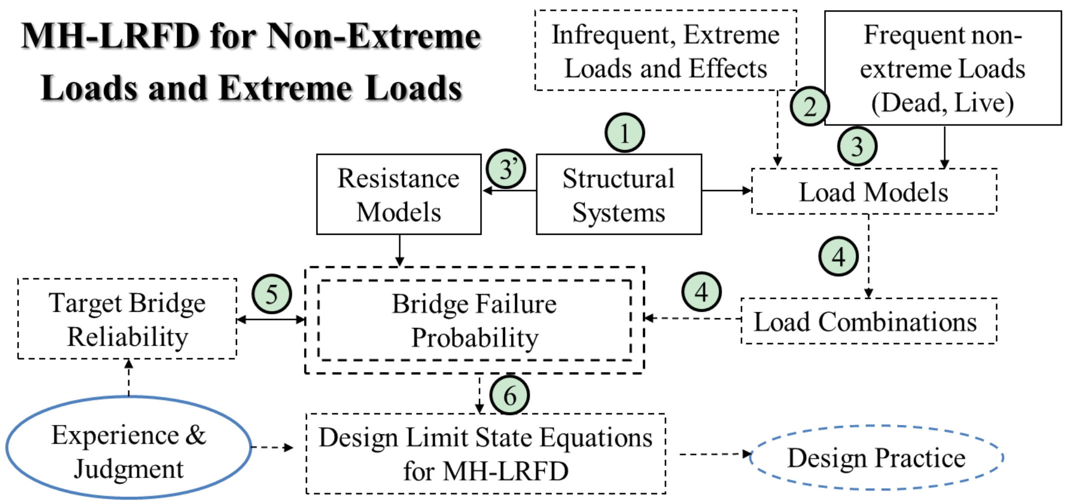

Figure 3. Flow chart for expanding LRFD to MH-LRFD

Some of the research challenges are marked as ① ~ ⑥. These difficulties may be grouped into two types. The first type requires theoretical effort so that the approach can be scientifically or mathematically explained and assumptions can be quantitatively estimated. These are more concentrated in steps ① ~ ④. The second type required considerable experience and sound professional judgment together with a sound theoretical base. These challenges are more prevailing in steps ④ ~ ⑥. The current project conducted at the University at Buffalo is more concerned with developing principles and approaches to address the first type of challenges, followed by a few case studies to illustrate the methodology to develop extreme event design limit states. This study will provide recommendations for further work including tasks to address issues involved in steps ④ ~ ⑥ to realize design guidelines for professional bridge designers.

Very briefly the challenges in steps ① ~ ④ are as follows:

- Hazard data: As mentioned earlier, a lack of data on historical hazard intensity and damage information is a major problem that leads to a number of subsequent challenges.

- Load models: Because the lack of historical records on extreme natural hazard events, the distribution of extreme hazards (and therefore their load effects) cannot be determined. Combinations of probability density function (PDF) require that these functions are “addable” or “combinable”, such as “normal” or “lognormal” distributions. A second challenge is to address the random nature of extreme natural hazard events. They are basically time-varying random variables or “random processes”. Furthermore, probabilistic combination of two or more random processes will require enormous amount of integrations and calculations.
- Resistance models: Normally to formulate bridge resistance models is a challenge due to the fact there are many different types of bridges. In this study, the process is to extend the current LRFD into MH-LRFD to maintain consistency of past efforts. Certain hazards directly affect the resistance of the bridge such as the scour effects. Because reliability-based approach is a force-based method, this “capacity change” is converted to an “equivalent load effect” so that failure probabilities may be combined on the same theoretical platform (Liang and Lee 2013). Thus, the resistance model formulated for LRFD will be used in this study in floor of devoting effort to address the challenges created by the lack of hazard and damage data due to infrequent extreme natural events and the difficulties of calculating all the failure probabilities due to individual and combined (consequential and simultaneous) events. (steps ②, ③ and ④)
- Load combinations: Probability combination and random processes with unknown distribution does not cause a standard approach. Many researchers such as Ferry-Borges (Borges and Castanheta 1972), Wen (Wen 1977), Turkstra and Madsen (Turkstra and Madsen 1980), Ghosn et al. (Ghosn 2003), Liang and Lee (Liang and Lee 2012) proposed different methods to combine time-varying loads and calculate the failure probability of a structure. Each methodology has advantages and limitations thus the optimal selection for different hazards and/or the possible combinations is case-specific. For extreme hazard events, only portion of the hazard (the critical portion of high intensity) is used through a “normalization” process of approximation so that this process of the PDF may be used to combine with other PDFs.
- Failure probabilities: To calculate the failure probabilities for non-extreme load combination was a straight forward process in formulating the current AASHTO LRFD. There only the truck load is a random process, and the PDF can be treated as a normal distribution. For two or more random processes, to calculate all the failure probabilities due to single and combinations of events is extremely complex. A “partial” failure probabilities approach is developed to systematically exhaust all possibilities in this study (Liang and Lee 2012).

Case Studies to Illustrate the Framework

A typical three-span R.C. girder bridge located at the Bay Area is used to illustrate the application of the analytical framework to establish the extreme event design limit state, shown in Figure 4. These cases are considered:

- Non-extreme load and earthquake
- Non-extreme load and vessel collision
- Non-extreme load and scour

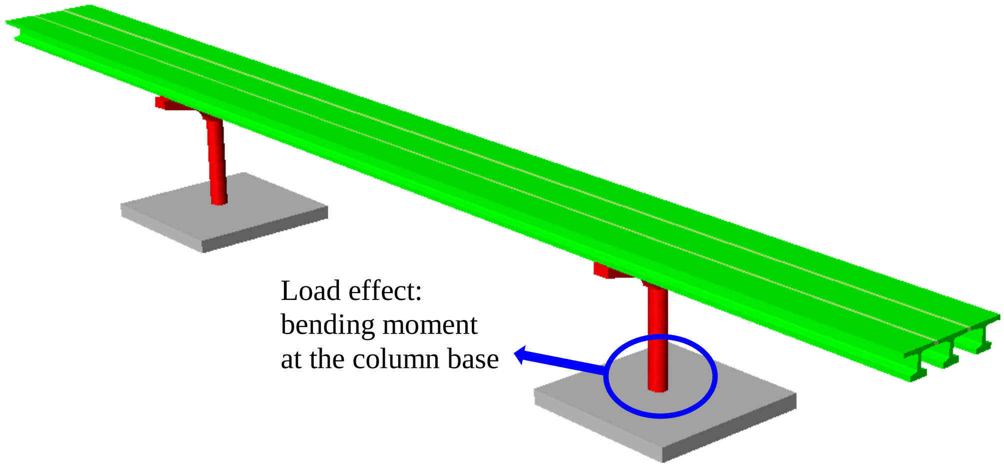

Figure 4. A typical three-span R.C. girder bridge example

These simple case studies are given only to illustrate the methodology for steps □ ~ □ for the case of combined non-extreme loads and earthquake, vessel collisions, or scour effects. Detailed case studies will be carried out and described as individual publications.

Summary

This paper describes the formulation of specific extreme event design limit state (e.g. the limit state for non-extreme load with the earthquake load effects) by using the all-hazard, reliability-based approach. Several future challenges towards the development of a comprehensive MH-LRFD are also described. The important outcome of this study is to define missing links in formulating comprehensive reliability-based MH-LRFD with primary emphasis given to the important extreme event design limit states.

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