ESTABLISHING RELIABILITY-BASED DEMAND FOR BRIDGE DESIGN UNDER MULTI-HAZARD LOADS

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<u>Abstract</u>

Under a Federal Highway Administration (FHWA) research contract at the Multidisciplinary Center for Earthquake engineering Research (MCEER), reliability-based bridge design principles and approaches for establishing Multi-Hazard Load and Resistance Factors Design (MH-LRFD) are explored. A theoretical framework to systematically establish important load combinations is developed (20). The objective of this short paper is to outline this framework and to briefly describe the major challenges of the on-going research project without mathematical formulations and results. Several relevant publications to this project including a few currently under preparation by the researchers are given in the Bibliography.

Introduction

The currently used AASHTO LRFD specifications are a reliability-based approach with the design limit states calibrated only for dead load and frequent live load. When the frequently applied loads are combined with infrequent extreme hazard loads, the probability-based methodology used to establish the AASHTO LRFD cannot be readily used. In professional practice today bridges are typically proportioned by using the LRFD and checked for strength against extreme load effect(s). The latter are available in different forms including several guide specifications published by AASHTO. Relative importance among regular loads and extreme loads and their various combinations is not known unless all loads are considered on the same platform.

Since 2008, with the support of FHWA, a research program has been carried out at MCEER which explore guiding principles, analysis and design approaches to consider all frequent and infrequent load effects on the same reliability-based platform, so that failure probabilities of the bridge due to individual loads and their combinations may be compared, and design limit states may be further developed for those cases the risks are not negligible. A theoretical framework is established to target the establishment of Multi-Hazard (MH) LRFD that are compatible with the current LRFD. In this formulation, a number of significant challenges have been identified that must be overcome, and certain assumptions and simplifications must be made and quantitatively justified.

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Due to the lack of statistical data of extreme hazard loads (which are most likely time variables and the corresponding bridge damage/failure information), there exists a fundamental question whether or not MH-LRFD is necessary and can be successfully accomplished today). Furthermore, certain extreme hazards do not use force as the basis of design (e.g. scour is capacity-based and earthquake is moving towards performance-based.) Yet structural reliability is force-based consideration. Recognizing these facts, the objectives of using the MH-LRFD platform may be regarded as (1) to have a common ground to compare and evaluate all the possible individual and combined load effects on a bridge (or bridge components) so that those load effects with relatively low risk may be ignored in bridge design established on a quantitative base; (2) to pursue those important load effect combinations and to systematically improve the AASHTO LRFD extreme event design limit states; and (3) to identify and recommend important research opportunities for future study. This paper briefly summarizes the objectives and challenges of this current MCEER research project.

<u>1. Bridge Reliability</u>

Bridge reliability under frequent loads

The current AASHTO LRFD is based on the consideration of bridge reliability, which theoretically should also be suitable for most MH loads. In general, the basic relationship between bridge failure probability p_f and reliability p_r is

$$\mathbf{p}_{\mathrm{r}} = 1 - \mathbf{p}_{\mathrm{f}} \tag{1}$$

which implies that to consider the reliability is equivalent to consider the failure probability

The basic formula of bridge failure probability is

$$P(L \ge R) = p_f \tag{2}$$

where L is maximum load effect and R is resistance, both are random variables (RV). The case ($L \ge R$) is an event. That is, equation (2) implies the probability of such event is the failure probability. From (2), the load and resistance factors can be systematically determined. The established procedure to obtain the load factors from (2) is briefly summarized in the following:

Suppose L and R follow normal distributions, a standardized variable β can be specified directly relating to the failure probability p_f . That is, with known p_f , β is uniquely determined. It is defined as the reliability index.

 β is a function of the means and standard deviations of L and R. Therefore, with known β , as well as the variation of L and R, the exact relationship between mean values of L and R, denoted as μ_L and μ_R , respectively are given as

$$\mu_{\rm L} = \eta \ \mu_{\rm R} \tag{3}$$

where η is a proportional coefficient.

The mean values of L and R are proportional to the design nominal values, denoted by NL and NR, and the proportional coefficients are known. Generally, we have

$$B_{(.)} N_{(.)} = \mu_{(.)} \tag{4}$$

where $B_{(.)} N_{(.)}$ and $\mu_{(.)}$ are bias, nominal values and mean value of load (.)

From the relationship between mean value of L and R described in (3) and (4), the relationship between the nominal design values can be written as

$$\gamma \,\mathrm{NL} = \Phi \,\,\mathrm{NR} \tag{5}$$

where NL and NR are respectively the nominal load and resistance.

Practically speaking, the load can be a combination of dead and live load, whose design nominal values are denoted as DL and LL. Usually, the ratio between DL and LL are also known. We can uniquely rewrite (5) as

$$\gamma_{\rm D} \, \mathrm{DL} + \gamma_{\rm L} \, \mathrm{LL} = \Phi \, \mathrm{NR} \tag{6}$$

Equation (6) is referred to as the design limit state equation, and γ_D , γ_L and Φ are the load and resistance factors. They directly and uniquely represent the bridge reliability. These factors quantitatively and qualitatively express the physical implications of the safety factors, used in ASD. This is an attractive feature because the bridge designers will have more confidence.

Bridge reliability under frequent and extreme loads

If the loads L are not random variables but sequences of random variables (random process), there are several challenges that need to be addressed before establishing the load and resistance factors. We do not have sufficient information on the intensity and frequency of occurrence of extreme loads and the corresponding damage/failure models of bridges.

To address bridge reliability among various frequent and infrequent loads that are random processes, we need to reconsider the formulation of bridge failure probability. In equation (2), L is the maximum value of load, which can be a single type of load; it can also be a load combination. A major difficulty is how to calculate the load combination with some loads that are time variables.

Although the dead load is time invariant, live load is time variable. The reason that dead load and live load can be added directly in the formulation of the AASHTO LRFD is because there is only one time variable load. In the case of more than one time variable loads, unless all the data of the possible time histories and amplitudes of all those loads are available, the reliability index cannot be directly obtained. Because of the lack of data, what we can do is to provide a "best" estimate to establish the reliability indices.

The best estimation can be made through a process called partial failure probabilities. This method separates these loads under certain conditions. After the separation, we will have several sub-cases and in each sub-case we only have one time variable load. In so doing, each sub-case is exactly like the situation of dead plus live load and this process can lead to a partial failure probability. The total failure probability is the sum of these partials failure probabilities.

$$p_f = p_{f1} + p_{f2} + p_{f3} + \dots \tag{7}$$

In equation (7), the second subscript 1, 2, 3, ... stands for the first, second, third, ... type of loads, which can be the dead load plus one single type of load, or they can also be the dead load plus combined loads, where the combined loads mean pure load combinations without the chance of one type of load being single.

In so doing, each partial failure probability can be used to determine a partial reliability index β_i and equations similar to (3) in format can be obtained

$\mu_{L1} = \eta_1 \ \mu_R$	
$\mu_{L2} = \eta_2 \ \mu_R$	(8)
$\mu_{L3} = \eta_3 \ \mu_R$	

Here, the subscripts L_1 , L_2 and L_3 , etc. are load effects, for example, L_1 can be DL + LL, L_2 can be DL + EQ, L_3 can be DL + LL + EQ, etc.

From equation (8), with a few additional simple steps, we can obtain the required design limit state equations dead, live and earthquake loads as:

 $\gamma_{\rm D} \, \mathrm{DL} + \gamma_{\rm L} \, \mathrm{LL} + \gamma_{\rm E} \, \mathrm{EQ} = \Phi \, \mathrm{NR} \tag{9}$

Since these load effects are calculated together, equation (9) is therefore a reliability-based design limit state equation, in which all loads are considered equally in their probabilistic contributions to the failure of a bridge. The concept of all-inclusive effect will provide comprehensive bridge reliability, which is comparatively more rigorous and the resulted load factors should be more accurate.

2. Selection of Loads

The second challenge to establish MH-LRFD is to determine the loads that should be considered for bridge failure and those that may be neglected.

One of the feasible criteria for load rejection is the value of partial reliability. Generally, if a partial failure probability is κ times smaller than the allowable failure probability, the corresponding load or load combination may be rejected. This criterion may be expressed as:

 $p_{\rm fi} \le \kappa \, p_{\rm f} \tag{10}$

where $\kappa = 0.1$ is considered to be a reasonable value by the researchers after certain simulations (not given herewith).

The advantage of using (10) is to significantly simplify the set of limit equations without scarifying the design accuracy.

3. Equivalent Load Effect

The third challenge to formulate MH-LRFD is for important hazards that directly affect the bridge capacity such as the foundation movements, fire damage and bridge scour. To include scour in formulating the bridge failure probability as an example, it is necessary to transform its capacity effect to equivalent load effect. In the following, scour effect is briefly addressed.

With the presence of scour, the resistance of the bridge, R will be reduced, say, by ΔR . Therefore, equation (2) is re-written as

 $P(L \ge R - \Delta R) = p_f \tag{11}$

in which ΔR is also a random variable.

Equation (11) can be further rewritten as

$$P(L + \Delta R \ge R) = p_f \tag{12}$$

where the reduction of bridge resistance can be treated as an equivalent load ΔR , based on which we can determine the corresponding "load factor" $\gamma_{\Delta R}$

Furthermore, we can find the relations between the reduction ΔR and the scour depth D_C , which is usually a design parameter when bridge scour is considered. It can be shown that the mean values of ΔR and D_C , denoted as $\mu_{\Delta R}$ and μ_C , have a deterministic relation given by

 $\mu_{\Delta R} = f(\mu_C) \tag{13}$

With the help of (13), we can have an equivalent load factor γ_{CD} for the nominal scour depth CD. Therefore, the bridge scour hazard may be included into the total bridge reliability design.

The above concept can be extended to other non-force based effects. In so doing, all the significant natural hazards can be included in a uniform formula, the formula of bridge reliability.

4. Range of Acceptable Reliability

The load and resistance factors are established through certain bridge component reliability. They should not change for different bridge designs. However, variations in design will always exist (different bridge types and/or dimensions). Therefore, design sensitivity analysis should be conducted by varying the size, the material type, the span, the height, and other bridge parameters, denoted by BP, to see how the load and resistance factors change.

 $\delta(BP) \rightarrow \delta(\gamma_{i}, \Phi) \tag{14}$

If the load and resistance factors (γ_i , Φ) are fixed, then the reliability will vary, that is

$$\delta(BP) \rightarrow \delta(\beta) = \Delta\beta \tag{15}$$

The challenge is the need for a criterion to quantify the result of sensitivity study. The researchers are using the variation range of reliability indices. With a variation of the bridge design parameters and with fixed value of load and resistance factors, the reliability index will change. Suppose β is the desired reliability index, with the variation, we will have β_U

and β_L (denoting the upper and lower limit of the indices). Therefore, the difference, or the range of reliability index, is given by

 $\Delta\beta = \beta_{\rm U} - \beta_{\rm L} \leq [\Delta\beta] \tag{16}$

This range must be limited to within a certain level, denoted by [(.)].

There is a need to simplify the complexities involved in formulating the design limit state equations. With different loads and their combinations, and types of bridge components, the resulting design limit state equations will yield large numbers of different values of reliability indices. Conversely, with a fixed value of reliability index, the number of corresponding limit state equations can be significantly large, which is not convenient, nor necessary for practical applications. The challenge is with acceptable range of reliability indices, we must try to reduce the sets of limit state equations for practical bridge design applications.

Based on the above approach, the reliability index will be limited to a reasonable range so that the design limit state equation can be suitable for the design of specific bridge components. Furthermore, this approach will simplify the design limit state equations.

5. Load Importance Factor

Different weighting functions or importance factors have been used to take care of the relative importance of specific situations and/or consequences in establishing the demand for bridge design. For example, importance factors are used for different types and/or locations of bridges. Another example is the weighting function of different type of seismic regions for earthquake resistant design of structures.

These weighting functions have been used primarily from the viewpoint of the relative importance of the bridge capacity to damage/failure. From the viewpoint of MH loads, due to the significantly large differences of their amplitude and occurrence rate, large differences among the load factors after the failure probability analyses will occur. Because all the loads are considered on the same platform, these differences in load factors in the limit state equations will not alter the designs too much. However, when the load condition and/or the types of bridge component changed, these loads must be reconsidered. This will result in many extra limit state equations. By considering the weighting functions of loads, the sets of limit state equations will be reduced.

There are several reasons for considering different weighting functions for extreme loads. First, the failure of a bridge or a bridge component has not been rigorously defined. The consequence of a special "failure" of different location and of different type can be rather distinct.

Secondly, the cause of a bridge failure due to different loads can receive rather different public opinions. For example, the public may be more tolerance of a bridge failure due to certain extremely rare natural hazard loads, but be more critical of the failure due to regular loads.

To emphasize the importance of load specification, the researchers recommend the concept of load importance factors. As an example, denoting the load importance factors for dead, truck and earthquake load effect by $I_{(.)}$. I_D , I_T and I_E , respectively, the load importance factor I(.) on both sides of equation (4) for these three loads will not change the relationship between the nominal and mean values of a load, namely

 $\mathbf{I}_{(.)} \, \mathbf{B}_{(.)} \, \mathbf{N}_{(.)} = \mathbf{I}_{(.)} \, \boldsymbol{\mu}_{(.)} \tag{17}$

This multiplication will affect the final determination of the load and resistance factors. To establish the values of the load importance factor is a challenging process, but it is essential in establishing design guidelines.

It should be noted that, while the load importance factors affect the load factors, they virtually do not appear in the design procedure. Instead, they are used for the purpose of code-generation.

<u>Summary</u>

The AASHTO LRFD is based on the realization of bridge reliability. It specifies the values of loads, as well as designs the resistance of bridge according to acceptable failure probability. When a bridge only subjects to dead and live load, the failure probability is calculated and the bridge reliability analysis is carried out fully with reasonable accuracy. For engineering practice, the corresponding load and resistance factors are all calibrated.

Bridges at various locations will be subjected to other extreme loads for which the bridge reliability becomes far more difficult to model. An incremental approach has been used to artificially include those loads with partial safety factors, based on engineering experiences and judgment. In other words, in so doing, the factors of dead and live load are obtained through reliability analysis and others are obtained by using different approaches. This mixed method is a departure from the track of rigorous bridge reliability analysis. In certain cases, such designed bridge is not sufficiently safe while in other cases, the design is not cost-effective.

There is a need to handle MH-loads on the same platform with the regular loads. That is, all hazard loads applying on a bridge, as long as they can affect the bridge safety, should be

equally considered. All the loads factors should be calculated based on the entire bridge failure probability. To do this, several significant challenges are facing the researchers. This short paper briefly summarizes these difficulties and the approaches that are being pursued to address these challenges by the researchers.

Acknowledgement

This study carried out at MCEER is supported by the Federal Highway Administration (Contract No. DTFH61-08-C-00012).

References

- (1) AASHTO LRFD Bridge Design Specifications, First Ed., 1994.
- (2) Kulicki, J.M. (1998). *NCHRP Report 198: Development of Comprehensive Bridge Specifications and Commentary*, Transportation Research Board of the National Academies, Washington, DC.
- (3) Kulicki, J. M., Mertz, D. R. and Wassef, W. G. "Load and resistance factor design for highway bridges," FHWA HI-95-0017, 1995
- Nowak, A. S. (1993). "Calibration of LRFD Bridge Design Code." Department of Civil and Environmental Engineering Report, UMIE 92-25, University of Michigan, 1993
- (5) Nowak, A.S. (1999). *NCHRP Report 368: Calibration of LRFD Bridge Design Code,* Transportation Research Board of the National Academies, Washington, DC.
- (6) Kulicki, J. M. (1999). "Design Philosophy of Highway Bridges," Bridge Engineering Handbook, 1999.
- (7) Lwin, M. M. (1999). "Why the AASHTO Load and Resistance Factor Design Specifications?" Transportation Research Record Paper No. 99-0935, 1999
- (8) AASHTO Guide Specifications for LRFD Seismic Bridge Design 2nd ed (2011), American Association of Sate Highway and Transportation Officials.
- (9) AASHTO Guide Specifications for Bridge Vulnerable to Costal Storms (2008), American Association of Sate Highway and Transportation Officials.
- Ellingwood B., Galambos, T.V., MacGregor, J.G., and Comell, C.A. (1980).
 Development of a Probability Based Load Criterion for American National Standard A58, National Bureau of Standards, Washington, DC.
- (11) Moses, F. (2001). NCHRP Report 454: Calibration of Load Factors for LRFR Bridge Evaluation, Transportation Research Board of the National Academies, Washington, DC.
- Simon F.Bailey and Rolf Bez (1999). Site specific probability distribution of extreme traffic action effects. Probabilistic Engineering Mechanics 14 (1999) 19-26
- Michael P. Enright, Dan M. Frangopol (1999). Reliability-based condition assessment of deteriorating concrete bridges considering load redistribution. Structural Safety 21(1999) 159-195
- (14) Ferhat Akgul, Dan M.Frangopol (2004). Time-dependent interaction between load

	rating and reliability of deteriorating bridges. Engineering Structures 26(2004)1751-1765
(15)	Wen, Y.K. Hwang, H. and Shinozuka, M. (1994). "Development of
	reliability-based design criteria for buildings under seismic load." Technical
	Report, NCEER-94-0023 (1994). State University of New York at Buffalo.
(16)	A. S. Novak and K. R. Collins (2000). "Reliability of Structures" McGraw Hill,
	2000
(17)	M. Ghosn, F. Moses and J. Wang (2003). "Design of highway bridges for extreme
	events NCHRP report 489"
(18)	S. E. Hida, (2007). "Statistical significant of less common load combinations", J of
	bridge engineering, ASCE
(19)	Turkstra, C.J., and Madsen, H. (1980). "Load Combinations in Codified Structural
	Design," ASCE, Journal of Structural Engineering, Vol. 106, No. 12; pp.
	2527–2543.
(20)	G. C. Lee, Z. Liang, J.J. Shen and C. Huang (2012). "A Framework for
	Establishing Equal Reliability-based Demand for Bridge Design under
	Multi-Hazard Loads," in preparation.
(21)	G. C. Lee, Z. Liang, J.J. Shen and J. S. O'Connor (2011) "Extreme Load
	Combinations: A Survey of State Bridge Engineers" Technical Report
	MCEER-11-0007 Oct 14, 2011, State University of New York at Buffalo.
(22)	Z. Liang and G. C. Lee, G. F. Dargush and J. W. Song (2011). Structural Damping,
	Applications in Seismic Response Modification, CRC Press.
(23)	Matlab User's Guide (2000) The Math Works Inc. 4
(24)	Paloheimo E and Hannus M (1974) "Structural Design Based on Weighted

(24) Paloheimo, E. and Hannus, M. (1974). "Structural Design Based on Weighted Fractiles," *Journal of the Structural Division, ASCE*, Vol. 100, No. ST7, pp. 1367-1378 (1974).