Risk Assessment of Highway Bridges: A Reliability-based Approach

by

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Abstract: Many countries are currently experiencing deteriorating bridge networks due to aging and growth of vehicular loads in both magnitude and volume. Repair and rehabilitation are necessary to preserve the load capacity and service performance of these bridges. Highway bridges need to be assessed to identify the structurally deficient ones early. In this way, the state, local, and federal policymakers can determine which bridges are in need of immediate attention. Note that the assessment of bridges involves a significant amount of uncertainty. To this end, the reliability theory of structures can be a helpful tool to quantify the risk involved in this process of bridge assessment. This paper addresses this issue and examines the safety and reliability of bridges using reliability-based algorithms.

Introduction

Structural safety has traditionally been described and quantified in terms of factors of safety. The theory of structural reliability instead quantifies structural safety using a measurement of risk, taking into account the uncertainty involved. It is also worth mentioning that structural safety is time variant. This is because the load demand and the capacity of a structure may change over time. For example, many developed countries are currently experiencing a problem of aging and deteriorated bridge networks. These structures' safety has been of concern also due to observed growth of load in both magnitude and volume. Evaluation, repair, and rehabilitation are necessary for the preservation of the load capacity and service performance of these existing bridges. To minimize cost of replacement or repair, the evaluation needs to accurately reveal the current load-carrying capacity of the bridge and to cover future loads and further changes in the capacity.

This study examined 10 randomly selected bridges in the state of Michigan. Safety and reliability of these bridges were assessed using the reliability-based algorithms that measure the safety reserve in a structure covering the focused uncertainty involved. The concept of structural reliability was used for the assessment of bridges. Bridge reliability will be measured using the structural reliability index β, which has been used in several recent research projects related to bridge safety [1, 2, 3], including NCHRP Project 12-33, Development of LRFD Bridge Design Specifications. In that project, the LRFD bridge design code was calibrated with respect to structural reliability index β. The design load was examined in the context of the load and resistance factor design (LRFD) following requirements of the LRFD bridge design code [4]. The target reliability index of 3.5 for calibrating the AASHTO LRFD Bridge Design Specifications [5] was used as the criterion for evaluating the reliability of the bridges.

Structural Reliability Algorithm

The reliability of a structure is defined here as its probability to fulfill the safety requirement for a specified period or its lifetime. An important component of structural reliability is concerned with the calculation or estimation of the probability of a limit state violation for the structure during its lifetime. The probability of occurrence of structural failure or a limit state violation is a numerical measure of the likelihood of its occurrence. Its estimate may be obtained using measurements of the long-term frequency of occurrence of the interested event for generally similar structures or using numerical analysis and simulation. Reliability estimates for structures are often obtained using analysis and simulation, based on measurement data for the elements involved in modeling. For example, for highway bridge structures, statistics of data for these elements are used in modeling, such as bridge components' strengths, sizes, deterioration rates, truck load magnitudes, traffic volume, etc.

The likelihood that a random variable may take a particular value is described by its probability distribution function [6] or cumulative distribution function (CDF) and probability density function (PDF). The most important characteristic parameters of a random variable are its mean value or average value, standard deviation, and probability distribution type. The standard deviation gives a measure of dispersion or variability. The standard deviation of a random variable R with a mean μ_R is often symbolized as σ_R. A dimensionless measure of the variability is the coefficient of variation (COV), which is the ratio between the standard deviation and the mean value, σ_R / μ_R.

The margin of safety for a bridge component can be defined as

$$Z = R - S, \qquad (1)$$

where R is the resistance or the load-carrying capacity of the structural component, and S is the load effect or the load demand to the component. They are modeled as random variables here because their uncertainty is evident. In general, the uncertainty associated with the resistance is due to material production and preparation process, construction quality control, etc. The uncertainty associated with load effect is related to truck weight, truck type, traffic volume, etc.

The probability of failure P_f is the probability that the resistance R is lower than the total applied load S:

$$P_f = P_r\left[R \le S\right] = P_r\left[Z \le 0\right] = \int_{-\infty}^{0} f_z(z)dz = F_z(0)\,, \tag{2}$$

where $P_r\left[E\right]$ is the probability of occurrence of the event E, $f_z(z)$ is the probability density of the variable Z, and $F_z(0)$ is the value of the CDF for Z at $Z=0$. Thus, the probability of failure is obtained by summing the probabilities that Z has an outcome smaller than 0. It is also represented by the cumulative probability distribution function $F_z(0)$. Note that the failure probability in equation (2) refers to a load effect in a structural component. Hence, this definition can be applied to a variety of load effects, such as moment, shear, and even possibly displacement. It also can be applied to a variety of bridge structural components, such as beams, slabs, and piers.

When the probability densities of R and S are available, equation (2) can also be expressed as

$$P_f = \int_{-\infty}^{+\infty} F_R(x) f_s(x)dx\,, \tag{3}$$

where $f_s(x)$ and $F_R(x)$ are the PDF of S and the CDF of R, respectively.

The structural reliability is defined as the probability that R is greater than S (or Z is greater than 0). It is also called the probability of survival P_s and is thus defined as the complement of the probability of failure:

$$P_s = 1 - P_f\,. \tag{4}$$

Structural safety can be measured by structural reliability index β [7]. The reliability index β is defined as follows using equation (2)

$$\beta = \phi^{-1}(1 - P_f), \tag{5}$$

where $\phi^{-1}(.)$ is the inverse function of the standard normal random variable's CDF. Equation (5) indicates that β is inversely monotonic with P_f. That is to say, a small P_f leads to a large β, or a large P_f to a small β. Thus, a large β indicates a safer structural component, and a small β indicates a less safe one.

Dead Load Effect Statistics

The dead load was modeled as a uniformly distributed load. The nominal values were calculated using the available bridge plans for the 10 sample bridges provided by the MDOT. Each dead load has an associated bias and coefficient of variation (COV). The COV was defined as the ratio of the standard deviation to the mean value. The dead load bias, D_{bias}, was expressed in terms of the nominal dead load effect, D_{nom}, and the mean dead load effect, D_{mean}, as

$$D_{bias} = \frac{D_{mean}}{D_{nom}}. \tag{6}$$

Since the nominal value of a dead load effect was estimated according to the bridge's plans, the mean value of the dead load effect was readily obtained by multiplying the nominal value by the bias.

Live Load Effect Statistics

Modeling the live load effect statistics of a bridge is not a trivial task mainly because it requires measurement data to cover their variation over a long period of time. Such data are usually not available. Thus, using the available measurement data that were collected over only a shorter period of time would require the prediction or projection of future loads. Therefore, bridge load modeling is often associated with a certain degree of subjective judgment of uncertainty. It is important, however, to note that "the objective of load modeling is not to come up with an exact mathematical formulation of the loads and their effects, but to develop models to represent the most salient features of the loading phenomenon" [8].

Weigh-in-motion (WIM) data were used as live loads for the bridge structures for this study. These data were collected using WIM scales. These scales are dynamic weighing systems that determine weights while vehicles are in motion. They enable vehicles to be weighed with little or no interruption of their travel. WIM scales have been designed to sense the weights of the axles passing over the instrument through the use of piezo sensors, strain gauges, or hydraulic or pneumatic pressure transducers. The readings are transmitted to a receiving unit, where they are converted to actual weights [9].

This study used the WIM truck weight data from four different types of highways referred to as Functional Classes (FC). They included Principal Arterial – Interstate – Rural (FC01), Principal Arterial – Other – Rural (FC02), Principal Arterial – Interstate – Urban (FC11), and Principal Arterial – Urban (FC12). These WIM weight data were collected over only a period of several days for each site. To perform the reliability analysis for the entire lifespan of the bridges, it was necessary to project the live load effect (moment or shear) to the expected bridge life (75 years).

For modeling flexure and shear effect of truck live load (moving load), moment and shear influence lines were developed first for each bridge's critical sections. Each influence line for a particular section and a particular load effect was used individually to obtain live load effect data for that section and load effect. Then, every truck in the WIM dataset was "run" through the influence line to find the truck's maximum load effect, using a computer program. The input parameters of the computer program are the influence lines and WIM dataset. For each influence line, after all the trucks in the WIM dataset had been used in this simulation process, a set of maximum live load effects was obtained to generate the statistics for that load effect. The results of maximum load effect for all the trucks consequently provided a set of data for modeling the random variable of that load effect.

Once the live load effect statistics for each critical section on each bridge were determined as described, the data were projected to a 75-year statistical distribution. The following approach was used for this projection.

First, an equivalent number of days of data (*EDD*) was determined using the following equation:

$$EDD = \frac{m}{ADTT}, \tag{7}$$

where m is the number of trucks in the dataset used for a case of reliability analysis, and $ADTT$ is the average daily truck traffic for the focused bridge site. Essentially, EDD indicates the equivalent days of WIM data used for the particular site focused in the reliability analysis.

Secondly, an empirical CDF was constructed by sorting the dataset from smallest to largest load effects for the m trucks included in the dataset. The corresponding value of the CDF for the i^{th} ranked load effect can be expressed as

$$F_{i,\, for\ EDD\ days} = \frac{\sum_{j \le i} n_j}{m} = Prob\left[L < L_i\right]_{for\ EDD\ days}, \tag{8}$$

where n_j is the number of trucks including load effects falling in the j^{th} interval of the CDF. Thus, F_i is the cumulative probability for the load effect L to be lower than the i^{th} interval represented by L_i.

Thirdly, the projected CDF of L for 75 years was then obtained using the EDD defined in equation (7) and the number of EDD in 75 years, N, as

$$N = \frac{(75\,years)(365\,days/year)}{EDD}. \tag{9}$$

The projected CDF, $F_{i,75}$ was estimated using

$$F_{i,75} = F_i^N \quad (10)$$

This computation was based on an assumption that each time period of duration *EDD* within the time period of 75 years is statistically independent from the others.

Bridge Beam Capacity Statistics

To calculate the capacity of the bridge beam, basic principles of engineering structural analysis/structural mechanics were used. In this case, the bridge plans used for construction were reviewed, and moment or shear capacities were computed. The determined values were taken as nominal resistance for probabilistic modeling. It should be noted that in the calculation of capacities, no resistance factors (i.e., strength reduction factors) were applied.

Reliability Index Calculations

This study used the structural reliability concept to evaluate the structural reliability of the 10 highway bridges. These bridges were randomly selected from the suite of bridges constructed or re-constructed after 1990 in the state of Michigan. Two types of superstructures were considered for this investigation: steel beam bridges (steel) and pre-stressed concrete I-beam bridges (concrete). Five bridges of each type were evaluated. A target reliability index of 3.5 was used in this study. This value was arbitrarily selected to provide the same average safety margin in the LRFD code. Note that the target level of 3.5 was selected not as an absolute criterion but rather a relative norm in the AASHTO LRFD code calibration process as the average of β levels.

For the reliability assessment of bridge components, the safety margin in equation (1) was further detailed as

$$Z = R - (D + L), \quad (11)$$

where $(D + L) = S$. D and L are respectively dead and live load effects. Live load here refers to truck load effect to the bridge component. Both D and L were also modeled as random variables. To estimate the reliability index for the bridges, it was necessary to estimate the statistical distributions for the load effects as well as the structural resistance. The mean and COV of the total load effect S were derived from the mean and COV of the dead load effect D and live load effect L.

Assuming that D and L were statistically independent of each other, the standard deviation σ_S was expressed as

$$\sigma_S^2 = \sigma_D^2 + \sigma_L^2, \tag{12}$$

where σ is the standard deviation, and subscripts S, D, and L are respectively for total, dead, and live load effect. The mean value for the total load effect S was then the sum of the means of D and L

$$\mu_S = \mu_D + \mu_L, \tag{13}$$

where μ indicates the mean. The COV of the total load effect was then expressed as

$$V_S = \frac{\sigma_S}{\mu_S}. \tag{14}$$

The reliability index β defined in equation (5) was calculated using the First Order Reliability Method [10]. However, since both the load S and resistance R were assumed to be log-normally distributed, the calculation of the reliability index was simplified to

$$\beta = \frac{\ln(\mu_R) - \ln(\mu_S)}{\sqrt{V_R^2 + V_S^2}}, \tag{16}$$

where μ_R and μ_S represent the means of the resistance and total load effect, and V_R and V_S are their coefficients of variation, respectively. Figure 1 presents a flowchart of the overall procedure of reliability index analysis.

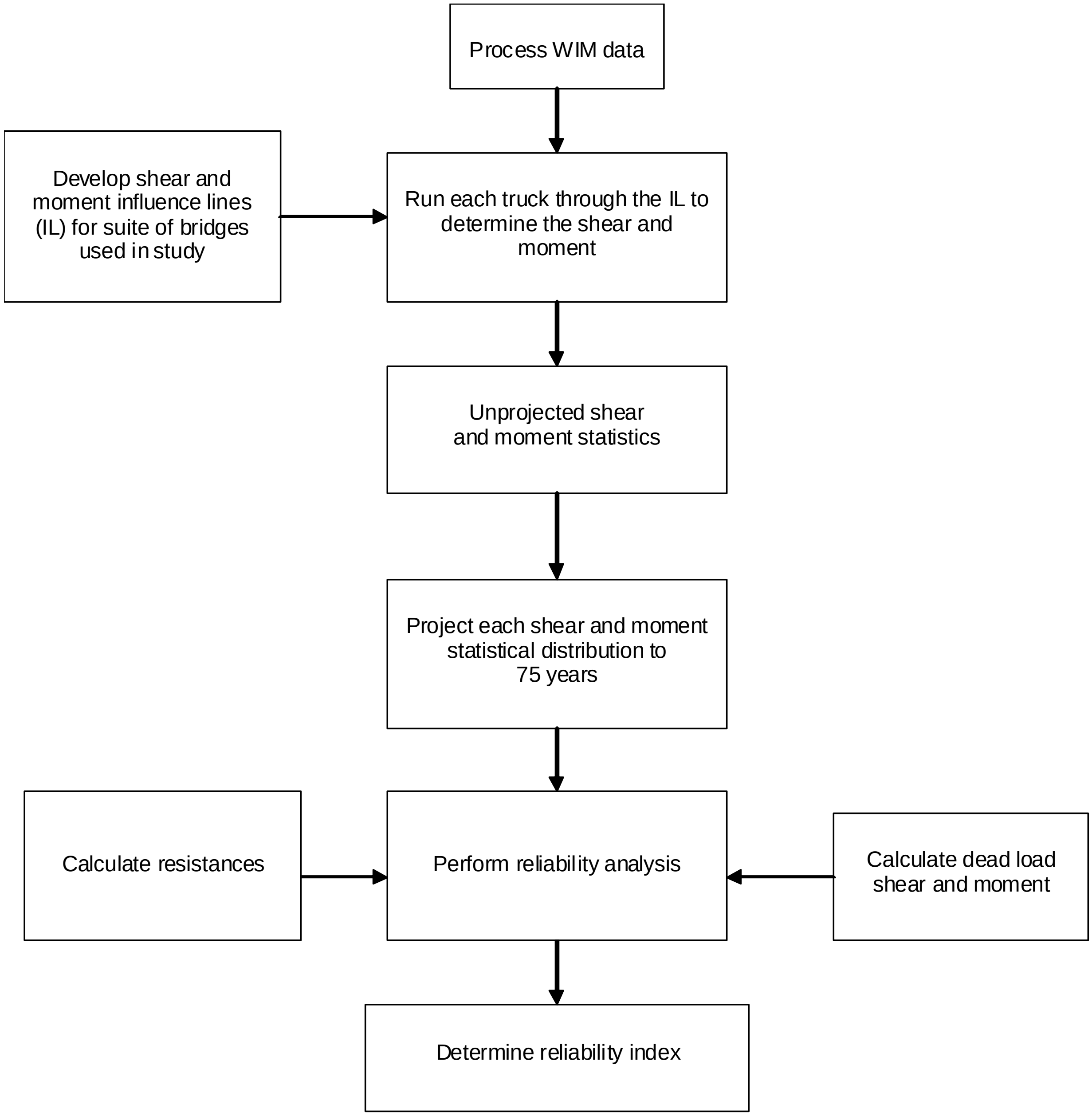

Figure 1: Flowchart of reliability index calculation

Results

The reliability indices of the 10 sample highway bridges were calculated following the overall procedure shown in Figure 1. The results are shown in Figure 2 and Figure 3. As discussed earlier, the reliability index calculation model used here refers to beam flexure or beam shear.
It can be seen from Figure 2 and Figure 3 that the reliability index β values for moment ranged from 3.6 to 5.8. In comparison, the β values for shear ranged between 4.9 and 8.1. It can be seen that the values for the steel bridges and concrete bridges followed similar trends. The results show that the bridges under FC11 and FC12 consistently have the lowest β values. These lower levels of β values are attributable to the heavier truck loads that are expected in FC11 and FC12, because these two functional classes are in the urbanized areas.

Using the target reliability index of 3.5 as a threshold, results have shown that the bridges investigated in this study are adequate. Note also that the target value of 3.5 is used for a single structural component (i.e., a bridge beam) and not the entire bridge structural system. Hence, a value above 3.5 does not necessarily mean the bridge is safe, because it is not the component that determines the safety of a bridge, but the system.

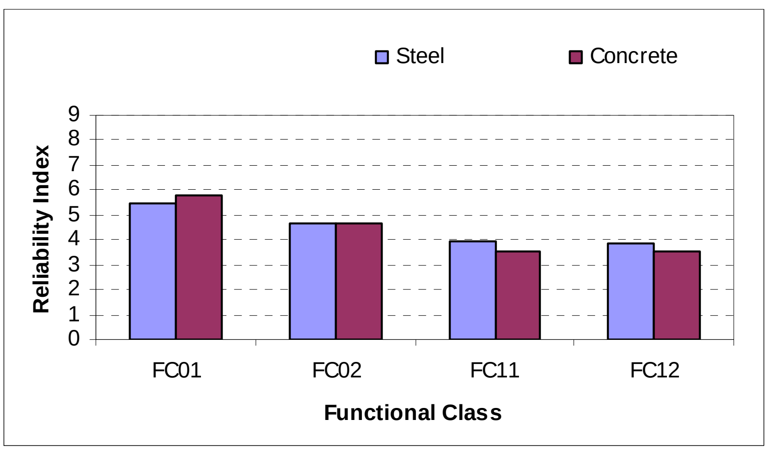

Figure 2: Comparison of reliability indices for moment

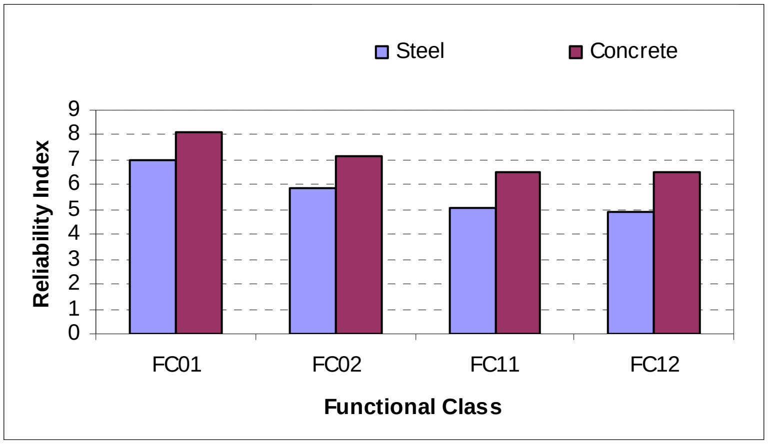

Figure 3: Comparison of reliability indices for shear

Conclusions

The safety and reliability of highway bridges are essential for the nation's economic growth. Bridge structural adequacy can be assessed using the reliability-based approach. Being able to identify structurally deficient bridges will help the policymakers prioritize those in need of immediate repair, rehabilitation, or even replacement. As a result, this will help maintain bridge systems to keep them safe and sound throughout their lifespan.

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References

[1] Nowak, A.S. (1999). Calibration of LRFD Bridge Design Code. NCHRP Report 368, Transportation Research Board, National Academy Press, Washington, D.C., U.S.A.

[2] Moses, F. and Verma, D. (1987). Load Capacity Evaluation of Existing Bridges. NCHRP Report 301, Transportation Research Board, National Academy Press, Washington, D.C., U.S.A.

[3] Fu, G. and Hag-Elsafi, O. "Vehicular Overloads: Load Model, Bridge Safety, and Permit Checking." *ASCE Journal of Bridge Engineering*, Vol. 5, No. 1, Feb. 2000, 49–57.
[4] AASHTO (1998). "LRFD Bridge Design Specifications." 2nd Ed., Washington, D.C., U.S.A.
[5] Nowak, A.S. (1999). Calibration of LRFD Bridge Design Code. NCHRP Report 368, Transportation Research Board, National Academy Press, Washington, D.C., U.S.A.
[6] Ang, A-H.S., and Tang, W.H. (1975). "Probability Concepts in Engineering Planning and Design, I." John Wiley & Sons, New York.
[7] Frangopol, D.M. (1999). Bridge Safety and Reliability. American Society of Civil Engineers, U.S.A.
[8] Thoft-Christensen, P. and Baker, M.J. (1982) "Structural Reliability Theory and Its Applications." Springer-Verlag, Berlin.
[9] Traffic Monitoring Guide, U.S. Department of Transportation, Federal Highway Administration, October 1992.
[10] Madsen, H.O., Krenk, S., and Lind, N.C. (1986). "Methods of Structural Safety." Prentice Hall, Inc. Englewood Cliffs, NJ, U.S.A.

Biography

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