AC 2008-1012: RELIABILITY OF BRIDGES: SIGNIFICANT ADDITION TO CIVIL ENGINEERING CURRICULUM

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Reliability of Bridges: Significant Addition to Civil Engineering Curriculum

Abstract

Rapid highway system development in the United States in the 1960's and 1970's has resulted in a large number of bridges reaching a stage in need of repair, rehabilitation, or replacement. Truck loads have also been steadily increasing since then. This has made the situation even worse. Many developed countries are currently experiencing a problem of aging and deteriorated bridge networks as well as observed growth of load in both magnitude and volume. These structures' safety has been of concern. The bridges experiencing vehicular overloads are subjected to a higher risk of distress, damage, and even catastrophic failure that will jeopardize human lives. 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. Note that this 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.

Addition of a semester-long course on reliability of bridges in the civil engineering curriculum can greatly help the students understand the fundamental concepts of bridge safety. Civil engineering graduates will have the capability in evaluating bridge safety which they can confidently use in their future career. As a result, this will encourage students to specialize in the field of bridge reliability and eventually the nation's bridge assessment experts will grow in number. These experts will have the technical know-how to help maintain bridge infrastructures to avoid catastrophic failures and most significantly of all, save lives.

Introduction

The load carrying capacity of highway bridges is clearly influenced by the standard design load used in their design. The design load also has a significant effect on the durability of these bridges. Highway bridges usually possess reserved strength to accommodate occasional overloads although they were designed for standard load. This additional amount may be substantial depending on a number of factors. However, many countries allow overloads on their highway systems. In some states of the U.S.A., for example, vehicles that exceed the national truck weight limit are allowed to cross the bridges. This issue becomes critical when actual truck loads are noticeably higher than the design load.

Safety and reliability of these bridges will be assessed using the reliability-based algorithms that will measure the safety reserve in a structure covering the focused uncertainty involved. The concept of structural reliability will be 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 can be 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] can be used as the criterion for evaluating the reliability of the bridges.

Assessment of the bridges in terms of their safety and reliability may usefully be incorporated into the civil engineering courses. Development of "Reliability of Bridges" course may be a significant addition to the civil engineering curriculum. The need for safe and reliable bridges is very essential for the growth of the nation. Thus, offering a course that deals with reliability of bridges is very significant.

Course Description and Objective

The Reliability of Bridges course will be a full three credit-hour undergraduate elective course in a semester system. The course will be intended for senior level civil engineering students. Its objective is to introduce students to the concept and fundamental skills for bridge reliability assessment. Upon completion of the course, the students are expected to be able to evaluate highway bridges according to US specifications.

The course is primarily a lecture course. In addition to traditional homework assignments and exams, a term project will be required from the students. The term project will enhance students' learning through evaluating existing highway bridges to prepare them for the types of problems they will encounter in the real world. This will offer them hands-on experience on the assessment of the reliability of bridges. As a part of the project, they may have to visit the WIM stations and the bridges used in their study. The class may be divided into groups of three or four. Each group may evaluate two to three existing highway bridges. Towards the end of the semester, each group is expected to complete and present their project results to the class and submit a written report of the project. This will help students develop their oral and written communication skills.

The following algorithms will be among the important sections of the course that can be used for the term project.

Structural Reliability Algorithm for Bridge Structures

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

$$Z = R - S \tag{1}$$

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 Eq. (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, Eq. (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 greater than 0). It is also called probability of survival P_s and 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 (2)

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

where $\phi^{-1}(.)$ is the inverse function of the standard normal random variable's CDF.

When the resistance and load effect can be modeled as normal random variables independent of each other, the safety margin Z is then also a normal random variable. In this case the reliability index β can be more easily expressed as:

$$\beta = \frac{\mu_Z}{\sigma_Z} \tag{6}$$

where μ_z and σ_z are the mean and the standard deviation of random variable Z. They can be computed as follows according to (1):

$$\mu_Z = \mu_R - \mu_S \tag{7a}$$

$$\sigma_Z = (\sigma_R^2 + \sigma_S^2)^{1/2} \tag{7b}$$

where μ and σ are symbols for the mean and standard deviation. Subscripts R and S indicate the random variables referred to. Thus substituting (7) into (6) leads to

$$\beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \tag{8}$$

For the reliability assessment of bridge components, the safety margin in Eq. (1) can be further detailed as

$$Z = R - (D + L) \tag{9}$$

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 are also modeled as random variables. In order to estimate the reliability index for bridges, it is necessary to estimate the statistical distributions for the load effects as well as the structural resistance.

This section will provide students the understanding of the concept of reliability analysis. The succeeding section discusses the modeling of these variables.

Modeling of Dead and Live Load Effects on Bridges

Modeling the effects of bridge loads is not a trivial task mainly because it requires measurement data to cover their variation over a long period of time. Very often such data are not available. Thus, it may require the prediction or projection of future loads, using measurement data collected over a shorter time period. 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].

Dead Load Effects

Although the dead load of a bridge system is not considered to vary significantly with time, the actual value of the load is uncertain. In addition, the analysis of the dead load effect on the bridge structure also involves a degree of uncertainty, for example, due to the assumptions about the structural members' boundary conditions, etc. For many bridges, for example, the primary dead load is due to the weight of the primary beams, the deck, and the deck's surface. The uncertainties in predicting the magnitude of the dead load are due to variations in the density of the materials used to form the deck and other members as well as the variations in the dimensions of these members.

The dead load effect's nominal values can be calculated using the available bridge plans. The dead load is assumed to act as a uniformly distributed load to the focused bridge member. Each dead load has an associated bias and coefficient of variation (COV). The COV is defined as the ratio of the standard deviation to the mean value. The dead load bias, D_{bias}, is expressed in terms of the nominal dead load effect, D_{nom}, and the mean dead load effect, D_{mean} as

$$D_{bias} = \frac{D_{mean}}{D_{nom}} \tag{10}$$

In the dead load effects calculations, the students will learn how to interpret bridge architectural and detail drawings. This will give them the training that they may be able to apply into any other infrastructure drawings.

Live Load Effects

There are a large number of transient loads that are normally applied on highway bridges. These include all moving loads as well as temperature effects, wind and earthquake loads. For typical short to medium span bridges, the most important loads are those due to moving vehicular traffic including their static and dynamic effects. Although these two effects occur simultaneously as one or more vehicles move across the bridge structure, it has been traditional in bridge engineering practice to treat the static effect separately from the dynamic effect. With this approach, bridge members are analyzed for the static effect of the vehicles and then a dynamic amplification factor is used to account the effect of bridge vibrations due to moving vehicles.

There are two existing methods for measuring weights of trucks. One is static weighing and the other is dynamic weighing. Static weighing involves stopping a vehicle and measuring its weight statically, the weight of which is termed as *static weight*. Dynamic weighing allows a vehicle to be weighed while in motion, or dynamically, the weight of which is termed as *weigh-in-motion* (WIM) *weight*. Dynamic weighing through high-speed WIM systems provides continuous unbiased weighing of practically all vehicles passing the system. They are also hardly noticeable that the drivers are not aware of the weighing operation and do not try to avoid it. WIM 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]. Dynamic truck weighing is more advantageous than static weighing. For this reason, only WIM data are to be reported to the Federal Highway Administration (FHWA) Truck Weight Study. Hence, WIM data become readily available from state Department of Transportation (DOT). WIM data are used as live load of the bridge structures under investigation.

Since WIM data are usually readily available from state DOT's, this is a good way of training students how to get in touch with the DOT officials. They may also be able to observe how the data are being collected by visiting the WIM stations.

Data Projection

Note that there is no 75 year WIM data collected yet that can be used to analyze reliability of bridges for its lifespan. Sometimes available WIM data were collected only over a period of several days for each site. In order to perform the reliability analysis for the entire lifespan of the bridges, it is 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 will need to be developed first for each bridge's critical sections. Each influence line for a particular section and a particular load effect will be used individually to obtain live load effect data for that section and load effect. Then every truck in the WIM dataset will be "run" through the influence line to find the truck's maximum load effect, using a computer program provided by the instructor. 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 would be obtained to generate the statistics for that load effect. The results of maximum load effect for all the trucks consequently will provide a set of data for modeling the random variable of that load effect. The following approach is used for this projection.

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

$$EDD = \frac{m}{ADTT} \tag{11}$$

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 is 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

$$F_{i,for\,EDD\,days} = \frac{\sum_{j \le i} n_j}{m} = Prob\left[L < L_i\right]_{for\,EDD\,days} \qquad (12)$$

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 is then obtained using the EDD defined in Eq. (11) and the number of EDD in 75 years, N, as

$$N = \frac{(75\,years)(365\,days/year)}{EDD} \qquad (13)$$

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

$$F_{i,75} = F_i^N \qquad (14)$$

This computation is based on an assumption that each time period of duration EDD within the time period of 75 years are statistically independent from one another.

In the process of data projection the students will learn structural analysis, statistics, and computer program application. These will equip them with the technical knowledge that they need in their engineering career.

Figure 2 presents a flowchart of the overall procedure of reliability index analysis.

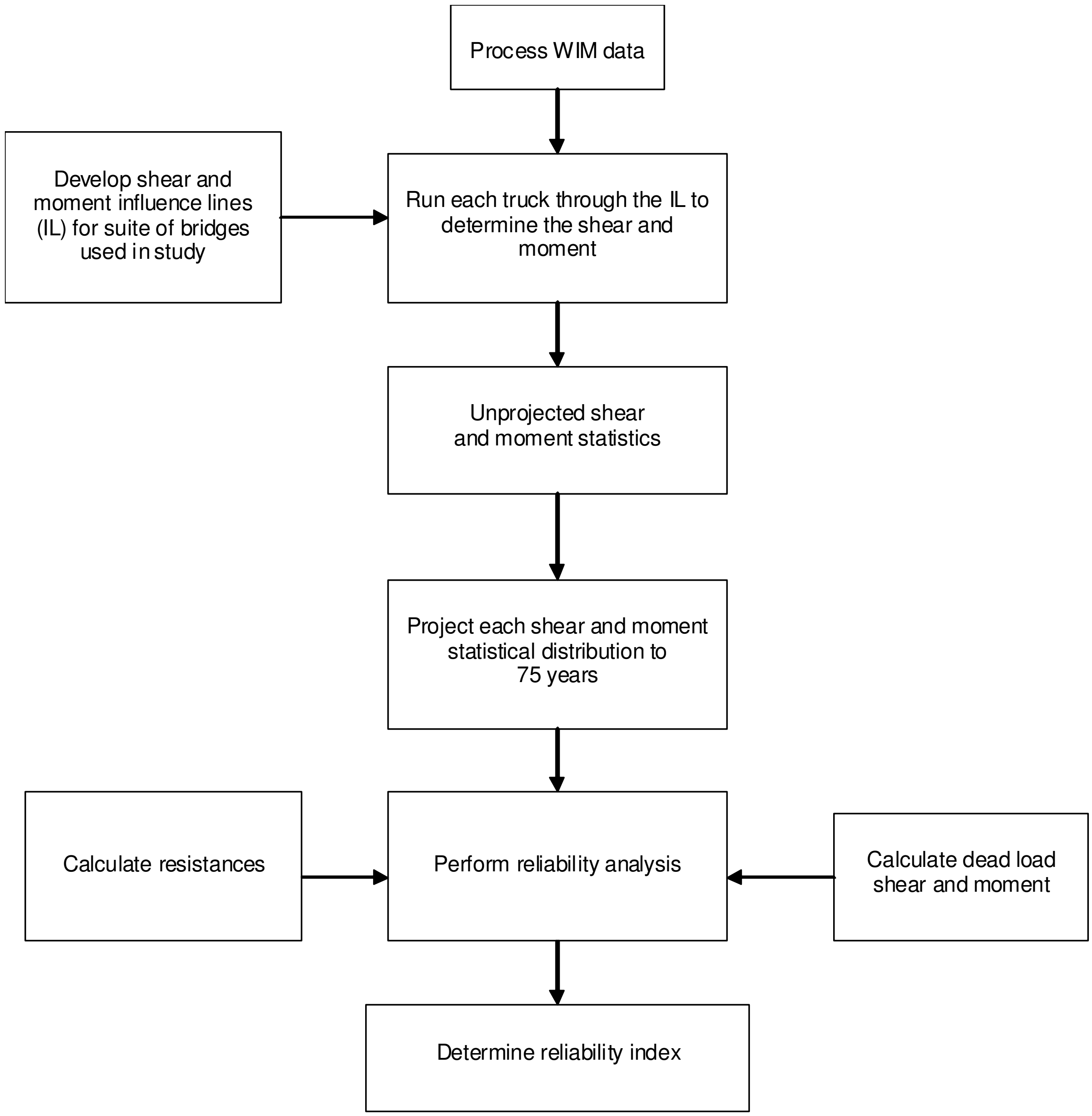

Figure 2 Flowchart of reliability index calculation

Conclusions

Safe and reliable public infrastructures are very essential for the nation to prosper and grow. With funding limitations, the challenge for policymakers at the state, local, and federal level is to determine which bridges are the highest priority for repairs. Incorporating a course in reliability of bridges into the civil engineering curriculum will produce civil engineering graduates with the capability of bridge reliability assessment. This will also draw more students to be interested in specializing into bridge reliability and eventually produce more bridge assessment experts in the nation. In this way, structurally deficient bridges can be identified early and be repaired to make them safer. This will help in maintaining current bridge infrastructures to avoid catastrophic failures. As a result, not only bridges are saved but most importantly, human lives.

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