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Reliability analysis of circular reinforced concrete columns subject to sequential vehicular impact and blast loading

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ABSTRACT

This study investigates the first-order second-moment structural reliability of circular reinforced concrete (RC) bridge columns subjected to vehicular impact, explosive blast, and sequential vehicular impact and explosive blast loading. The analysis is performed for five vehicle types of increasing size, mass, and explosive charge capacity. The structural reliability under vehicular impact is shown to be highly sensitive to column diameter, reinforcement ratio, and vehicle velocity. The structural reliability under explosive blast loading is shown to be highly sensitive to column diameter, reinforcement ratio, and blast standoff distance. In general, the structural reliability is lower under explosive blast loading. The structural reliability under sequential loading is evaluated by the newly proposed resistance reduction method and by fault tree analysis. A resistance reduction factor for the second event is defined as a function of the probability of failure under the first event. The resistance reduction method is shown to be more conservative than fault tree analysis and has the added benefit of allowing for the derivation of the density function for performance under sequential loading.

1. Introduction

Human safety and asset protection are the fundamental tenets of structural design. To that end, structures are designed to withstand self-weight, service loads, and environmental loads as deemed appropriate by relevant design codes [1]. Economic concerns and the low probability of occurrence generally preclude the design of civilian structures to withstand hazardous loadings such as impact or explosive blast. Traditionally, only military or other high-risk structures warrant these considerations. However, with increasing terrorist activity, the design of civilian infrastructure to withstand such hazardous loads is of increasing importance.

Existing design codes allow for individual application of hazardous loadings but do not include provisions for sequential or simultaneous application of multiple hazardous loadings [1,2]. The ability of a structure to resist damage is dependent not only on the design of the structure, but also on the loads and combinations thereof experienced by the structure [3]. Consideration of loads in sequence is of particular importance in the case of hazardous loadings. An improved understanding of residual capacity in structural elements is necessary to more adequately model the stability of damaged structures [4]. A structure may suffer from reduced load capacity as the result of some initial loading and may then be immediately subjected to an additional load. For example, a structure may be subject to sequential vehicle impact and blast loadings when a vehicle carrying an explosive charge collides with a structural element. This type of even may be accidental or the result of an intentional act of terrorism.

Buildings have typically been the focus of blast damage analysis, but it is valuable to extend these analyses to bridge structures for several reasons [5,6]. The social and economic impact of removing bridges from service in the event of damage is significant [7]. Bridges are also in most cases easily accessible, relatively unsecured, and subject to limited surveillance. Bridge piers are of particular interest because local failure of these individual components often leads to progressive failure of the entire structural system. A number of studies have investigated the individual—but not sequential—effects of vehicular impact and explosive blast loading on bridge piers [8–12].

Vehicular impact is the third leading cause of bridge damage or failure [8,13]. Damage in vehicle-bridge impact events occurs simultaneously to the vehicle and the bridge element as a result of the compliance of the vehicle [9]. The failure mechanisms in this type of impact are similar to those in static loadings and can therefore be treated as such [9]. Though short in duration, blast loadings are particularly catastrophic due to their high intensity. An explosive blast results in a very high-velocity shock wave, which is the primary cause of damage; if the charge weight and standoff distance are known, then

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it is possible to estimate the resulting damage to a structure [5,6,14,15].

The objective of this study is to examine the effects of sequential vehicular impact and blast loading on the structural reliability of circular reinforced concrete (RC) bridge piers. To that end, this paper will discuss:

1. The probability of failure of a circular RC bridge pier subjected to vehicular impact and the impact loading factors that most contribute to high probabilities of failure;
2. The probability of failure of a circular RC bridge pier subjected to blast loading and the blast loading factors that most contribute to highly probable failure; and
3. The probability of failure of a circular RC bridge pier subjected to sequential vehicular impact and blast loading.

2. Analytical procedure

2.1. First-order second-moment (FOSM) reliability analysis

Reliability analyses are performed to evaluate the performance of structures in real-world conditions with uncertain loadings and structural details. Simple structural analysis will show if a structure will or will not fail under precise conditions; in cases where the structural demand or resistance are non-deterministic, a reliability analysis is instead used to determine the likelihood of failure. The FOSM reliability analysis described here is conducted according to the following procedure for the individual cases of vehicular impact and explosive blast loading:

1. Identify the system and define the limit state equation (performance function);
2. Identify variables as deterministic or non-deterministic; assign values and distributions according to relevant literature and building code;
3. Analytically solve for the FOSM mean-value reliability index and probability of failure; and
4. Validate the FOSM mean-value results using Monte Carlo analysis.

The structural reliability under sequential loading is then analyzed by the resistance reduction method and by fault tree analysis.

2.1.1. FOSM reliability analysis for a single event

The performance function for a system takes the general form $P = Z - Q$ where Z is the resistance or capacity and Q is the demand or load. The performance function is defined such that:

$$P(Z,Q)\begin{cases} >0 \text{ for a safe structure} \\ =0 \text{ at the limit state} \\ <0 \text{ for failure} \end{cases} \quad (1)$$

The resistance Z and demand Q are functions of a number of variables which are either deterministic or non-deterministic. The former are known with certainty while the latter are continuous random variables that follow some known or assumed frequency distribution. In simple cases where Z and Q are functions of one or perhaps two random variables, the probability density function associated with $P(Z,Q)$ may be solved analytically. The probability of failure P_f can then be found by integration of the resulting density function over the failure region (i.e., $P(Z,Q) < 0$). The reliability index β is the inverse of the coefficient of variation of $P(Z,Q)$. If $P(Z,Q)$ is Gaussian, or can be thus approximated, the reliability index and probability of failure are related by Eq. (2), where Φ^{-1} is the inverse of the tail probability function of the standard normal distribution.

$$\beta = -\Phi^{-1}(P_f) \quad (2)$$

It is often the case that Z and Q are complex functions of many non-deterministic variables. It may then be impractical or impossible to analytically solve the density function associated with $P(Z,Q)$. The reliability index for a linear performance function $P(Z,Q) = a_0 + \sum_{i=1}^{n} a_i X_i$ is given by Eq. (3), where μ_{X_i} and σ_{X_i} are the mean and standard deviation of X_i [2].

$$\beta = \frac{a_0 + \sum_{i=1}^{n} a_i \mu_{X_i}}{\sqrt{\sum_{i=1}^{n} (a_i \sigma_{X_i})^2}} \quad (3)$$

When the performance function is non-linear, it is convenient to construct a linear approximation of the performance function by Taylor series expansion. The reliability index is then given by Eq. (4) [2].

$$\beta = \frac{P(\mu_{X_1},\mu_{X_2},\dots,\mu_{X_n})}{\sqrt{\sum^{i=1n} (a_i \sigma_{X_i})^2}} \quad \text{where } a_i = \frac{\partial P}{\partial X_i}\bigg|_{\text{evaluated at mean values}} \quad (4)$$

Eq. (2) still provides a valid approximation of the probability of failure as long as the density function associated with $P(Z,Q)$ can be assumed Gaussian (or approximately so). In either case, an approximation of the density function associated with $P(Z,Q)$ can be found by recognizing that the reliability index is the inverse of the coefficient of variation (i.e., $\beta = \mu/\sigma$) and that the density function is centered about the expected value of the performance function $\mathrm{E}[P(Z,Q)] = P(\overline{Z},\overline{Q})$, where $\overline{Z}$ and $\overline{Q}$ are the mean values of the resistance and demand.

It may also be convenient to adopt a numerical approach for reliability analysis. In this case, the Monte Carlo method can be employed. If the resistance is $Z(\boldsymbol{X})$ and the demand is $Q(\boldsymbol{Y})$, where $\boldsymbol{X} = \{X_1,X_2,\dots,X_m\}$ and $\boldsymbol{Y} = \{Y_1,Y_2,\dots,Y_n\}$, then a set of N random observations can be generated using the known density function associated with each X_i and Y_i. The density function associated with $P(Z,Q)$ can then be approximated by the frequency distribution of the set $\boldsymbol{P}_k = Z(\boldsymbol{X}_k) - Q(\boldsymbol{Y}_k)$ where $k = 1,\dots,N$. A numerical approach may be favored over an analytical solution for a number of reasons. It is convenient to assume that the density function associated with $P(Z,Q)$ is Gaussian (or approximately so). This may be a poor assumption if any X_i or Y_i are not Gaussian. The Monte Carlo method can be used to evaluate the suitability of this assumption. If a relatively small number of X_i or Y_i are non-Gaussian, or the non-Gaussian variables are approximately Gaussian (e.g., some log-normal, beta, or Poisson distributions), the set P_k may closely resemble a Gaussian, and Equations (2)–(4) remain valid. In cases where the set P_k is decidedly non-Gaussian, then the cumulative frequency distribution resulting from the Monte Carlo analysis must be used to approximate the reliability index and probability of failure. The main drawback of the Monte Carlo method is slow convergence; Monte Carlo analyses are known to converge at a rate of the inverse square root of the number of simulations ($1/\sqrt{N}$). This is of increasing importance as the number of non-deterministic variables increases. Alternative methods such as the Latin Hypercube sampling method offer improved computational efficiency and fast convergence, but the more ubiquitous Monte Carlo method is used in this paper.

2.1.2. FOSM reliability analysis for sequential loading

The structural reliability of a system subject to sequential events is typically modeled by fault tree analysis, wherein the probability of failure of a system subject to n independent loadings is defined according to the laws of compound probability [3]. The probability of failure due to the sequential loadings $P_f(E)$ is given by Eq. (5) where $P_f(E_i)$ is the probability of failure of the system due to the i-th event.

$$P_f(E) = 1 - \prod_{i=1}^{n} [1 - P_f(E_i)] \quad (5)$$

Eq. (5) is derived with the assumption that the failure events are independent. This is a poor assumption in the case of sequential loading, because the damage that occurs in the structure due to the first loading necessarily increases the probability of failure due to successive loadings. Take, for example, a simple case where the probability of failure of a column under impact loading is one-half and the probability of failure