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Reliability assessment of aging structures subjected to gradual and shock deteriorations

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ABSTRACT

Civil structures and infrastructure facilities are susceptible to deterioration posed by the effects of natural hazards and aggressive environmental conditions. These factors may increase the risk of service interruption of infrastructures, and should be taken into account when assessing the structural reliability during an infrastructure's service life. Modeling the resistance deterioration process reasonably is the basis for structural reliability analysis. In this paper, a novel model is developed for describing the deterioration of aging structures. The deterioration is a combination of two stochastic processes: the gradual deterioration posed by environmental effects and the shock deterioration caused by severe load attacks. The dependency of the deterioration magnitude on the load intensity is considered. The Gaussian copula function is employed to help construct the joint distribution of correlated random variables. Semi-analytical methods are developed to assess the structural failure time and the number of significant load events (shocks) to failure. Illustrative examples are presented to demonstrate the applicability of the proposed model in structural reliability analysis. Parametric studies are performed to investigate the role of deterioration-load correlation in structural reliability.

1. Introduction

Civil infrastructure facilities are often exposed to severe operating or environmental conditions during their service life, which are responsible for the deterioration of structural strengthen and stiffness with time. The failure of important structures, caused by either environmental or anthropogenic extreme events, may lead to substantial economic losses to the facility owner or occupant and further a ripple effect in the surrounding community. Recently, public awareness has been raised significantly regarding infrastructure performance in the context of community resilience, for which the research community and engineers are seeking advanced implementations for building and construction practice. With this regard, reliability analysis is a frequently used tool in terms of evaluating and managing structural safety and serviceability, aimed at providing quantitative information that a structure can withstand future extreme events with an acceptable level of reliability during its future service life. There has been considerable amount of literature published in the past two decades regarding safety evaluation and damage assessment of existing aging structures [1–13]. Many factors such as environmental conditions, variation in load intensity over time, and quality of periodic maintenance, are believed to have essential impacts on structural safety. However, the exact influence of these factors are, for the most cases, difficult to predict. Due to the presence of time-dependent behavior of both structural resistance and load process, the safety assessment and/or service-life prediction of deteriorating structures should be performed using reliability-based methods, considering the time-dependent characteristics and the uncertainties associated with both the load and resistance [14,15]. Mori and Ellingwood [1] proposed a methodology for assessing structural time-dependent reliability considering both the randomness of resistance and the stochastic nature of load. This method was further used to predict the remaining service-life of deteriorating reinforced concrete (RC) structures [16,7,2]. However, Mori and Ellingwood [1] assumed that the load process is stationary, i.e., the statistical parameters of load intensity and frequency are time-invariant during the structure's lifetime. The assumption of stationary load process may become untenable in many cases, where the load intensity and (or) frequency may change in time (e.g., [17–19]). Recognizing this, Li et al. [20] improved the method by Mori and Ellingwood [1] to account for the non-stationarity in load process in structural reliability assessment. However, relatively rudimentary models as in existing studies have been employed to account for the main characteristics of structural deterioration [16,10,1,20–23], which has been assumed to be either fully-correlated or deterministic, and is independent of the

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load process. In fact, the resistance deterioration of aging structures is a stochastic random process by nature [24–26], and is positively related to the load history by noting that a greater load intensity may result in a severer physical damage (e.g., crack on concrete structures) and further an acceleration to the deterioration process (e.g., the chloride-induced corrosion of reinforced steel bars) [27]. Moreover, significant load events (shock events) also contribute to the accumulation of structural fragility [28–30], indicating again the positive correlation between deterioration and load processes. As a result, it is of importance to develop a deterioration model for structural reliability analysis, which accounts for the potential deterioration-load correlation. This paper proposes a new deterioration model for aging structures that can be used in time-dependent structural reliability analysis. The resistance deterioration is modeled as a combination of gradual and shock processes, both are stochastic with a dependency on the load effects. The Gaussian Copula function is employed to describe the deterioration-load correlation. Semi-analytical methods are developed to assess the time-dependent structural reliability incorporating the proposed deterioration model. Illustrative examples are presented to show the applicability of the proposed model in structural reliability analysis. Parametric studies are performed to investigate the role of resistance deterioration and deterioration-load correlation in structural safety.

2. Existing models of resistance deterioration

The environmental or operating conditions are responsible for the deterioration of in-service structures. For example, possible aging mechanisms of RC structures, as revealed in early studies (e.g., [31]), may include sulfate attack, alkali-silica reaction, corrosion of steel bars, frost attack, chloride (Cl^-) penetration and carbonation. Since the deterioration is a complex process and may include multifarious mechanisms [14,26], significant efforts have been made to capture the deterioration characteristics based on experimental laboratory data [32–35]. Zhong et al. [33] proposed to use a factor to account for the stiffness degradation of RC structures. The accuracy of the method was examined through a comparison with the data from laboratory experiments. Ma et al. [34] utilized the statistical data obtained from experimental tensile tests on corroded RC specimens to quantitatively measure the variation associated with the structural resistance. However, the service conditions of structures may differ dramatically from those in the laboratory. The extrapolation of experimental data is often questionable in reliability analysis of real structures [14]. Moreover, the data fitting-based models may lead to a significantly biased estimate if the sample size is limited. Alternatively, many researches have proposed physics-based stochastic models for the deterioration process, where the undetermined parameters may be calibrated using observed data. Mathematically, for an aging structure, the time-variant resistance varies with time according to

$$R(t) = R_0 \cdot G(t) \tag{1}$$

where $R(t)$ is the resistance at time t, R_0 is the initial resistance and $G(t)$ is the deterioration function. R_0 is a random variable with uncertainty arising from the material and geometry properties and can be simplified as deterministic for the case where its uncertainty is negligible compared with that associated with the deterioration process. $G(t)$ is a monotonous (non-increasing) stochastic process with the exclusion of rehabilitation or other types of strengthening. Mori and Ellingwood [1] modeled the deterioration function $G(t)$ as deterministic, taking the form of Eq. (2) corresponding to three dominant deterioration mechanisms based on [31]:

$$G(t) = \mathrm{E}[G(t)] = 1 - a \cdot t^{\eta} \tag{2}$$

where E( ) is the expectation of the variable in the bracket, a is a parameter accounting for the deterioration rate and η is a parameter indicating the deterioration type. For example, η=1, 2 or 0.5 corresponds to the deterioration mechanism of corrosion, sulfate attack or diffusion-controlled aging, respectively. In order to reflect the uncertainty associated with $G(t)$, a frequently used deterioration model is given by [14]

$$X(t) = \alpha(t - T_I)^{\beta} \otimes \epsilon(t),\ t > T_I;\ G(t) = \tilde{f}(X(t)) \tag{3}$$

where T_I is the time of corrosion initiation; $X(t)$ denotes a deterioration parameter such as the loss of section or the depth of penetration; α and β are parameters that can be determined from regression analysis of experimental data; $\otimes \in \{+,\times\}$; $\epsilon(t)$ is the random error item, which is usually assumed to follow a lognormal ($\otimes = \times$) or normal ($\otimes$=+) distribution; $\tilde{f}$ is a deterioration function with respect to $X(t)$. However, this model may lead to an increasing deterioration trajectory since ϵ may be less than 0 for $\otimes$=+ or less than 1 for $\otimes = \times$, which is unrealistic since the structural resistance should be non-increasing over time. Bhattacharya et al. [36] proposed a model for the time-variant corrosion loss of RC bridges, $C(t)$, which takes the form of

$$\frac{dC(t)}{dt} = \begin{cases} 0, & t \le T_I \\ \beta(t - T_I)^{\gamma} e^{\eta(t)}, & t > T_I \end{cases} \tag{4}$$

where β and γ are two time-invariant parameters, $\eta(t)$ is a 0-mean exponentiated noise item satisfying

$$\frac{d\eta(t)}{dt} = -k\eta(t) + \sqrt{D}\,\xi(t) \tag{5}$$

in which k and D are two constants while $\xi(t)$ is the white noise (Note that β and η here are different from those used in Eqs. (2) and (3)). With Eq. (4), the deterioration function $G(t)$ can be obtained by $G(t) = f[C(t)]$, where $f(\cdot)$ is a deterioration function with respect to the corrosion rate $C(t)$. While the model in [36] presents a non-increasing deterioration process which agrees well with the realistic case physically, it includes too many parameters so that the calibration of the parameters becomes challenging with limited observed data. The Gamma process has been used to model the deterioration process of aging structures [24–26,37–39], which is relatively simple but yet can describe the non-increasing characteristics and the auto-correlation of structural deterioration. For a reference period of t years, $(0, t]$, the deterioration function $G(t)$ can be obtained by dividing the interval $(0, t]$ into m sections, i.e., $(0, t_1]$, $(t_1, t_2]$, …$(t_{m-1}, t_m = t]$. Supposing that the increment of deterioration within the ith interval is D_i (a Gamma distributed random variable), we have

$$G(t) = 1 - \sum_{i=1}^{m} D_i \tag{6}$$

where each D_i is assumed to have an identical scale parameter so that $\sum D_i$ also follows a Gamma distribution with the same scale parameter of D_i. However, the Gamma process-based model assumes that the deterioration process is independent of the load process. By noting the dependency of the resistance deterioration on external loads, Kumar and Gardoni [40] and Kumar et al. [41] modeled deterioration as a combination of gradual and shock processes, with the latter dependent on the shock events. The potential correlation between the gradual deterioration and loads, and the correlation between gradual and shock deteriorations were not considered in their studies. This paper develops a new resistance deterioration model for time-dependent reliability assessments.

In the proposed framework, the deterioration process is considered as a combination of gradual and shock deteriorations as suggested in the literature [38,40,41]. The load process, the gradual deterioration, and the shock deterioration are all modeled as stochastic processes, and the mutual correlations between the two deterioration mechanisms and shock events are accounted for.