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Time-dependent reliability of aging structures in the presence of non-stationary loads and degradation

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ABSTRACT

Civil infrastructure performance and reliability may be affected by deterioration in strength or stiffness caused by service or environmental conditions or by systemic changes in load beyond the baseline conditions assumed for design. These changes should be considered when assessing a structure for its continued future reliability in service. This paper presents an improved method for evaluating time-dependent reliability of structures taking these factors into account. The method enables the impact on safety and serviceability of non-stationarity in the load and resistance deterioration processes to be assessed quantitatively. Parametric analyses show that the reliability is sensitive to the load intensity at the end of the service period, moderately sensitive to the initial and final mean occurrence rates of load events and the nature of these increases in time, and relatively insensitive to the nature of the increase in mean load intensity. A realistic time-dependent model of structural resistance is proposed and the role played by the auto-covariance in the resistance degradation process is investigated. The auto-covariance in stochastic resistance plays a significant role in time-dependent reliability assessment. Assuming that the time-dependent resistance is 'fully correlated' generally gives a reasonable estimation of structural reliability, while assuming that the resistances are statistically independent at two points in time may cause the failure probability to be overestimated.

1. Introduction

Civil infrastructure may suffer from severe operating or environmental conditions in service. Such conditions may cause changes in strength and stiffness of structures beyond the baseline conditions assumed for their design. Structural deterioration may impair the safety and serviceability of structures, and should be considered when evaluating their fitness for continued service, a process which must provide quantitative evidence that they can withstand future extreme events with an acceptable level of reliability during their future service lives.

There are many classes of buildings and other constructed facilities for which degradation in service is either known or believed to have an impact on structural safety. Due to socio-economic constraints, many degraded structures are still in use. Much research has been conducted in the past two decades on the safety evaluation and damage assessment of existing structures [17,18,9,11,2,23,5,12,24,14,22]. Many factors, including environmental conditions, variation in load intensity over time, and quality of periodic maintenance may affect the structural degradation process. However, the exact influence of these factors can be difficult to predict. Because of this time-dependent behavior and the presence of uncertainties, the safety evaluation and service-life prediction of deteriorating structures should be based on reliability concepts and methods, considering the time-dependent characteristics of both the load and resistance [8]. The methodology developed by Mori and Ellingwood [17] was one of the first attempts to assess time-dependent reliability of structures considering both the randomness of resistance and the stochastic nature of load, and was used to predict the remaining service-life of deteriorating concrete structures [10,12,18]. However, Mori and Ellingwood assumed that while the initial resistance was random, the time-dependent function describing resistance degradation was deterministic. Thus, the stochastic nature of time-dependent resistance deterioration was not considered in their work. In addition, Mori and Ellingwood treated the loads during the service life as a stationary random process consisting of a sequence of identically distributed and statistically independent loads, with a constant mean occurrence rate over the service life of the structure. Such stationary load models are unrealistic in many cases. For example, live load studies for highway

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bridges have revealed that the number of trucks and the relative frequency of heavy vehicles are gradually increasing [19]. Moreover, in a study of wind loads, Knutson et al. [13] estimated that in the 21st century, hurricane wind speeds may increase by as much as 20% around the world; furthermore, the CCSP [21] found that the frequency of hurricanes may increase as well as hurricane wind speeds. Therefore, a methodology is needed to consider the non-stationary stochastic nature of both structural loads and time-dependent deteriorating resistance in assessing the reliability of structures.

This paper proposes a method that can be used to estimate the time-dependent reliability of aging structures in the presence of non-stationarity in structural loadings and variability in structural deterioration. The effect of increasing load intensity or increasing occurrence rate of load events due to increasing service and environmental demands, as well as the variability and correlation in the resistance degradation process, on time-dependent structural reliability is investigated. The stochastic resistance degradation model that is proposed is consistent with the physics of deterioration and permits stochastic dependence in degraded resistance with time to be modeled through the auto-covariance in resistance degradation. Numerical results illustrate the importance of considering these non-stationary stochastic effects on time-dependent reliability.

2. Models for loads and resistance

2.1. Non-stationarity in structural loads

Significant load events occur randomly in time with random intensities. If the load intensity varies negligibly or slowly during the interval in which it occurs, and there is no dynamic response, its effect on the structure may be considered as static and for the purpose of reliability analysis, the load intensity may be treated as constant during the load event. With the exception of dead load, the duration of significant load events is generally short, and such events occupy only a small fraction of the total life of a structure. Under these assumptions, a time-varying structural load can be modeled as a sequence of randomly occurring pulses with random intensity, $S_1, S_2, \ldots S_n$ at times $t_1, t_2, \ldots t_n$ with a small duration, τ, as shown in Fig. 1. The duration, τ, is sufficiently small that it may be assumed that no degradation takes place during the load event.

Based on the forgoing description of load events, a Poisson point process provides a simple model of significant load random occurrence; the probability that $N(T)$ load events occur within the time interval $(0, T]$ is expressed by:

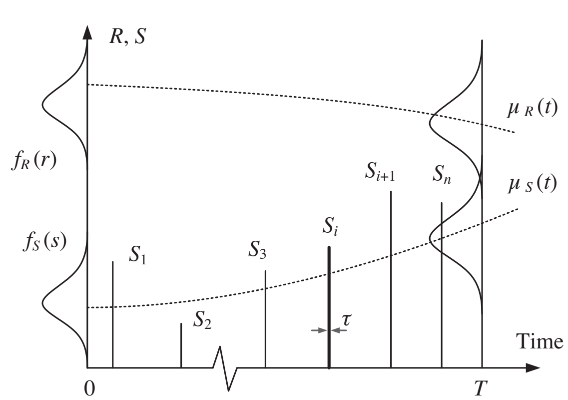

Fig. 1. Schematic representation of load process and degradation of resistance (after [17]).

$$P[N(0,T] = n] = \frac{(\lambda T)^n \exp(-\lambda T)}{n!}; n = 0, 1, 2, \ldots \quad (1)$$

where $P[\ ]$ is the probability of the event in the bracket and λ is the mean occurrence rate of the loads, which is assumed to be constant over time. In the simplest model, the load sequence S_j, $j = 1, 2, \ldots n$, is assumed to consist of identically distributed and statistically independent load pulses, with intensities described by the cumulative distribution function (CDF), $F_S(s)$. The load process so described is a stationary stochastic process. The load process model used by Mori and Ellingwood [17] was based on these assumptions. To consider the time dependence of load occurrence and intensity, the mean occurrence rate, λ, or/and the CDF of the load intensity must be treated as time-varying, described as a function of time, $\lambda(t)$ and $F_S(s,t)$ respectively. The probability of $N(t)$ load events occurring then is:

$$P[N(0,T] = n] = \frac{\left(\int_0^T \lambda(t)\mathrm{d}t\right)^n \exp\left(-\int_0^T \lambda(t)\mathrm{d}t\right)}{n!}; n = 0, 1, 2, \ldots \quad (2)$$

A sample function of the load process is illustrated in Fig. 1, in which $\mu_S(t)$ = mean load intensity as a function of time.

2.2. Deterioration in structural resistance

Assuming that structural resistance deteriorates with time, the time-dependent degraded resistance is:

$$R(t) = R_0 \times G(t) \quad (3)$$

where $R(t)$ is the resistance at time t; R_0 is the initial resistance (a random variable) and $G(t)$ is the degradation function (a stochastic process).

The stochastic process model of deterioration described by $G(t)$ is non-stationary in nature. Models of structural deterioration that have been used in previous time-dependent reliability analysis of ageing infrastructure are, for the most part, rudimentary [10,16,8]. Structural deterioration often has been modeled for time-dependent reliability assessment using simple equations of the form:

$$G(t) = a(t - T_I)^b + \epsilon(t), t > T_I \quad (4)$$

where a and b are parameters determined from an analysis of experimental data; $\epsilon(t)$ is a zero-mean stochastic process that accounts for randomness in the observed data and T_I denotes the random time required to initiate deterioration. To avoid the possibility of $G(t)$ becoming negative or its derivative becoming positive which is inconsistent with the physics of deterioration, Bhattacharya et al. [4] suggested the following model:

$$\frac{\mathrm{d}G(t)}{\mathrm{d}t} = a(t - T_I)^b \exp(\epsilon(t)), t > T_I \quad (5)$$

in which $\epsilon(t)$ is a zero-mean stationary process, which is given as:

$$\frac{\mathrm{d}\epsilon(t)}{\mathrm{d}t} = -k\epsilon(t) + \sqrt{D}W(t) \quad (6)$$

in which k and D are constants and $W(t)$ is Gaussian white noise. (Note that constants a and b in Eqs. (4) and (5) are not the same.) This model avoids the possibility of $G(t)$ increasing over time and permits the correlation in degradation to decrease as the time instants become more widely separated. However, this model requires additional parameters which are difficult to calibrate to experimental data, and thus is hard to implement in practical engineering analysis. To model the degradation of structural members, Gamma processes have been used by some researchers [6,20], based on the assumption that the increments of deterioration are independent, positive and isotropic for every uniform time-partition. A Gamma process depends on two parameters, shape factor