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System reliability assessment of deteriorating structures subjected to time-invariant loads based on improved moment method

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ABSTRACT

The time-variant system reliability analysis is a significant topic in the field of reliability engineering. Although progress has been made, there remain multiple challenges in the existing methods including the explosive number of possible failure modes, requiring correlation information, and excessive computational efforts.

In the present work, an improved moment method with high accuracy, efficiency and robustness is proposed for system reliability analysis of deteriorating structures. First, by introducing the complete system failure process, an equivalent time dependent performance function describing a deteriorating structural system is obtained. Second, a point estimate method based on the adaptive trivariate dimensional decomposition is adopted to calculate the first six moments of the performance function. And third, a saddlepoint approximation involving the first six moments is developed to estimate the system failure probability. Several examples are investigated to verify the accuracy, efficiency and stability of the proposed method.

1. Introduction

With the increasing awareness and importance of probability-based design methods and the development of modern computational techniques, reliability analysis has been playing an increasingly significant role in the area of structural engineering [1,2].

In general, structural reliability analysis is usually classified into two categories: structural member reliability and structural system reliability [3].

The structural member reliability considers only single performance function, and has gradually developed to maturity with typical methods including: FORM [2], SORM [2], response surface method [4] and Monte Carlo method (MCM) [2] etc. This kind of reliability not only covers the reliability of structural member, but also includes the reliability of structural system with one failure mode, which considers certain response of structural system, such as displacement response, base shear and so on, exceeding a threshold as limit state [16–19]. As long as one failure mode is considered, whether a structural member or a structural system is analyzed, it is essentially a structural member reliability, and the methods mentioned above can be applied.

The structural system reliability considers multiple failure modes, and classical system reliability, which focuses on the collapse or forming mechanisms of perfectly elasto-plastic and elastic-brittle structures [3,5,6,10], is an important part of it. There usually exist multiple potential failure paths that lead to the collapse of structure, thus methods based on the dominant failure modes are developed naturally for the classical system reliability, which mainly include two steps: (i) identifying the dominant failure modes of a structure, including β-unzipping method [3], branch and bound method [3], truncating enumeration method [5], criterion methods [6] and so on; and (ii) approximating its reliability based on the identified failure modes, including the PNET [7], the lower-upper bound method [8,9]. Although the achievements were fruitful, this family of methods has common restrictions that: (i) the number of failure modes increases dramatically as the structure redundancy increases [11]; and (ii) the correlation information between failure modes is difficult to evaluate. In most cases, the correlation coefficients are assumed empirically when unavailable [12,13]. Furthermore, the system reliability with multiple correlated failure modes may be difficult to evaluate even if the correlation information is known. MCM can also be applied to classical system reliability, and various techniques focusing on efficient samplings and variance reduction have been developed [14,15]. However, the efficiency and robustness of these methods requires further discussion and verification.

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Due to ageing, corrosion, fatigue and other damage scenarios, an engineering structure usually deteriorates gradually with time, and the time-variant reliability analysis is developed. Many researches devoted to time-variant structural member reliability analysis [21–24]. Comparatively speaking, only a few attempts have been made to study the reliability of time-variant structural system forming mechanisms [25–28], which is also named as time-variant classical system reliability in this paper. Most of these works are based on the assumption that all failure modes are given, and the structural system is described logically as series, parallel, and hybrid cases [25–27]. However, the identification of dominant failure modes is a vital and complicated step when dealing with complex structures, and the restrictions of combination explosion and unclear correlation information still exit for these methods. What's more, for deteriorating structural systems, there exists another major challenge that the dominant failure modes may change with time [28]. Therefore, the traditional methods based on failure mode identification become even less applicable for deteriorating structural systems, due to the fact that it is required to trace and identify dominant failure modes at different points of time [28].

To avoid the restrictions of traditional system reliability methods, Chen and Li [29] proposed the development process of nonlinearity, which is also defined as complete system failure process [30]. Based on this idea [29,30], the classical system reliability is effectively described by a single equivalent performance function. However, only non-deteriorating structures are discussed so far.

This work focuses on evaluating the time-variant classical system reliability. By extending the complete system failure process to deteriorating structures, and then combining with improved high-order moment method, a comprehensive solution is proposed. It is organized as follows. In Section 2, an equivalent performance function for system reliability of deteriorating structures is formulated based on the complete system failure process; the moments of this performance function is evaluated by the adaptive trivariate dimensional decomposition method; and the deteriorating system reliability is evaluated by the saddlepoint approximation with the first six moments. Several examples are presented in Section 3 to verify the accuracy, efficiency and robustness of the proposed method. Finally, some conclusions are summarized in Section 4.

2. Improved moment method for system reliability of deteriorating structure

2.1. Equivalent performance function based on the complete system failure process and Rosenblatt transformation

Based on the complete system failure process [29,30], structural failure can be described appropriately by a single performance function.

2.1.1. Complete system failure process for deteriorating structural system

Consider a perfectly elastoplastic structure with a random vector $\boldsymbol{\Theta} = \{\boldsymbol{\Theta}_L, \boldsymbol{\Theta}_S\}$, in which all variables are mutually independent, $\boldsymbol{\Theta}_S$ and $\boldsymbol{\Theta}_L$ are random vectors of structural parameters and loads respectively. Define $\Theta_{L,1}$ as the reference load, $\boldsymbol{\Theta}_L$ can be rewritten as

$$\boldsymbol{\Theta}_L^T = \Theta_{L,1} \times \begin{Bmatrix} 1 \\ \Theta_{L,2}/\Theta_{L,1} \\ \cdots \\ \Theta_{L,s1}/\Theta_{L,1} \end{Bmatrix} = \Theta_{L,1} \times \begin{Bmatrix} 1 \\ Q_2 \\ \cdots \\ Q_{s1} \end{Bmatrix} = \Theta_{L,1} \cdot \mathbf{Q}^T \quad (1)$$

in which superscript T denotes transpose of vector, $\mathbf{Q}$ is the load ratio vector, and

$$Q_i = \frac{\Theta_{L,i}}{\Theta_{L,1}} i = 1, \ldots, s1 \quad (2)$$

In regard to the complete system failure process [29,30], consider loads $F{\cdot}\boldsymbol{r}$ imposed on the structure, as the load F increases, the nonlinearity of the structure gradually develops till a mechanism occurs, meanwhile F reaches the bearing capacity $F_{\max}$. Apparently, the structural system fails when $\Theta_{L,1} > F_{\max}$, and structure remains safe when $\Theta_{L,1} < F_{\max}$. In other words, the system reliability of an elasto-plastic structure is equivalent to the probability of its ultimate capacity being greater than the applied load. Because $F_{\max}$ is the function of both $\boldsymbol{\Theta}_S$ and $\mathbf{Q}$, which is determined by $\boldsymbol{\Theta}_L$ according to Eq. (2), $F_{\max}$ can be formulated as $F_{\max}(\boldsymbol{\Theta}_S, \boldsymbol{\Theta}_L)$. Therefore, the equivalent performance function of the classical system reliability is

$$Z = F_{\max}(\boldsymbol{\Theta}_S, \boldsymbol{\Theta}_L) - \Theta_{L,1} \quad (3)$$

For example, a multi-story frame subjected to lateral loads $\{\theta_{L,1}, \theta_{L,2}, \theta_{L,3}\}$ is illustrated in Fig. 1. Let $\theta_{L,1}$ be the reference load, $\{\theta_{L,1}, \theta_{L,2}, \theta_{L,3}\} = \theta_{L,1}{\cdot}\{q_1, q_2, q_3\}=\theta_{L,1}{\cdot}\boldsymbol{q}$. The complete system failure process is represented by relationship between displacement response Δ and F. As the structure collapses or forms a mechanism, F reaches the bearing capacity $F_{\max}$. Based on Eq. (3), the performance function value is $F_{\max}-\theta_{L,1}$.

For a deteriorating structural system, some structural parameters become time-variant random variables, loads and other structural parameters are still considered as time-invariant random variables, and the performance function can be rewritten as

$$Z_t = F_{\max}(\boldsymbol{\Theta}_{SP}(t), \boldsymbol{\Theta}_{SV}, \boldsymbol{\Theta}_L) - \Theta_{L,1} \quad (4)$$

where $\boldsymbol{\Theta}_{SP}(t)=\{\Theta_{SP,1}(t),\ldots,\Theta_{SP,s2}(t)\}$ represents the time-variant structural parameter sub-vector of $\boldsymbol{\Theta}_S$, $\boldsymbol{\Theta}_{SV} = \{\Theta_{SV,1},\ldots,\Theta_{SV,s3}\}$ represents the time-invariant structural parameter sub-vector of $\boldsymbol{\Theta}_S$.

2.1.2. Modeling of deteriorating structural parameters

Consider $\Theta_{SPi}(t)$ as a element from time-variant vector $\boldsymbol{\Theta}_{SP}(t)$, the deterioration model $\Theta_{SPi}(t) = \Theta_{SPi0}{\cdot}\delta(t)$ is used in recent decades [41–43], where Θ_{SPi0} is the initial random variable, and $\delta(t)$ is a monotonically decreasing deterministic function describing deterioration. However, this type of deterioration model implicates strong assumption that explicit linear relation is indicated between any order moment of $\Theta_{SPi}(t)$ and corresponding order moment of Θ_{SPi0}, namely $M_q(\Theta_{SPi}(t)) = [\delta(t)]^q{\cdot}M_q(\Theta_{SPi0})$, where $M_q(.)$ represents the qth central moment of random process or random variable in the bracket. Therefore, this deterioration model results in the phenomenon that the mean value decreases with t, but the coefficient of variation remains invariant and inalterable along time.

In this work, another class of random process is selected as the basic form of deterioration model, which is based on the idea that the distribution parameters of deterioration model are described by specific time-variant functions. In this way, the stochastic characteristics of proposed deterioration model can be described more

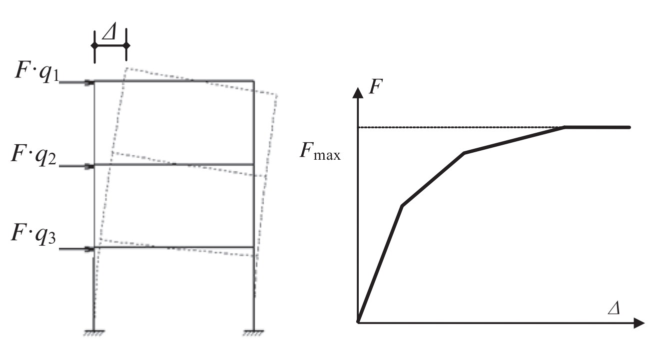

Fig. 1. Illustration for complete system failure process.