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Research paper

An efficient method of system reliability analysis of steel cable-stayed bridges

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ABSTRACT

The IHS-EIS method is developed for reliability analysis of steel cable-stayed bridges by integrating the improved Latin Hypercube (IHS) and a proposed effective importance sampling (EIS). All nonlinearity sources of bridges are directly captured by the proposed practical advanced analysis (PAA) using catenary elements for cables and beam-column elements for pylons, girders, and cross beams. The innovation of the proposed method comes from both PAA for performing structural analysis and IHS-EIS for solving reliability analysis. Compared to commercial software ABAQUS, the computational cost of structural analysis is significantly reduced by using the proposed PAA method. IHS-EIS can accurately capture the failure probability of structure and considerably decrease the number of samples in comparison with Monte Carlo simulation, importance sampling, Latin hypercube, and subset simulation methods. Three mathematical examples and two steel frames are first presented to demonstrate the accuracy and efficiency of IHS-EIS. This method is then applied for the semi-harp type of a steel cable-stayed bridge. The reliability sensitivity of the bridge is also investigated.

1. Introduction

Steel cable-stayed bridges have been widely applied to the design and construction of bridge structure in recent years because of their benefits of aesthetic appearance, economical utilization, and innovative technique. However, they are known as large-scale and highly nonlinear structures due to the cable sag effect, the stress-strain behaviors of materials, and the axial force-bending moment interaction in girders and pylons. As a consequence, the structural analysis of steel cable-stayed bridges requires nonlinear inelastic analysis, which demands excessive computational time. Currently, the reliability analysis has attracted significant attention from researchers since geometric and material properties and applied loads of structure are uncertain parameters. The process of reliability analysis of highly nonlinear structures also demands excessive computational time because it includes repeated structural analyses. Therefore, it is necessary to develop an efficient method of reliability analysis of steel cable-stayed bridges, one that is (1) a fast and accurate structural analysis scheme and (2) a robust reliability analysis.

Reliability analysis methods in the literature can be divided into two categories: analytical methods and simulation methods. The analytical methods, such as first-order reliability (FORM) and second-order reliability (SORM), allow estimating structural reliability by using only the means and variances of random variables and the definition of limit state function (LSF) at the most probable points (MPP) [1–3]. The drawback of these methods is that their errors are relatively large in highly nonlinear systems. Unlike the analytical methods, the simulation methods such as the Monte Carlo simulation (MCS) are superior for reliability analysis of highly nonlinear systems since they are very simple and accurate for large samples [4–5]. However, the excessive computational cost of these methods prevents them from wide application for practical designs. To reduce the computational effort, several variance reducing techniques have been proposed so far, e.g. Latin hypercube (LHS) [6], quasi-Monte Carlo [7], directional sampling [8], importance sampling (IS) [9], subset simulation (SS) [10], and line simulation (LS) [11]. Among these techniques, IS is very effective for structural reliability analysis since it is easy for application and the results of this technique are highly accurate. However, the efficiency of IS is considerably reduced when the number of random variables increases.

Although many studies related to structural reliability analysis have been done, there have been relatively few works concerning the reliability analysis of cable-stayed bridges. Among these studies, Bruneau [12] used FORM to investigate the reliability of cable-stayed bridges ignoring all geometric nonlinear behaviors. The results are unreliable because the cable-stayed bridge responses

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are significantly influenced by geometric nonlinearities [13,14] furthermore, the distribution of random variables cannot be accurately described by using FORM. Cheng and Xiao [15] and Cheng [16] used the response surface method (RSM) with the second-order polynomial of response surface function (RSF) to estimate the serviceability reliability of cable-stayed bridges. Although RSM seems to be an effective method for reliability analysis, since a few of designated sample points are required to construct RSF [17], the failure probability of highly nonlinear structures cannot be accurately estimated by using this method [18,19]. Additionally, the efficiency of RSM is significantly reduced in many cases where finding the center point of RSM design requires a large number of iterations. Cavdar et al. [20] and Han [21] used stochastic finite element analysis (SFEA) based on the perturbation method to analyze the reliability of cable-stayed bridges. The results show that this method is efficient, and its computational cost is lower than simulation methods. However, the perturbation method can be only applied for random variables with low coefficient of variation (COV) [22].

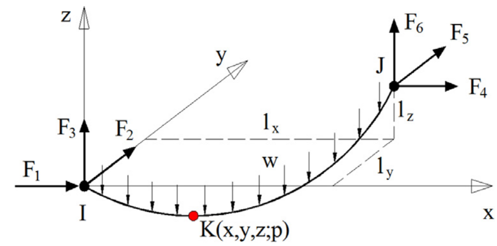
This paper therefore attempts to develop a robust method for reliability analysis of steel cable-stayed bridges. This method, called IHS-EIS, is formed for solving the reliability analysis part by integrating the improved Latin hypercube sampling (IHS) given in Ref. [23] and the effective importance sampling (EIS) proposed herein. In order to capture the nonlinear inelastic behaviors of structures, the practical advanced analysis (PAA) based on the beam-column approach and the catenary cable model is developed. The proposed method is robust and efficient due to both PAA and IHS-EIS. While the computational time of structural analysis is significantly reduced by using PAA, IHS-EIS allows accurate capture of the failure probability of structures and considerable reduction of the sample number in reliability analysis. In this study, only independent variables but not correlated variables are considered.

The paper is organized as follows: Section 2 describes the proposed PAA method for structural analysis of steel cable-stayed bridge. Section 3 presents the structural reliability analysis, while Section 4 shows the proposed reliability analysis procedure of steel cable-stayed bridge. Section 5 discusses three mathematical examples and two steel frames to verify the proposed method, and the application of this method to the semi-harp type of a steel cable-stayed bridge is presented in Section 6. Finally, some conclusions are detailed in Section 7.

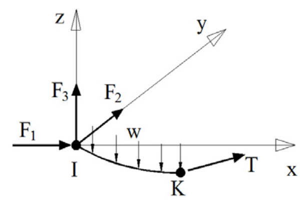
2. PAA of steel cable-stayed bridge

The member-based design method, based on the effective length factor in conventional design codes and standards, faces some major limitations since the interaction of stability and strength between the member and whole system is not directly considered. This means that this method cannot show any exact signals of structure against failure. Furthermore, in the design process of this method, the elastic analysis is firstly applied to determine member forces of structural members, and then the inelastic analysis is used to calculate the strength of an individual member, which is now treated as an isolated member. It is important to note that system compatibility is neglected in the strength equations of individual member as given in specifications. Therefore, this two-stage process is not reasonable because all members cannot be guaranteed to maintain their design loads under the deformed configuration.

To overcome the aforementioned limitations of the member-based design method, PAA methods are employed in analysis and design of steel structure, e.g. plastic zone methods [24,25] and plastic hinge methods [26,27]. In plastic zone methods, structural members and their cross-sectional areas are divided into several elements. Although plastic zone methods are known as the “exact" methods, they are not popularly applied in practical design because of their intensive computational time. Unlike plastic zone methods, in the plastic hinge method, only one or two elements per member are needed to accurately predict nonlinear inelastic responses of the structure, so the computational time is significantly reduced.



(a) Three-dimensional catenary cable



(b) Forces on a segment of cable

Fig. 1. Three-dimensional catenary cable element.

From above discussions, the plastic hinge method is employed to estimate nonlinear inelastic behaviors of steel cable-stayed bridges in this study. The cables of the bridge are simulated as catenary elements, while pylons, girders, and cross beams are modeled as beam-column elements.

2.1. Catenary cable element

There are several methods in the literature for modelling cables of cable-stayed bridges, such as truss element, multiple-straight link, truss with modified elastic modulus (Ernst modulus), elastic catenary element, etc. The comparison of different cable modelling investigated by Freire et al. [28] shows that cable sag effect is the most important nonlinear effect in cable-stayed bridges. The results also indicate that solutions are unreliable in many case studies by modelling cables as a truss element or using the Ernst modulus equation. As a consequence, cables in steel cable-stayed bridges are modeled as catenary elements in this study.

Considering an elastic catenary cable under the distributed self-weight ω as shown in Fig. 1a. Assuming the cable has the unstressed length of L_0 and is perfectly flexible. Considering the point $K(x, y, z)$ on the cable. The unstrained and strained lengths under self-weight of the cable from K to I is s and p, respectively. The geometric function of K is as follows:

$$(dp)^2 = (dx)^2 + (dy)^2 + (dz)^2, \tag{1}$$

The equilibriums of the cable part IK can be obtained from Fig. 1b as follows:

$$T\left(\frac{dx}{dp}\right) = -F_1, \tag{2a}$$

$$T\left(\frac{dy}{dp}\right) = -F_2, \tag{2b}$$