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Fatigue assessment of multi-loading suspension bridges using continuum damage model

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ABSTRACT

Long-span steel suspension bridges carrying both highway and railway have been built in wind-prone regions. The fatigue assessment of such bridges under the combined action of railway, highway, and wind loading represents a challenging task in consideration of uncertainties in both fatigue loading and fatigue resistance. This paper presents a framework for fatigue assessment of a long-span suspension bridge under combined highway, railway, and wind loadings using a continuum damage model. The continuum damage model (CDM) is first established based on continuum damage mechanics with an effective stress range and an effective nonlinear accumulative parameter to represent all of the stress ranges within a daily block of stress time history of the bridge. The CDM is then applied to estimate damage accumulation of the Tsing Ma suspension bridge at fatigue-critical locations, and the results are compared with those estimated by the linear Miner's model. A limit state function for fatigue reliability analysis based on CDM is also defined by introducing proper random variables into CDM. The Monte Carlo simulation (MCS) is then adopted to generate the random variables and to calculate failure probability. Finally, the failure probabilities of the Tsing Ma Bridge at the end of 120 years are estimated for different loading scenarios. The results demonstrate that the fatigue condition of the Tsing Ma Bridge at the end of its design life depends on loading scenarios.

1. Introduction

Long-span steel suspension bridges carrying both highway and railway have been built in wind-prone regions. The fatigue assessment of such bridges under the combined action of railway, highway, and wind loading represents a necessary but challenging task. The fatigue assessment of a multi-loading suspension bridge shall be based on multiple loading-induced stress response time histories rather than the simple summation of fatigue damage induced by individual loading. As a result, databases of railway, highway, and wind loading shall be built and the corresponding stress time histories shall be generated in different ways because of different properties of loading type. Also, given that a great number of multiple loading-induced stress response time histories are required for a complete fatigue assessment, a computationally efficient approach for dynamic stress analysis and an engineering procedure for determining fatigue-critical locations shall be developed. Furthermore, fatigue damage accumulation involving fatigue crack initiation and growth is actually a nonlinear process during the service life of a bridge [1,2]. The fatigue damage accumulation also involves many uncertainties in both fatigue loading and fatigue resistance [3,4]. For a bridge subjected to multiple types of loading, uncertainties become more complicated, making the fatigue assessment of such a bridge difficult to be performed.

The Miner's rule is widely used in civil engineering for fatigue damage and reliability analysis of steel structures [4,5]. However, the Miner's rule is a linear damage model and does not address actual physical mechanism of fatigue crack initiation and growth. The Miner's rule also does not consider the fatigue loading sequence effect, leading to either overly optimistic or pessimistic results [6]. Fatigue damage models based on continuum damage mechanics have been recently proposed in the field of engineering mechanics to deal with the mechanical behavior of a deteriorating medium at the continuum scale [7–9]. These fatigue damage models are highly nonlinear in terms of damage evolution. Some of these models were also tried by some researchers to estimate fatigue damage of long-span suspension bridges under single type of loading [10,11], but none of these investigations refer to fatigue damage assessment of suspension bridges under multiple types of loading and fatigue reliability analysis with uncertainties.

In this connection, this paper presents a framework for fatigue assessment of a long-span suspension bridge under combined highway, railway, and wind loadings using a continuum damage model. The continuum damage model (CDM) is first established

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based on continuum damage mechanics with an effective stress range and an effective nonlinear accumulative parameter to represent all of the stress ranges within a daily block of stress time history of the bridge. The CDM is then applied to estimate damage accumulation of the Tsing Ma suspension bridge at fatigue-critical locations, and the results are compared with those estimated by the linear Miner's model. A limit state function for fatigue reliability analysis based on CDM is also defined by introducing proper random variables into CDM. One of the random variables is the daily sum of m-power stress ranges, and its probability distribution is determined based on the measurement data recorded by the structural health monitoring system installed in the bridge. The Monte Carlo simulation (MCS) is then adopted to generate the random variables and to calculate failure probability. Finally, the failure probabilities of the Tsing Ma Bridge at the end of 120 years are estimated for different loading scenarios.

2. Continuum damage model

The continuum damage model (CDM) proposed in this study for fatigue assessment of long-span suspension bridges under multiple loadings is based on continuum damage mechanics with an effective stress range and an effective nonlinear accumulative parameter to represent all of the stress ranges within a daily block of stress time history of the bridge. Thus, the basic theory of the continuum damage mechanics is briefly introduced first for the sake of completion.

2.1. Basic theory of continuum damage mechanics

The damage growth of a material is considered to consist of a progressive internal deterioration that causes some loss in the effective cross-section area that carries loads. In the continuum damage mechanics, the damage index D for isotropic damage is often defined as

$$D = \frac{S - \widetilde{S}}{S} \tag{1}$$

where S is the nominal cross-section area and $\widetilde{S}$ is the effective cross-section area when loss due to damage is taken into account. Based on thermodynamics and dissipation potential, the rate of damage for high-cycle fatigue can be expressed as a function of the accumulated micro-plastic strain, the strain energy density release rate, and the current state of damage [8]. The micro-plastic strain, which is often neglected in a low-cycle fatigue problems, and its accumulation must be considered for high-cycle fatigue damage, even if macro-plastic strain is not present [12]. In a one-dimensional situation, the equation for the rate of fatigue damage $\dot{D}$ can be given as

$$\dot{D} = \frac{\sigma^2|\sigma - \bar{\sigma}|^{\beta'}}{B'(1-D)^{\alpha}}\langle\dot{\sigma}\rangle \tag{2}$$

where $\bar{\sigma} = \sigma_m$ is the mean stress over the stress cycle; the symbol $\langle\rangle$ denotes the McCauley brackets, where $\langle x\rangle = x$ for $x > 0$ and $\langle x\rangle = 0$ for $x < 0$; and α, β', and B' are the material parameters. Eq. (2) is a general constitutive model for high-cycle fatigue and can be integrated over time for cycles with different mean stresses and stress ranges. For instance, if $\bar{\sigma} = 0$ and the variation of $(1-D)^{\alpha}$ in a single stress cycle is neglected, then integrating Eq. (2) over the cycle yields

$$\frac{\delta D}{\delta N} = \frac{2\sigma_a^{\beta'+3}}{B'(\beta+3)(1-D)^{\alpha}} \tag{3}$$

where σ_a is the amplitude of the stress cycle. By considering the mean stress effect [13], Eq. (3) can be rewritten as [12]:

$$\frac{\delta D}{\delta N} = \frac{[(\sigma_r + 2\sigma_m)\sigma_r]^{\frac{(\beta'+3)}{2}}}{B(\beta'+3)(1-D)^{\alpha}} \tag{4}$$

where $B = 2^{\beta'+2}B'$. Integrating this equation over N stress cycles, in which $\sigma_m = 0$ and σ_r = constant, yields the damage accumulation.

$$D = 1 - \left[1 - \frac{(\alpha+1)}{B(\beta'+3)}(\sigma_r)^{(\beta'+3)}N\right]^{\frac{1}{(\alpha+1)}} \tag{5}$$

Many experiments have been conducted on the fatigue failure of structural details under different constant stress ranges, and S–N curves have been established based on these experimental results [14]. Given that far few experiments have been conducted to determine the parameters B, β', and α in Eq. (5), they can be expressed by using parameters of the S–N curves [10]. The number of stress cycles to failure N_f under the stress range σ_r *($\sigma_r \geqslant \sigma_r, 0, \sigma_{r,0}$ is the fatigue limit) can be determined based on the British S–N curves [14].*

$$N_f = K_2(\sigma_r)^{-m} \tag{6}$$

Eq. (5) can then be written as

$$N_f = \left[1 - (1-D_f)^{(\alpha+1)}\right]\frac{B(\beta'+3)}{(\alpha+1)}\sigma_r^{-(\beta'+3)} \tag{7}$$

where the damage at failure, D_f, is an intrinsic material property that is dependent on the durability of the material [1,15]. As the values of α adopted for different amplitudes of stress ranges occurring on a bridge are deemed to be sufficiently large to make $[1-(1-D_f)^{(\alpha+1)}]$ very close to one, the parameters B, β', and α can be expressed by m and K_2 by comparing Eqs. (6) and (7).

$$\begin{cases} \beta' + 3 = m \\ \frac{B(\beta'+3)}{\alpha+1} = K_2 \end{cases} \tag{8}$$

Substituting this equation into Eq. (5) gives

$$D = 1 - \left[1 - \frac{1}{K_2}(\sigma_r)^{\mathrm{m}}N\right]^{\frac{1}{\alpha+1}} \tag{9}$$

To extend the approach to fatigue analysis under variable-amplitude loading, Eq. (9) is expressed as

$$D(k) = 1 - \left[(1 - D(k-1))^{(\alpha_k+1)} - (\sigma_{r,k})^{\mathrm{m}}/K_2\right]^{\frac{1}{\alpha_k+1}} \tag{10}$$

where $\sigma_{r,k}$ and α_k are the stress range and nonlinear accumulative parameter for the kth stress cycle, respectively, and $D(k)$ is the cumulative fatigue damage after the kth stress cycle. The equation can also be derived using stepwise iteration from the initial damage $D(0) = 0$.

$$\begin{cases} D(1) = 1 - \left[1 - (\sigma_r, 1)^{\mathrm{m}}/K_2\right]^{\frac{1}{\alpha_1+1}} \\ D(2) = 1 - \left[(1 - D(1))^{(\alpha_2+1)} - (\sigma_r, 2)^{\mathrm{m}}/K_2\right]^{\frac{1}{\alpha_2+1}} \\ \cdots \\ D(k) = 1 - \left[(1 - D(k-1))^{(\alpha_k+1)} - (\sigma_{r,k})^{\mathrm{m}}/K_2\right]^{\frac{1}{\alpha_k+1}} \end{cases} \tag{11}$$

2.2. Nonlinear properties of fatigue damage accumulation

Fatigue damage accumulation is nonlinear because it is induced by fatigue crack initiation at a very slow pace, then fatigue crack growth at a relatively fast pace, and finally fatigue failure suddenly. In the continuum damage mechanics-based fatigue damage model, the nonlinear accumulative parameter α is the parameter that controls the nonlinearity. Numerical simulations are carried out at this point to study the sensitivity of α to fatigue damage accumulation. In the simulations, the constant stress range σ_r = 80 MPa is used,