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Reliability updating and prediction of bridge structures based on proof loads and monitored data

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HIGHLIGHTS

- A new updated method of resistance model based on proof loads and resistance degradation model was provided.
- A new predicted method of monitored load effects was provided.
- A reliability updating and prediction approach was provided based on updated resistance model and predicted load effects.

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ABSTRACT

Bridge deterioration with time and ever increasing traffic loads raise concerns about reliability of aging bridges. One of the ways to predict reliability of aging bridges is to build reasonable resistance prediction model and load effect prediction model. In this paper, to obtain the predicted resistance, by the truncated method or Bayesian method, the initial resistance probability model is updated with the structural proof loads which are greatly less than the resistance of a bridge, reduce uncertainty in the bridge resistance and so increase the bridge reliability; to predict the time-variant load effects which is treated as a time series, the Bayesian dynamic models (BDMs) are introduced and adopted to predict the structural load effects based on the monitored data (everyday monitored extreme stresses). Finally, with the predicted resistance and load effects, the structural reliability indices are solved and predicted with First Order Second Moment method (FOSM), and three numerical examples are provided to illustrate the feasibility and application of the built prediction model in this paper.

1. Introduction

In China, as civil infrastructure systems age [5], the number of dangerous bridge was on the rise from 1999 to 2007 which is shown in Fig. 1; the concern for economically sustainable maintenance practices is increasing. In addition, it is very important to understand the safety and serviceability performance of critical infrastructure components. Commonly the structural performances include degradation resistance, structural system reliability, and member reliability. Especially the reliability of an aging bridge is a time-variant property which is dependent on the history of both the applied loads and the remaining strength of the structural elements [8]. The reliability of bridges with non-degrading resistance can be accurately predicted using established time-variant vehicle live load models and structural reliability methods and the corresponding reliability model [1,2,7,14,25,20], but based on structural health monitored data, load history and resistance degradation model, the research, on real-timely predicting and assessing the reliability of deteriorated bridge structures, is at the initial stage in the world.

Under the actions of long-term aggressive natural environment, traffic loads and even overloads [10], a lot of bridges are suffering various damages and deficiencies, which make the structural resistance decrease with time and cause the structural performance degradation, and further have serious impact on the remaining life of an existing structure [3,34]. Therefore, it is very important to assess the loading capacity of the existing bridges to guarantee the structural safety over their service life. The key issue to achieve an accurate assessment is to make full use of available information, such as loading history, maintenance history and deterioration history, etc. where, loads histories include structural experienced actual loads in the service periods and the design loads. In this paper, two methods (The truncated method and Bayesian method) [23] to update the capacity assessment of existing bridges were presented, in which load history and bridge degradation, as well as the associated uncertainties, were taken into account.

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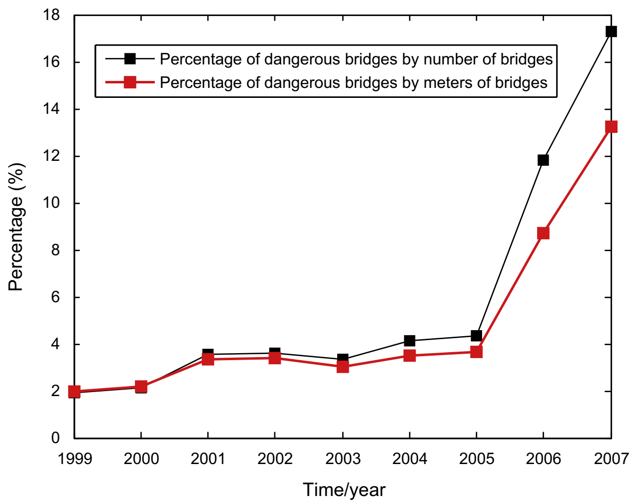

Fig. 1. The percentage of dangerous bridge from 1999 to 2007 in China.

Through health monitoring for bridges, the structural basic status, including strain, stress and deflection of specified structural components or structures, can be obtained. About the health monitoring, much research is conducted, such as the data transition system, data acquisition technology, system integration technology [19,4,15,16], modal parameter identification, structural damage detection technology, data modeling and monitored data-based reliability assessment [11,30,6,13,18,21,26–28,31,32,35,36,40,41], however, based on the real-time monitored data, the research on real-timely predicting the structural reliability have not been widely studied in the world.

In this contribution, considering the uncertainty of structural off-line time-dependent health monitored extreme data which is time-variant monitored data in the past few days and not in the present and the future days, combinational Bayesian dynamic models is introduced to combine the monitored data with the structural load effect prediction model. Based on bridge structural health monitored extreme stress data, the combinational Bayesian dynamic linear models are given. Finally based on the combinational prediction model of health monitored extreme stress data and the updated load capacity probability distribution parameters (mean and variance), the real-time updated predicted reliability indices of bridge structures are solved with FOSM method. The proposed updated methods and combinational prediction model are applied to an existing bridge and two numerical examples which illustrate the accuracy of the two updated methods and prediction model of monitored data.

2. Updating of resistance probability model based on load history and resistance degradation model

Structures subjected to environmental attack can experience changes in resistances which are time-variant and degraded, where, the degraded changes model of resistance is called as resistance degradation model. The load histories are mainly the proof loads which are divided into two types: deterministic proof loads and stochastic ones. The information about deterministic proof loads is obtained through load tests; the aim of load test is to know the actual working state of the bridge, and then judge the load-carrying capacity of bridge structures. Actual service loads of existing structures belong to stochastic proof loads. Different stochastic loads have different distribution types.

In this paper, two methods, which are namely the truncated method and Bayesian method, are provided to updating the resistance probability model based on load history and resistance degradation model.

2.1. Updating of resistance probability model based on deterministic proof loads

2.1.1. The truncated method I (Updating the initial probability model of resistance)

Suppose that structural resistance and load effects are mutually independent, the resistance's initial probability density function (PDF) and cumulative distribution function (CDF) are respectively $f_R(x)$ and $F_R(x)$. After experiencing the deterministic proof load R_p, the structure is still safe, which show structural resistance $R > R_p$, then with the truncated method, the $f_R(x)$ is updated and transferred into $f_{R,up}(x)$, the corresponding $F_R(x)$ is also updated and transferred into $F_{R,up}(x)$.

Before structure experiences the proof load R_p, the relationship between resistance' PDF and CDF is

$$\int_{-\infty}^{+\infty} f_R(x)dx = F_R(R_p) + \int_{R_p}^{+\infty} f_R(x)dx \tag{1}$$

After structure experiences the proof load R_p, there is

$$\int_{R_p}^{+\infty} f_{R,up}(x)dx = 1 \tag{2}$$

Based on Eqs. (2) and (1), we can know that after experiencing the deterministic proof load R_p, the resistance's truncated PDF is

$$f_{R,up}(x) = \begin{cases} \frac{f_R(x)}{1-F_R(R_p)}, & x \geqslant R_p \\ 0, & x < R_p \end{cases} \tag{3}$$

The updated mean value and variance are respectively:

$$\mu_{R,up} = \int_{-\infty}^{+\infty} x f_{R,up}(x)dx = \frac{\mu_R - \int_{-\infty}^{R_p} x f_R(x)dx}{1 - F_R(R_p)} \tag{4}$$

$$D_{R,up} = \frac{D_R - (\mu_{R,up} - \mu_R)^2 - \int_{-\infty}^{R_p} (x - \mu_{R,up})^2 f_R(x)dx}{1 - F_R(R_p)} \tag{5}$$

where μ_R and D_R are respectively the mean value and variance of resistance before updating.

For different priori distributions of resistance, the parameters of resistance's updated posteriori distributions are different.

If the priori distribution of structural resistance is normal, then the updated mean value and variance are respectively:

$$\mu_{R,up} = \frac{\mu_R - \int_{-\infty}^{R_p} x f_R(x)dx}{1 - \Phi\left(\frac{R_p - \mu_R}{\sigma_R}\right)} \tag{6}$$

$$D_{R,up} = \frac{D_R - (\mu_{R,up} - \mu_R)^2 - \int_{-\infty}^{R_p} (x - \mu_{R,up})^2 f_R(x)dx}{1 - \Phi\left(\frac{R_p - \mu_R}{\sigma_R}\right)} \tag{7}$$

If the priori distribution of structural resistance is lognormal, then the updated mean value and variance are respectively:

$$\mu_{R,up} = \frac{\mu_R - \int_{-\infty}^{R_p} x f_R(x)dx}{1 - \Phi\left(\frac{\ln R_p - \lambda_R}{\zeta_R}\right)} \tag{8}$$

$$D_{R,up} = \frac{D_R - (\mu_{R,up} - \mu_R)^2 - \int_{-\infty}^{R_p} (x - \mu_{R,up})^2 f_R(x)dx}{1 - \Phi\left(\frac{\ln R_p - \lambda_R}{\zeta_R}\right)} \tag{9}$$

where λ_R and ζ_R are distribution parameters of resistance's priori distribution, and $\lambda_R = \ln\left(\frac{\mu_R}{\sqrt{1+\delta_R^2}}\right), \zeta_R = \sqrt{\ln(1 + \delta_R^2)}$.