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Fatigue reliability assessment of ageing railway truss bridges: Rationality of probabilistic stress-life approach

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ABSTRACT

Rail authorities all over the world are paying attention to extend the service lives of railway bridges. The famous Miner's rule employed deterministic or probabilistic fatigue assessment approaches are generally used to predict remaining fatigue life of ageing railway bridges. Under many variable amplitude loading conditions, life predictions have been found to be unreliable since Miner's rule does not properly take account the loading sequence effect. Therefore, this paper presents a comparison of a new probabilistic fatigue assessment approach with deterministic approach consisting of a new damage indicator, which captures the loading sequence effect of variable amplitude loads more precisely than the Miner's rule. The comparison is performed by applying both fatigue assessment approaches to predict the remaining fatigue life of an ageing railway bridge. This comparison intends to conclude the possibility of capturing uncertainty behind loading sequence effect by proposed probabilistic fatigue assessment approach. Initially the paper presents the both approaches. Then the proposed approaches are applied to predict the fatigue lives of an ageing railway bridge. Finally predicted fatigue lives are compared and rationality, significance and validity of the proposed approaches are discussed.

1. Introduction

Majority of the railway bridges in the world are exceeding their design lives and bridge authorities are working on precise life extension methods [1–3]. As a result, a significant amount of research are ongoing for development of precious structural health monitoring and life assessment methods [2–12]. As railway bridges are vulnerable for time-dependent fatigue damage due to cyclic nature of traffic loads, the assessment of remaining fatigue life of railway bridges for continuing services has become more important than ever, especially when making decisions regarding structure replacement and other major retrofits. However, this task is difficult due to the increase of axel load and corrosion deterioration on bridges.

The fatigue assessment of structures is mainly done by either deterministic or probabilistic approach. Most of deterministic fatigue assessment approaches of railway bridges are generally based on the combination of measured stress histories under actual traffic load [12,13], Miner's rule [14] and railway code provided fatigue curve (also referred *S-N* or Wöhler curve). Although the mentioned deterministic approach predicts the remaining fatigue life, the uncertainties inherent in the fatigue evaluation process are not captured. These uncertainties are found in the process of determination of stress histories (i.e. structural analysis, field measurements, load testing, loading sequence and respective histories), selecting detail categories, choosing fatigue damage theories [15,16].

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The probabilistic fatigue assessments are originated to capture the effect of these uncertainties more precisely. This approach is generally based on probability of fatigue failure associated reliability index. Fatigue reliability index provides a tool for predicting the remaining fatigue life [16]. A number of studies on the reliability analysis have been done for fatigue life prediction of bridges. Imam et al. [17] has proposed a probabilistic fatigue assessment methodology for riveted railway bridges under historical and present-day train loading. Kwon and Frangopol [18] have performed fatigue reliability assessment of steel bridges using the probability density function (PDF) of the equivalent stress ranges obtained by filed measurement data. Ni et al. [19] has proposed a fatigue reliability model for fatigue life and reliability evaluation of steel bridges with long-term monitoring data, which integrates the probability distribution of hot spot stress range with a continuous probabilistic formulation of Miner's damage cumulative rule. Recently, Kwon et al. [15] and Soliman et al. [16] have proposed a probabilistic bilinear stress- life approach for better fatigue assessment of steel bridges. Miner's rule has been used as the fatigue damage theory for above mentioned probabilistic models.

The Miner's rule is the simplest and the most commonly used fatigue life prediction technique. One of its interesting features is that life calculation is simple and reliable when the detailed loading history is unknown. However, under many variable amplitude loading conditions, life predictions have been found to be unreliable since it does not properly take account the loading sequence effect [20–22]. Therefore, it is uncertain to use the Miner's rule for remaining fatigue life estimation of railway bridges because most of the railway bridges are subjected to variable amplitude loadings. None of research studies have confirmed about the consideration of the loading sequence effect on probabilistic fatigue assessment approaches.

To overcome this problem to some extent, objective of this paper is to compare probabilistic fatigue assessment approach with deterministic approach consisting of a new damage indicator (i.e. damage stress model) [22], which captures the loading sequence effect of variable amplitude loads more precisely than the Miner's rule. The comparison is performed by applying both fatigue assessment approaches to predict the remaining fatigue life of an ageing railway bridge. This comparison provides an indication of rationality of probabilistic stress-life fatigue approach for ageing railway bridges.

2. Fatigue reliability assessment using stress-life approach

This section introduces a precise probabilistic fatigue assessment approach and a recently proposed deterministic fatigue assessment approach. The first approach generally is based on probability of fatigue failure associated reliability index. The second approach is based on a new damage indicator, which captures the loading sequence effect more preciously than the Miner's rule.

2.1. Fatigue reliability index

This section proposes a method to determine fatigue reliability index of bridges based on probabilistic bilinear *S-N* approach. The fatigue reliability of a structural component or a detail category is related to the probability of not violating a particular fatigue limit state. Based on the limit state function (i.e. $g(t) = R - S$), the failure probability of a structural member or a detail category is defined as $P_f = P(g(t) < 0)$.

The reliability index provides a measure of fatigue damage of the considered detail category of the bridge. In other word, reliability index defines the probability of violating fatigue limit state. The fatigue reliability index is defined as,

$$\beta = \phi^{-1}\left(1 - P_f\right) \tag{1}$$

where ϕ^{-1} is the inverse of the standard normal cumulative distribution function. The corresponding fatigue limit state function can be derived as,

$$g(t) = \Delta - D \tag{2}$$

where Δ is Miner's critical damage accumulation index, which is assumed to be lognormal distribution with a mean value of 1.0 and coefficient of variation (COV) of 0.3 and D is the Miner's damage accumulation index, which can be derived as,

$$D = \begin{cases} \dfrac{N(t)}{A_1}(S_{re}^L)^{m_1} & for N(t) \le \dfrac{A_1}{CAFT^{m_1}} \\ \dfrac{N(t)}{(CAFT^{m_2-m_1} \times A_1)}(S_{re}^B)^{m_2} & for N(t) > \dfrac{A_1}{CAFT^{m_1}} \end{cases} \tag{3}$$

where S_{re}^L and S_{re}^B are equivalent constant amplitude stress ranges calculated using linear and bilinear *S-N* approach respectively as shown in Eq. (4). The *CAFT* designated as constant amplitude fatigue threshold. The m_1 and m_2 are the slopes of stress-life fatigue curve above and below the *CAFT*, respectively. The A_1 is the fatigue detail coefficient above the *CAFT* of the fatigue curve. The $A_2 = A_1 CAFT^{m_2-m_1}$, is the fatigue detail coefficient bellow the *CAFT* of the fatigue curve. The $N(t)$ is the number of cycles that considered detail category has subjected at the life time of t. The m_1, m_2, *CAFT* and $N(t)$ are considered as the deterministic parameters. The stress range S_{re}, fatigue detail coefficient A_1 are considered as random variables.