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Fatigue Life Prediction of Steel Bridges Considering Earthquake Loading

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1. Introduction

Bridges are generally subjected to high cycle fatigue (HCF) caused by usual traffic loadings. However, a number of fatigue failures of bridges have been reported in the past that cannot be explained by HCF. Studies on these failures reveal that extreme loading such as earthquakes is one of the reasons for these failures. During earthquake, some members may be subjected to stresses in plastic range. The plastic strains may cause low cycle fatigue (LCF) damage in those members and may lead to a reduced service life of bridges. The combined HCF and LCF has not been studied in bridges. The commonly used approach of damage prediction in other fields is based on Coffin-Manson strain-life relationship with Miner's rule (Suresh 1998). However, it has been revealed that Miner's rule does not predict correct results in variable amplitude loadings since it cannot capture the loading sequence effect. The objective of the paper is to propose a new fatigue model to predict combined HCF and LCF damage of bridges caused by traffic and earthquake loadings. Initially, the proposed model is introduced. Then, verification of the proposed model is explained. Finally, the proposed model is applied to a bridge member to confirm the applicability and significance of the proposed model.

2. Proposed fatigue model

The model considered failure mechanism is based on total strain.

2.1. Strain-life curve

The proposed curve consists of two parts as shown in Fig. 1. The first part corresponds fatigue life of plastic strain cycles ($\varepsilon \geq \varepsilon_y$) which usually affects LCF. To describe this part, Coffin-Manson strain-life curve is utilized as shown below.

$$\varepsilon = \frac{\sigma_f'}{E}(2N)^b + \varepsilon_f'(2N)^c \tag{1}$$

where ε is the applied strain amplitude, N is the number of cycles to failure, σ_f' is the fatigue strength coefficient, b is the fatigue strength exponent, ε_f' is the fatigue ductility coefficient, c is the fatigue ductility exponent and E is the elastic modulus of the material.

The second part describes the fatigue life of elastic strain cycles ($\varepsilon < \varepsilon_y$) which usually affects HCF. This part of curve represents hypothetical fully known curve. The shape of the curve is obtained by directly transforming the previous fully known stress-life curve to elastic strain-life curve (Siriwardane et al. 2008) as shown below.

$$\varepsilon = \varepsilon_e\left(\frac{N+N_u}{N+N_e}\right)^{b'} \tag{2}$$

where ε_e is the strain amplitude of the fatigue limit, N_e is the fatigue life at ε_e. The ε_y and N_y are the yield strain and the corresponding number of cycles to failure. The b' is the slope of the finite life region.

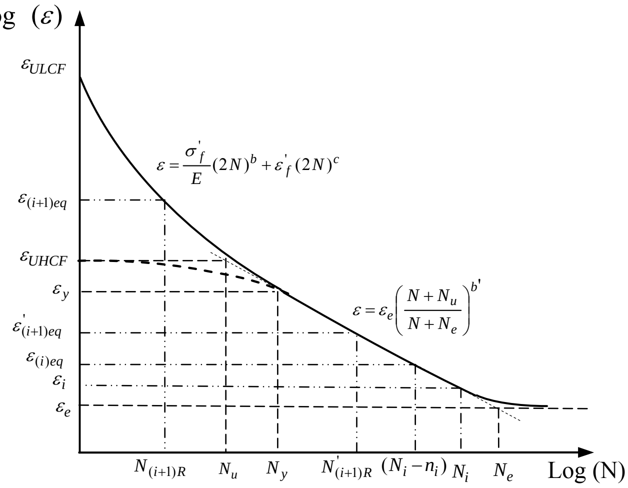

Fig. 1. Proposed strain-life curve.

2.2. Damage indicator

Suppose a component is subjected to a certain strain amplitude $(\varepsilon)_i$ of n_i number of cycles at load level i, N_i is the fatigue life (number of cycles to failure) corresponding to $(\varepsilon)_i$ (Fig. 1). Therefore, the reduced life at the load level i is obtained as (N_i–n_i). The equivalent strain $(\varepsilon)_{(i)eq}$ (Fig. 1), which corresponds to the failure life (N_i–n_i) is defined as i^{th} level damage equivalent strain. Hence, the new damage indicator, D_i is stated as below.

$$D_i = \frac{(\varepsilon)_{(i)eq} - (\varepsilon)_i}{(\varepsilon)_u - (\varepsilon)_i} \tag{3}$$

and $(\varepsilon)_u$ is expressed

$$(\varepsilon)_u = \begin{cases} \varepsilon_{ULCF} & (\varepsilon)_i \geq \varepsilon_y \\ \varepsilon_{UHCF} & (\varepsilon)_i < \varepsilon_y \end{cases} \tag{4}$$

Assuming the end of i^{th} loading level, damage D_i has been accumulated (occurred) due to the effect of $(\varepsilon)_{i+1}$ loading cycles, the damage is transformed to load level $i+1$ as below.

$$D_i = \frac{(\varepsilon)'_{(i+1)eq} - (\varepsilon)_{i+1}}{(\varepsilon)_u - (\varepsilon)_{i+1}} \tag{5}$$

and $(\varepsilon)_u$ is expressed

$$(\varepsilon)_u = \begin{cases} \varepsilon_{ULCF} & (\varepsilon)_{i+1} \geq \varepsilon_y \\ \varepsilon_{UHCF} & (\varepsilon)_{i+1} < \varepsilon_y \end{cases} \tag{6}$$

Then, $(\varepsilon)'_{(i+1)eq}$ is the damage equivalent strain at loading level $i+1$ is calculated. Then, the corresponding equivalent number of cycles to failure $N'_{(i+1)R}$ is obtained from the strain-life curve as shown in Fig. 1. From that, the corresponding residual life at load level $i+1$ (number of cycles is n_i+1), $N_{(i+1)R}$ is calculated as,

$$N_{(i+1)R} = N'_{(i+1)R} - n_{(i+1)} \tag{7}$$

Therefore, strain $(\varepsilon)_{(i+1)eq}$, which corresponds to $N_{(i+1)R}$ at load level $i+1$, is obtained from the strain-life curve as shown in Fig. 1. Then the cumulative damage at the end of load level $i+1$ is defined as,

$$D_{(i+1)} = \frac{(\varepsilon)_{(i+1)eq} - (\varepsilon)_{i+1}}{(\varepsilon)_u - (\varepsilon)_{i+1}} \tag{8}$$

At the first cycle the equivalent strain $(\varepsilon)_{(i)eq}$ is equal to $(\varepsilon)_i$ and the corresponding damage indicator becomes D_i=0. Similarly at the last cycle, the damage indicator becomes D_i=1 when $(\varepsilon)_{(i)eq}$ is equal to $(\varepsilon)_u$. Therefore, the damage indicator is normalized to one (D_i=1) at the fatigue failure of the material. Hence, the above procedure is followed until D_i=1.

3. Verification of the proposed fatigue model

Six fatigue tests of Inconel 718 nickel base super alloy were carried out both under increasing type step loading (Pattern A) and variable amplitude repeating block loading (Pattern B) (Cook 1982). Failure number of cycles of these tests was predicted by the proposed model. In addition, Miner's rule employed previous model was used to predict the number of cycles to failure. The obtained results are plotted in Fig. 2. The illustrations of Fig. 2 convince that the proposed method has better correlation with experimental results than Miner's rule employed previous model.

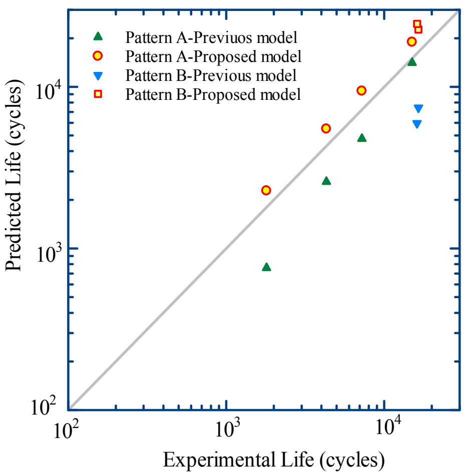

Fig. 2. Comparison of predicted and experimental lives for Inconel 718.

4. Case study: Fatigue life estimation of a bridge member

Fatigue life estimation of a bridge member is discussed in this section. One of the bracing members of the longest railway bridges in Sri Lanka is selected for the life estimation (Fig. 3). Life estimations are especially based on secondary stresses and strains, which are generated around the riveted connection of the member due to stress concentration effect of primary stresses caused by usual traffic and earthquake loadings. It was analysed for usual traffic and earthquake loadings.

Fig. 3. A view of the bridge.

From the primary stress distribution of usual traffic and earthquake loadings, secondary stress distribution was obtained by FEM. Then, secondary strain distributions were obtained. They were deduced to mean strain zero cycles with the use of Goodman relation. Rainflow cycle counting method was used as the cycle counting technique. Earthquake was assumed to occur at different times (from the construction) during the bridge life and resulting fatigue lives were estimated. The obtained results are given in Table 1.

Table 1 Comparison of calculated fatigue lives

Time of earthquake (years)	Previous model (Miner's rule)		Proposed model	
	Fatigue life (years)	Percentage reduction of life (%)	Fatigue life (years)	Percentage reduction of life (%)
5	26.5	35.4	22.0	63.3
10	26.5	35.4	24.0	60.0
20	26.5	35.4	29.0	51.7
30	30.0	26.8	34.0	43.3
40	40.0	2.4	41.0	31.7
50	-	-	50.5	15.8
54	-	-	54.0	10.0
Without earthquake	41.0	-	60.0	-

These results show that percentage reduction of the life is higher when earthquake occurs in the beginning of the bridge life.

5. Conclusions

A new model for combined damage of HCF and LCF was proposed. A verification of the model was conducted by comparing the predicted lives with experimental lives due to uniaxial variable amplitude loading for one material. It was shown that the proposed fatigue model gives a realistic fatigue life for the combined damage of HCF and LCF in uniaixial variable amplitude loading situations where detailed stress histories are known. The proposed fatigue model was utilized to estimate the fatigue life of a bridge member. Case study realized the importance of consideration of the earthquake induced LCF damage in addition to HCF damage due to usual traffic loading in steel bridges. The importance of accurate prediction of combined damage of HCF and LCF was also confirmed.

References

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