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Mesoscopic Law of Multiaxial Fatigue for Railway Bridges

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1. Introduction

The stress concentration effect in connections between the primary members of bridges was found to be one of main reasons for fatigue damage (Siriwardane et al. 2007 & 2008). Most of such connections are subjected to multiaxial fatigue and it has been found that more precise high cycle multiaxial theories exist in mesoscopic scale than commonly used macroscopic scale (Morel et al. 1998). Recently, one mesoscopic scale fatigue model (Jabbado et al. 2008) was developed to obtain more precise estimation to multiaxial fatigue. However, experimental comparisons of this theory (model) have exhibited a certain amount of deviation for multiaxial fatigue life due to variable amplitude loading conditions since the considered damage law is Miner's rule. Therefore this paper proposes a new mesoscopic scale fatigue model to estimate multiaxial high cycle fatigue life for variable amplitude proportional loading.

2. Proposed fatigue model

The model considered failure mechanism is based on accumulated inelastic meso-strain.

2.1 Accumulated plastic meso-strain per stabilized cycle

Considering the mesoscopic scale elasto-plastic behavior accumulated plastic meso-strain (ε_s^{pc}) per stabilized cycle in proportional loading is found to be (Jabbado et al. 2008),

$$\varepsilon_s^{pc} = \frac{4}{\sqrt{3}}\frac{2k^* - k_{max} - k_{min}}{c} \quad (1)$$

where $c = b + 2\eta$. The b and η are the mesoscopic linear hardening and the shear modulus respectively. The k^* is the radius of the smallest hypersphere which contains the entire history of the macroscopic deviatoric stress amplitude. The k_{max} and k_{min} are the maximum and the minimum values of mesoscopic yield stresses and these are dependent of macroscopic hydrostatic stress amplitude.

2.2 Mesoscopic law of fatigue life

The mesoscopic law of fatigue life for constant amplitude proportional loading is described as (Jabbado et al. 2008),

$$N = A(\varepsilon_s^{pc})^{-\xi} \quad (2)$$

where N is number of cycles to crack nucleation. The ξ, A are material parameters to be determined from fatigue tests.

2.3 Damage indicator for variable amplitude loading

The hypothesis behind this fatigue law is that if the physical state of damage is the same, then fatigue life depends only on the loading condition. Suppose a component is subjected to a certain accumulated plastic meso-strain $(\varepsilon_s^{pc})_i$ per stabilized cycle of n_i number of cycles at load level i, N_i is the fatigue life corresponding to $(\varepsilon_s^{pc})_i$ (Fig. 1). The accumulated plastic meso-strain $(\varepsilon_s^{pc})_{(i)eq}$, which corresponds to the residual life ($N_i - n_i$), is named as i^{th} level damage accumulated plastic meso-strain. Hence, new damage indicator, D_i is stated as,

$$D_i = \frac{(\varepsilon_s^{pc})_{(i)eq} - (\varepsilon_s^{pc})_i}{(\varepsilon_s^{pc})_u - (\varepsilon_s^{pc})_i} \quad (3)$$

where $(\varepsilon_s^{pc})_u$ is the intercept in Fig. 1 with the ordinate at one-quarter of first fatigue cycle.

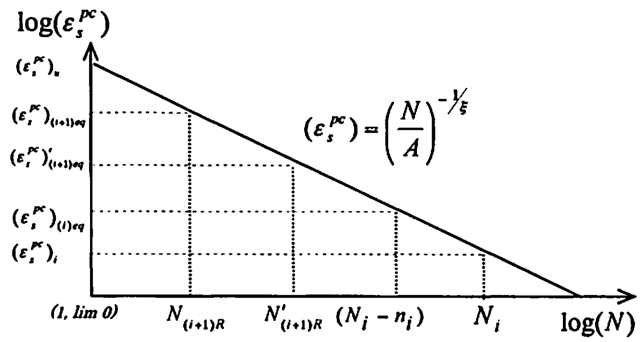

Fig. 1. Schematic representation of mesoscopic law of fatigue life for constant amplitude loading

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

$$D_i = \frac{(\varepsilon_s^{pc})'_{(i+1)eq} - (\varepsilon_s^{pc})_{i+1}}{(\varepsilon_s^{pc})_u - (\varepsilon_s^{pc})_{i+1}} \quad (4)$$

The $(\varepsilon_s^{pc})'_{(i+1)eq}$, which is damage equivalent accumulated plastic meso-strain at loading level $i+1$, can be calculated from Eq. (4) and the corresponding equivalent number of cycles to failure $N'_{(i+1)R}$ can be obtained from the Eq. (2) as shown in Fig. 1. Supposing that $(\varepsilon_s^{pc})_{i+1}$ is subjected to $n_{(i+1)}$ number of cycles, the corresponding residual life at load level $i+1$, $N_{(i+1)R}$ is calculated as,

$$N_{(i+1)R} = N'_{(i+1)R} - n_{(i+1)} \quad (5)$$

Hence damage accumulated plastic meso-strain $(\varepsilon_s^{pc})_{(i+1)eq}$, which corresponds to $N_{(i+1)R}$ at load level $i+1$, can be obtained from the Eq. (2) as shown in Fig. 1. Then the cumulative damage at the end of load level $i+1$ is defined as,

$$D_{(i+1)} = \frac{(\varepsilon_s^{pc})_{(i+1)eq} - (\varepsilon_s^{pc})_{i+1}}{(\varepsilon_s^{pc})_u - (\varepsilon_s^{pc})_{i+1}} \quad (6)$$

The damage indicator is normalized to one (D_i=1) at the fatigue failure of the material.

2.4 Determination of model parameters

All six parameters are similar to previous mesoscopic model (Jabbado et al. 2008). Therefore, the determination method is also similar to the previous model and those are identified by using two fatigue limits and one *S-N* curve.

3. Verification of proposed fatigue model

In this section, the multiaxial fatigue test results of two materials (18G2A & 10HNAP steels) are compared with the theoretically predicted fatigue life. The comparisons between the calculated lives and the experimental results are shown in Fig 2. In addition to this, experimental lives are compared with three previous theoretical approaches. This verification reveals the validity of the proposed model.

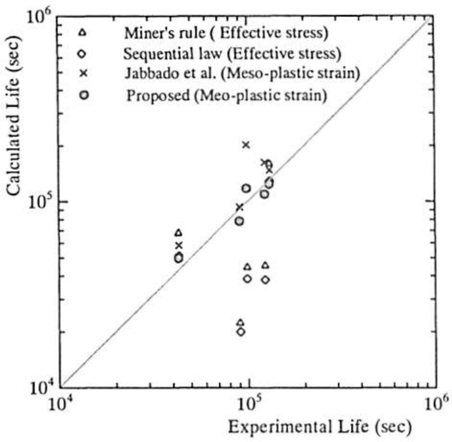

Fig. 2. Comparison of fatigue lives

4. Case study: Fatigue life estimation of a connection

One of the critical connections (Fig. 3) which were found from a detailed investigation (Siriwardane et al. 2007) of one of the longest railway bridges in Sri Lanka is selected for the life estimation.

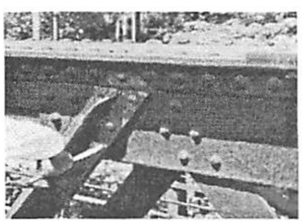
Fig. 3. Riveted connection

4.1 Stress analysis

The fatigue damage is evaluated based on the state of stress due to release of contact (tightness) of rivet while all the rivets have low clamping force. Therefore, a critical member without rivets was considered for analysis (Fig. 4).When the rivet is not properly in contact with the plate, the particular rivets tend to transfer less or zero amount of total load. The other rivets, which are carrying the load, are called as active rivets. In this study, fatigue lives were evaluated stepwise by reducing the contribution of active number of rivets in the connection. Analysis shows that stresses are operating well below the yield limit of the material and highly stressed locations are subjected to biaxial proportional state of stress.

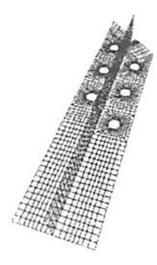
Fig. 4. FE mesh

4.2 Estimation of accumulated plastic meso-strain

The obtained principle stress variations were reduced into a series of equivalent stabilized cycles which give the same damage to the material using rainflow cycle counting technique. The material parameters $\alpha, \beta, \gamma, \xi$, c and A for Wrought iron were calculated as 1.0832, 15 MPa, 0.0473, 1.36, 12923 MPa and 613 respectively. Hence, the accumulated plastic meso-strain per each stabilized cycle is calculated using Eq. (1) and plotted in Fig. 5 for the two considered cases.

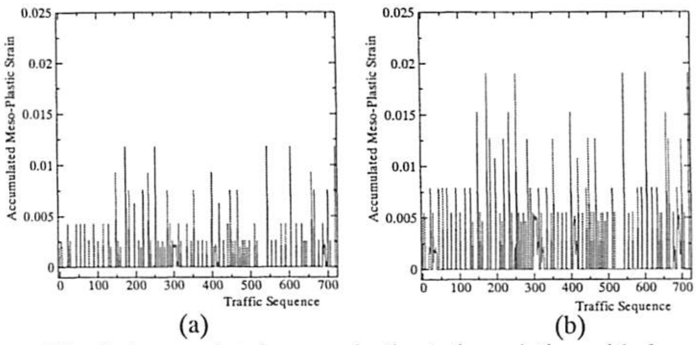

Fig. 5. Accumulated meso-plastic strain variation with the traffic sequence per single day at present: (a). when all six rivets are active, (b). when two rivets are active

4.3 Fatigue life estimation

The proposed fatigue model was utilized to predict the service life of a riveted connection (Table 1). The defined fatigue life describes the time duration from the date when considered feature of riveted connection appeared, to the date of fatigue failure. The predicted values were also compared with three previous models based estimations as shown in Table 1. The comparisons revealed that the proposed fatigue model based estimations deviate from previous fatigue theories based estimations.

Table 1: Comparison of fatigue lives of riveted connection

Active number of rivets at connection	Fatigue life (months)			
	Effective stress based approach		Mesoscopic plastic strain based approach	
	Miner's rule	Sequential law	Jabbado et al.2008	Proposed model
6	1957	1315	361	294
5	927	607	235	192
4	533	341	146	123
3	299	192	117	101
2	93	66	96	75

5. Conclusions

The study shows that the proposed multiaxial fatigue model gives a much more realistic fatigue life to variable amplitude proportional loading situation where detailed stress histories are known. Further verifications of proposed model in difficult loading situations are currently under way.

References

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