Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 64 (1991)

Artikel: Fatigue and life prediction for high-speed railway bridges

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DOI: https://doi.org/10.5169/seals-49356

Fatigue and Life Prediction for High-Speed Railway Bridges

Fatigue et durée de vie restante pour les ponts ferroviaires à grande vitesse

Ermüdungs- und Restlebensdauer-Prognose für Hochgeschwindigkeits-Eisenbahnbrücken

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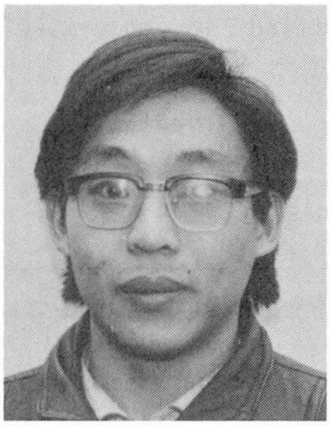

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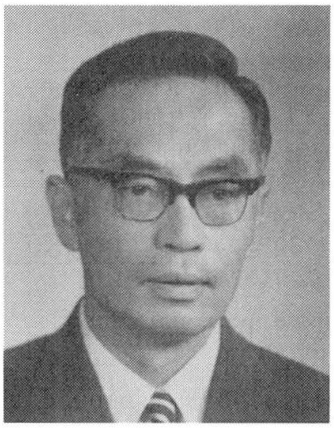

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SUMMARY

The authors discuss several problems associated with fatigue damage assessment and remaining life prediction.

RESUME

Les auteurs examinent quelques uns des problèmes relatifs à l'évaluation des dommages dus à la fatigue et à l'estimation de la vie restante.

ZUSAMMENFASSUNG

Einige spezifische Probleme, welche mit der Auswertung der Ermüdungsschädigung und der Prognose der Restlebensdauer verbunden sind, werden diskutiert.

1. INTRODUCTION

High-speed railway is the main tendancy of modern railway transportation. In France and Japan, vehicle speed of high-speed railway has reached about 300 to 400 Km/h. In China, decision has also been made to develop quasi-high-speed railway (about 160 to 200 Km/h) in recent years on some busy railway lines such as the Guangzhou-Shenzhen line. CARS and other railway institutions are doing site investigation of the existing tracks and bridges to assess their dynamic responses and remaining strength capacities at the speed of 160 Km/h.

The explicit effects of high-speed train on bridge structures are the larger impact and the higher fatigue frequency. Hence, high-speed railway bridge undertakes more serious fatigue effects than that on common lines. So we must pay more attention to fatigue problems of structures and do research on the fatigue behavior of high-speed railway bridges. In this paper, the authors will discuss several important problems associated with fatigue damage assessment and remaining life prediction of existing bridges which will be modified to undertake high-speed transportation.

2. FATIGUE DAMAGE AND S-N CURVE

According to Damage Theory by Lemaitre, we have

$$\underset{\sim}{\sigma} = (1-D)\ \underset{\sim}{E} : \underset{\sim}{\varepsilon}^{e}$$

$$\dot{D} = A\ y^{s}\dot{p}$$

$$y = \frac{\sigma_{eq}^{2}}{2(1-D)}\left[\ 2/3(1+\mu) + 3(1-2\mu)\left(\frac{\sigma_{m}}{\sigma_{eq}}\right)^{2}\ \right]$$

where $\underset{\sim}{E}$ is elastic tensor of undamaged material, y is called strain release rate of damage, σ_m is average stress, and σ_{eq} is Von-Mises equivalent stress.

Using Ramberg-Osgood hardening rule in case of multiaxial stress state, it can be obtained [3]

$$\dot{D} = B\,\tilde{\sigma}_{eq}^{\beta}\ \dot{\tilde{\sigma}}_{eq}$$

where $\tilde{\sigma}_{eq} = \sigma_{eq}/(1-D)$

$$B = A/2^{s}\left[2/3(1+\mu) + 3(1-2\mu)\left(\frac{\sigma_{m}}{\sigma_{eq}}\right)^{2}\right]^{s} M/K^{M}$$

$$\beta = 2s + M - 1$$

In case of proportional loading, B and β are constant, and the following equations can be obtained,

for symmetrical stress fatigue ($\rho = -1$)

$$\frac{\delta D}{\delta n} = 2B/(1+\beta)/(1-D)^{1+\beta}\ [\Delta\sigma_{eq}/2]^{1+\beta} \qquad (1)$$

for pulse stress fatigue (ρ =0)

$$\frac{\delta D}{\delta n} = B/(1+\beta)/(1-D)^{1+\beta}\ 2^{1+\beta}\ [\Delta\sigma_{eq}/2]^{1+\beta} \qquad (2)$$

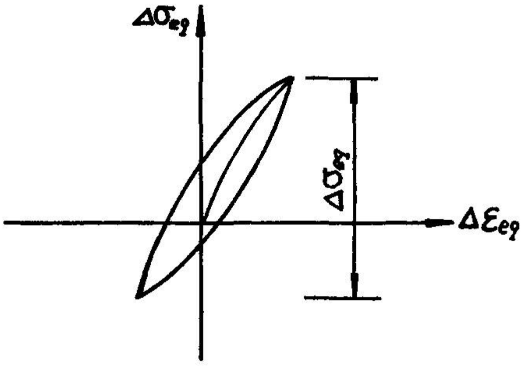

Fig.1 Stress-Strain Cycle

In case of constant range fatigue, we obtain

$$D = 1-(1-n/N)^{\frac{1}{2+\beta}} \qquad (3)$$

$$N(\Delta\sigma_{eq}/2)^{1+\beta} = \begin{cases} (1+\beta)/2/B/(2+\beta) & \text{for } \rho=-1 \\ (1+\beta)/2^{1+\beta}/B/(2+\beta) & \text{for } \rho=0 \end{cases}$$

where n represents number of fatigue cycle, and N is the number of cycles at fatigue failure of material.

These equations demonstrate fatigue damage and fatigue life behaviors of materials respectively

Therefore, S-N relation for a real component of bridge can be expressed experimentally as

$$N(\Delta\sigma_{eq}/2)^{\alpha} = C \qquad (4)$$

and the damage accumulating rule for such a component can be described with equation (3), in which D behaves nonlinearly with (n/N)

3. NONLINEAR DAMAGE ACCUMULATING RULE AND REMAINING FATIGUE LIFE

3.1 Nonlinear Damage Accumulating Rule

In case of variable range fatigue, from equation (3) we get

$$\delta D = 1/(2+\beta)/(1-D)^{1+\beta}\delta(n/N) \quad (5)$$

For a definite loading history (n_i, N_i), equation (5) can be integrated into

$$D = 1-[1-\sum_i(n_i/N_i)]^{\frac{1}{2+\beta}} \quad (6)$$

According to Miner's rule

$$D_M = \sum_i (n_i/N_i)$$

So D and D_M have following relation (see Fig.2),

$$D = 1-(1-D_M)^{\frac{1}{2+\beta}}$$

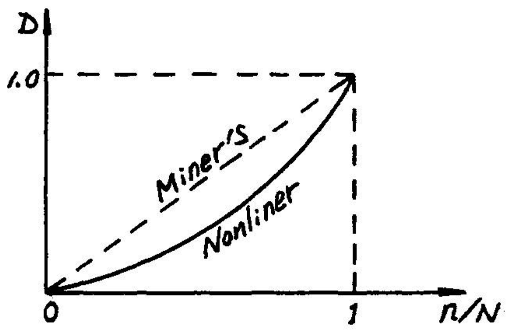

Fig. 2 Fatigue Damage Accumulating

3.2 Remaining Fatigue Life

In case of constant range fatigue, assuming D_0 represents fatigue damage at the moment from which the remainig life is considered, we can obtain the remaining fatigue life as

$$n' = (1-D_0)^{2+\beta} N$$

In case of variable range fatigue, we assume that loading spectrum per year is unchanged, hence

$$D_0 = 1-[1-N_p\sum_i (n_i/N_i)]^{\frac{1}{2+\beta}}$$

where N_p represents fatigue history passed (in year). Therefore the remaining fatigue life can be obtained as

$$n' = (1-D_0)^{2+\beta}/\sum_i(n_i/N_i)$$

4. FATIGUE DAMAGE ASSESSMENT OF EXISTING BRIDGES

Assessment approach of fatigue damage for existing structures has been discussed in many papers [1,2,5]. In this paper, the authors will suggest a method based on the quasi-static concept.

From continuum damage mechanics,

$$D = 1-\sigma/\tilde{\sigma} \doteq 1-(\Delta\varepsilon_o/\Delta\varepsilon)$$

If the initial strain range , $\Delta\varepsilon_o$, and the present strain range, $\Delta\varepsilon$, are known, D can be obtained. Generally, it is difficult to get $\Delta\varepsilon_o$. However, we can calculate D by using the results $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$ from two times of experiments.

$$(1-D_1)/(1-D_2) = (\Delta\varepsilon_2/\Delta\varepsilon_1)$$

From equation (6)

$$D_1 = 1-[1-N_p\sum_i(n_i/N_i)]^{\frac{1}{2+\beta}}$$

$$D_2 = 1-[1-(N_p+N)\sum_i(n_i/N_i)]^{\frac{1}{2+\beta}}$$

where N is the time interval (in year) between two times of investigation. So N_p, D_1 and D_2 can be assessed and calculated.

If load spectrum in remaining time is $(\tilde{n}_i, \tilde{N}_i)$, then

$$D_1 = 1-[1-N_p'\sum_i(\tilde{n}_i/\tilde{N}_i)]^{\frac{1}{2+\beta}}$$

Therefore the remaining life is

$$n' = (1-D_1)^{2+\beta}/\sum_i(\tilde{n}_i/\tilde{N}_i)$$

Analytical flowchart for damage assessment and remaining life prediction for existing bridges is shown in Fig. 3.

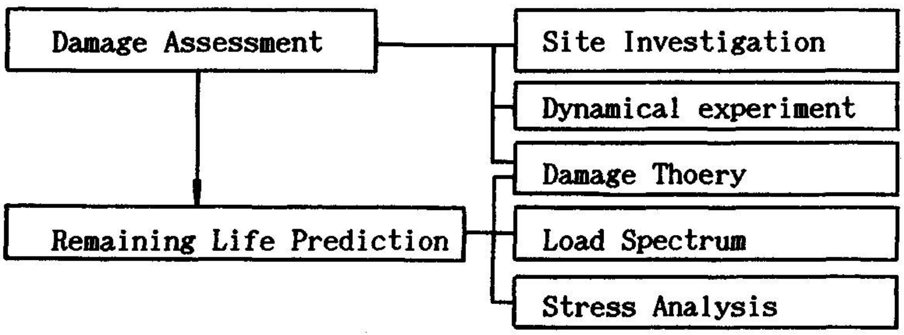

Fig.3 Analytical Flowchart

For high-speed railway bridges, more attention should be paid to load spectrum.

5. AN EXAMPLE

Sketch of Puyangjiang River Railway Bridge, situated on Zhejiang-Jiangxi Line, is shown in Fig.4. The 32m plate girder was fabricated in 1972. The stress spectra of the longitudinal girder and the cross beam were obtained by CARS in 1983.

The S-N curve for welded component proposed by AREA was chosen to predict fatigue damage and remaining fatigue life of the plate girder. The analytical results are listed in Tab.1 and Tab.2.

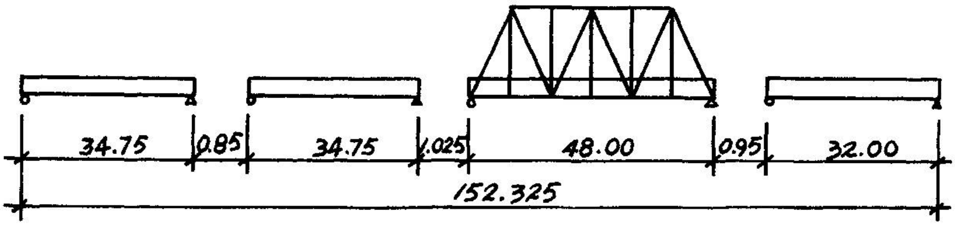

Fig.4 Sketch of Puyangjiang River Bridge

Table 1. Fatigue damage at the lifetime of 100 years

	Main girder	Longitudinal girder	Cross beam
D	1.89	0.623	0.235
D		0.216	0.065

Table 2. Total fatigue life and remaining life (in year)

	Main girder	Longitudinal girder	Cross beam
Total	52.9	160.5	425.5
Remaining	34.9	142.5	407.5

6. CONCLUSIONS

Fatigue damage assessment and remaining fatigue life prediction are very important subjects for existing structures,especially for high-speed railway bridges. Based on continuum damage mechanics, a nonlinear damage accumulating rule, damage assessment approach and remaining life prediction method have been proposed and proved by field tests on Puyangjiang River Bridge in this paper.

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