FATIGUE LIFE PREDICTION OF COPED STEEL BEAMS BASED ON CONTINUUM DAMAGE MECHANICS

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Introduction

Decision concerning the maintenance of an existing bridge gives serious impact on the traffic patterns and economy of the surrounding community. Thus, it is important to extend the lifetime of a bridge structure and evaluate the fatigue damage evolution accurately. In the steel bridge, Coped stringers, floor beams, diaphragms have been commonly used to frame one member to another. In these coped members, the beam flanges must often be coped to provide enough clearance for the supports. The geometric discontinuities at cope corner produce not only the reduction of cross sectional bending resistance, but also the high stress concentration in the web, and it induces the high cycle fatigue cracking around the cope up to final structural member failure[1)]. It is therefore the high cycle fatigue life prediction of coped steel beams, was carried out by using continuum damage mechanics (CDM).

Analytical Method

In this study, the analytical method of high cycle fatigue failure based on CDM is proposed. The basic concept of CDM considers the damage variable as the degree of degradation of material in the homogeneous field. Thus, the basic image of damage variable D is defined as the loss of effective area in the meso-scale that is defined by so-called 'representative volume element (RVE)' (numerically Gauss point)[2)], see Fig. 1.

$$D = \frac{A_D}{A_0} \tag{1}$$

where A_0 : the total area of considered plane, A_D: the area of all micro-defects

In general, damage is caused by the accumulated plastic strain due to stress concentration in the neighborhood of micro defects, and it is defined as

$$dp = \sqrt{(2/3)de_{ij}^{p}de_{ij}^{p}} \tag{2}$$

where dp: the accumulated plastic strain increment

It is assumed that damage occur when the accumulated plastic strain, p exceeds a certain value $p_D(=e_{pD}(s_u - s_f)/(s_{eq} - s_f))$, and rupture occurs at the meso-scale (macrocrack initiation), when damage variable reaches the critical value Dc(Fig. 2).

For high cycle fatigue, there is no plasticity occurs on the macro scale, but there is micro cracking due to irreversible plastic strain on the micro-scale μ. Thus, the damage evolution is derived from the associated flow rule with the strain energy density release rate Y and the potential of dissipation F_D at micro scale as

$$dD = \frac{\partial F_D^m}{\partial Y^m} d\, l^m = \left(\frac{Y^m}{S}\right)^s dp^m \tag{3}$$

where S: a material parameter (see in Table 1).

In order to calculate the high cycle fatigue damage evolution in the RVE, the stresses at micro scale s_{ij}^m are evaluated from the macro scale stresses s_{ij} by introducing two-scale model based on the localization of self-consistent scheme[3)].

$$s_{ij}^{m} = s_{ij} - aEe_{ij}^{mp} \tag{4}$$

where $a = (1-b)/(1+n), \quad b = 2(4-5n)/15(1-n)$ (5)

From the yield condition at the micro scale taken kinematics hardening X^m into account and the plastic threshold at microscale taken equal to the fatigue limit s_f.

$$f^m = \left(\frac{s^m}{1-D} - X^{mD}\right)_{eq} - s_f = 0 \tag{6}$$

with the law of localization Eq. (4); it is possible to compute the damage evolution up to failure as a function of the macro-scopic stresses as

$$dD = \left[\frac{(s_{eq} + ks_f)^2 R_n^m}{2ES(1+k)^2(1-D)^2}\right]^s \frac{ds_{eq}}{C(1+k)} \quad if \quad s_{eq} \ge s_f \tag{7}$$

where the triaxiality function $R_n^m = \frac{2}{3}(1+n) + 3(1-2n)\left[\frac{s_H(1+k)}{s_{eq} + ks_f}\right]^2$ (8)

s_{eq} : von Mises equivalent stress; k=3aE/2C; C: Kinematic hardening parameter.

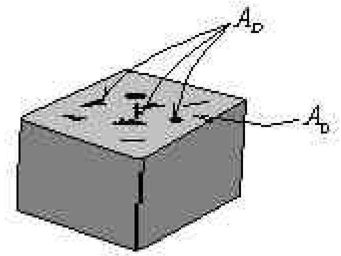

Fig. 1 Basic definition of damage variable

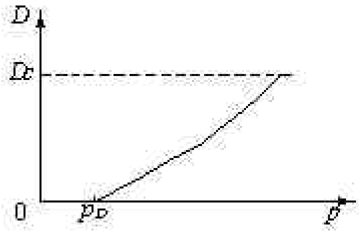

Fig. 2 Damage evolution

Table 1. Material properties

Elastic modulus	E	2x10^5 MPa
Poison's ratio	v	0.3
Fatigue limit stress	s_f	160 MPa
Yield stress	s_y	240 MPa
Ultimate stress	s_u	300 MPa
Strength of damage	S	2.4 MPa
Exponent of damage	s	2
Damage threshold	e_{pD}	0.44
Critical damage	D_c	0.9
Hardening parameter	C	2000 MPa
Micro-crack closure	h	0.2

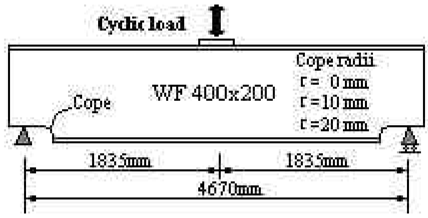

Fig. 3 Cope steel beam model

Keyword: Fatigue life prediction, Coped steel beams, Continuum damage mechanics, self-consistent scheme.

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In order to take into account the different behaviors in tension and in compression, the strain energy release rate Y is defined as

$$Y^m = \frac{1+\nu}{E}\left[\frac{\langle s^m_{ij}\rangle\langle s^m_{ij}\rangle}{(1-D)^2} + h\frac{\langle -s^m_{ij}\rangle\langle -s^m_{ij}\rangle}{(1-Dh)^2}\right] - \frac{\nu}{E}\left[\frac{\langle s^m_{kk}\rangle^2}{(1-D)^2} + h\frac{\langle -s^m_{kk}\rangle^2}{(1-Dh)^2}\right] \tag{9}$$

where $\langle . \rangle$ means the positive part, i.e., $\langle x \rangle = x$ if $x > 0$, $\langle x \rangle = 0$ if $x \le 0$, and h is the crack closure parameter.

Analytical Results

For the purpose of analyzing the fatigue damage, simple support coped beam models are examined (Fig.3). The applied load and cope radius are regarded as the two major analytical parameters. The main difficulty is the identification of the material properties as there is no way to measure directly the behavior at the micro scale. If we assume that the material parameters at the micro scale are of the same as at the macro scale, the material parameters have been identified as **Table 1**. The FE program has been implemented coupled with damage evolution, and the HCF damage analysis of coped beams carried out until Crack initiation (D=Dc) and propagation with damaged zone, subsequence completely damaged zone ultimately leads to failure of structures. In this analysis, the 30mm crack size (damaged zone) at the cope corner is assumed to be the failure condition.

From analytical results, it was observed that the effect of cope radius to damage evolution is shown in **Fig.4**. The fatigue damage growth is slower with increasing cope radius. This is because the higher stress concentration is produced by the smaller cope radius. As we can also see from **Fig. 5**, the damage distribution of coped beam at cope corner is larger with decreasing cope radius. It is also found that the fatigue life increase with increasing in cope radius (**Fig. 6**). Therefore, it is recognized that the cope radius affect to fatigue life of coped steel beam.

The influence of applied mean stress to the fatigue life is shown in **Fig. 7**. It is found that, the fatigue life increase with decreasing mean stress. This is because the larger mean stress produces high tensile stress, which must induce damage growth faster. As the effect of microcrack closure during loading in tension and compression are different (the microcrack open larger in tension).

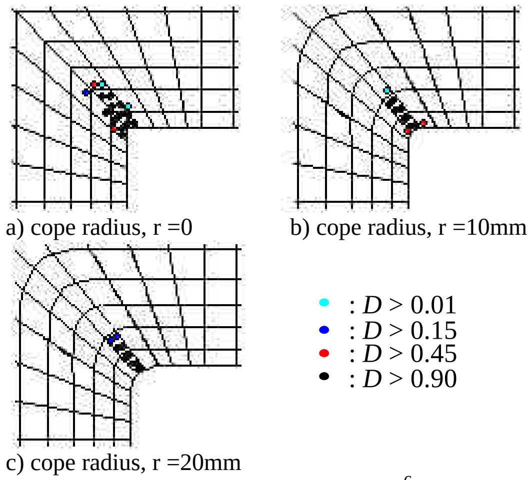

Fig. 5 Damage distribution (10^6cycles)

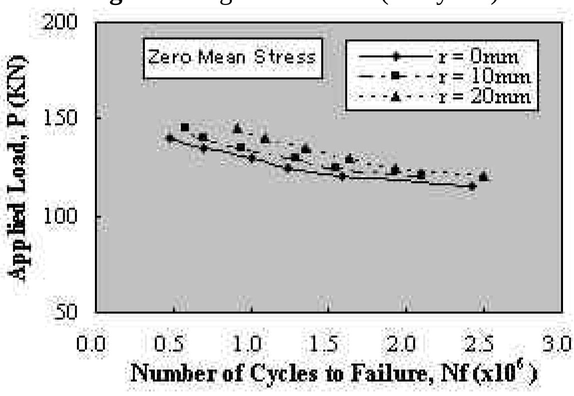

Fig. 6 Effect of cope radius to fatigue life

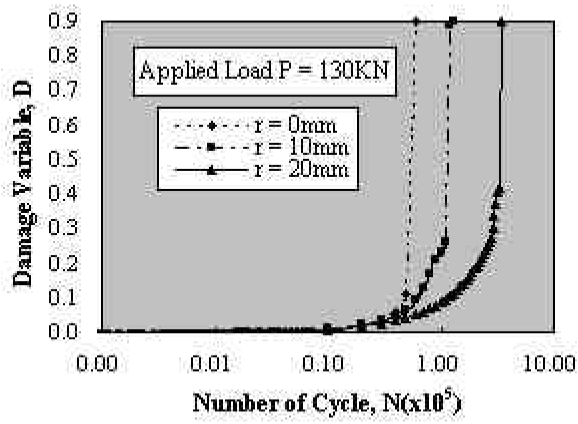

Fig. 4 Effect of cope radius to damage evolution

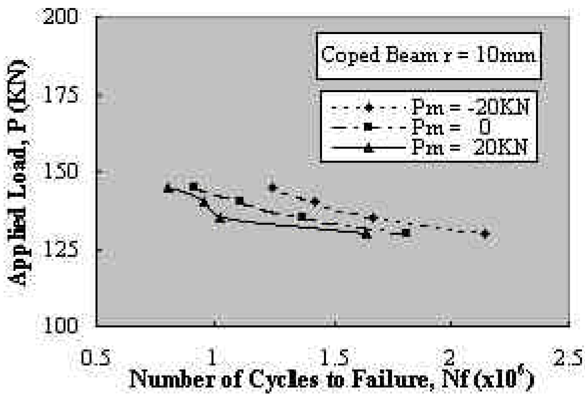

Fig. 7 Effect of mean stress to fatigue life

Conclusions

High cycle fatigue damage analysis and lifetime prediction of coped steel beams were carried out by using damage mechanics. For high cycle fatigue, damage occurs due to the micro-plastic strain evolution. Thus, in this study, a two-scale model was introduced to evaluate the micro strains and stresses from the macro stresses by means of the localization law. The effect of cope geometry was considered to investigate the localization of fatigue damage, and found that cope radius affect to the fatigue damage evolution and fatigue life due to the high stress concentration at the cope corner. It was also found that the mean stress influence on the fatigue life due to the microcrack closure. These results confirmed that the proposed analytical method could simulate the HCF damage behavior of a typical steel structural member. It also could give reasonable results for fatigue life prediction of coped steel beams. Therefore, to improve the damage evolution law and perform the experimental identification of material properties, the fatigue life prediction can be obtained accurately by using the proposed method.

References

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