PROPOSAL OF FATIGUE DESIGN METHOD FOR STRUCTURAL DISCONTINUITES CONSIDERING STRES GRADIENT

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Abstract

This paper discusses a method that focuses not only on peak stresses but also on stress gradients to rationalize fatigue design using a low-alloy steels. First, fatigue strength reduction ratios are associated with stress gradients rather than stress concentration factors. Next, to verify the stress gradient method, fatigue tests were conducted on hole-notched specimens. Finally, the fatigue life was predicted, considering the stress gradient at the notch root. The predicted atigue lives agreed well with the experimental results. It was confirmed that the fatigue life can be predicted more accurately than the conventional peak stress method.

1. Introduction

Fatigue failures always occur in the stress concentrated area. A designer must consider the fatigue reduction by the stress concentration. A designer analyze peak stresses of a component and evaluate whether the fatigue life computed from the peak stress satisfies the design life. As noted in many textbooks, however, a fatigue life prediction at a stress concentrated part based on a peak stress always provides an overly conservative estimate. In order to eliminate this conservatism and to rationalize a fatigue design, we propose a design method based on not only the peak stress, but also on the stress gradient.

2. Fatigue analysis for structural discontinuites

While discussing the notch effect in a low-cycle fatigue, a stress–strain relation at he notch root has to be considered. Neuber led the following rule among an elastic stress concentration factor K_t, an elasto-plastic stress concentration factor K_σ, and an elasto-plastic strain concentration factor K_ε at the notch root [1].

$$K_\mathrm{t}^2 = K_\sigma K_\varepsilon \tag{1}$$

Manson et al.[2] replaced K_t in Eq. (1) with fatigue-strength reduction factor K_f. Considering the definitions of K_σ and K_ε, Eq. (1) can be rewritten as follows:

$$K_\mathrm{f}^2 = \frac{\Delta\sigma}{\Delta S}\frac{\Delta\varepsilon}{\Delta e} \tag{2}$$

where, ΔS and Δe are nominal stress and strain ranges applied to a notched member, $\Delta\sigma$ and $\Delta\varepsilon$ are local stress and strain ranges at the notch root, respectively. By multiplying both sides with the modulus of longitudinal elasticity E, and transforming, Eq. (2) becomes

$$K_\mathrm{f}\sqrt{\Delta S \Delta e E} = \sqrt{\Delta\sigma\Delta\varepsilon E} \tag{3}$$

As $\Delta e E$ is equal to ΔS,

$$K_\mathrm{f}\Delta S = \sqrt{\Delta\sigma\Delta\varepsilon E} \tag{4}$$

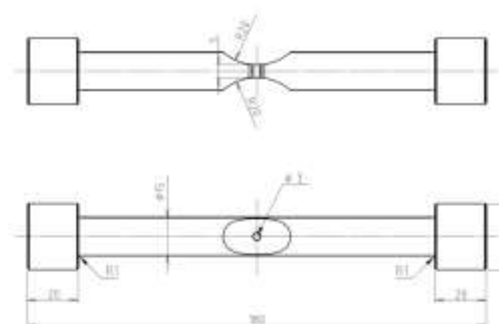

Fig.1 – Details of hole-notched specimen.

If we prepare a fatigue curve of smooth specimen with the horizontal and vertical axes representing fatigue life, and $\sqrt{\Delta\sigma\Delta\varepsilon E}$, respectively, we can predict the fatigue life of notched specimens using the nominal stress and strain.

With the widespread usespread of 3D CAD, elastic FEA has been commonly used for designing. The stress determined by FEA is the maximum stress. When the nominal stress and strain are limited to the elastic region, the stress range calculated by using FEA, $\Delta\sigma_{\mathrm{FEA}}$ is can be expressed as:

$$\Delta\sigma_{\mathrm{FEA}} = K_{\mathrm{t}}\Delta S \tag{5}$$

by substituting Eq. (5), Eq. (5) can be rewritten as:

$$\frac{K_{\mathrm{f}}}{K_{\mathrm{t}}}\Delta\sigma_{\mathrm{FEA}} = \sqrt{\Delta\sigma\Delta\varepsilon E} \tag{6}$$

by using Eq. (6), the fatigue life of the notched member (the structural discontinue part) can be predicted from the FEA result.

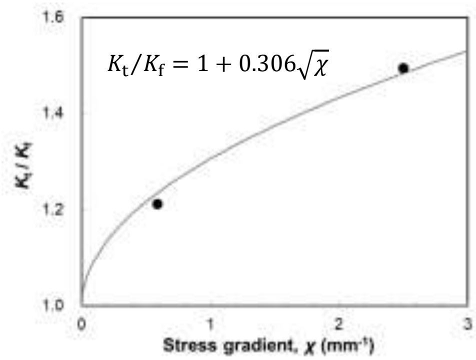

Fig.2 – Relation between $K_{\mathrm{t}}/K_{\mathrm{f}}$ and stress gradient.

Regarding $K_{\mathrm{t}}/K_{\mathrm{f}}$, Siebel et al. [3] found that $K_{\mathrm{t}}/K_{\mathrm{f}}$ for the fatigue limit was governed by the stress gradient χ at the notch. The absolute value of the gradient varies in accordance with the applied stress. Therefore, the stress gradient which was normalized by the maximum stress at the notch root was used here. The normalized stress gradient can be expressed using the following equation:

$$\chi = \left|\frac{1}{\sigma_{\max}}\frac{\mathrm{d}\sigma(x)}{\mathrm{d}x}\right|_{x=0} \tag{12}$$

3. Verification

To verify the proposed method, a fatigue test was performed using a hole-notched specimen of a low-alloy steel (JIS SQV2A) shown in Fig. 1. As the relation $\chi - K_{\mathrm{t}}/K_{\mathrm{f}}$ for the material was not yet available, it was substituted with literature data of a carbon steel and shown in Fig. 2.

A fully-revesed load-controlled fatigue test was conducted, and the relation between nominal stress and fatigue life is shown in Fig. 3. The solid line in the figure represents the smooth curve. When compared at a nominal stress, the fatigue strength of hole-notched specimen was lower than that of the smooth specimens. From the FEA result of hole-nothced speicmen, the stress gradient χ and stress range $\Delta\sigma_{\mathrm{FEA}}$ at the notch root were obtained to predict the fatigue life by the proposed method. The predicted fatigue lives are compared with the experimentalesults and shown in Figure 4. The dashed lines indicate the boundaries of factor of 2. Figure 4 also shows the fatigue life prediction results by the maximum stress, which is widely used in the current design. Most of the fatigue life prediction results by the proposed method are within the factor of 2. On the other hand, the method based on the maximum stress always gave conservative prediction results.

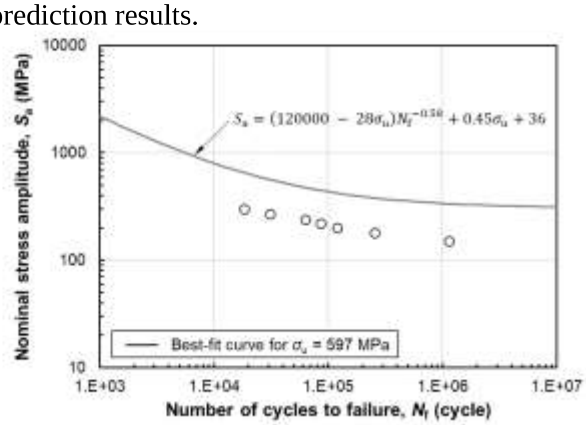

Fig.3 – Fatigue test results.

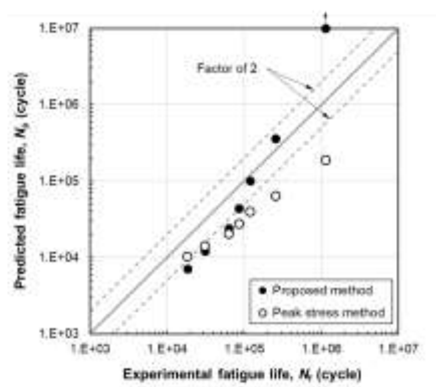

Fig.4 – Validation results of proposed method.