Study on Elastic-Plastic Strain Behavior of Notched Specimen

(5. Consideration on Fatigue Life and Cyclic Strain Behavior of Steel under Cyclic Tensile Load)

by

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The strains ahead of notches in steel plate specimens have been investigated using strain gages in order to find the relationship between the cyclic strains under cyclic tensile load and the fatigue life in the range of $10^4$–$10^6$ cycles. From the cyclic strains measured, the relationships between strain range, mean strain, plastic zone size and the number of cycles, as well as the strain distribution near notches have been investigated. Two types of cyclic strain behavior near notch roots have been found; in one type the mean strain and the plastic zone increase as the number of cycles increases and in another type the mean strain and the plastic zone remain constant with increasing cycles. The author thinks that these two types of cyclic strain behaviors are effective knowledge to evaluate the fatigue life of notched specimens. The experimental results and their discussion are presented.

1. Introduction

Two estimation methods of fatigue life in high cycle region and low cycle region are applied to fatigue design of machinery parts and structural members. Fatigue life in high cycle regions during stress control test has been estimated using the $S_R$–$N_f$ curve and the $K$–$K_f$ relation, where $S_R$ is the stress range and $N_f$ is the number of cycles until smooth specimens fracture, $K$ is the elastic stress concentration factor of notched specimens and $K_f$ is the fatigue strength reduction factor for notched specimens. Recently, the linear notch mechanics has been presented to estimate the fatigue limit of notched specimens.

Fatigue life in low cycle region during the strain control test has been estimated using the $\varepsilon_R$–$N_f$ curve and $K_\varepsilon$ curve, where $\varepsilon_R$ is the cyclic strain range and $K_\varepsilon$ is the strain concentration factor of notches. And the fatigue strength reduction factor in low cycle region have been also presented.

The fatigue life of notches during the stress control test in medium cycle regions, where the fatigue life is in the range of $10^4$–$10^6$ cycles, contain complicated phenomena regarding stress or strain behavior ahead of notches, and a proper method to estimate the fatigue life has been seldom presented. In this study, cyclic elastic-plastic strain behavior ahead of notches in steel plate specimens under cyclic tensile load is investigated using strain gages, and some experimental results and their discussion are presented. This paper's contents is nearly same as one of the paper presented in ICF9 held in Sydney Australia on March 1997.

2. Materials, specimens and experimental procedures

The chemical compositions and the mechanical properties of the material used are shown in Table 1 and Table 2 respectively. The specimens are shown in Fig. 1.a and the notches are V-notch with 120 degree flank angles. One series of specimens used are specimens in which the notch root radiuses are 2, 4, 10 mm with constant notch depth of 6 mm and another
series are specimens in which the notch depths are 10, 11, 18 mm with constant notch root radius of 8 m m\(^{8,9,10}\). Strain gages with gage length of 0.2 mm are attached to the notch roots, and strain gages with gage length of 1 mm are attached ahead of the notch root at distance of 2 mm as shown in Fig. 1. b. The cyclic tensile fatigue test was conducted with MTS fatigue test machine and the strains were recorded continuously using dynamic strain recorder.

3. Experiment results

Fig. 2. a shows the definitions of strain, \(\varepsilon_{\text{max}}, \varepsilon\), the notch root radius, \(\rho\) and the distance from the notch root, \(r\). Fig. 2. b shows the definitions of maximum strain, strain range, mean strain and minimum strain.

Table 1 Chemical compositions (%)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Ca</th>
</tr>
</thead>
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<tr>
<td>0.24</td>
<td>0.22</td>
<td>0.50</td>
<td>0.012</td>
<td>0.016</td>
<td>0.07</td>
<td>0.15</td>
<td>0.13</td>
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</tbody>
</table>

Table 2 Mechanical properties

<table>
<thead>
<tr>
<th>Modulus of elasticity</th>
<th>199 GPa</th>
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<tbody>
<tr>
<td>Yield stress</td>
<td>273 MPa</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>457 MPa</td>
</tr>
<tr>
<td>Elongation</td>
<td>38 %</td>
</tr>
</tbody>
</table>

3.1 Relationship between net stress and number of cycles until specimen fracture

All fatigue data tested were plotted on the \(S_R-N_f\) diagram of Fig. 3 in which \(S_R\) is the range of net stress and \(N_f\) is the number of cycles until specimens fracture. The range of \(N_f\) is from \(10^5\) cycles to \(10^6\) cycles, which is the medium cycle region. In Fig. 3, two types of cyclic strain behavior has been found; one type is that the mean strain increases as the number of cycles increases and other type is that the mean strain remains constant with increasing cycles. These two types are expressed as I.M.S. (Increasing Mean Strain) and C.M.S. (Constant Mean Strain) respectively. The transition region of these two types of strain behaviors may exist at \(N_f\) of about \(2.5 \times 10^5\) cycles and at \(S_R\) of about 250 MPa.
3.2 Behavior of cyclic strain range and mean strain near notches

Typical cyclic behavior of the specimens tested are shown in Fig. 4, 5, 6. In these figures, strain ranges str1, str2 etc. mean the strain ranges at the positions of the strain gages attached to the specimens and 1 is the strain at the notch roots and 2, 3 etc. are strains ahead of notch roots at distance of 2 mm, 4 mm, from the notch roots as shown in Fig. 1. Also the mean strains stm1, stm2 etc. mean the mean strain at each position of the strain gages.

In Fig. 4, the mean strains increase as the number of cycles increases (I.M.S.). The strain range at the notch root increases initially and keeps nearly constant value of about 0.4%. The mean strain at notch root increases steadily from 0.35% to about 1.6% as the number of cycles increases.

Strains ahead of notches have similar changes, but these changes are smaller.

In the case of two specimens with different notch root radiuses (S<sub>r</sub>245MPa, K<sub>2.4</sub>R4 and S<sub>r</sub>244, K<sub>2.4</sub>R8) of Fig. 5 and Fig. 6, mean strains are nearly constant with an increasing number of cycles (C.M.S.). In the specimen of the notch root radius 4 mm of Fig. 5, the strain range at the notch root, 0.34%, does not change with an increasing number of cycles and the mean strain at the notch root increases a little at first, but soon becomes a constant value, 0.62%, with an increasing number of cycles. In the specimen of the notch root radius of 8 mm of Fig. 6, both strain range and mean strain at the notch root remain constant values of 0.35% and 1.05% respectively.

Next, in I.M.S. and C.M.S. mentioned above, the author investigates the strain concentration factor, K<sub>e</sub>, the strain distribution, ε<sub>r</sub>, the relative strain ratio...
distribution, $\varepsilon / \varepsilon_{\text{max}} - \tau / \rho$, and the plastic zone size in front of notches. The plastic zone size have been simply defined based on the assumption that the material yields when the maximum principal strain in front of notches exceeds the uniaxial yield strain without considering the yielding criteria in biaxial stresses in front of notches. The yielded region estimated by the maximum principal strain coincides nearly same with one by Mieses's yield criteria within difference of 10% in case of small yielded region.

Fig. 7 shows the relationship between the strain concentration factor and the number of cycles where the strain concentration factor have been defined as the division of the maximum strain at notch roots by the net strain based on the net section area. In I.M.S. the strain concentration factors increase with the number of cycles and in C.M.S. the strain concentration factors are nearly constant with increase in the number of cycles. Fig. 8 shows the changes in strain distribution, strain ratio distribution and plastic zone size.
size with an increasing number of cycles in I.M.S. corresponding to Fig. 4. It has been found that the maximum strain at the notch root and the plastic zone size ahead of the notch root (shown on the x-axis) increases with an increasing number of cycles, and strain ratio distributions at the notch become steeper with an increasing cycles.

In C.M.S. of Fig. 9 and 10 (corresponding to Fig. 5, 6 respectively), it has been found that the maximum strain at notch root and the plastic zone size are constant with an increasing number of cycles, and the strain ratio distributions also remain constant with increase in the number of cycles. It seems that both strain distributions near notches of Fig. 9 and Fig. 10 are similar in spite of different notch root radiuses since strain ratios are 0.20 and 0.18 respectively at the nondimensional distances of 0.5 in Fig. 9 and 0.25 in Fig. 10 which correspond to the distance from notches of 2 mm. The strain ranges of Fig. 5 and Fig. 6 are nearly same since these values are 0.34% and 0.35% respectively. Therefore, the difference between the fatigue lives of Fig. 9 and Fig. 10 is small.

In the fatigue design of notched plates under the load control conditions, the author thinks that in the cycle region of C.M.S., the method using the $S_R-N_f$ curve and the $K-K_f$ curve based on the stress range in high cycle fatigue can be applied to estimate fatigue life and that in the cycle region of I.M.S., the $\epsilon_R-N_f$ curve based on the strain range in the low cycle fatigue and the effect of increasing mean strain on fatigue life should be considered to estimate fatigue life.

Fig. 8 Change of strain distribution, strain ratio distribution and plastic zone size with increasing number of cycles for specimen K2. 2-SR274-R8D10B60 (I.M.S., $N_f = 125851$ cycles )

Fig. 9 Change of strain distribution, strain ratio distribution and plastic zone size with increasing number of cycles for specimen K2. 4-SR245-R4D6B40 (I.M.S., $N_f = 317000$ cycles )
1. In medium fatigue cycles region where the fatigue life is in the range of $10^4$-$10^6$ cycles, two types of the strain behavior near notches have been found. One type is strain behavior where the mean strain at the notch roots and near notches increases with an increase in the number of cycles (I.M.S.) and another type is strain behavior where the mean strain at the notch roots and near the notches is nearly constant with an increase in the number of cycles (C.M.S.).

2. In I.M.S., the strain distributions ahead of notches become steeper with an increase in the number of cycles and the plastic zone sizes in front of notches become larger with an increase in the number of cycles.

3. In C.M.S., the strain distribution and the plastic zone size ahead of notches are nearly constant with an increase in the number of cycles.

4. In I.M.S. and C.M.S., the strain range is nearly constant during the fatigue cycles.

5. In the fatigue design of the notched plate under the load control condition, the author thinks that in the cycle region of C.M.S., the method using $S_R-N_f$ curve and $K-K_f$ curve based on the stress range in high cycle fatigue can be applied to estimate fatigue life and that in the cycle region of I.M.S., the $S_R-N_f$ curve based on the strain range in the low cycle fatigue and the effect of increasing mean strain on fatigue life should be considered to estimate fatigue life.

References

(1) Nishitani, H., Linear notch mechanics as an extension of linear fracture mechanics, Role of fracture mechanics in modern technology, pp. 25-37, Elsevier, Amsterdam, 1987


(3) Stowell, E. Z., Stress and strain concentration at a circular hole in an infinite plate, NACA, Tech. Note 2073, 1950

(4) Manson, S. S., Hirschberg, M. H., Crack initiation and propagation in notched fatigue specimen, NASA TMX-52126, 1965


(6) Iida, K., Notch effect on strain-controlled low-cycle fatigue strength of 80 kg/mm² high tensile steel, Zosen-kyoukai-ronbunsyu, Vol. 119, pp123-133, 1966


(10) Shingai, K. Strain distribution and cyclic strain behavior ahead of V-notch in notched plate specimen under tensile load, Proceeding of 4th. joint symposium of Cheju National University and Nagasaki University on science and technology, Cheju National University, pp87-96, 1996