Estimation of local cyclic stress ratio due to confined notch plasticity

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ABSTRACT

An FE analysis was used to determine the elastic and elastic-plastic stress distributions at 3 different keyhole notch geometries in compact tension specimens. This enabled an estimate to be made of the local cyclic stress ratio, R_{Local} (σ_{min,local}/σ_{max,local}), variation within the notch plastic zone with increasing distance from the notch root. This was carried out for both plane stress and strain conditions. Use of the local stress ratio was made to truncate, where appropriate, the value of the stress intensity range, ΔK, for nominal stress ratios of 0.1 and 0.7. Fatigue crack growth life predictions for small corner cracks at notches, based on this approach are shown to be more accurate than when based on the nominal stress ratio (R) value.

INTRODUCTION

An important element in the structural integrity assessment of many components or structures involves the prediction of fatigue crack growth (FCG) behaviour whilst under the influence of stress concentration features. This is particularly so in gas turbine applications where the material may be subjected locally to stresses greater than the elastic limit at notches, fastener holes or other necessary design features.

Fatigue life assessment must include an understanding of the influence of the notch geometry and the resultant stress field on both the crack formation (if not already present) and subsequent crack propagation phases of life. For the purposes of analysis the crack propagation phase may be sub-divided into
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growth through a notch plastic zone followed by growth through the elevated elastic stress field [1].

Earlier Studies (2,3) have been concerned with establishing reliable methods of fatigue life prediction of notched components with physically short fatigue cracks under essentially elastic conditions at the notch root. Experiments were carried out with keyhole notched compact tension (CT) specimens in nickel base superalloys in which measured FCG rates were used to infer values of stress intensity range (ΔK). When these inferred values of ΔK were compared with those estimated using an analysis developed by Chell [4], it was shown that in the absence of microstructural short crack effects and any crack interaction mechanisms, the theoretically based ΔK predictions were highly conservative.

This paper focuses on the modification of the cyclic stress ratio (R = \( \sigma_{\text{min}}/\sigma_{\text{max}} \)) locally at the notch root due to confined notch plasticity and its influence on fatigue crack growth rate and consequent fatigue life.

FINITE ELEMENT ANALYSIS OF KEYHOLE NOTCH COMPACT TENSION SPECIMENS.

A finite element analysis was performed using the Pafec Interactive Graphics, System, PIGS, and finite element software, PAFEC-FE. Three two dimensional meshes of 8 noded isoparametric quad elements were constructed (Figure 1 is typical) to represent the following keyhole notch geometries.

<table>
<thead>
<tr>
<th>Table 1 - Keyhole Notch Dimensions</th>
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<tr>
<td>Notch Depth (mm)</td>
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<tr>
<td>10.4</td>
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<tr>
<td>12.5</td>
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<td>13.25</td>
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Since the specimens possess a plane of symmetry half the specimen was modelled and the nodes in that plane restrained in the direction normal to the plane. In order to prevent rigid body motion a single node in the symmetry plane was restrained in the appropriate direction. Three tensile loads were determined which would generate a notch plastic zone of approximately 1.0 mm in extent, as measured from the notch root for each of the notch geometries.

These loads were applied to their associated mesh as a series of point loads over two elements. Typical elastic stress distributions are shown in Figures
2(a) and (b). The same loads were used in deriving the elastic plastic stress distributions shown in Figure 3(a) and (b) for plane stress and in Figures 4(a) and (b) for plane strain, where the non-linear material behaviour was simulated as a series of linear responses.

STRESS RATIO MODIFICATION

The FE distributions of elastic and elastic-plastic stresses provide a means of establishing a local stress ratio distribution by using the principle of superposition. Under conditions where plasticity is generated at a notch the stress ratio within the notch plastic zone is different to that of the applied remote load cycle since within the enclave the maximum stress is limited to some value dependant on the stress state. As the specimen is unloaded, it recovers elastically and may cause compressive stresses at the notch root, if the stress range of the cycle is of sufficient magnitude. From a knowledge of the elastic and elastic-plastic stress distributions it is possible to estimate the variation of the local stress ratio around the notch. The technique used in this estimation is illustrated in Figure 5. A proportion of the elastic stress distribution, corresponding to the nominal stress ratio, is taken at a number of positions along the projected crack path. These ranges are then superimposed onto the elastic-plastic stress distribution at the relevant positions along the crack path thus enabling a distribution of minimum local stress to be determined. Hence, given that the maximum is that shown in the elastic plastic stress distribution, the distribution of local stress ratio can be determined along the crack path.

The local stress ratio distributions for the two notch geometries and nominal stress ratios are shown in Figures 6(a) and 6(b). For a nominally applied stress ratio of 0.1 both notch geometries clearly show a region close to the notch root, where the local stress ratio is negative. As the distance from the notch root increases the local stress ratio recovers to a value above that applied remotely. Beyond this the local stress ratio decays towards the nominally applied stress ratio. For a nominal stress ratio of 0.7 the same suppression, peak and decay of local stress ratio is observed, however, the magnitude of the elastic stress range is not sufficient to generate local compressive stress at the notch root.

RESULTS AND DISCUSSION

Load control fatigue crack growth tests were conducted at the two nominal stress ratios of 0.1 and 0.7 using keyhole CT specimens in Waspaloy with small corner cracks at the notch bore extremities. Full details of which are given in (5) and (6). A stress intensity factor solution due to Chell (4) was used to correlate the growth rates and life predictions made, the results of which are shown in Figure 7(a). The degree of conservatism associated with
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the R = 0.1 data is somewhat greater than that associated with the R = 0.7 data. It is suggested that this is due to the effect of the interaction between the notch plastic enclave and the surrounding elastic bulk discussed above. By considering the stress ratio modification (Figure 6) and assuming that closure occurs at zero stress the values of ΔK for R = 0.1 are truncated. Since no local compressive stresses are generated at a nominal stress ratio of 0.7 only the R = 0.1 data is affected. The resulting life prediction plot (Figure 7(b)) clearly shows that the inclusion of the effects of local R decreases significantly the degree of conservatism of the R = 0.1 life predictions to a level equivalent to the R = 0.7 data.

CONCLUSIONS

Elastic and elastic-plastic finite element analyses have been used in the determination of local stress ratio modification due to confined notch plasticity.

Fatigue crack growth life predictions for small corner cracks at notches, based on this local approach are shown to be more accurate than when based on the nominal stress ratio.

ACKNOWLEDGEMENTS

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REFERENCES


Figure 1: CT specimen geometry and FE mesh for $D = 10.4$ mm, $\rho = 2.0$ mm

Figure 2: Elastic stress distributions for notch geometries
(a) $D = 10.4$ mm, $\rho = 2.0$ mm
(b) $D = 13.25$ mm, $\rho = 3.25$ mm
Figure 3: Elastic-plastic stress distributions under plane stress conditions for notch geometries
(a) $D = 10.4$ mm, $\rho = 2.0$ mm (b) $D = 13.25$ mm, $\rho = 3.25$ mm

Figure 4: Elastic-plastic stress distributions under plane strain conditions for notch geometries
(a) $D = 10.4$ mm, $\rho = 2.0$ mm, (b) $D = 13.25$ mm, $\rho = 3.25$ mm
Figure 5: Schematic showing derivation of local stress ratio

\[ \Delta \sigma = (1 - R_{\text{nominal}}) \sigma_{e_{x_1}} \]

\[ \sigma_{\text{max}} = \sigma_{p_{x_1}} \]

\[ R_{\text{local}} = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \]
Figure 6: Local stress ratio distributions for notch geometries
(a) $D = 10.4 \text{ mm}, \rho = 2.0 \text{ mm}$  (b) $D = 13.25 \text{ mm}, \rho = 3.25 \text{ mm}$
Figure 7: Correlation between predicted and experimental fatigue crack growth lives based on (a) nominal stress ratio, R, (b) local stress ratio $R_1$. 

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