FATIGUE CRACK GROWTH UNDER NON-PROPORTIONAL LOADING

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INTRODUCTION

Fracture Mechanics has frequently been used to analyse the growth of fatigue cracks and a large number of papers on the Linear Elastic Fracture Mechanics (LEFM) behaviour of long cracks have been published for uniaxial loading conditions. However, only a few papers on biaxial proportional loading, and one or two papers for non-proportional loading are available. Here we describe many engineering situations, flaws may not be able to vary with mode crack growth in different conditions but also change. Consequently, the analysis of mixed mode crack growth in different load states, which is the topic of this study, is important because of: (1) the way different types of crack growth are available, and (2) the effects of non-proportional loading on fatigue crack growth and cyclic plasticity.

DIFFERENT TYPES OF CRACK TIP PLASTIC ZONES

With regard to the case of an inclined crack in a plate subjected to biaxial cyclic loads (Fig. 1), if the two loads are out-of-phase, or if the load amplitudes are in-phase but the strain state \(\lambda = \lambda_x/\lambda_y\) is different for the mean and cyclic components, (i.e. \(\lambda = \lambda_x\)) then non-proportional loading will arise. For proportional loading, the crack tip maximum plastic zone direction always remains constant (Fig. 2). In the case of non-proportional loading, since the crack tip stress intensity factor ratio \(K_{II}/K_I\) changes continuously during a cycle then the maximum plastic zone direction also changes, and both the crack tip maximum tensile and shear strains change during a cycle. Hence the slip systems operating in the crack tip neighbourhood have to change correspondingly.

Fig. 2 shows the monotonic plastic zones corresponding to the applied loads at various times in the cycle. It therefore follows that the build-up of dislocations caused by the crack tip reversed plastic deformation will be distributed over different slip systems, and will no longer be concentrated as in the proportional loading case. In other words, for non-proportional loading the intensity of plastic strain accumulation in the maximum shear direction ahead of the crack path must be lower than that for proportional loading, if the values of \(\Delta K_I\) and \(\Delta K_{II}\) are equivalent in each case.

THE EFFECT OF NON-PROPORTIONAL LOADING ON THRESHOLD

Experiments on 316 stainless steel show that for both proportional and non-proportional mixed mode loading there is a threshold, below which no crack growth was observed. Above this threshold, an initial shear mode crack growth is observed. For specimens that used a narrow slot to simulate a crack, a mode-I branch crack appeared after a short period of shear mode coplanar growth. However, in previous experiments [2] with pre-fatigue cracked specimens, because of crack surface sliding friction induced by the mode-II displacements and toughness of the fracture surface the shear cracks were non-propagating, and a branch crack was formed only when the stress intensity factors were above an upper bound threshold.

For any fixed ratio of \(\Delta K_{II}/\Delta K_I\), fatigue thresholds obtained under non-proportional loading show higher values than those for proportional loading [3] (see Table 1). With proportional and non-proportional loading, the influence of the crack tip stress intensity factor ratio \(K_{II}/K_I\) on fatigue thresholds is significant.

Table 1. The Influence of Non-proportional Loading on Fatigue Thresholds

<table>
<thead>
<tr>
<th>(\lambda_c)</th>
<th>(\lambda_m)</th>
<th>(\Delta K_{II}/\Delta K_I)</th>
<th>(\Delta K_I)</th>
<th>(\Delta K_{II})</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5</td>
<td>-0.5</td>
<td>3</td>
<td>1.24</td>
<td>3.75</td>
</tr>
<tr>
<td>-0.5</td>
<td>+0.5</td>
<td>3</td>
<td>1.51</td>
<td>4.53</td>
</tr>
<tr>
<td>-0.176</td>
<td>-0.176</td>
<td>0</td>
<td>0</td>
<td>3.88</td>
</tr>
<tr>
<td>-0.176</td>
<td>+0.25</td>
<td>0</td>
<td>0</td>
<td>4.47</td>
</tr>
</tbody>
</table>
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As the crack extends, the effect of changing maximum shear direction under non-proportional loading becomes less important because the cracks always tend to the pure mode I direction. Immediately after the crack branches, the crack growth rate under non-proportional loading may be lower than for proportional loading but as the branch crack extends the crack growth rates for proportional, non-proportional and pure mode-I loading become very similar. As shown by Fig. 3, all the experimental results are eventually within a narrow band. In Fig. 3 the crack tip cyclic plastic zone size $r_p$ was estimated from both stress intensity factor ranges and

![Graph showing relationship between crack growth rate and crack tip cyclic plastic zone size.](image)

Fig. 3 Relationship between crack growth rate and crack tip cyclic plastic zone size.
T-stress ranges (irrespective of the mean stress components), with the Von Mises Yield Criterion [4].

As the crack branch extends and stress intensity factor ranges become higher, many slip systems of different grains at various orientations can operate in the crack tip region. While the distribution of slip bands in the crack tip zone of a polycrystalline material is quite random, the plastic deformation at the crack tip may be considered as typical of continuum plasticity. The crack growth mechanism, in this case, is dependent on a plastic decohesion process [5], in which the crack tip is successively blunted and resharpened in each cycle, and fractographs do not depict crystallographic features (unlike near threshold growth, Fig. 4a), but rather a flat and featureless topography (Fig. 4b).

Fig. 3 also shows a linear relationship between crack growth rate and branched crack tip cyclic plastic zone size. This is in agreement with dimensional analysis [6] which predicts that, if there are no size effects arising from specimen geometry or microstructural features, the crack extension in each cycle should be proportional to the crack tip plastic zone size.

CONCLUSIONS

1) Under mixed mode non-proportional loading, fatigue thresholds are higher than for proportional loading because crack tip plasticity is diffuse.

2) For both proportional and non-proportional loading, the crack propagation path is well predicted by the $\Delta K_{\text{max}}$ criterion.

3) At the very beginning of crack branching, the crack growth rate in non-proportional loading may be lower than that of proportional loading, but as the crack grows the propagation rates become very similar, and the cracks tend to the pure mode-I direction and growth rate.

REFERENCES


