Use of Ductile Tearing in Plant Assessments

Ainsworth R A[(1)], Sherry A H[(2)] and Wardle G[(2)]
1) British Energy Generation Ltd, United Kingdom
2) AEA Technology plc, United Kingdom

ABSTRACT

Defect assessment procedures, such as R6, provide methods for the use of stable ductile tearing in fracture mechanics calculations and also include advice on interactions between ductile tearing and fatigue crack growth. However, the practical use of tearing is largely restricted to short-term fault conditions because of uncertainties about tearing-fatigue interactions under normal operational load histories. Experimental and analytical work has been performed to examine the effects of load history on ductile tearing in an austenitic Type 316 steel plate and a well-characterised ferritic A533B-Class 1 steel plate. For the ferritic steel, tests have been performed at 20°C and 288°C for both negative and positive load ratios, and thermal cycling tests have been performed with monotonic loading at 20°C and fatigue cycling at 288°C. For the austenitic steel, a similar experimental programme has been followed but restricted to tests at 20°C without thermal cycling. The total crack extension measured in the tests has been compared with the simple sum of baseline ductile tearing and fatigue crack growth data. Subtracting the baseline fatigue crack growth from the total observed crack extension leads to J-resistance curves which are elevated compared with the baseline data. To complement the experimental programme, the Gurson local approach model has been applied for the ferritic steel to a number of complex load histories. It has been found that crack growth by an intervening mechanism such as fatigue leads to an increase in tearing resistance as a result of re-sharpening of the crack tip and as a result of crack extension through the ductile fracture process zone, consistent with the experimental observations. This paper summarises the experimental and numerical programmes and the principal results. The implications for the use of ductile tearing in practical assessments of nuclear plant are discussed. Associated advice for inclusion in defect assessment procedures, such as R6, is presented.

INTRODUCTION

Assessments of defects in engineering components require a measure of the fracture resistance of the material. For ductile steels, the fracture resistance is often characterised in terms of an initiation fracture toughness and the subsequent ductile tearing resistance as measured on standard fracture mechanics test specimens. In practice, an engineering definition of initiation is taken in terms of typically 0.2mm of crack extension.

Defect assessment procedures, such as R6[1] and British Standards BS7910[2], provide methods for assessments both at initiation and after some ductile crack growth. However, ductile tearing assessments are often restricted to infrequent or fault loadings because of concerns about the transferability of resistance curve data, measured under monotonic loading, to plant which experiences complex histories of loading and temperature.

To address these transferability issues, experimental test programmes on austenitic and ferritic steels have been performed. These have involved load and temperature histories representative of plant conditions and are described first in this paper. Then some associated numerical work is summarised. Finally, advice for inclusion in practical defect assessment procedures is given.

EXPERIMENTAL PROGRAMMES

The austenitic material used was a Type 316L(N) stainless steel in 25mm thick plate form. Standard ductile tearing and fatigue crack growth tests were performed on 25mm thick compact tension specimens, the former having a width w=50mm, the latter having w=100mm. Eight tests on compact tension specimens with w=50mm were then performed under load histories which led to both ductile tearing and fatigue crack growth. The schematic load history is shown in Figure 1. The number of fatigue cycles at the intermediate loading positions varied from 250 to 2500, there were either two or three intermediate fatigue loading positions and the R-ratios in fatigue were either 0.2 or ~0.1. All tearing and fatigue-tearing testing was performed at room temperature on specimens with a nominal initial normalised crack depth a/w=0.55; pure fatigue specimens had an initial a/w=0.3.

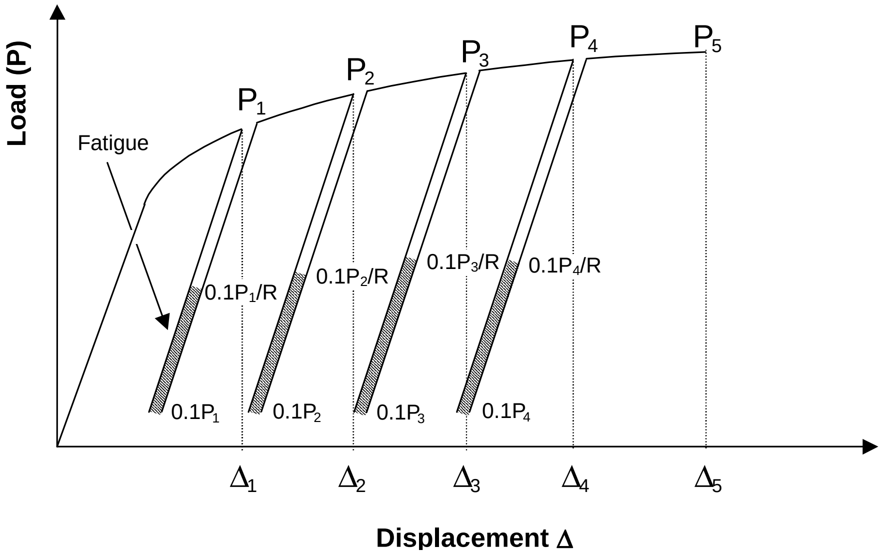

Figure 1. Schematic load-displacement curves for austenitic tests

The ferritic material used was a well-characterised A533B-Class 1, 150mm thick steel plate. Standard fatigue and fracture toughness data were obtained on compact tension specimens of 40mm thickness at both room temperature and 288°C. Similar tearing-fatigue tests to those shown schematically in Figure 1 were also performed at room temperature and 288°C. In addition, tests with negative R-ratios (R = -0.5 and R = -1.0) and some temperature cycling tests with tearing at room temperature and fatigue cycling at 288°C were carried out.

For the austenitic material, the measured amounts of ductile tearing, Δa_t, are compared in Figure 2 with values of J deduced from the measured load-displacement records. For both R=0.2 and R=0.1, it is apparent that the data are comparable to the base-line tearing data with a tendency for the intermediate fatigue cycling to have slightly elevated the resistance curve.

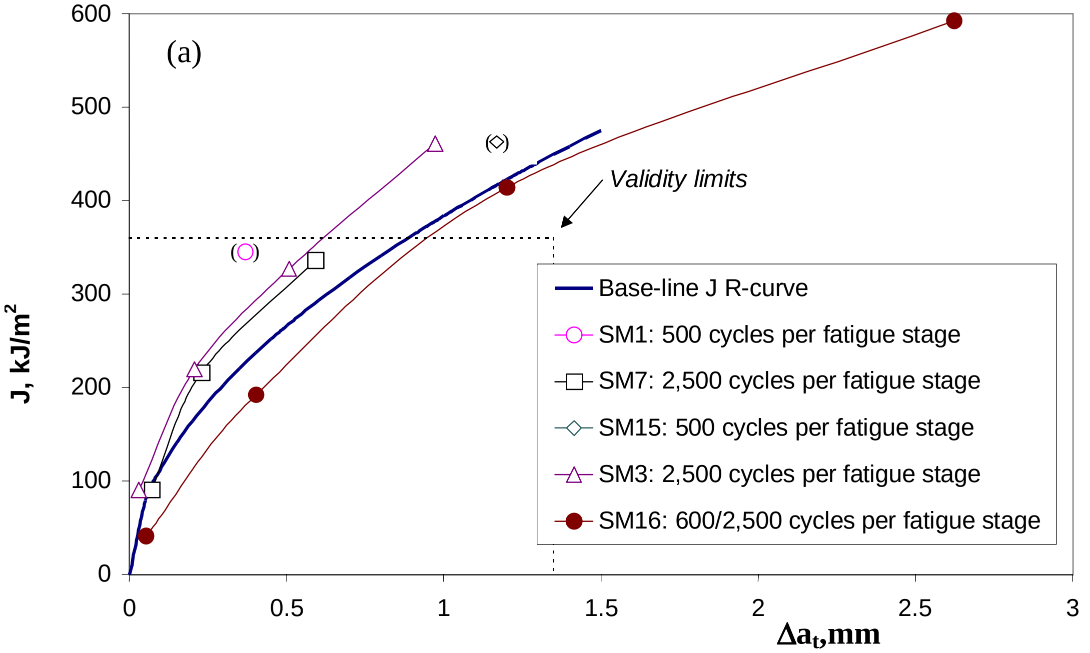

Figure 2(a) Austenitic tearing-fatigue data compared with base-line data for R=0.2. Bracketed data indicate Δa_t values inferred from baseline fatigue data.

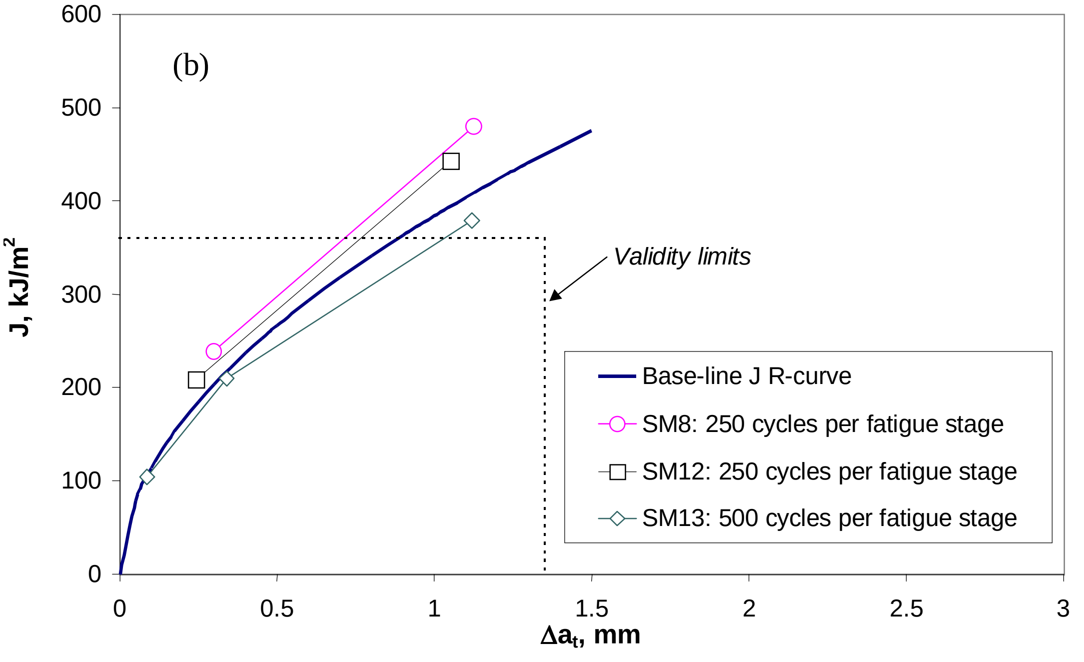

Figure 2(b) Austenitic tearing-fatigue data compared with base-line data for R=0.1.

Figure 3 shows the fatigue crack growth increments in the same tests as a function of the applied stress intensity factor range. For the R=0.2 tests, the data are comparable with the base-line fatigue crack growth data with a tendency for fatigue crack growth per cycle to be reduced. For R=0.1, the measured data generally lie above the base-line Paris law at ΔK values greater than $\sim 60\text{MPa}\sqrt{\text{m}}$. Under these conditions, significant increases in crack mouth opening displacement were observed during the fatigue cycles and the peak crack-driving-force was close to or above the initiation toughness. It is likely, therefore, that the differences in Figure 3(b) are due to a combination of plasticity (so that ΔJ should be used instead of ΔK) and ductile crack growth occurring within each fatigue cycle. This is discussed further below.

Results for the ferritic steel at room temperature showed similar trends to those found in the austenitic tests. This is illustrated in Figure 4(a) which shows the resistance curve data from base-line tests and tearing-fatigue tests of the type shown in Figure 1 (with R=0.1 and R=0.2) with Δa_t taken as the total measured crack extension minus the total measured fatigue crack extension. If the values of Δa_t are taken as total measured crack extension minus fatigue crack extension calculated from base-line fatigue crack growth data, then Figure 4(b) results. These figures demonstrate that it is conservative to simply sum separately calculated fatigue and tearing contributions to crack growth. Results at 288°C showed similar trends to those in Figure 4(a) but with more variability when plotted as shown in Figure 4(b).

Testing on the ferritic steel under more complex loading histories is continuing. Initial results have been obtained for monotonic loading at room temperature combined with cyclic loading at 288°C. R-ratios of 0.1 and 0.55 have been used. Figure 5 shows data similar to the plot in figure 4(a). Apart from one test point, the tests with temperature cycling show a similar resistance curve to the base-line data at room temperature.

The measured fatigue crack extensions in these tests showed similar trends to those in Figure 3 for austenitic material. For R=0.1, the da/dN values at lower ΔK values tended to lie below the Paris line but for higher ΔK values tended to lie above the Paris line. However, in contrast to the austenitic tests where the minimum load was fixed at 0.1 of the maximum applied load, (see Figure 1), in these latter tests the minimum load was typically 0.5 times the maximum applied load. Therefore, similar to the austenitic tests, elevated fatigue crack growth may have been due to the effects of plasticity or tearing within the fatigue cycle. These effects may be expected to be more marked for the cycling at 288°C since both the yield stress and the tearing resistance are lower at 288°C than at room temperature.

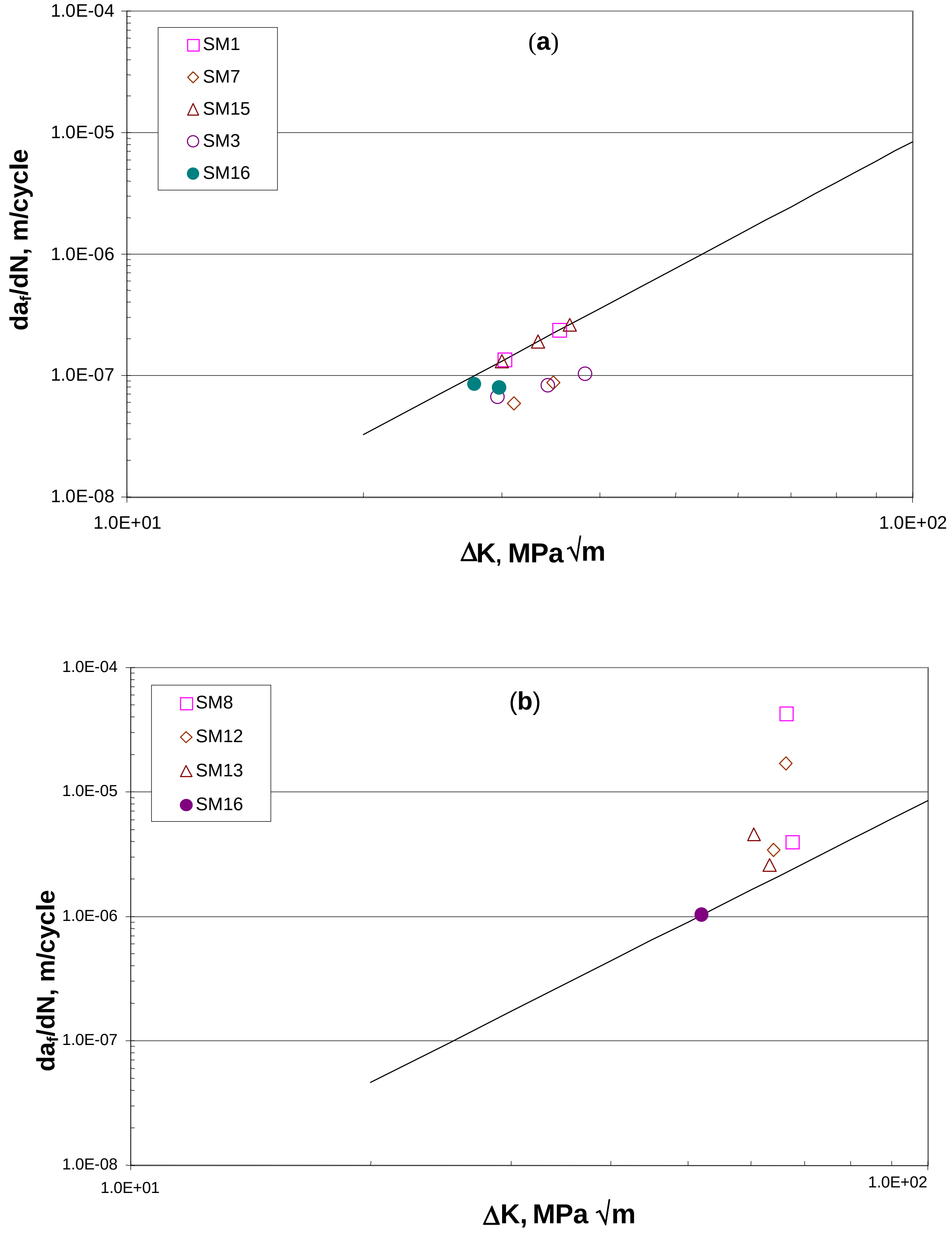

Figure 3. Fatigue crack growth in austenitic tearing-fatigue tests compared with base-line fatigue data: (a) R=0.2; (b) R=0.1.

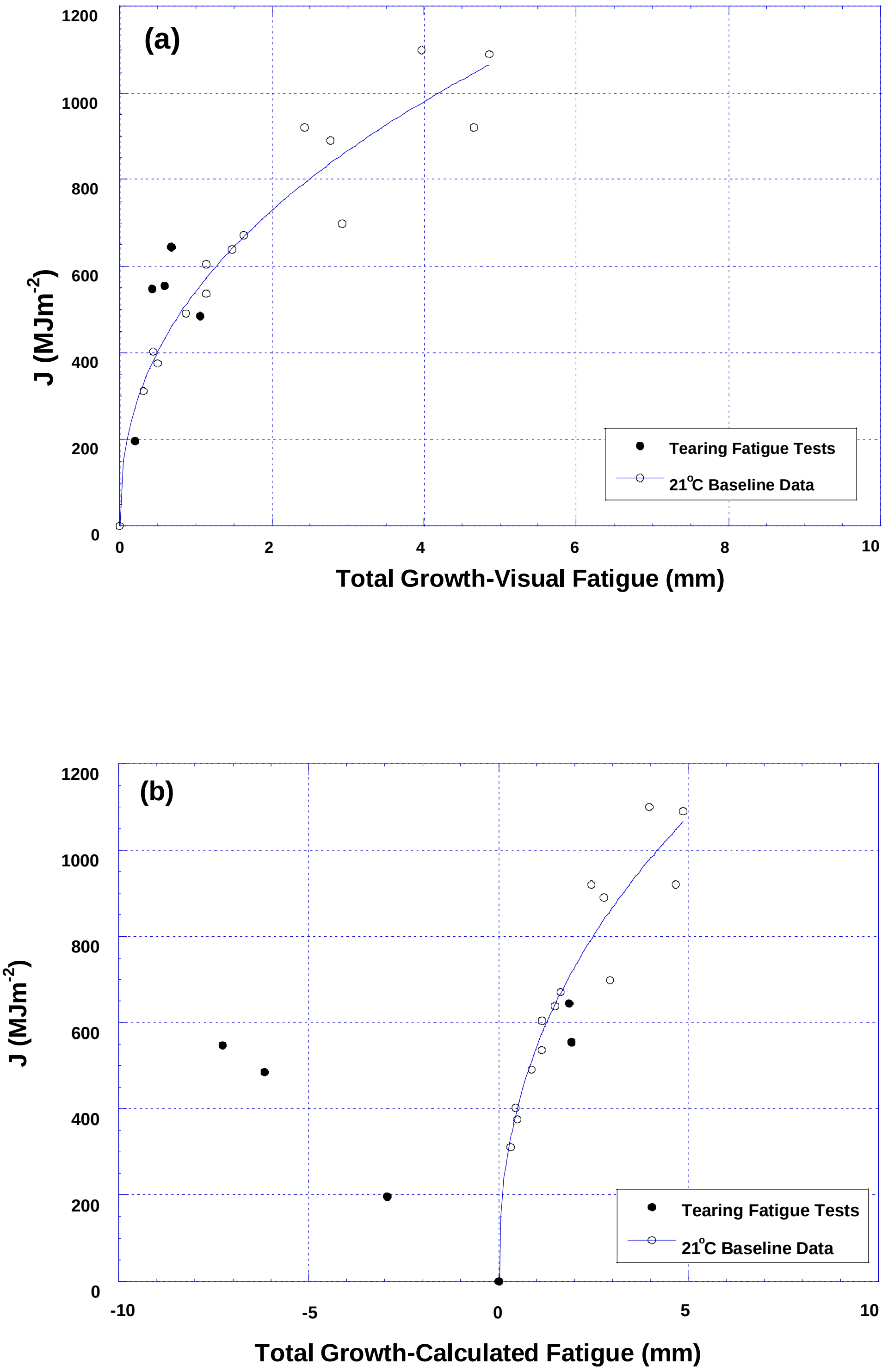

Figure 4 Ferritic tearing-fatigue data at room temperature compared with base-line data: (a) $\Delta a_t = \Delta a_{total} - \Delta a_{measured\ fatigue}$; (b) $\Delta a_t = \Delta a_{total} - \Delta a_{calculated\ fatigue}$

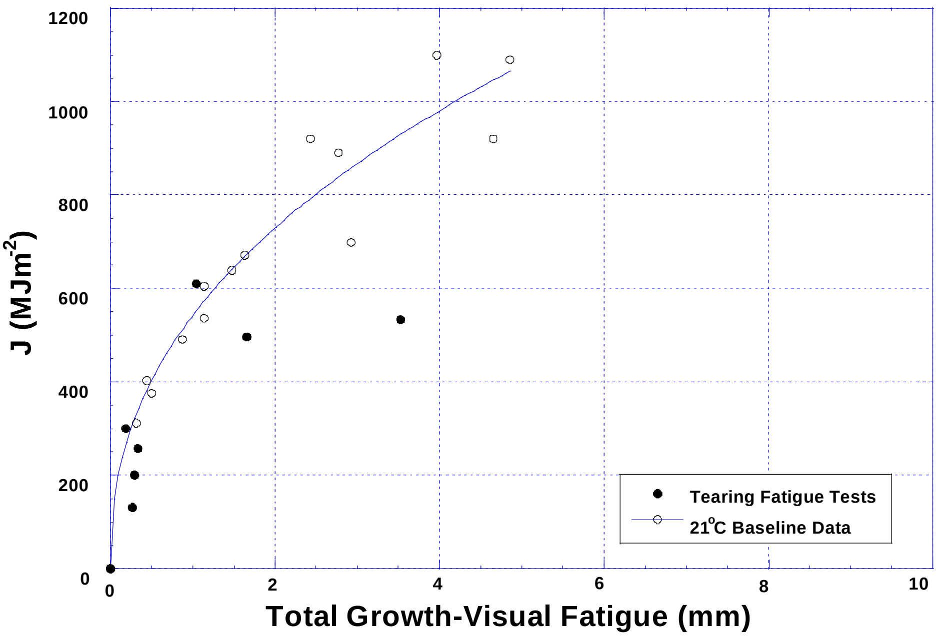

Figure 5 Ferritic tearing data at room temperature for tests with fatigue cycling at 288° C:

$$\Delta a_t = \Delta a_{total} - \Delta a_{measured\ fatigue}$$

NUMERICAL MODELLING

To provide insight into the load-history tests, the Gurson local approach model [3] has been applied to three load histories: monotonically increasing load (case LH1); load-unload-reload (case LH2); and load-unload simulated fatigue crack growth-reload (LH3, LH4, LH5). In the last case, three different increments of fatigue crack extension were simulated (0.125, 0.25 and 0.5mm, respectively).

A 2-D plane strain finite-element model with an array of square elements of side equal to 0.125mm at the crack tip was used to model a compact tension specimen. The parameters in the Gurson model were calibrated to closely produce room temperature tearing resistance curve data for A533B steel and the load-displacement curves of selected experiments.

For the load-unload-reload case (LH2), where the unload was down to 0.1 of the maximum load, ductile tearing on the reload occurred at lower displacements than for monotonic loading (LH1) but the overall effect on the resistance curve was small, as shown in Figure 6.

When fatigue crack growth increments were modelled by node release, yielding occurred earlier on the reload due to the increased crack length but an elevation in the resistance curve relative to monotonic loading was found, Figure 6. This is attributed to a number of factors. First, the simulated crack extension by fatigue leads to a sharp crack which requires a re-blunting prior to subsequent tearing. Secondly, crack extension by fatigue occurs through the process zone of ductile damage, so that the crack tip moves to a region where there are less well developed voids or no voids at all. Finally, cyclic hardening or softening may effect material response. In the calculations reported here, isotropic hardening has been used, but the effect of this assumption is not expected to be large since material ahead of the advancing crack experiences increasing strain rather than stable cyclic behaviour.

The effects in Figure 6 have been compared with the room temperature tests on the A533B steel reported above. The data tend to lead to an increase in the resistance curve greater than the increase calculated. This is attributed to: the testing including more than one stage of fatigue crack growth; greater fatigue crack growth in the tests than in the simulation; and, the fatigue cycling contributing to an increase in the area under the load-displacement curve and therefore to the experimental J but in the simulation this was not included.

PRACTICAL APPLICATIONS

The experimental and numerical results described above provide confidence in the use of ductile tearing in practical applications which involve cyclic loading and temperature variations. Some issues relevant to practical applications are discussed in this section and then practical advice is given for inclusion in defect assessment procedures.

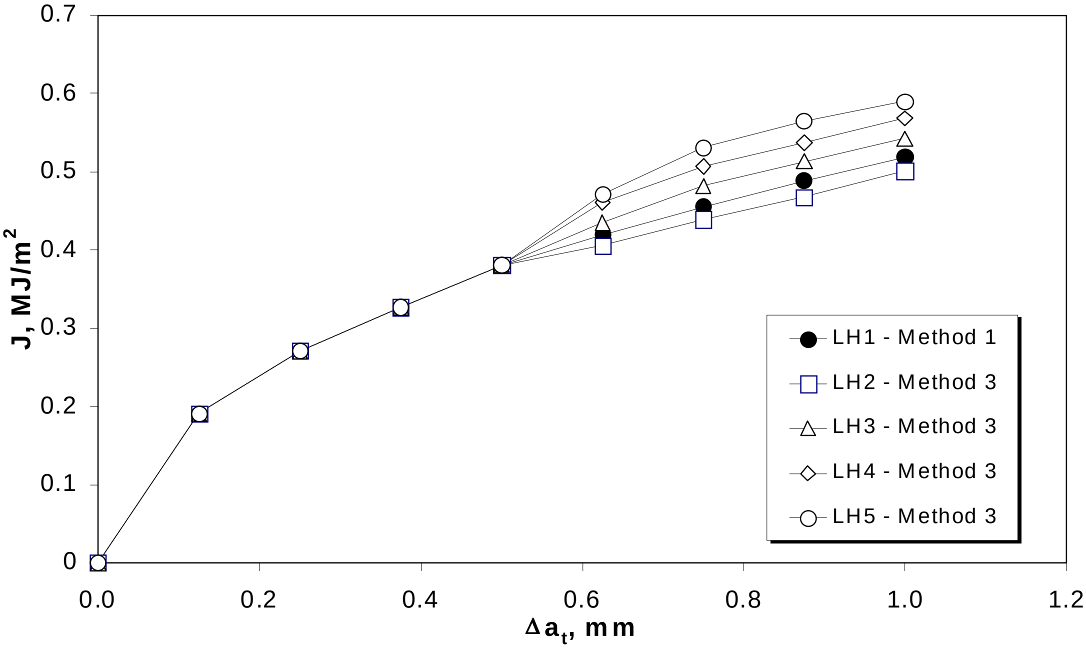

Figure 6 Resistance Curves from Gurson Local Approach Calculations

First, for practical assessments the total crack extension can be taken as the sum of separately calculated fatigue and tearing components. This is consistent with proposals in [4, 5] and advice currently in R6 [1].

Secondly, although fatigue crack growth is usually calculated from the stress intensity factor range using a Paris Law, it is important to address aspects of plasticity. Plasticity leads an increased strain range at the crack tip and this may lead to increased fatigue crack growth. An empirical approach to addressing this is to use a cyclic ΔJ instead of ΔK for calculating fatigue crack growth. Plasticity may also occur at the peak of a cycle to an extent sufficient to cause ductile tearing [4]. For example, for loadings of the schematic type shown in Figure 1 it may be necessary to consider tearing not only under the loading $P_1 \rightarrow P_5$ but also within the fatigue cycles if the peak load within these cycles is high.

Thirdly, experimental evidence suggest that significant crack closure can occur when the stress intensity factor ratio, R, in the fatigue cycle is negative and then linear summation of fatigue and tearing may not be valid [6].

Fourthly, detailed tearing-fatigue calculations are not needed for assessing ductile instability [7]. Whether or not ductile tearing occurs in a stable manner depends only on the load and current crack size, not how this crack size was generated, when using standard assessment procedures. Therefore, margins against stability are estimated in a standard manner based on the maximum loading that a component is likely to experience.

Finally, standard restrictions on the use of stable tearing apply. That is, extensive ductile crack extension beyond the validity limits in fracture toughness tests can not be assessed unless there is evidence that extensive data can be conservatively transferred to components.

The above considerations lead to the following proposal for advice to be included in defect assessment procedures for components subjected to fatigue cycles where the maximum loading is such that ductile tearing may also occur: the total crack extension Δa_{total} is simply

$$\Delta a_{total} = \Delta a_f + \Delta a_t \qquad (1)$$

where the fatigue component is usually evaluated from a Paris law and the stress intensity factor range, ΔK. However, an empirical law based on ΔJ should be used when plasticity occurs in a fatigue cycle. The tearing component, Δa_t, is deduced from a tearing analysis using procedures such as R6 [1] performed for the maximum load in the cycle for a crack size equal to the initial crack size plus the total crack extension, Δa_{total}. Unlike fatigue, Δa_t is not evaluated cycle-by-cycle but tearing may need to be assessed under those loadings leading to fatigue crack growth in addition to infrequent or fault loadings. In practice, iterations are needed to perform the calculations as follows:

(i) calculate Δa_f from cycle-by-cycle calculations;

(ii) calculate the limiting crack size $a = a_o + \Delta a_{total}$ from a ductile tearing analysis for a single application of the maximum load experienced by the component,

(iii) $\Delta a_t = \Delta a_{total} - \Delta a_f$

(iv) repeat steps (i) – (iii) allowing for any increased crack size due to tearing in the fatigue calculations until convergence is achieved.

The procedure should not be applied when significant crack closure is expected (R<0) or for ductile crack extensions beyond standard validity limits.

CONCLUDING REMARKS

This paper has summarised experimental and numerical programmes performed to address the treatment of tearing-fatigue interactions within structural integrity assessments. The results have shown that a linear summation of tearing and fatigue contributions to crack extension generally provides a conservative approach. When significant plasticity occurs a fatigue crack growth law based on ΔJ should be used. The procedure should not be included when significant crack closure is expected, R<0.

Acknowledgement. This paper is published with permission of British Energy Generation Ltd and AEA Technology plc.

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