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PRACTICAL ASPECTS OF FATIGUE CRACK GROWTH IN RAIL AND STRUCTURAL STEELS

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INTRODUCTION

The fatigue strength of the majority of railway components is determined by the resistance of the material to crack initiation and early growth. This is particularly true for rails, the brittle nature of which means that only very short cracks can be tolerated. The more ductile structural steels are generally used in the welded condition, and because flaws and stress concentrations present may drastically reduce the initiation period, the majority of life is expended propagating small cracks. This situation is complicated by the gross stress concentrations of the weldments themselves.

In order to quantify the fatigue crack initiation and propagation behaviour of components constructed from such materials, a major research programme is being undertaken at British Rail. Included in this is work on small plate specimens with a central hole. This geometry allows the investigation of several properties, in particular the influence of a gross stress concentration. Furthermore, the specimen configuration is economical, allows fully reversed loading and can be extracted from the web of rails manufactured under standard conditions.

From the wide range of rail and structural steels investigated, four materials have been selected for presentation as representative of the main categories of alloys tested to date.

EXPERIMENTAL DETAILS

The chemical composition of the tested steels are listed in Table 1. All the tests were conducted under constant amplitude, fully reversed, sinusoidal loading in a servo-hydraulic test machine with load control. Axial alignment was ensured by the use of a liquid metal lower grip. Two travelling microscopes were used to determine crack length measurements, and growth rates were obtained by dividing small increments of crack length by the change in number of applied cycles. Variations in crack front curvature were taken to be small and as the method was based on differences of surface measurement, no corrections to the growth rate were employed.

Crack propagation data is frequently characterised in terms of the crack tip stress intensity factor, ΔK. For a specimen of this type (Figure 1) asymmetrical crack growth frequently occurs, as it is highly improbable that cracks will initiate at both sides of the hole simultaneously. This, together with the proximity of the crack tips to the specimen boundaries influences the stress intensity values. Hence an analysis method, consisting of taking previously derived solutions [1,2], and compounding them in the manner suggested by Cartwright and Rooke [3] to

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produce values of stress intensity factors for new configurations, was adopted.

The geometry shown in Figure 1, with cracks of different lengths growing from each side of the central hole, was considered. There already exists a solution derived by Isida [1] for a non-symmetrical crack in a finite width plate. This was associated with the expression obtained by Newman [2] for a crack growing from the edges of a hole, to produce the stress intensity factors for the combined case, a different value being obtained for each tip. The resulting equations are:

$$\Delta K_{(L_1)} = \Delta\sigma \sqrt{\pi} \left(\sqrt{a}\, F_{(1)_{L_1}} + \sqrt{L_1}\, F_{(2)_{L_2}} - \sqrt{L_1 - r} \right)$$

$$\Delta K_{(L_2)} = \Delta\sigma \sqrt{\pi} \left(\sqrt{a}\, F_{(1)_{L_2}} + \sqrt{L_2}\, F_{(2)_{L_2}} - \sqrt{L_2 + r} \right)$$

where L_1 is the length of the shorter crack, taken from the edge of the hole to the crack tip.
L_2 is the length of the longer crack, taken from the edge of the hole to the crack tip.
$F_{(1)_L}$ is the factor tabulated in [1] to allow for asymmetric crack growth in a finite width plate.
$F_{(2)_L}$ is the factor tabulated in [2] to allow for the presence of the hole.
r is the hole radius.
a is one half of the sum of L_1, L_2 and $2r$.

RESULTS AND DISCUSSION

Crack Propagation

The preceding analysis was used to produce ΔK versus da/dN plots for the various materials. Mean lines derived from the mass of data for each alloy are plotted in Figure 2. A factor of 1.25 on ΔK is representative of the scatter obtained, results for both crack tips falling very close together. It can be seen that for the range of growth rates measured, 10^{-8} to 10^{-4} m/cycle, there is only a small variation between the fatigue crack propagation behaviours of the materials examined. The structural steel gave the poorest results, the standard composition rail steel proving to be slightly inferior to the other two. It is evident that, notwithstanding the specific development of the improved rail steel to possess high fracture toughness, there is no major reduction in crack growth rate.

These results are in agreement with those of other workers e.g. [4,5] in that variations in material composition have a minor effect on crack growth behaviour in the middle, steady state portion of the da/dN vs ΔK plot. Scatter on the data will further mask any differences, so that other criteria are more strongly relevant in the selection of material for a particular application.

Short Cracks (Plasticity Effects)

It was observed for the structural steel that at applied stress ranges over some 290 MPa the fatigue crack growth rate curves deviated from the basic characteristic (Figure 3). The phenomenon was displayed by the other materials, although it was more pronounced for this particular steel.

A possible explanation lies in the fact that the same specimens were used for both initiation and propagation studies. In order to achieve the former there must necessarily be some plastic deformation at the edge of the hole. For the lowest stress levels, near the fatigue limit, the effect will be confined to the immediate vicinity of the hole, with elastic conditions across the remainder of the plate. In these circumstances the concept of Linear Elastic Fracture Mechanics (LEFM) is directly applicable, with only small errors arising from the limited plastic zone. However, for higher stresses the area subjected to plastic deformation is extended, and such analyses break down. Indeed much faster growth rates were observed, by more than an order of magnitude in some cases.

This effect will be significant where fatigue life predictions are being undertaken for welded components. In such cases high K_t values, considerably greater than the 2.55 employed in the present investigations, will occur together with very short cracks or crack like defects. If LEFM is applied then the analysis will be seriously non-conservative until the crack has grown into the elastic region.

An extensive test programme is being undertaken at BR in order to examine this phenomenon of cracks subjected to plastic deformation. Since the behaviour of the material is a crucial factor in determining the extent of plasticity under given loading conditions, a much more material dependent analysis will be necessary, rather than the LEFM techniques generally employed. It is anticipated that a link will be made between the very disparate methods of initiation prediction and elastic fracture mechanics.

Stress Life Data

In addition to the crack propagation results, conventional stress-life (S-N) plots were produced (Figure 4). It can be seen that the structural steel is somewhat inferior to the rail steels, for which the results lie in a narrow scatter-band. The newer rail steels display little if any improvement over the standard rail steel.

Included in the same figure is data showing the relative significance of the initiation and propagation portions of the life to failure for the structural steel. The end of the initiation period was taken arbitrarily to be when a crack of 0.5 mm was observed.

At short lives (less than 10^4 cycles) failure occurs very rapidly once a crack has been initiated and hence the propagation phase is less important, although still significant. The initiation phase also dominates at the fatigue limit, since until a crack is formed the propagation stage cannot proceed. In the middle region, however, fatigue crack growth is somewhat more important.

Hence the presence of defects in a structure where a large proportion of applied loadings falls in the middle region will be less significant than when the structure is designed to a fatigue limit. In the former case the drastic effect on the initiation period will only reduce the life by a factor of about 2, whereas in the latter case failure will occur at stresses lower than predicted.

CONCLUDING REMARKS

i) A stress intensity factor analysis has been successfully developed for centre-notched plate specimens in which asymmetrical crack growth occurs.

ii) The fatigue crack growth properties of a selection of rail and structural steels have been evaluated. A high degree of similarity, particularly for the rail steels, was observed.

iii) Short cracks initiated from a stress concentration at high nominal stresses do not demonstrate growth rates predicted on the basis of Linear Elastic Fracture Mechanics. This accelerated growth is thought to be due to the local plasticity preceding crack growth.

iv) In terms of fatigue life prediction the assumption that total damage is attributable to either crack initiation or growth will not produce greatly erroneous results for a wide spread of expected lives. Both methods, if applied correctly, will produce conservative results.

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Table 1

Material	%C	Si	Mn	S	P	Ni	Cr
≠BS4360-43A	0.23	0.05	0.79	0.051	0.016	0.11	0.06
*BS11 (Standard)	0.55	0.35	1.43	0.026	0.048	0.01	0.01
*Improved (Fracture Tough)	0.40	0.27	1.50	0.040	-	0.03	0.02
*UIC - (Grade A)	0.72	0.27	0.95	0.019	0.025	0.03	0.02

≠ Structural Steel * Rail Steels

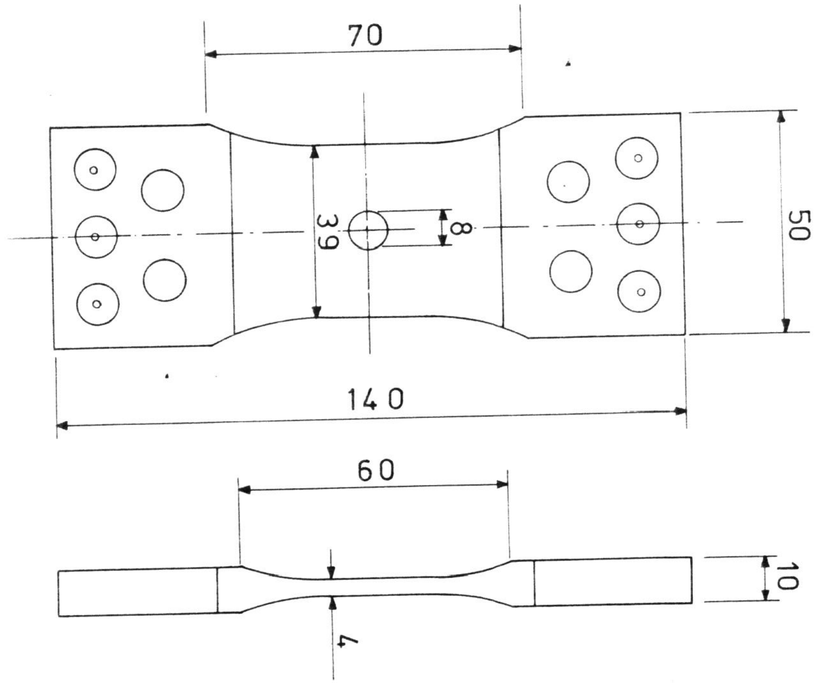

Figure 1 Notched Plate Fatigue Test Specimen (All dimensions in mm.)

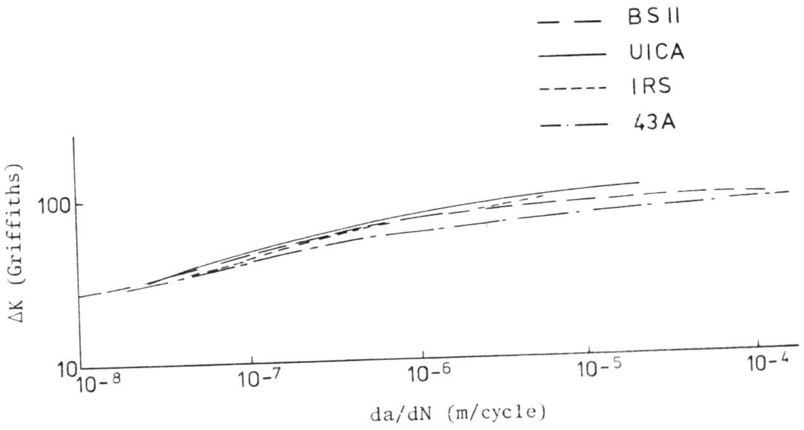

Figure 2 Crack Growth Results for Structural and Rail Steels

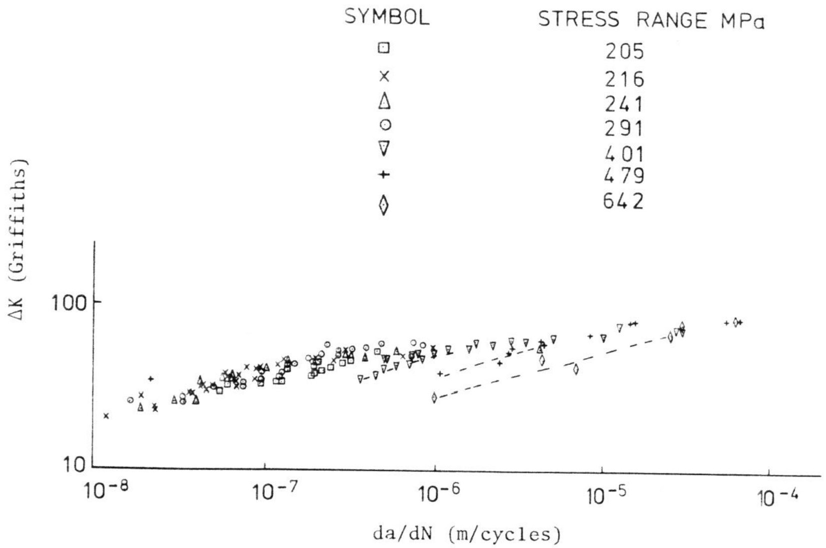

Figure 3 Crack Growth Results for Structural Steel

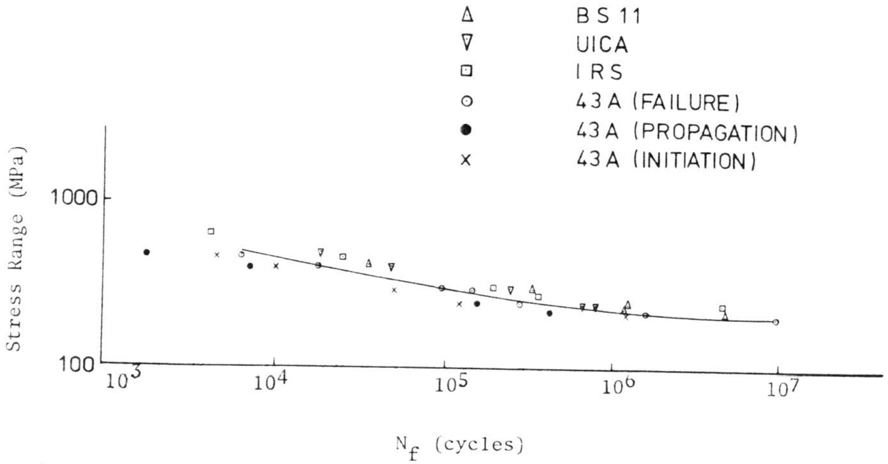

Figure 4 Stress Range Life Results for Structural and Rail Steels