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FATIGUE LIFE PREDICTION FOR FILLET WELDED DETAILS UNDER SERVICE LOADINGS

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INTRODUCTION

Welded joints are a constant source of fatigue problems. It is essential that the design process for such joints includes a realistic fatigue life prediction technique. This paper reports a series of tests aimed at assessing the accuracy of recently developed fatigue life prediction methods used by British Rail. The important elements of these methods are included in the fatigue clauses of the recently revised British Standard: 153[1] which is used extensively for the design of welded structures and components in Britain. Steel plate laboratory specimens containing fillet welded attachments [2] were subjected to variable-amplitude loading histories which are closely related to the strain variations experienced by welded components in service. Life predictions based on a knowledge of the nominal stress spectra experienced by the weld details are compared with actual test lives obtained.

THE FATIGUE LIFE PREDICTION PROCESS

At this stage it is expedient to outline briefly the three inter-linked stages which constitute the prediction process which, although relatively straightforward, are frequently misused. Fatigue damage is assumed to accumulate linearly, as proposed by Palmgren [3] and Miner [4]. It is necessary to reduce the complex service history into individual events (cycles and reversals) consistent with basic material behaviour. Estimates of the damage caused by these events are made by comparison with conventional constant-amplitude fatigue data. Many of the inaccuracies in life prediction which have been ascribed to deficiencies in the Palmgren-Miner linear damage rule are now known to result from inaccurate signal analysis or from badly chosen basic fatigue data.

Earlier work [5,6] has justified the use of the "Rainflow" cycle counting technique to interpret random loading histories. This method accurately reflects the non-linear behaviour of materials and extracts cycles and reversals (half-cycles) which are entirely compatible with constant-amplitude cycles and reversals. It is essential to establish the correct relationship between measured stress, or strain, and consequent fatigue damage. Many of the inaccuracies in life estimation stem from inadequate or incorrect basic constant-amplitude fatigue data. For welded structures the fatigue clauses of British Standard: 153[1] outline two approaches to the problem of fatigue life prediction. They are based on:

i) Nominal stress range-fatigue life curves. Nominal mean stress is no longer considered significant and the fatigue damage process for welded joints is simply related to range of stress [7].
ii) Linear elastic fracture mechanics crack growth data.

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Nominal Stress Range-Fatigue Life (S/N)

Constant-amplitude fatigue data for welded joints are only clearly defined between 10^5 and 2×10^6 cycles to failure. The relationship beyond endurance and stress range for lives of less than 10^5 cycles is the scope of this paper. The long life region (beyond 2×10^6 cycles) is of major importance for most structures in service. The majority of stress cycles in service spectra would not cause failure if applied exclusively. However, when they occur together with higher stress cycles in the variable-amplitude spectra they do contribute to fatigue damage. The standard makes allowance for the damage caused by these low stress cycles by progressively reducing the cut off, or fatigue limit, stress as a function of accumulated damage or crack length. This is equivalent to extending the S/N line into the long life region with a shallower slope as first suggested by Haibach [8]. The position of this change of slope and the amount of rotation are based on Fracture Mechanics considerations. The standard identifies this change of slope at 10^7 cycles and adopts the following relationships between nominal stress range (ΔS) and life (N_f):

$$\log N_f = 12.24 - 3 \log \Delta S \qquad N_f < 10^7 \text{ cycles} \tag{1}$$

$$\log N_f = 15.73 - 5 \log \Delta S \qquad N_f > 10^7 \text{ cycles} \tag{2}$$

Linear Elastic Fracture Mechanics

Since a fracture mechanics analysis has been used to assess the damage contribution of low stress cycles in variable-amplitude spectra, it is a logical step to extend the analysis to cover all stress levels. This is supported by many investigations suggesting that the fatigue of a welded component consists entirely of the growth of a crack from the inevitable pre-existing crack-like defect [9]. The crack propagation equation $da/dN = C(\Delta K)^m$ is repeatedly applied to the nominal stress spectrum experienced at the weld detail. After each application the value of the current crack size and the stress concentration factor are modified according to the amount of crack advance. The standard assumes an initial defect of 0.15 mm exists in the joint and the value of the stress intensity magnification factor, M_K, is derived from a finite element analysis of a similar weld detail [10].

EXPERIMENTAL PROCEDURE AND RESULTS

The variable-amplitude testing programme was carried out in a closed-loop, axial, servo-hydraulic test facility. A 440 kN actuator applied the loads which were measured by means of a load cell in series with the specimen. The specimens were manufactured by manually welding an attachment to 16 mm thick structural steel plate for B.S.4360 Grade 50B. This type of detail is a common source of fatigue problems on fabricated steel structures. Two samples of variable-amplitude loading histories were applied to the welded steel specimens:

i) A sixty minute sample of laboratory generated random signal containing frequencies ranging from 0 to 30 Hz. The stress range distribution was similar to that experienced by many components during service in the railway industry.

ii) A history recorded from a strain gauge attached close to a critical weld detail on the fabricated bogie of a British Rail main-line electric locomotive. The recording was made as the locomotive travelled over 36 miles of main line track whilst maintaining an average speed of 100 mph.

The selected history was repeatedly applied to specimens until failure occurred. The severity of the signal was adjusted for each test to obtain endurances ranging from 3 days to about 10 weeks.

In the early stages of each test a sample of the load cell output was fed through an "Analog-to-Digital" converter into a small 8 K computer. This computer was programmed to carry out a "Rainflow" cycle count and a concurrent cumulative damage analysis. At the end of the sample the computer printed out the stress range distribution together with a life prediction based on pre-selected basic fatigue data.

The actual test lives are compared with the predictions based on the S/N approach in Figure 1, and the linear elastic fracture mechanics approach in Figure 2.

DISCUSSION OF RESULTS

Nominal Stress Range-Fatigue Life Approach

The excellence of the results confirms the validity of extending the stress-life line beyond the constant-amplitude fatigue limit with a shallower slope. The results support the use of the simple relationship between fatigue life and nominal stress range, where nominal mean stress is ignored. In the region above the fatigue limit the proposed S/N line overestimates the damage contribution of higher stress levels and underestimates the damage caused by stresses approaching the fatigue limit level. For the very long life tests (>4×10^7 cycles) the S/N line overestimates the damage contribution of the low stress ranges below the constant-amplitude fatigue limit. In these tests the maximum nominal stress range experienced by the detail would not, if repeatedly applied, cause a failure earlier than 10^6 cycles.

Overall, it appears that even more accurate life predictions would be achieved if the S/N line was made steeper in the stress region above the change of slope at 10^7 cycles. Beyond this a much shallower slope is implied. It is likely that the S/N line for this type of detail, derived from earlier constant-amplitude tests [7] and incorporated in the standard, has been produced using test data obtained at stress levels exceeding the cyclic yield stress of the material. The S/N line would become steeper if these suspect results were not included. This corroborates the argument that the proposed slope is not steep enough above the fatigue limit.

Linear Elastic Fracture Mechanics Approach

For each test the actual lives are within 2 standard deviations of the mean predicted lives. However, the predictions obtained using this approach initially become more non-conservative as the actual lives increase. This suggests that a more realistic estimate of the crack advancement caused by low stress cycles would be obtained if the proposed straight line relating crack growth rate and stress intensity range was rotated to give a reduced slope.

The use of linear elastic fracture mechanics to assess the growth rate of the very small cracks or defects which exist in most welded joints is obviously questionable. A more realistic life prediction technique will only become available when the effects of local plasticity are accounted for.

CONCLUSIONS

i) The fatigue life prediction process proposed in British Standard: 153, using "Rainflow" cycle counting, nominal stress-fatigue life data or crack growth rate data, and the Palmgren-Miner linear damage hypothesis has been shown to be very satisfactory for fillet welded joints subjected to random load histories.

ii) Further investigations to establish an improved relationship between nominal stress range and fatigue life will be necessary to obtain more accurate fatigue life predictions for finite life.

iii) The linear elastic fracture mechanics approach, when applied to welded joints, is limited by the number of necessary assumptions and approximations. More accurate predictions would be obtained using a more realistic relationship between crack growth rate and stress intensity range, involving adjustments to the slope of the line, at the upper and lower ends.

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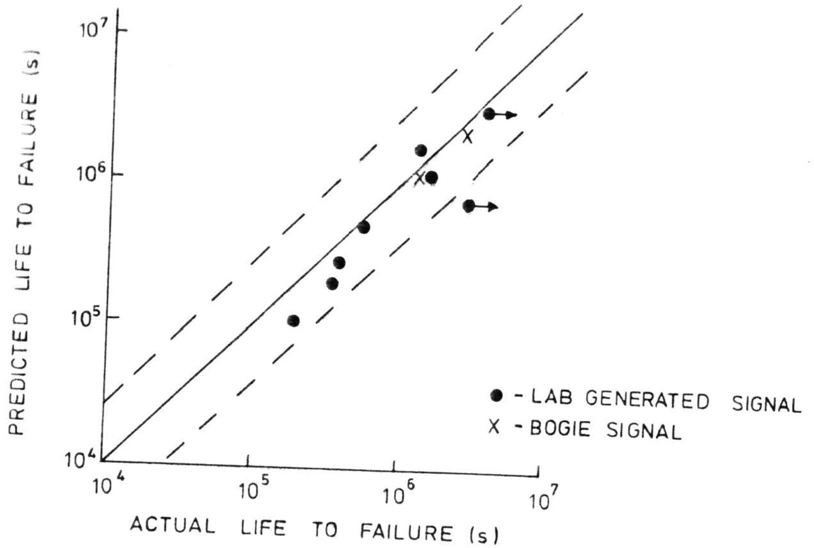

Figure 1

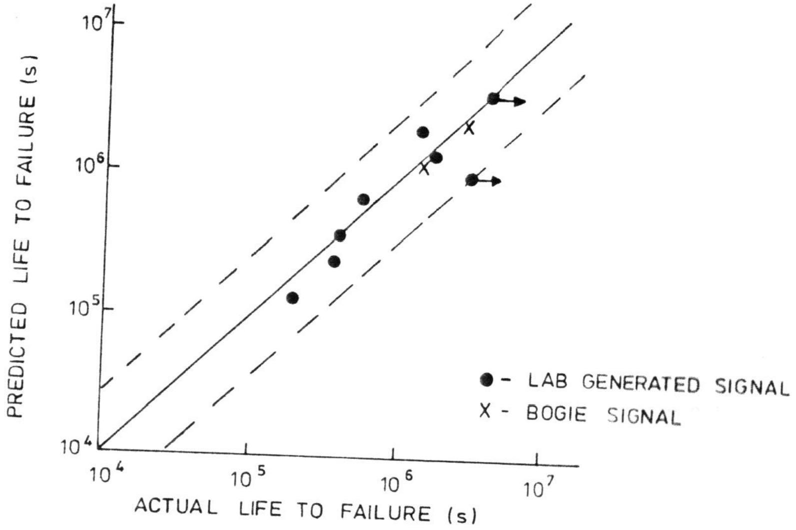

Figure 2