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Structural analysis of weldments in 316L (N) steels

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ABSTRACT

The structural integrity of components is of fundamental importance to the safety of any industrial plant but it is especially so in the case of the nuclear industry. This study, instigated by the CEC DGXI, WGCS contract RA1 CT/94/0234-UK, has been carried out to consider the assessment of weldments in design codes and standards, and the validation of currently implemented weldment factors which are applied to the results obtained from analysing parent material in order to take into account the weld metal.

INTRODUCTION

Historically, fatigue life assessment of welded joints(or weldments) have been based on that of the parent metal, factored by a suitable margin to take account of the material and geometric discontinuities. These factors are derived empirically from test data, usually from uniaxial specimens, by comparing the parent metal behaviour with that of the welded specimen. However, there is a need for a more fundamental understanding of the complex interactions between the material interfaces and how these effect the performance of weldments under plant operating conditions.

Realistic experiments on weldments are difficult to conduct and those involving thermal shock in sodium are difficult to analyse and interpret in a fundamental sense. However, AEA Technology has carried out a series of tests on thick section weldments under fully reversed bending on a number of materials including Type 316L(N) steel. Tests conducted on plates under reverse bending can use realistic proportions of weld metal to parent material and realistic weld preparations and procedures. Although it is difficult to measure strains directly at high temperatures, they can be inferred from a temperature independent calibration of specimen deflection against strain and from a knowledge of the stress-strain relationships of the component parts. Reverse bending has an additional advantage of being able to supply simultaneous data on the influence of compressive and tensile hold periods under creep-fatigue loading. Also the plate-like specimens, in which the width and operating length are, respectively, 10 and 20 times the thickness of the material, allow the unfettered growth of incipient cracks.

A study, instigated by the CEC, has been carried out to analyse some of these tests by considering the material variation of the weld and parent metal, using simplified or inelastic analysis. This work is fully described in a report[1] for the CEC.

This report summarises the experimental tests that were carried out, the results of the structural analyses undertaken and the conclusions of the study.

DESCRIPTION OF THE EXPERIMENT

Materials and Specimens

Tests were carried out on a 25mm thick Type 316L(N) plate, with a transverse weld. These specimens have a single sided vee preparation and were manufactured and inspected to RCC-MR[2] requirements. The weld was a full penetration, single sided butt, with a TIG root run and MMA capping runs. On completion the welds were ground flush and received a full radiographic analysis to RCC-MR standards.

Fatigue tests were conducted at a temperature of 550±3°C and at nominal total strain ranges between 0.3 and 1%, and creep-fatigue tests at strain ranges of 0.4, 0.6 and 1%, with a 1 hour hold period. All tests were conducted at a strain rate of approximately 0.03% per second. Three rigs, as illustrated in Figure 1, were utilised during the programme. These experiments are described in greater detail in the report by Bretherton [3].

Material Properties

The cyclic stress-strain properties and creep deformation data of the Type 316L(N) parent material and associated weld metals were determined in a separate programme of uniaxial materials tests. All tests were carried out at 550°C.

Experimental Results

The majority of the tests failed in the weld metal with the exception of the fatigue test at 0.3% total strain range. This behaviour is consistent with the cyclic stress-strain properties of the constituent materials. A fatigue strength reduction factor of 1.5 was indicated for this geometry.

Creep-fatigue tests on the austenitic welds with hold periods of 1 hour have produced a reduction in cycles to failure compared with the fatigue tests; the endurance decreasing with increasing hold period. All the creep-fatigue tests failed in the weld.

STRUCTURAL ANALYSIS

The objective of the study was to understand the interactions between the weldment constituents and to interpret the experimental results. These calculations would allow a critical analysis of the data used in the interpretation of the experimental results, especially concerning the strain values, not directly measured in the tests. Each of the study participants carried out analyses and assessment as follows:

AEA Technology carried out an inelastic analysis of the continuous cycling test at 0.6% strain range using the ORNL [4] constitutive model to describe material behaviour. The resulting values of stress and/or strain ranges have been used to carry out a life assessment using the UK Strain Based[5] design procedures

ENEA carried out an inelastic analysis of the continuous cycling test at 0.3% strain range, with and without a one hour hold time, using the Guionnet [6] constitutive model to describe material behaviour. Assessment of fatigue and creep fatigue damage has been carried out using the ASME Code Case N-47 [7].

CEA Saclay carried out analyses of the 0.6% continuous cycling test using the simplified methods of Roche[8] and Zarka[9]. A fatigue and creep-fatigue assessment has been carried out using the RCC-MR design rules.

DISCUSSION OF ANALYSES

Finite Element Model

All the participants have represented the specimen as a two dimensional plane strain model, thus any anisotropic material properties have been ignored. In each case, half of the specimen was modelled with symmetry applied at the centre-line of the specimen.

A typical finite element mesh, as used by ENEA and CEA is shown in Figure 2. Both used the finite element program Castem 2000 for the calculations. AEA Technology used the finite element code ABAQUS.

A description of the analyses carried out is provided in the CEC report[1]. A description of the results obtained is given in the following Sections.

Structural Analysis of Continuous Cyclic Test at 0.3% Strain Range

ENEA carried out an inelastic analysis of this test using the Guionnet constitutive model. The results from this analysis are summarised at four nodes, D0, D3, DF and D4, see Figure 3.

The analysis predicts that the maximum strain range occurred at node D4, which is at the HAZ/parent boundary. It can be seen that there is an enhancement in the strain at this position of 3.82/3.0 = 1.27.

Using these results, a best estimate calculation of the fatigue damage was carried out for each of the above nodes using fatigue endurance data. This is compared in Table 1 with the design prediction carried out using ASME Code Case N47. The assessment is based upon the applied strain range of 0.3% and is calculated with and without a fatigue strength reduction factor (FSRF) of 1.5.

Assessment Point	Strain Range (%)	Predicted Cycles to Failure
D0	0.293	>1E6
D3	0.250	>1E6
DF	0.218	>1E6
D4	0.382	210294
ASME - Parent	0.300	3090
ASME - FSRF=1.5	0.300	835
Experiment	0.300	185708

Table 1 Comparison of Predicted Failure - 0.3% Applied Strain Range

The predicted endurance using the ASME design is very conservative when compared with the observed experimental failure. The finite element analysis has correctly predicted that failure occurs within the parent material, though the predicted failure time, based on uniaxial test data, is non-conservative.

The design code indicates that the maximum strain range, and hence failure, occurs in the weld metal. However, analysis using representative material properties of the weld has indicated failure in the parent material.

Structural Analysis of Continuous Cyclic Test at 0.6% Strain Range

AEA Technology predicted the behaviour of the weldment using the ORNL constitutive model with parameters based on 10th or saturated cyclic behaviour. CEA Saclay predicted the strain range using the Roche and Zarka method to show the influence of the weld size and characteristics of the weld.

In both cases there was a significant enhancement in strain when the individual properties of the weld were considered. They both showed that the maximum strain was concentrated in the weld. The calculated maximum strain range was between 0.64 and 0.87%, 1.61 and 1.64%, and 0.707 and 1.27% for the methods using inelastic analysis, Roche and Zarka respectively. Thus, from the inelastic analysis the strain enhancement was between 1.15 and 1.5, and the simplified analysis predicted an enhancement between 1.14 and 2.44.

An assessment of the fatigue life was carried out using the UK strain based rules and RCC-MR based on the results from the inelastic analysis and simplified analysis respectively.

The predictions made are summarised in Table 2 below and are related to the maximum strain range obtained in the model.

Design Code/Procedure	ORNL Analysis 10th Cycle Parameters	ORNL Analysis 100th Cycle Parameters	Roche Method	Zarka Method
RCC-MR Design Curve(1)	-	-	24	190
RCC-MR Best-Fit Curve(2)	-	-	150	1400
UK Strain Based Rules Design Curve(3)	-	375	-	-
UK Best Estimate Curve(4)	4201	1850	-	-

Table 2 Comparison of Predicted Failure - 0.6% Applied Strain Range

Notes
(1) RCC-MR design fatigue curve given in Appendix A3-1S
(2) Best-fit curve is the design curve without the reduction factors of 2 and 20
(3) UK Strain Based fatigue curve
(4) Fatigue endurance data obtained from uniaxial tests at 550°C

The observed experimental failure occurred after 9489 cycles in the weld. All of the above correctly predict that failure will occur in the weld.

Structural Analysis of Cyclic Test at 0.6% Strain With One Hour Hold Period

AEA Technology carried out an assessment of this test using homogeneous parent material properties and the UK strain based rules.

CEA Saclay carried out a best-fit assessment using the RCC-MR design rules without the factor of 0.9 on creep and the 2 and 20 factors on fatigue. The coefficient of weld rupture characteristics, Jr, was taken as 1.

The predicted cycles to failure are summarised in Table 3 for each of the methods examined.

Method	Predicted Cycles to Failure
Roche /RCC-MR(Best Estimate)	70
Zarka/RCC-MR (Best Estimate)	600
RCC-MR Best estimation from fatigue test	1500
ORNL Inelastic /UK Strain Based Procedure	133

Table 3 Comparison of Predicted Failure - 0.6% Strain Range with one hour hold period

The observed experimental failure occurred after 4578 cycles. All of the above predictions are conservative in comparison. It must be emphasised that the RCC-MR predictions are best estimates, indicating that the RCC-MR method for creep-fatigue evaluation is over-conservative.

CONCLUSIONS

Each of the methods of analysis used indicated a strain enhancement occurs in the weld or parent material depending on the applied strain range. Thus a FSRF of one is under estimated and 1.25 may not be conservative.

The structural analyses using materials data representative of the weld and parent metal indicated that the FSRF may be as much as 1.5 as found in the experimental tests.

A FSRF of between 1.15 and 1.5 has been calculated using inelastic analysis, whilst simplified methods indicate a factor between 1.14 and 2.44. The simplified methods appear to over-estimate the strain enhancement in the weld region.

The analyses correctly predicted the position of failure based on maximum strain range. However, the evaluation of the predicted strains can only be obtained by comparison with local strain gauge measurements at the weld.

The fatigue strength reduction factor needs to consider not only the type of joint and the inspection, but also the parameters that enhance the effect of elastic follow-up:

- differences in the relative properties of weld and parent material
- variation in geometry
- variation in loading

The RCC-MR route for creep-fatigue evaluation is over conservative, even with a Jr coefficient of 1.

The UK strain based rules are also very conservative. This is due to the design margins incorporated implicitly in the procedures for limiting the extent of crack growth, creep damage and for assessing the interaction between these damage mechanisms.

ACKNOWLEDGEMENT

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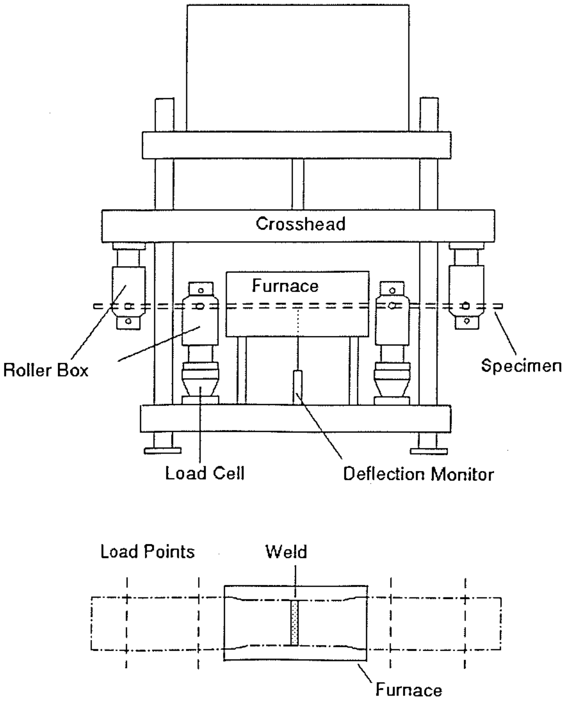

Figure 1 Schematic of Machine used for the experimental tests

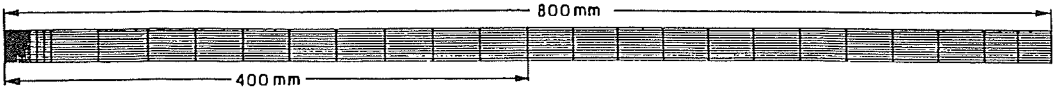

Figure 2 Finite Element Model

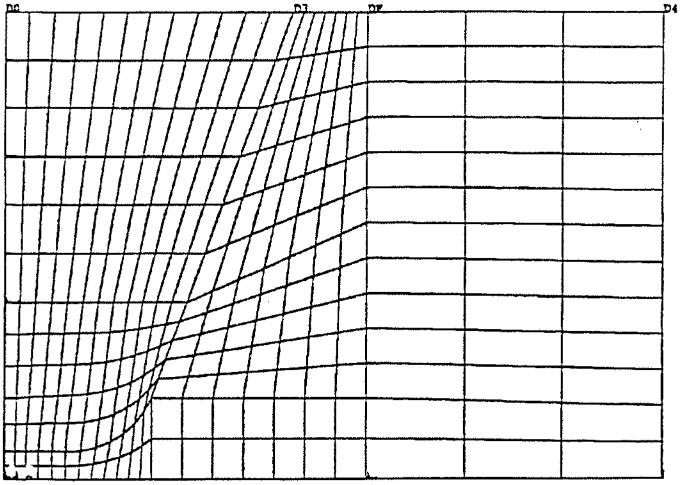

Figure 3 Identification of Nodes Used For Assessment