The Effect of Combined Applied and Residual Stress on Creep Crack Initiation in Stainless Steel

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Abstract

A novel experimental system involving three bars in parallel that permits C(T) specimens to be subjected to both applied and residual stresses. The system also allows the effects of elastic follow-up to be considered. The C(T) specimen lies within the centre bar, surrounded by two outer bars. The complete system is preloaded to create residual stresses in the structure, and then externally loaded. Two sets of systems are created, one with low elastic follow-up, the second with a high value. In addition to combined loading tests, conventional load controlled tests were conducted on C(T) specimens to act as a reference condition.

The mechanical behaviour of the system is compared with finite element simulations and simple models. It is found that the time for the crack to initiate increases in the case of combined loading conditions compared to load controlled conditions at the same total reference stress. The longer initiation times are a consequence of the relaxation and redistribution of the residual loads in the structure. The initiation time is also a function of the elastic follow-up.

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1. Introduction

Stresses applied to components can be classified into primary and secondary stresses [1]. Primary (load controlled) stresses are produced by applied external loads such as pressure, dead weight or interaction from other components and can induce plastic collapse. Secondary (deformation-controlled) stresses are generally produced as a result of internal mismatch caused by, for example, thermal gradients and weld residual stresses [2]. Residual
stresses are usually treated as secondary stresses. However, in certain circumstances they must be classed as primary. For example, in a cracked structure where the fit-up residual stresses do not self-equilibrate across a ligament, the residual stresses may provide a significant contribution to the plastic collapse of the ligament. Whether they do or not depends on how the residual forces change as a crack grows and plastic deformation accumulates in the structure. This in turn depends on the level of elastic follow-up (EFU).

It is always desirable to fabricate laboratory sized test specimens that contain well defined residual stress fields and conduct validation experiments on these specimens. This is usually done by introducing localized regions of residual stress through welding or local compression [3]. The specimens are then tested under load controlled [4, 5] and occasionally under displacement controlled conditions [6]. However, practical structures are subjected to stresses that arise from a combination of residual and applied stresses. The relaxation of residual stress in one location is compensated by changes in residual stress distribution in other locations so as to retain equilibrium, i.e. components are often subjected to combined displacement and load controlled conditions. A recent review of methods [7] of introducing residual stress in creep conditions concluded that new methods should be sought which represent more practical situation and also consider the consequences of elastic follow-up in the structure.

The purpose of this paper is to illustrate a three bar test rig that was designed [7] to introduce combinations of residual and applied stresses into a compact tension C(T) specimen. The rig also allows the effects of elastic follow-up to be considered. This paper describes the three bar test rig and the method of introducing residual stresses and controlling elastic follow-up. The rig was designed to study C(T) specimens, but to avoid conventional pin loading, the specimens were loaded through screw fittings. Therefore, in parallel to combined residual and applied stress tests in the three bar rig, load controlled tests were conducted using revised C(T) specimens. The experimental and finite element analysis findings are then reported.

2. Experimental Rig Design

The three bar rig illustrated in Fig. 1 was designed and developed [7] so that residual stresses can be introduced through displacement incompatibility and has the option for further application of external load to the test rig. The rig consists of two parallel outer bars B, each of stiffness $K_{\text{out}}$, a central bar A, with stiffness $K_{\text{in}}$ in series with a C(T) specimen having stiffness $K_s$. The initial misfit displacement $X$ permits an initial tensile residual force to be introduced into the C(T) specimen, with balancing compressive forces in the outer bars. Once the misfit is introduced the test rig is in equilibrium. Additional loads can then be applied to the system, thereby introducing a combination of residual and applied forces to the C(T) specimen.

![Fig. 1 Three bar structure](image-url)
The relative stiffness of the C(T) specimen to the stiffness of the middle and outer bars plays an important role in determining the overall elastic follow-up, Z, of the test rig and is given by

\[ Z = Z_{eff}Z_s \]  \hspace{1cm} (1)

where, \( Z_{eff} = \left(1 + \frac{\kappa_{eff}}{\kappa_{in}}\right) \) and \( Z_s = \left(1 + \frac{\beta}{\kappa_{eff}}\right) \). \( \beta = \frac{K_{in}}{K_s} \). \( \frac{1}{\kappa_{eff}} = \frac{1}{\kappa_s} + \frac{1}{\kappa_{in}} \). \( \alpha_{eff} = \frac{2K_{out}}{K_{eff}} \).

A detailed derivation of eq. (1) is given in [8]. When Z is close to 1 the system corresponds to displacement control while for Z greater than 5 it is considered to be close to load control [1]. Two experimental test rigs with different elastic follow-up values were designed using this concept; rig 1 to provide \( Z = 2 \) and rig 2 with \( Z > 6 \). The overall arrangement of the test rig-1 is shown in Fig. 2 and more details about the design of the test rig are given in [7, 9].

Fig. 2 Three bar test rig (All dimensions in mm)
Capacitance gauges were mounted on C(T) specimens to measure load line displacements while two linear voltage displacement transducers (LVDT) were mounted on each side of the upper and lower sections to measure the total displacement of the structure. High temperature strain gauges were mounted on the middle and side bars to measure strains and determine the corresponding forces in each bars. Thermocouples were connected to measure the specimen temperature, room temperature and temperature close to the position of the strain gauges. A direct current potential drop (PD) system was connected to the C(T) specimen to measure crack initiation and growth. The overall arrangement was fitted into a creep test rig so that an external load was applied to the assembly via a lever arm arrangement.

3. Experimental Study

3.1. Specimen Preparation

The C(T) specimens were manufactured from ex-service Type 316H stainless steel according to ASTM 1457 [10]. A screw fitting arrangement (see Fig. 2) rather than pins were used to transmit loads to the C(T) specimen. This arrangement was adopted to provide an accurate measurement of stiffness. Electric discharge machining (EDM) was used to create 2mm long pre-cracks (essentially notches of 0.1 mm diameter) into the specimens such that the crack length to width (a/W) ratio of 0.5 was achieved. The pre-cracked specimens were then side grooved each side by 10 % of their thickness. The details of the specimens are given in Table 1, where W is width, B is gross section thickness, Bn is net section thickness and a0 is initial crack length.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>W (mm)</th>
<th>B (mm)</th>
<th>Bn (mm)</th>
<th>a0 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALS-01</td>
<td>38.01</td>
<td>19.12</td>
<td>15.88</td>
<td>19.54</td>
</tr>
<tr>
<td>ALS-02</td>
<td>38.07</td>
<td>19.12</td>
<td>15.83</td>
<td>19.30</td>
</tr>
<tr>
<td>AMS-01</td>
<td>37.99</td>
<td>19.13</td>
<td>15.86</td>
<td>19.27</td>
</tr>
<tr>
<td>AMS-04</td>
<td>37.83</td>
<td>19.04</td>
<td>15.36</td>
<td>19.36</td>
</tr>
</tbody>
</table>

Having introduced the desired residual stress into the C(T) specimen, the entire assembly was then subjected to an applied load. The residual force in all three bars, load line displacement of the C(T) specimens, potential drop readings and overall extensions of the rigs were recorded during each test.

3.2. Creep Crack Initiation Tests

In total four creep crack growth tests were carried out using the revised C(T) specimen. Two constant load tests were conducted using conventional lever arm creep test rigs and one each on two three bar test rigs. The test conditions for all the tests are summarized in Table 2.

The reference stress in Table 2 was determined from [1]

$$\sigma_{ref} = \frac{p}{WBnL_n}$$

(2)

where $n_L$ is a normalised limit load function given by

$$n_L = \sqrt{(1+\gamma)(1+\gamma(a/W)^2)-(1+\gamma(a/W))}$$

with $\gamma = 2/\sqrt{3}$

Potential drop was used to monitor the crack extension and once the tests were stopped, the specimen’s
broken open to measure final crack lengths.

Table 2. Summary of creep crack initiation tests

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test type</th>
<th>Initial residual force (kN)</th>
<th>Initial residual reference stress (MPa)</th>
<th>Applied load (kN)</th>
<th>Applied reference stress (MPa)</th>
<th>Total initial reference stress (MPa)</th>
<th>Final crack growth (mm)</th>
<th>Test duration (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALS-01</td>
<td>Constant load</td>
<td>--</td>
<td>--</td>
<td>14.11</td>
<td>280</td>
<td>280</td>
<td>0.848</td>
<td>541</td>
</tr>
<tr>
<td>ALS-02</td>
<td>Constant load</td>
<td>--</td>
<td>--</td>
<td>12.46</td>
<td>240</td>
<td>240</td>
<td>0.882</td>
<td>1508</td>
</tr>
<tr>
<td>AMS-01</td>
<td>Combined loading</td>
<td>9.38</td>
<td>180</td>
<td>5.15</td>
<td>100</td>
<td>280(241*)</td>
<td>0.107</td>
<td>3816</td>
</tr>
<tr>
<td>AMS-02</td>
<td>Combined loading</td>
<td>6.36</td>
<td>130</td>
<td>5.43</td>
<td>110</td>
<td>240</td>
<td>0.17</td>
<td>4229</td>
</tr>
</tbody>
</table>

*Reference Stress at the end of loading process

4. Finite Element Analysis

Finite element analysis was carried out using commercial ABAQUS version 6.12 [11]. The compact tension C(T) specimen was modelled in 3D using 20,000 solid brick elements. Only one symmetry plane was used in the FEA model which included the mid-thickness plane of the C(T) specimen. The C(T) specimens modelled included side grooves as well as different fatigue pre-crack lengths as shown in Table 1.

Stress-strain material data for 316H austenitic stainless steel [5] were used in the analysis. For the creep analysis an EDF subroutine [12] was incorporated in the analysis which made use of the RCC-MR creep law [13]. The experimental results under load control study were used initially to tune the EDF creep subroutine.

The three bar structure shown in Fig. 2 was modelled in 3D using 30,000 solid brick elements in ABAQUS version 6.12. To model screw loading contact was made between the C(T) specimen and the middle bar. The introduction of a misfit allowed the system to acquire residual stress by transferring load from the middle bar to the outer bars via the bottom end section. As in load controlled simulations only one symmetry plane about the mid-thicknesses of the C(T) specimen and three bars was used. Loading was carried out at one end of the structure with the opposite end constrained in all directions. By changing the dimensions of the bars two different elastic follow up systems were modelled. In the present paper preliminary results for low EFU and load control are presented.

5. Results and Discussion

In test AMS-01 a residual force of 9.38 kN was first introduced into the C(T) specimen, while for test AMS-02 test the residual force was 6.36 kN. It was observed that in both cases, the total compressive residual force in the side bars was approximately equal to the tensile residual force on the C(T) specimen. Figure 3 shows a comparison of the forces versus total load line displacement of the three C(T) specimens. Points A1 and A2 correspond to the initial residual forces on the two specimens. The lines A1B1 and A2B2 correspond to the specimen load-displacement paths during the application of the external loads. Lines B1C1 and B2C2 correspond to the locus of load relaxation with time for each specimen.
The rate of load relaxation was a function of the elastic follow-up provided by each test rig. When external load was applied to specimen AMS-01 in rig 1, with $Z = 2.15$, load relaxation occurred reducing the load on the C(T) specimen from about 14.53 kN to 12.4 kN (see Fig. 4). Also shown is the predicted relaxation in the middle bar from finite element analysis. A good correlation exists between the measured and the predicted force relaxation. However, since crack growth was not considered in the simulations the overall stiffness in the FEA model does not change and therefore the stress does not relax as much as the measured above 2000 hours. In rig 2, with $Z=7.34$ there was no relaxation during application of external load (see Fig. 5) and this is a result of the high elastic follow-up in rig 2 and hence negligible relaxation occurred during the loading phase.

Having applied an external load to each test rig and retained the loads at a constant value, creep in each C(T) specimen caused the total load to relax. In specimen AMS-01 rapid force relaxation was observed in the initial 1000 hrs from 241 MPa to 170 MPa compared to 5 MPa of stress relaxation in specimen AMS-02 for the same duration (see figures 5-6). Figure 6 revealed that at the end of 3800 hrs the crack developed in AMS-01 was 0.1 mm compared to 0.15 mm in AMS-02 test. Both combined loading tests took significantly more time to provide the same crack extension compared to constant load test at same initial total reference stress.
The experiential load displacement data obtained from the creep crack growth tests were used to determine material resistance and creep toughness. The material resistance \( J_{\text{Total}} \) was determined [14] using

\[
J_{\text{Total}} = \frac{\eta U_{\text{Total}}}{\beta_n(W-a_o)}
\]

where, for a C(T) specimen,

\[
\eta = 2 + 0.522 \left(1 - \frac{a_o}{W}\right), \quad 0.45 \leq \frac{a_o}{W} \leq 0.7
\]

and \( U_{\text{Total}} \) is total area under the load-displacement curve.

The material creep toughness \( K_{\text{mat}}^c \) was evaluated directly from experimental load total displacement data, [1, 4], using

\[
K_{\text{mat}}^c = \left[ K_e^2 + \left(\frac{E'\eta U_p}{\beta_n(W-a_o)}\right) + \left(\frac{n}{n+1}\right) \frac{E'\eta P\Delta_c}{\beta_n(W-a_o)}\right]^{0.5}
\]

where,

- \( K_e \) is the elastic stress intensity factor
- \( U_p \) is plastic area under load-displacement curve
- \( \Delta_c \) is the creep load line displacement

The values of \( J_{\text{Total}} \) and creep toughness calculated using eqn. 3 and 4 are plotted in Fig. 7 for all tests. The rapid relaxation of stress in the low EFU rig-1 led to a decrease in creep toughness with time.

![Fig. 7 Comparison of material resistance and creep toughness for ALS-02, AMS-01 and AMS-02](image-url)

![Fig. 8 Comparison of time for 0.1mm crack extension](image-url)

The time for 0.1 mm crack extension for the various tests is shown in Fig. 8. Excellent correlation exists between the measured and FEA predicted for the load control tests. Although the initial reference stress was the same for tests ALS-02, AMS-01 and AMS-02, the creep crack initiation times were significantly different. Relaxation of the load applied to the C(T) specimen in rigs 1 and 2 was the major contribution to the increased initiation time. Even for test AMS-02 performed on rig-2 with high EFU, the crack initiation time increased by 8 times greater when compared the constant load test, ALS-02.
6. Concluding Remarks

Practical structures are subjected to combinations of residual and applied stresses which in turn lead to mixed boundary conditions. Conventional laboratory creep tests do not represent these circumstances. A new test method based on a three bar structure has illustrated that residual stresses can be induced into a specimen at high temperature in a controlled manner and can be characterized easily within the test rig. Two test rigs were developed each with nominal elastic follow-up of about 2 and 7. The mechanical behaviour of the system is compared with finite element simulations and simple models. It is found that even though the initial reference stresses were the same compared with a load controlled test, the initiation times for the combined loading were longer, with increasing initiation times for lower values of elastic follow up. The longer initiation times are a consequence of the relaxation and redistribution of the residual loads in the structure.

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References