Effects of end loading on the creep failure behaviour of CrMoV welds in main steam pipelines

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Abstract

This paper describes an investigation into the effects of end (system) loading on the creep failure behaviour of internally pressurised thick walled pipe welds, using the FE method with simplified axisymmetric models. Steady-state and creep damage analyses were performed for a series of new, service-aged, and repaired welds in main steam pipes in power generation plants. The material properties used were related to CrMoV weldment materials at 640° C. Stress distributions were obtained and failure lives were predicted for each weld situation, under a closed-end condition and with additional axial loading. The rupture stresses showed very little variation across the heat-affected zone (HAZ), in the dominant stress regions, for closed-end loading. However, the variation is more significant when additional axial loading is applied. The results of damage variations across the HAZ in these critical regions confirmed the effect of end loading indicated by steady-state results. This suggests that, in addition to the pressure, for the welds investigated, there is a high probability of type IV cracking occurring in pressurised pipes, as the axial loading is increased, which is consistent with laboratory and power plant experience.

1 Introduction

Welds form an integral part of most power and chemical plant structures. At elevated temperature, the service lives of these structures are often governed by the creep behaviour of welds. Efforts have been made to understand creep stress distributions and deformation behaviour of welds and to predict the failure life. The complexity of the creep behaviour of welds is primarily due to the material inhomogeneity and the variable dimensions and shapes of welds (e.g. in weld
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repairs). In addition, the effect of system load on the failure behaviour may be significant. For instance, within the low temperature HAZ region of the welds in main steam pipelines, normally referred to as the type IV region [1], cracking is directly influenced by the local structural properties and is usually associated with excessive axial or bending stresses [2], caused by the system loading, such as end loads.

Because of the complex nature of the problem, exact analytical solutions cannot be obtained for the stresses and strains within welds under creep conditions. Therefore, numerical methods, such as the finite element (FE) method, are commonly used to obtain solutions for specific material properties, geometry and loading. Before accurate modelling can be performed, the material properties for each material zone must be determined. Laboratory creep testing is performed to generate creep properties for the parent, weld and HAZ materials and these can be used, together with the FE method, to determine the stress distributions in the various zones of welds and to predict the failure lives of welds.

Damage mechanics constitutive equations of the following type [3]:

\[ \dot{\varepsilon}^c_{ij} = \frac{3}{2} A \left[ \frac{\sigma_{eq}}{1 - \omega} \right]^n S_{ij} t^m \]  

(1a) and

\[ \dot{\omega} = \frac{M \sigma_r^x}{(1 + \phi)(1 - \omega)^\phi} t^m \]  

(1b)

where

\[ \sigma_r = \alpha \sigma_1 + (1 - \alpha) \sigma_{eq} \]  

(1c)

can be used in conjunction with the FE method to predict the life of components under creep conditions [e.g. 4]. If the material constants (A, m, n, M, α, φ and χ) are available for the parent, HAZ and weld materials, the technique can be used to predict the failure behaviour of welded components, e.g. [5]. However, precise material behaviour models, especially for the HAZ material, and also the FE damage codes required, are not widely available. In addition, damage mechanics analyses are usually lengthy. Therefore, in many cases, the results of steady-state analyses are used as a quick and easier alternative for life assessments of welds.

Steady-state creep solutions, using Norton’s creep law, i.e.

\[ \dot{\varepsilon}^c_{ij} = \frac{3}{2} A' \sigma_{eq}^{n'-1} S_{ij} \]  

(2)

can be obtained using commercial FE codes. It has been shown that for multi-material situations, such as welds, in which the difference in the creep strengths of the parent material (PM), heat affected zone (HAZ) and weld metal (WM) can be represented by using different A' and n' values for each region, the creep failure times can be estimated from the steady-state creep rupture stress, \( \sigma_{rs}^{ss} \), and the appropriate creep rupture material properties [6, 7], i.e.

\[ t_r^{ss} = \left[ \frac{1 + m}{M(\sigma_{rs}^{ss})^x} \right]^{1/(1+m)} \]  

(3)

This paper describes an investigation of the effects of end (system) loading on the creep failure behaviour of internally pressurised thick walled pipe welds, using the FE method with simplified axisymmetric three-material weld models. Steady-state and creep damage analyses were performed for a series of new, service-aged and fully repaired welds in main steam pipes in power generation
plants. The material properties used were those obtained from a 1/2Cr1/2Mo1/4V: 2 1/4Cr1Mo weldment at 640° C. Stress distributions were investigated and failure lives were predicted for each weld situation, under a closed-end condition and with additional axial loading. Based on the results obtained, the effects of the end load on the failure lives and failure position of these welds were identified.

2 Finite element modelling

2.1 Weld dimensions

The chosen pipe dimensions are typical of ferritic CrMoV main steam pipe lines in UK power plants. The pipe has an outer diameter, D, of 355.6 mm and a wall thickness, T, of 63.5 mm. A typical weld preparation was chosen for the new and aged pipe welds which has a weld interface angle, θ, of 15°, width of weld metal at the outer surface, w, of 46 mm and the width of HAZ, h, of 4 mm, Fig. 1(a). The weld dimensions for the fully repaired weld, Fig. 1(b), are similar to those of the new or aged weld, but with a weld width, w, of 80 mm.

![Figure 1: Schematic diagrams of a service-aged weld with damage and a fully repaired weld.](image)

2.2 FE models

In this investigation, the welds were assumed to consist of three distinct material zones, i.e. the parent material, heat-affected zone and weld metal, each of which has constant creep properties. Also, it was assumed that all welds are subjected to PWHT after fabrication. The material models for the new and aged welds consist of the new and service-aged parent, HAZ and weld materials. The full repair weld model consists of aged parent material, new weld metal and the HAZ in the aged parent material generated by welding, Fig. 1(b).

An axisymmetric pipe weld model, Figs. 2(a), was used in FE modelling. The pipe welds were subjected to an internal pressure, $p_i$, and a mean tensile end load, $\sigma_{ax}$. A uniform axial displacement was imposed on the ends of the pipes. An example of a mesh used for steady-state analyses is shown in Fig. 2(b). Steady-state analyses were performed using the ABAQUS FE code [8] and damage calculations were performed using an in-house FE-Damage code [9].
It should be noted that local stress singularities exist at the free surfaces of dissimilar material interfaces. However, based on previous work, it can be concluded that for practical weld situations, the influence of the stress singularity is unlikely to be significant [10]. Therefore, in this investigation, the effect of stress singularities was not taken into account in the FE analyses.

2.3 Creep properties used in FE modelling

The material data used in the FE analyses were obtained from the results of creep tests performed at 640° C, on the different constituents of the new, service-aged and fully repaired 1/2Cr1/2Mo1/4V: 2 1/4Cr1Mo pipe weld in a main steam pipeline [11]. The creep data for these materials, at 640° C, have been assessed and were found to be suitable for use in creep modelling [11]. The material constants in eqns (1) obtained for the various materials are given in Table 1 (σ in MPa and t in hour), where HAZ-1 is the HAZ generated in the aged parent material of the fully repaired weld. It should be noted that since in all cases, the values of the material constant m are zero, as shown in Table 1, the A' and n' values in eqn (2) are the same as the A and n values in eqns (1).

Table 1. Material constants for the CrMoV weldment materials at 640° C.

<table>
<thead>
<tr>
<th></th>
<th>New</th>
<th>New</th>
<th>New</th>
<th>Aged</th>
<th>Aged</th>
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<tr>
<td></td>
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<td>6.5991 x 10^{-16}</td>
<td>9.7181 x 10^{-15}</td>
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<tr>
<td>M</td>
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<td>5.7943 x 10^{-11}</td>
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<td>8.1202 x 10^{-13}</td>
<td>2.5 x 10^{-9}</td>
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<tr>
<td>φ</td>
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<td>4.1209</td>
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<td>χ</td>
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<td>4.0152</td>
<td>3.420</td>
<td>5.767</td>
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Figure 3: Variations of steady-state rupture stresses across the HAZ, along a line, parallel to and 3.8mm from the outer surface of the new, aged and fully repaired welds, with $\sigma_{av}/\sigma_{mh}$, for $p_i = 16.55$ MPa.

3 Results

For all weld cases, FE calculations were performed with an internal pressure, $p_i$, of 16.55 MPa, which is the operational pressure for the CrMoV pipelines, for a range of mean end loads, $\sigma_{ax}$, i.e. $\sigma_{av}/\sigma_{mh} = 0.306$ (closed-end case) to 1.0, which is the most extreme case allowed within some design codes [e.g. 12], where $\sigma_{mh}$ is the mean diameter hoop stress.

3.1 Steady-State Analysis

Detailed stress distributions within the welds were examined and the peak values and positions for the maximum principal stress, $\sigma_1$, von Mises equivalent stress, $\sigma_{eq}$, and rupture stress, $\sigma_r$, were obtained for each material zone. The failure lives were predicted using eqn (3), with the peak rupture stresses for each material zone. The failure life of each weld is the minimum failure time from all of the
material zones. The failure position within a zone was assumed to be the position where the maximum peak rupture stress occurs [6].

The variations of the rupture stress across the HAZ with $\sigma_{ax}/\sigma_{mh}$, near the outer surface, for the new, aged and fully repaired welds are shown in Figs. 3(a) to 3(c), respectively. It can be seen from Figs. 3 that when the end load is low, i.e. when $\sigma_{ax}/\sigma_{mh} < 0.5$, there is very little variation in the rupture stresses across the HAZ. However, when $\sigma_{ax}/\sigma_{mh} > 0.5$, there is significant variation in the rupture stresses across the HAZ and the peak values of the stresses move to the HAZ/PM boundary.

The results of the stress distributions have shown that in all of the three weld cases, the failure is dominated by the peak rupture stresses in the HAZ, and the failure positions are near the outer surface. As examples, the variations of the rupture stress across the HAZ, for the new, aged and fully repaired welds, for $\sigma_{ax}/\sigma_{mh} = 0.306$ and 1.0, are compared in Figs. 4(a) and 5(a), respectively, and the corresponding failure lives, predicted with these rupture stresses are shown in Figs. 4(b) and 5(b). It can be seen that, in all cases, the HAZ properties give the lowest failure lives for these welds, although the rupture stresses in the HAZ are the lowest. The peak rupture stresses in the HAZ with $\sigma_{ax}/\sigma_{mh}$ obtained for the new, aged and fully repaired welds are shown in Fig. 6 and the corresponding rupture lives predicted with the stresses are shown in Fig. 7. It can be seen from Fig. 7 that the differences in failure lives of the new, aged and fully repaired welds reduce significantly with increasing axial load, and when $\sigma_{ax}/\sigma_{mh} = 1.0$, the failure lives of the aged and fully repaired welds are similar to those of the new weld. The failure lives of the fully repaired weld, obtained from steady-state analyses, for $\sigma_{ax}/\sigma_{mh} = 0.306$ and 1, are 7,077 and 2,971 hours, respectively.

3.2 Damage Analysis

Damage failure modelling was performed for the new, aged and fully repaired welds, under the same loading conditions, as the steady-state analyses. When high damage accumulation, i.e., $\omega \to 1$, was achieved through a significant part of the wall thickness, creep failure was assumed to have occurred. It was found that the damage levels in the parent and weld materials were much lower than those in the HAZ for all of the time. Material failure (defined as $\omega = 0.99$) first occurred near the outer surface of the pipe in the HAZ and the failure area expanded and grew into the HAZ. Figs. 8(a) and 8(b) show typical results for the damage variations in and along the HAZ with time, close to the type IV region, with $\sigma_{ax}/\sigma_{mh} = 0.306$ (closed-end case) and 1.0, respectively; the origin for Figs. 8 is at the outer surface and the distance is normalised with respect to the total distance along the interface between the HAZ and parent material. It can be seen that for the maximum creep time for which results were obtained, more than half of the wall thickness of the pipe has reached the failure damage level. The failure lives of the fully repaired weld, obtained from damage analyses, for $\sigma_{ax}/\sigma_{mh} = 0.306$ and 1, are 10,740 and 3,745 hours, respectively.
In order to investigate the effect of end load on the failure position of the welds, damage variations across the HAZ, for different times, in the failure dominant area were investigated. The results obtained for the fully repaired welds for $\sigma_{ax}/\sigma_{mh} = 0.306$ and 1 are presented in Figs. 9(a) and 9(b), respectively. It is clear that for the closed-end situation, where no system load is applied, the damage distributions across the HAZ near the outer surface are fairly uniform for most of the creep time, Fig. 9(a). However, when $\sigma_{ax}/\sigma_{mh} = 1$, i.e. a high end (system) load is applied, the high damage values move to the HAZ/PM boundary, which is the position where type IV cracking occurs. This is consistent with the results obtained from the steady-state cracking occurs. This is consistent with the results obtained from the steady-state analyses, although in the steady-state analyses, the results presented are the rupture stresses. The rupture lives obtained
Figure 6: Variations of steady-state peak rupture stresses in the HAZ versus $\sigma_{ax}/\sigma_{mh}$, for the new, aged and fully repaired welds, with $p_i = 16.55$ MPa.

Figure 7: Variations of failure life versus $\sigma_{ax}/\sigma_{mh}$, obtained from steady-state and damage analyses, for new, aged and fully repaired welds, with $p_i = 16.55$ MPa.

Figure 8: Variation in and along the HAZ, near the type IV region of the fully repaired weld, at different times, with $\sigma_{ax}/\sigma_{mh} = 0.306$ and 1 ($p_i = 16.55$ MPa).

Figure 9: Variations of damage across the HAZ, along a line parallel to and 5.1mm from the outer surface of the fully repaired weld, at different times, with $\sigma_{ax}/\sigma_{mh} = 0.306$ and 1 ($p_i = 16.55$ MPa).
for the new, aged and repaired welds, with $\sigma_{ax}/\sigma_{mhl}$ from damage analyses, are compared in Fig. 7 with those obtained from steady-state analyses.

4 Discussion and conclusions

Steady-state creep and continuum damage FE analyses, using simplified three-material axisymmetric models, were performed for internally pressurised thick walled pipe welds under a closed-end condition and with additional axial loading, as allowed within the design codes. The geometry and loading conditions were typical of the main steam pipe lines in UK power plants. Materials data for three sets of low alloy ferritic steels were used, which relate to the new, service-aged and fully repaired CrMoV welds at 640° C, to illustrate the effects to be expected. Stress distributions were obtained and failure lives were predicted to show the effects of the end (system) load on the failure behaviour of the pipe welds.

The steady-state stress distributions obtained show the characteristic of off-loading, i.e. redistribution of stress, from the weaker to the stronger materials. For the new, aged and fully repaired welds investigated, failure is generally predicted to occur in the HAZ at or close to the outer surfaces of the pipe welds. Similar behaviour was observed in damage analyses, i.e. the damage level in the HAZ material is much higher than that in the parent and weld materials. This could, for the materials properties used, be the result of the relatively weaker rupture strength of the HAZ structures in each weld situation. However, it should be noted that a different behaviour could occur if the material property balance in the constituents of the welds was different. Further investigation may be required to study the behaviour of more general weld cases.

The present work which has used the results of steady state and continuum damage analyses, obtained numerically, has clearly identified the effects of end load on the creep failure behaviour of a number of thick walled pipe welds in main steam pipelines. Failure lives can be significantly reduced when additional axial load is applied. For the pipe welds investigated, the rupture stresses showed very little variation across the HAZ, in the failure dominant regions, for the closed-end loading case. However, the variation is more significant when additional axial loading is applied. In this case, the peak stresses across the HAZ move to a position adjacent to the HAZ/PM boundary. Results obtained for the damage variations across the HAZ, in the same area, demonstrate similar behaviour, i.e. higher damage accumulation occurs at the same interface when significant end (system) load is applied. This suggests that for the welds investigated, excessive axial loading, in addition to the internal pressure, results in a high probability of type IV cracking occurring, which is consistent with laboratory and plant experience.

The results obtained for the CrMoV pipe welds, using the material properties at 640° C, showed that failure life predictions based on steady-state analyses are conservative, compared to the corresponding damage predictions, underestimating the failure life by about 30-40% under closed-end condition and by about 20-30% when $\sigma_{ax}/\sigma_{mhl} \rightarrow 1$. However, the failure positions predicted by steady-state and continuum damage analyses were consistent.
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References