CREEP DEFORMATION OF TYPE 316H AUSTENITIC STAINLESS STEEL AT 550°C AND THE EFFECTS OF ELASTIC FOLLOW-UP

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ABSTRACT

Elastic follow-up occurs in structures when localized regions in a component undergo non-linear deformation while the surrounding global material remains elastic. Often, elastic follow-up is described as belonging to a set of boundary conditions that lie between load and fixed displacement control. This condition is known to exist in many engineering components operating at high temperature.

In this paper conventional creep models are described to illustrate the effects of elastic follow-up, particularly during primary creep of a Type 316H stainless steel operating at 550°C. Experiments to validate the models are explained and compared to the models. The experiments were set up to replicate two bar models subjected to remote fixed displacement. The forces in the experiment were allowed to relax for three different values of elastic follow-up. It is demonstrated that conventional creep stress relaxation (without elastic follow-up) can be described adequately by empirical forward creep equations. However, the predicted response when elastic follow-up is present is highly dependent on whether time or strain hardening behaviour is assumed. A differential strain hardening model, that takes account of prior accumulated strain and the rate of stress relaxation, is shown to provide an improved model.

INTRODUCTION

Robinson [1] introduced the term follow-up elasticity to explain the relaxation of bolted joints due to creep. Elastic follow-up occurs in many engineering components operating at elevated temperature and has therefore been increasingly considered in high temperature structure integrity assessments [2-4]. There have been only limited experiments conducted to investigate elastic follow-up during creep or stress relaxation and at strain concentrations [5-7]. The consequences of elastic follow-up has also been studied for creep-fatigue damage [8] and during crack initiation [9]. Of particular interest is the behaviour of simple two bar structures [10]. This model has been a convenient vehicle to provide a range of solutions for the elastic follow-up factor and permits variables in the system, such as the bar dimensions, working temperature and material properties to be changed.

The typical response of a stainless steel sample subjected to different loading and boundary conditions are shown in Figure 1. This curve is the stress-strain response of Type 316H stainless steel at 550°C. Prior to creep, the sample is loaded and exhibits initial elastic-plastic deformation. Then, depending the loading condition, the material is allowed to creep. When the sample is held at constant stress (i.e. with no spring effect or follow-up) the sample continues to deform. In contrast, when the sample is subjected to a fixed displacement the stress decreases with no further increase in the total strain of the sample. This corresponds to no elastic follow-up, defined as \( Z = 1 \). Between the conditions of constant stress or constant total displacement there are a variety of loading conditions, which can be thought as having an elastic spring in series with the creeping sample. The relative stiffness between the spring and the creeping
sample dictate the values of $Z$ [3, 10] and the trajectory of the stress-strain path in Figure 1 depends on the value of $Z$ [11].

![Figure 1: The stress-strain trajectories for loading up associated with forward creep ($Z \to \infty$), elastic follow-up ($1 < Z < \infty$) and stress relaxation ($Z = 1$) [11].](image)

In estimating the effects of elastic follow-up many models use empirical creep models, such as power law creep [6] and the RCC-MR [11] creep laws. These models are often created using data obtained from constant stress and constant load tests. For example, Wang et al. [11] used a conventional RCC-MR model to predict the influence of elastic follow-up on creep in a stainless steel, but these predictions had a number of limitations. In this paper this earlier work is extended and we first summarise a series of constant load creep experiments that are used to determine RCC-MR material constants for a Type 316H stainless steel tests at 550°C. This is followed by explaining a series of stress relaxation tests with and without elastic follow-up.

The RCC-MR equations, [12], assume that the creep curve is described by

$$e_c = e_{pc} + e_{sc} = e_{pc} + \dot{e}_{sc}(t-t_p)$$  \hspace{1cm} (1)

where $e_c$, $e_{pc}$ and $e_{sc}$ are total creep strain at time $t$, and corresponding primary creep strain and secondary creep strain respectively; $t$ and $t_p$ are the total and primary creep times in hours; and $\dot{e}_{sc}$ is the secondary stage creep strain rate. The equations for creep strain, according to [2], are

$$e_{pc} = C_1 t^C \sigma^n, \text{ For } 425°C \leq \theta \leq 700°C \text{ and } t \leq t_p$$  \hspace{1cm} (2)

$$e_c = C_1 t_p^C \sigma^n + C_2 \sigma^n(t-t_p), \text{ For } 480°C \leq \theta \leq 700°C \text{ and } t > t_p$$  \hspace{1cm} (3)

where $\sigma$ is the applied stress in MPa at time $t$ and $C$, $C_1$, $C_2$, $n$ and $n_1$ are the material constants, which are functions of temperature $T$. We assume conditions for constant temperature...
(550°C) and under conditions of constant stress, the time at the end of primary creep, \( t_p \), is determined as

\[ t_p = C_3 \sigma^{n_3} \]  

(4)

where

\[ C_3 = \frac{1}{(C_2 - 1)} \]  

(5)

and

\[ n_3 = \frac{n - n_1}{C_2 - 1} \]  

(6)

The transition from primary to secondary creep is given by the condition

\[ \dot{\varepsilon}_{pc} \leq \dot{\varepsilon}_{sc} \]  

(7)

where \( \dot{\varepsilon}_{pc} \) is the strain rate during primary creep.

In this paper these equations are used to predict the material behaviour during stress relaxation with elastic follow-up. As well as constant stress tests a variety of stress relaxation tests with elastic follow-up were conducted. All the experiments are explained in section 2 together with an evaluation of the creep constants. Predictions of creep stress relaxation including the effects of elastic follow-up are given in section 3. Concluding comments are made in section 4.

**MATERIAL, EXPERIMENTS AND RESULTS**

The main aim of constant load creep tests was to generate parameters for an empirical creep model, particularly the RCC-MR model. These empirical creep models were applied to estimate the material behaviour during creep stress relaxation with different levels of elastic follow-up.

**Material**

The material was an ex-service laboratory aged (EXLA) material, supplied by EDF-Energy. The 316H stainless steel was from header HYA 2D1/2 (cast 69431), that had been in-service for about 65,000 hours in the temperature range of 763K to 803K. This material was then exposed at 823K for 21,000 hours. The chemical composition of the ex-service laboratory aged material is given in Table 1.

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>Co</th>
<th>B</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06</td>
<td>0.4</td>
<td>1.98</td>
<td>0.021</td>
<td>0.014</td>
<td>17.17</td>
<td>2.19</td>
<td>11.83</td>
<td>0.10</td>
<td>0.005</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

**Constant load creep tests**

A series of constant load creep tests were conducted with the applied engineering stresses in the range of 126MPa to 356MPa at 550°C using constant load creep machines. The test specimens were designed to conform to ASTM E8 [14] and BS EN 10291 [15] standards with a diameter of 5.65 mm and gauge lengths of 28.25 or 35 mm. Typical results for the accumulated creep strains are shown in Figure 2 for a range of stresses. Curves of creep strains against time are shown. As shown in Figure 1, all tests exhibited plastic deformation during initial loading prior to creep.
Figure 2: Simulated creep curves using new RCC-MR constants for Type 316H stainless steel in ex-service laboratory aged (EXLA) condition with applied stress from around 120 to 360 MPa at 550°C. RCC-MR primary constants $H$ and $C_1$ described by stress dependent linear functions.

For the RCC-MR equations 1 to 3 it was required to determine three parameters for primary creep and two for secondary creep. First, times for the primary stage for all temperatures and stresses were obtained from experimental creep data. The parameters $C_3$ and $n_1$ in equation 4 were fitted using linear regression. The primary creep strain with respect to time at the same temperature can be, in many cases, be stress dependent. This is given by

$$\varepsilon_{pc} = C_1^p t_p^{C_2} \sigma^{n_1}$$  \hspace{1cm} (8)

The primary constants for the RCC-MR equations were determined through linear regression.

Previous work [13] assumed that the parameters $C_1$, $C_2$ and $n_1$ are only temperature dependent material constants and not stress dependent. To provide an improved fit to experimental data it was assumed that $H (= LnC_1)$ and $C_2$ are linearly dependent on stress, where

$$H \pm \delta H = a\sigma + (b \pm \delta b)$$  \hspace{1cm} (9)

$$C_2 \pm \delta C_2 = c\sigma + (d \pm \delta d)$$  \hspace{1cm} (10)

where $a$, $b$, $c$ and $d$ are material constants. The errors on $H(\delta H)$ and $C_2(\delta C_2)$ were obtained from errors on $b(\delta b)$ and $d(\delta d)$.

For this research we retained the same value for $n_1$, as given by the conventional RCC-MR data [13], and then determined new constants $H$ and $C_2$ for each test. The two linear Equations 9 and 10 were used to fit the constants $a$, $b$, $c$ and $d$, and meant that the values of $H$ and $C_2$ were dependent on the applied stress. In addition, $\pm \delta H$ and $\pm \delta C_2$ were the upper and lower bound values calculated from corresponding upper and lower bound constants $\pm \delta b$ and $\delta d$ respectively. The upper and lower bound curves correspond to $\pm \delta b$ standard deviations on the mean, assuming the slope and values of $a$ and $c$
were constant. Alternatively, we adopt H as an average value and only describe $C_2$ as a stress dependent linear function. Two sets of coefficients, $a, b \pm \delta b, c$ and $d \pm \delta d$ are given in Table 2.

Table 2: RCC-MR creep parameters described using by a linear function with applied stress for the primary components. The creep strain is absolute, stress in MPa, time in hour.

<table>
<thead>
<tr>
<th>Constants</th>
<th>$a$</th>
<th>$b \pm \delta b$</th>
<th>$c$</th>
<th>$d \pm \delta d$</th>
<th>$n_1$</th>
<th>$A$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>-0.0051</td>
<td>-28.838±0.3</td>
<td>0.003</td>
<td>-0.249±0.075</td>
<td>4.18</td>
<td>4.78810^{-27}</td>
<td>9.078</td>
</tr>
<tr>
<td>ii</td>
<td>0</td>
<td>-30.28821</td>
<td>0.0021</td>
<td>-0.0258±0.075</td>
<td>4.18</td>
<td>4.78810^{-27}</td>
<td>9.078</td>
</tr>
</tbody>
</table>

The second part of the RCC-MR equations (i.e equation 3) represents secondary creep. A power law equation was used to describe the secondary creep rate.

$$\dot{\varepsilon}_{sc} = A\varepsilon^n = A'\varepsilon^n \left(-Q/RT\right)$$  \hspace{1cm} (11)

where $R$ is the universal gas constant $8.31\text{J/(mol*K)}$; $Q$ is the activation energy; $T$ is the temperature in $K$. The material constants $A, A', n$ and $Q$ were obtained by using a linear regression. The resulting coefficients for the RCC-MR equations are summarised in Table 2.

Curves of creep strain as a function of time, created by using equations 1 to 3 together with the corresponding experimental constants in equations 5 to 8, are shown in Figure 2 together with experimental results for six constant load creep tests.

**Elastic follow-up tests**

Test machines were designed based around a three bar system, with a specimen, an elastic bar, and a load cell connected in series. This series system was then linked to outer parallel bars. Loading of the system was through a loading screw. By changing the sizes of the elastic elements or the specimen, a range of elastic follow-up factors (about $Z = 1, 5$ and 20) were obtained. Four different specimen sizes were used, with diameters, 4mm, 6mm or 7mm, and lengths 70mm, 150mm or 30m. Two rigs were very rigid and therefore provided a small elastic follow-up factor (about 1) when used with the longer specimen. In a third rig the specimen was connected to an elastic bar to obtain elastic follow-up factors of about 5 and 20 using the longer and shorter specimens respectively.

Nine high temperature tests were conducted and are summarised in Table 3 [11]. Specimens were tested at 550°C with tensile displacement applied by rotating a loading screw. The average strain rate during loading was about 0.004%/s. The extension of the specimen was measured using a pair of linear variable displacement transducers (LVDT) having a displacement resolution of 1μm. The loads were measured using compact load cells, located outside the furnaces and in series with the specimens.

Typical experimental results are shown in Figures 3 and 4. All tests were loaded to about the same initial stress of about 350MPa or 235MPa and then the specimens were allowed to relax with elastic follow-up factors equal to about 1.2, 4.7 and 21 respectively. Figure 3a and 4a show that the stress and strain trajectories for different levels of elastic follow-up during loading up and creep stress relaxation. Then the figures 3b to 3d and 4b to 3d show the corresponding stress relaxation with elastic follow-up factors of 1.2, 4.7 and 21. Irrespective of the level of elastic follow-up there was an initial rapid reduction in the stress. However, this reduction was substantial when $Z \approx 1$ and less so for high values of $Z$. The next section explains the predictions of stress relaxation.
Table 3: Summary of creep stress relaxation and elastic follow-up tests for Type 316 H stainless steel at 550°C [11].

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test Rig</th>
<th>Sample diameter/length (mm)</th>
<th>Initial applied Engineering/true stress (MPa)</th>
<th>Loading up elastic-plastic strain, %</th>
<th>Test duration (h)</th>
<th>Final true stress (MPa)</th>
<th>Designed/measured Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFU 1</td>
<td>3</td>
<td>4.04/70.56</td>
<td>326/357</td>
<td>9.67</td>
<td>860</td>
<td>181</td>
<td>1.2/1.4</td>
</tr>
<tr>
<td>EFU 2</td>
<td>3</td>
<td>6.07/70.76</td>
<td>328.5/349</td>
<td>6.19</td>
<td>703</td>
<td>222.5</td>
<td>4.5/4.6</td>
</tr>
<tr>
<td>EFU 3</td>
<td>1</td>
<td>7.01/31.2</td>
<td>329/351</td>
<td>6.6</td>
<td>1030</td>
<td>254</td>
<td>20/22</td>
</tr>
<tr>
<td>EFU 4</td>
<td>2</td>
<td>6.05/150.7</td>
<td>249/256</td>
<td>2.69</td>
<td>1132</td>
<td>148</td>
<td>1.2/1.2</td>
</tr>
<tr>
<td>EFU 5</td>
<td>2</td>
<td>6.03/150.9</td>
<td>255.5/264</td>
<td>3.42</td>
<td>17</td>
<td>215.5</td>
<td>1.2/1.2</td>
</tr>
<tr>
<td>EFU 6</td>
<td>1</td>
<td>7.01/31.2</td>
<td>248/254</td>
<td>2.38</td>
<td>2092</td>
<td>213</td>
<td>20/21</td>
</tr>
<tr>
<td>EFU 7</td>
<td>2</td>
<td>6.06/151.1</td>
<td>231/235</td>
<td>1.86</td>
<td>2613</td>
<td>125</td>
<td>1.2/1.8</td>
</tr>
<tr>
<td>EFU 8</td>
<td>1</td>
<td>6.01/151.4</td>
<td>230.5/233</td>
<td>1.14</td>
<td>1795</td>
<td>162.8</td>
<td>4.5/4.7</td>
</tr>
<tr>
<td>EFU 9</td>
<td>1</td>
<td>7.07/30.4</td>
<td>230.5/233</td>
<td>0.934</td>
<td>1918</td>
<td>192.5</td>
<td>20/21</td>
</tr>
</tbody>
</table>

Figure 3: Experimental data and predictions using RCC-MR based stress relaxation models for Type 316H stainless steel in the ex-service laboratory aged (EXLA) condition, (a) stress and strain trajectories during loading up and stress relaxation, (b) stress relaxation experimental data and predictions for Z=1.2, (c) stress relaxation experimental data and predictions for Z=4.7, (d) stress relaxation experimental data and predictions for Z=21.
Figure 4: Experimental data and predictions using RCC-MR based stress relaxation models for Type 316H stainless steel in the ex-service laboratory aged (EXLA) condition, (a) stress and strain trajectories during loading up and stress relaxation, (b) stress relaxation experimental data and predictions for $Z=1.2$, (c) stress relaxation experimental data and predictions for $Z=4.7$, (d) stress relaxation experimental data and predictions for $Z=21$ [11].

PREDICTIONS OF STRESS RELAXATION WITH AND WITHOUT ELASTIC FOLLOW-UP

In a stress relaxation test, the total strain state in a specimen after initial loading is given by

$$\varepsilon_e + \varepsilon_p + \varepsilon_c = \delta$$

(12)

where $\varepsilon_e$, $\varepsilon_p$, $\varepsilon_c$ and $\delta$ are elastic strain, plastic strain, creep strain and total strain respectively. The initial plastic deformation and total strain are constant during stress relaxation and therefore

$$\dot{\varepsilon}_e + \dot{\varepsilon}_c = 0$$

(13)

where $\dot{\varepsilon}_e$ and $\dot{\varepsilon}_c$ are elastic strain rate $\dot{\varepsilon}_e = -\sigma/E$ and creep strain rate in the specimen. The stress relaxation rate is given by

$$\dot{\sigma} = -\frac{1}{Z}\tilde{E}\dot{\varepsilon}_c$$

(14)
\[ \dot{\varepsilon}_c = (1-Z) \dot{\sigma}/E_i \]  

(15)

where \( Z \) is the elastic follow-up factor and \( \dot{\varepsilon}_c \) is the creep strain rate can be described by any creep equation. When \( Z > 1 \) the presence of elastic follow-up results in a slower stress relaxation rate and additional strain accumulation in a specimen.

Conventional time (TH) and strain hardening (SH) solutions for the rates of stress relaxation, and not taking into account the rates of change of stress in the creep equations, are given by

\[
d\sigma/dt = -\frac{1}{Z} E C_i C_z t_p^{C_z-1} \sigma_{n_i} 
\]

(16)  

\[
d\sigma/dt = -\frac{1}{Z} (E C_i)^{1/C_z} C_z \left[\sigma_0 - \sigma\right]^{(C_z-1)/C_z} \sigma_{n_i/C_z} \n
\]

(17)  

where \( \sigma_0 \) is initial applied stress in MPa. Assuming a primary creep law given by equation 2 and assuming that the sample is subjected to variable stresses a differential strain hardening (DSH) analysis for the creep rate is given by

\[
\dot{\varepsilon}_c = C_2 C_1^{1/C_z} \sigma_{C_z}^{C_z-1} + n_i \dot{\varepsilon}_c \frac{1}{\sigma} \n
\]

(18)

The creep strain at any time is given by

\[
\varepsilon_c = Z \frac{\sigma_0 - \sigma}{E} \n
\]

(19)

Substituting equation 19 into equation 18 and solving for the rate of stress relaxation gives

\[
d\sigma/dt = -\frac{1}{Z} (E C_i)^{1/C_z} C_z \left[\sigma_0 - \sigma\right]^{(C_z-1)/C_z} \sigma_{n_i/C_z} / \left[1 + n_i Z (\sigma_0 - \sigma) / \sigma\right] \n
\]

(20)  

Equations 20 reveals that the strain accumulation in a specimen due to elastic follow-up has a direct influence on the rate of creep stress relaxation.

Based on equation 4, the time for the primary stage, \( t_p \), during stress relaxation increases as the stress decreases. Hence, the time for the primary stage for stress relaxation is essentially infinite. This means that only the primary part of the RCC-MR equations is used to predict stress relaxation.

Predictions of elastic follow-up were made using equations 16, 17 and 20 together with the fitted material constants (ii) given in Table 2. The equations were solved using Matlab ode45 [16]. An example of predictions for elastic follow-up tests EFU 1 to 3 and 7 to 9 are shown in Figures 3 and 4. The differential strain hardening (DSH) stress equation always predicted the slowest stress relaxation.

Predictions for all tests are also illustrated in Figure 5. In each figure, the predicted relaxed stress is compared with the observed relaxed stress. The data points were derived with durations of 0.01, 0.1, 1, 10, 100, 500, 1000, 1500, 2000 and 2500 hours. When the prediction agrees perfectly with the observed stress, data would be expected to lie along a 45° line. Parallel lines
either side of the 45° represent the bounds on the predictions with positive and negative values representing an overestimate and an underestimate of predicted stress relaxation. It is important to note that an underestimate of stress relaxation also indicates that more creep strain is accumulated during stress relaxation than would be observed. Figure 5a shows that the time hardening analysis overestimates the level of stress relaxation for all of the tests and durations. Overall, the results show that when using a differential strain hardening model, DSH, the predicted stress relaxation agrees well with the observed relaxation in the long term. The predictions using this model lie between error bounds of about -18 MPa and 70 MPa, but the error narrowed to between -18 MPa and about 35 MPa for longer durations.

![Figure 5: Predicted stress relaxation with and without elastic follow-up for Type 316H stainless steel in the ex-service laboratory aged (EXLA) condition. Models using RCC-MR equations (a) time hardening (TH); (b) strain hardening (SH) model; and (c) differential strain hardening (DSH) model.](image)

**CONCLUSION**

Constants for primary and secondary creep deformation using the RCC-MR creep equations were obtained from constant load creep data for Type 316H stainless steel in the EXLA condition. Equations were derived to predict stress relaxation, with and without elastic follow-up, based on the RCC-MR equations. These models were then used to predict stress relaxation for a variety of initial stresses and elastic follow-up factors and compared with experimental data. Results for conventional time and strain
hardening were compared with a model that took account of the prior creep strain accumulation and rate of stress relaxation. The latter model provided an improved prediction compared to conventional models. The improved predictions illustrate that the creep stress relaxation rate was influenced by the creep strain in the specimen.

ACKNOWLEDGEMENTS

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