Numerical Analysis of Welded Branch Tube Operating in Creep Range

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Research Article

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Abstract

Pressure components used in energy and resources industries may be subjected to various damages including plasticity and creep. Life prediction of such components is an important consideration for engineers who design, build, or operate them. This paper aims to present a comprehensive study to investigate the problem of creep life assessment of a complex welded component containing multiple zones with different material properties unlike almost all of the previously developed methods that have been based on the secondary creep condition alone that cannot be considered as a true representative for the creep behaviour of materials. Thus, the necessary information to estimate the life of a branch tube based on the primary, secondary, and tertiary creep conditions are presented. Results confirm the experimental data from the literature producing the most conservative life.

1. Introduction

A wide range of materials is used in structures that are designed to operate in high-temperature conditions. The designer’s choice of material is usually dictated by cost and by such factors like its ability to carry the load to resist creep crack growth commonly referred to as type IV cracking [1, 2, 3]. In a time-dependent regime where creep properties control, there is a loss of material strength with time and this loss of strength does occur as a result of creep damage along the grain boundaries of the material which, in its early stages are concealed within the microstructure. In this regard, the development of models for practical yet sufficiently accurate creep life forecasting based on micro-structural modelling becomes even more complicated due to the variation of the material in the base, weld, and heat-affected-zone (HAZ) and variation of the microstructure within HAZ and their interactions [4].

There are several phenomenological models for creep life forecasting, including the reference stress method [5, 6], skeletal stress method [7], the THETA projection concept [8, 9], and continuum damage model [10, 11]. Each of which has its own limitations. In order to improve the present situation, the very complex behaviour of high-temperature weldments has to be further understood. The design codes, in general, do not specifically categorize welds as a significant factor. They are usually considered for by estimating a weld efficiency factor which is used to bench the allowed stress on a homogeneous component, and by stipulating that the ductility of any part of the weld should be adequate for the required use [12].

Based on this evidence, this paper describes the techniques to a multi-axial creep life forecasting of weldments to recognize the important damage mechanisms, and to determine an appropriate assessment for the damage accumulation. Section 2 presents the CDM constitutive model. Section 3 outlines the finite element model. Results are given in Sect. 4. Finally, a conclusion is given in Sect. 5.

2. Cdm Constitutive Model

The uniaxial creep strain constitutive model in function of time and stress can be expressed as [13]:

$$\epsilon^{cr} = \frac{B\sigma_0^n t_r^{1+m}}{(1+m)\left(\frac{1+\phi-n}{1+\phi}\right)\left(1-(1-\omega_r)^{1+\phi}\right)}\left[1-\left[1-\left(\frac{t}{t_r}\right)^{1+m}\left(1-(1-\omega_r)^{\phi+1}\right)\right]^{\frac{1-n+\phi}{\phi+1}}\right] \quad (1)$$

Therefore, under multiaxial conditions, Eq. (1) is determined in terms of the equivalent stress:

$$\epsilon_{eq}^{cr} = \frac{Bt^m\left(\sigma_{eq}\right)^{n-1}}{(1-\omega(t))^n}, \sigma_{eq} = \left(\frac{3}{2}S_{ij}S_{ij}\right)^{\frac{1}{2}} \quad (2)$$

Consequently, the instantaneous rupture damage $\omega(t)$ represented in a multiaxial state stress is expressed as:

$$\omega(t) = 1-\left[1-\frac{A(1+\phi)t^{1+m}}{1+m}\sigma_{eq}^{\chi}\right]^{\frac{1}{1+\phi}} \quad (3)$$

Respectively, the time-to-rupture under multiaxial conditions is implied by Eq. (4):

$$t_r = \left[\frac{(1+m)}{A(1+\phi)\sigma_{eq}^{\chi}}\left[1-\left(1-\omega_r\right)^{1+\phi}\right]\right]^{\frac{1}{1+m}} \quad (4)$$

At time-to-rupture $\omega_r = 1$. Therefore, Eq. (4) is reduced to:

$$t_r = \left[\frac{(1+m)}{A(1+\phi)\sigma_{eq}^{\chi}}\right]^{\frac{1}{1+m}} \quad (5)$$

In order to correlate the damage under uniaxial tension with the damage under multiaxial stress states, Hayhurst [14, 15] proposed the following mixed criteria for the equivalent stress:

$$\sigma_r = \alpha\sigma_1 + (1-\alpha)\sigma_{eq} \quad (6)$$

3. Finite Element Model And Material Data

A medium bore branch vessel subjected to constant pressure and temperature has been reported to a weld failure after 20,000 hours of operation. Table 1 represents the dimensions of the vessel as reported in Ref. [12].

Table 1
Dimensions of the vessel

R_o (mm)	R_i(mm)	r_o(mm)	r_i(mm)
232.5	212.5	63.5	55.5

The Parent Material (PM) was made of $0.5\% Cr$, $0.5\% Mo$, $0.25\% V$, and the welding material was $1\mathrm{CrMoV}$. The mechanical tensile properties and the uniaxial creep rupture data are given in Table 2 and Table 3. The HAZ was modeled with a 3 mm thickness bounding the welded design at an angle of 45^0. The vessel was subjected to uniform internal pressure of 4 MPa. An axial load of 12.94 MPa was applied to the top end of the welded tube representing the closed-end cap. Also, the main vessel closed-end limit was modeled with a loading pressure of 20.29 MPa. Due to symmetry, only one-quarter of the vessel was created.

Figure 1 shows the boundary conditions applied to the model. One hundred and seventy-three thousand 3D structural Quad elements are generated using Ansys workbench R17.2. The highly uniform mesh was produced using the sweep method, and mappable faces with a minimum edge sizing of 0.25 mm.

Table 2
Mechanical tensile properties [16]

At 565°C	E MPa	ν	σ_y MPa	$\epsilon_y \times 10^{-4}$	σ_{UTS} MPa	$\epsilon_{UTS} \times 10^{-2}$
0.5%Cr,0.5%Mo,0.25%V	184200	0.3	110	7.1	143	2.5
$1\mathrm{CrMoV}$	163000	0.3	93	6.4	230	6.7

ANSYS Usercreep.F was compiled for the finite element analysis with a FORTRAN subroutine code to link the creep constitutive equations defined by equations (2), (3), (5) and (6) to ANSYS code [17].

Table 3
Uniaxial creep data [18]

	n	B	m	A	ϕ	α	χ
PM- HAZ	4.8971	2.853e-16	-0.203	2.264e-11	5.414	0.6	3.011
WM	4.354	1.94e-15	-0.351	8.325e-13	1.423	0.43	3.955

4. Results And Discussion

Figure 2 shows that at time = 0 hours the von Mises equivalent stress was higher than the yield stress by 30%, which makes from the vessel a good candidate to study the impact of creep on the branch tube deformation. The maximum computed value displays 168 MPa. Also, at t=0 hour the von Mises equivalent stress distribution in the HAZ and the WM at the inner lower surface of the tube had just reached the yield strength indicating plastic deformation in these regions (Figure 3). With the passage of time and due to creep and further plastic deformation, the von Misses equivalent stress distribution (Figure 4) was transferred from the WM to the HAZ causing further plastic and creep deformation in HAZ. This resulted in equivalent stress of 73 MPa at the inside surface of the upper and the lower HAZ, and 68 MPa throughout the weld thickness localized at the outside surface. The corresponding first principal stresses at time-to-rupture are depicted in Figure 5.

Referring to Fig. 5, the computed first principal stresses at the lower mid-wall of the HAZ were higher than those in the weld with a peak value of 91 MPa, indicating that the creep deformation occurs within the HAZ and part of the PM throughout the wall thickness at the crotch side of the main vessel (Fig. 6). The obtained computed results confirm those found experimentally in Ref. [12]. Figure 6 shows the von Mises equivalent localized stress of the branch vessel showing the flank surface and the crotch surface. As might be expected, the stress distribution decreases gradually throughout the wall thickness of the tube until the steady-state stress occurs at the outer surface. After the passage of time, the equivalent stress was transformed from the PM and they were concentrated in the HAZ. The maximum equivalent computed stress displays a value of 74.45 MPa at the crotch. As a consequence, no significant stress redistribution at the flank section is detected due to the follow-up creep deformation and the variation of stresses with time is minimized.

Figure 7 shows the distribution of the hoop and radial stresses for the welded tube. It determines the initial elastic stresses due to creep. It is apparent that the hoop stress at the outer surface of the crotch surface side is governing. This is due to the high negative (compressive) radial stress at the inner surface of the flank side. The distribution of the radial stress varies with an abrupt change occurring across the heat-affected zone due to the differences in the creep characteristics of the different part of the tube (PM, HAZ and WM). Also, the difference in the material properties resulted in this severe stress redistribution from the weld metal into the heat-affected zone and the parent metal corresponds to a severe stress gradient observed in the heat-affected zone. Also, Figure 7 shows the severity of the hoop stress concentration in the HAZ which is growing throughout the wall thickness of the pipe, whereas little stress is conceded by the weld metal.

The maximum equivalent total creep strain occurred at the crotch surface side of the lower HAZ, the variation of which with time is depicted in Fig. 8. Although the solution was set up to 100,000 hours with a small interval of time steps equivalent to 0.25 increments, the code is stopped when the solution starts to diverge at 22,998 hours indicating a severe local collapse due to the difference in the material properties resulted in this severe stress redistribution. Thus, the creep life forecasting of weldment in this paper was evaluated by setting a lower limit and an upper to service life corresponding to 10,000 hours and to 20,000 hours respectively [19]. Hence, the remnant life is calculated by evaluating firstly the rupture stress using the upper limit rupture lives. The obtained results show that the rupture stress for the PM is computed to be as 88.2 MPa, whereas the HAZ and the WM exhibits a stress-to-rupture of 83.8 MPa and 74.16 MPa respectively. Consequently, the time-to-rupture for the PM is calculated to be 16,633 hours, follow as the time-to-rupture for the HAZ and the WM are calculated to be 11,875 hours and 12,887 hours respectively. Notably, these results confirm those determined experimentally [12], with 18,101 hours for the PM and 15,958 hours for the HAZ, conceding the life prediction for each zone using different material properties. The obtained computed values indicate that the HAZ is the weakest whereas the PM is the strongest. Regarding the lower limit rupture lives, the damage starts to develop at the inner surface of the HAZ and continues to grow radially towards the outer surface until a steady state of stress distribution occurs. Thus, as suggested in Ref. [19], life calculation based on a steady-state failure criterion is valid were stress distribution is less significant. As a result, the time-to-rupture for the PM is calculated as 8,317 hours, and appropriately the time-to-rupture for the HAZ and the WM are calculated to be 5,938 hours and 6,444 hours respectively. The obtained results confirm those estimated in Ref. [12].

5. Concluding Remarks

This paper verifies the use of the CDM for predicting lives of branch components with different zones and material properties to complex elastic-creep damage under multi-axial stress/strain fields. It is shown that the CDM described in Sect. 2 can conservatively predict the lives of the branch components. Note that the pertinent material data for creep analysis are usually obtained from complex high-temperature testing. As a result, the pertinent material data and experimentally determined lives may be contaminated with scattering. It is obvious that any uncertainties in the pertinent material properties, loading, and geometry dimensions of the component can substantially increase the error in the predicted lives of the components. For example, the geometry of the HAZ of the vessel considered in this paper was assumed to have the same material properties as the PM. Also, the geometry of the HAZ is assumed to have a 3 mm thickness. Therefore, depending on the uncertainties in the required data for a life prediction, one needs to apply the appropriate factor of safety to computed life. Although the results have been presented for a particular geometry for the HAZ for branch tube with material properties that might not correspond to the real situation, it is feasible to conclude that CDM can accurately predict the area under the tertiary creep localized through the wall thickness at the crotch surface side of the main vessel, indicating an off-loading of stress from the WM to the HAZ, and by postulating that the welded pipe is subject to a hoop stress governance. This analysis is relevant as it confirms with the steady-state analysis determined experimentally.

Nomenclature

Nomenclature

σ_0	:	Applied stress
σ_r	:	Rupture stress
σ_1	:	First principal stress
σ_y	:	Yielding stress
σ_{eq}	:	Equivalent stress
ε_{eq}^{cr}	:	Equivalent Strain
ε^{cr}	:	Creep strain
$\dot{\varepsilon}^{cr}$	:	Creep strain rate
$\omega_r/\omega(t)$	:	Rupture damage parameter/instantaneous damage parameter
E	:	Modulus of Elasticity
m	:	Strain Hardening exponent
t	:	Time
t_r	:	Time-to-rupture
n	:	Creep stress exponent
B	:	Creep Stress Coefficient
α	:	Material properties that depends on temperature
A, χ, φ	:	Damage material properties
S_{ij}	:	Deviatoric stress
CDM	:	Continuum Damage Mechanics
PM	:	Parent Material
HAZ	:	Heat Affected Zone
WM	:	Weld Material

Declarations

Conflict of interest statement

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest, or non-financial interest in the subject matter or materials discussed in this manuscript.

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