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Application of ductility exhaustion based damage model to predict creep rupture time of grade 92 steel

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Abstract. To accurately predict the creep rupture time of notched bar becomes a challenge to academia and structural engineer due to complex stress-strain distribution around the notch throat. This paper presents a Finite Element (FE) simulation employing ductility exhaustion based damage model to predict creep rupture time of multiaxial notched bar Grade 92 steel. Three different notch acuity, $\eta = 2.5, 5.0$ and 12.0 were simulated and the FE predicted rupture time was compared to the available experimental rupture data. The reduction of creep ductility due to geometrical constraint is considered during the simulation by employing the void growth model. Further reduction in ductility in long term period arises from internal microstructural changes or damage is also accounted. Furthermore, empirical-type exponential prediction model coupled with skeletal stresses is applied to provide upper/lower bounds for short and long term rupture data. It is found that the FE prediction agreed well with the experimental data. At short-term, notched bar ruptured is controlled by the von-Mises stress while at long-term the rupture is controlled by the maximum principal stress.

1. Introduction

Grade 92 steel is widely used for a high-temperature application such as header and superheated pipes. After a certain period in service, damage in term of isolated creep voids have been observed mostly along the prior austenite grain boundaries (PAGB) and sub-grain [1]. Over the time, these microvoids joining up and then becoming oriented voids or microcracks. Regular inspection is necessary to monitor the progress of the damage. The remaining life of the damaged component can be estimated using two main predictive models namely time-based (life fracture rule [2]) and strain-based models. Mathematically, the models can be expressed as follows:

$$\omega = \sum \frac{t_n}{t_{rn}} \quad (1)$$

$$\omega = \int_0^t \frac{\dot{\epsilon}_c}{\dot{\epsilon}_f} dt \quad (2)$$

where t_n and t_{rn} is the in-service duration and time to rupture, respectively. The time to rupture can be easily calculated for a uniaxial sample since the stress distribution along the gauge length is uniform and approximately equal to the remote stress. However, choosing the right stress to perform the prediction is paramount important for notched bar sample as the stress and creep strain distribution at



the notched area is non-uniform and rather complex. The application of Eqn. (1) to the case of complex stress state such as in notched bar leads to underestimate result. The $\dot{\epsilon}_c$ and ϵ_f^* in Eqn. (2) are the equivalent creep strain and multiaxial ductility, respectively. Damage predicted using the strain-based model in Eqn. (2) is based on the ductility exhaustion concept whereby the failure is assumed to occur when the accumulated creep strain reaches the critical value. For the case of notched bar, the local damage, ω is usually calculated numerically by incorporating Eqn. (2) into Finite Element (FE) analysis. Applying the model in Eqn. (2), however, requires careful determination of material ductility or failure strain because the overall prediction result is greatly depending on this value.

This study attempts to predict the creep rupture time of notched bar of Grade 92 steel using finite element analysis employing ductility exhaustion based damage model. The effect of geometrical constraint due to notch and local constraint on ductility is accounted. Furthermore, the upper/lower bounds of the data which covers both short and long term rupture data are estimated.

2. Methodology

2.1. Finite Element Analysis

The FE modelling is carried out using commercial FE Abaqus software v6.13, employing the elastic-plastic-creep material properties. The elastic deformation is modelled according to the Hooke's law while the plastic deformation is assumed to obey the power law relation with isotropic strain hardening behaviour. The total strain is given as:

$$\epsilon_T = \epsilon_e + \epsilon_p + \epsilon_c \quad (3)$$

The creep strain rate, $\dot{\epsilon}_c$ is modelled to follow the Norton power law and can be expressed as:

$$\dot{\epsilon}_c = A\sigma^n \quad (4)$$

Notched bar specimens having an acuity level (defined as net diameter/notch radius) of 2.5, 5.0 and 12.0 are modelled. The notched bar diameter, D and the net diameter, d is 5 mm and 3 mm, respectively. The modelling accounts the geometric and loading symmetric conditions, therefore, only a quarter of the specimen gauge length is analyzed as an axis-symmetric model. An appropriate boundary condition is applied including the prescribed pressure, P on the top surface as shown in Figure 1.

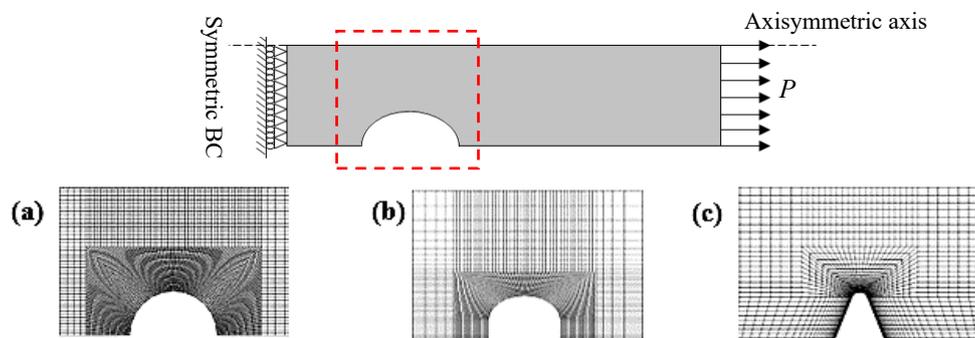


Figure 1. Details FE model with mesh: (a) acuity = 2.5, (b) acuity = 5.0 and (c) acuity = 12.

The model is meshed with continuum axis-symmetric quadrilateral elements with reduced integration scheme. The model consists of 11255-12472 nodes and 11025-12200 elements depending on the notch geometry. The details of FE mesh design at the notched throat area is shown in Figure 1. The failure strain value of Grade 92 steel is observed dependent on strain rate [3]. The best fit line of the available creep failure strain data is drawn according to Fermi' function [4] and is adopted in Abaqus through CREEP user subroutine. It should be noted that the lower plateau limit of failure

strain is assumed to be 10% of its maximum value since the long-term data up to this point is currently not available. Further reduction of failure strain due to the notch constraint is estimated using Eqn. (5).

$$\frac{\varepsilon_f^*}{\varepsilon_f} = \sinh \left[\frac{2}{3} \left(\frac{n-0.5}{n+0.5} \right) \right] / \sinh \left[2 \left(\frac{n-0.5}{n+0.5} \right) \frac{\sigma_m}{\sigma_e} \right] \quad (5)$$

Damage of the material is simulated using the ductility exhaustion based damage approach as described in Eqn. (2). The element is said to failure when the damage parameter, ω approaches unity at the gauss point. At failure point, the load-carrying capacity of the element is reduced to the value near zero. It is done by reducing the elastic modulus, E to 1.0% of its undamaged value. The progressive creep damage technique described above is implemented in Abaqus using the USDFLD subroutine. Table 1 shows the statics and creep properties of Grade 92 steel used in FE analysis.

Table 1. Statics and creep properties of Grade 92 steel at 600°C.

E (GPa)	K (MPa)	N	A_s (MPa ⁻ⁿ /h)	A_L (MPa ⁻ⁿ /h)	n_s	n_L
134	500.8	0.1	2.9×10^{-41}	8.7×10^{-26}	16.4	9.28

3. Estimating Upper/Lower Bounds of Notched Bar Rupture Data

The time to rupture against applied stress for Grade 92 steel under uniaxial stress state can be expressed as exponential relation:

$$t_r = F \exp^{-G\sigma} \quad (6)$$

where F and G are temperature-dependent material constant. The equation will be used as a basis in developing the model for predicting the rupture life of notched bar. The representative stress concept has been proposed [5] which is expressed in term of von-Mises, σ_{vm} and Maximum Principal Stress (MPS), σ_1 to estimate the rupture life of notched bar sample.

$$\sigma_{rep} = \alpha \sigma_1 + (1-\alpha) \sigma_{vm} \quad (7)$$

The rupture life of notched bar specimen, t_r can be rationalised by replacing the uniaxial stress, σ in Eqn. (6) by the representative stress, σ_{rep} given in the Eqn. (7).

$$t_r = F \exp^{-G[\alpha \sigma_1 + (1-\alpha) \sigma_{vm}]} \quad (8)$$

For the case where the rupture time is fully controlled by von-Mises stress ($\alpha=0$), Eqn. (8) can be reduced to:

$$t_r = F \exp^{-G[\sigma_{vm}]} \quad (9)$$

While, when the MPS takes over ($\alpha=1$), Eqn. (8) can be written as follows:

$$t_r = F \exp^{-G[\sigma_1]} \quad (10)$$

where, α is the rupture-controlled parameter. To apply the rupture life relation in Eqn. (8) to (10), the skeletal von-Mises and MPS is employed. The skeletal stress of various notch acuties can be calculated using the normalized stress factor recommended in the code of practice document [5]. Furthermore, the rupture data of Grade 92 steel at 600°C (approximately 38 data points) was collected from various sources and the best fit line was drawn to determine the constant F and G . Noted that the value of F and G in Eqn. (9) - (10) are 4.94×10^8 and 0.074, respectively.

4. Results and Discussion

Figure 2 compares the experimental data [1] with the simulation result for all cases. The over- and underestimate life curve with a factor of +/- 2 is also drawn to observe the variation of predicted result. Clearly, all the predicted rupture time falls within the factor of 2. It suggests the appropriateness of the employed techniques in predicting the rupture time.

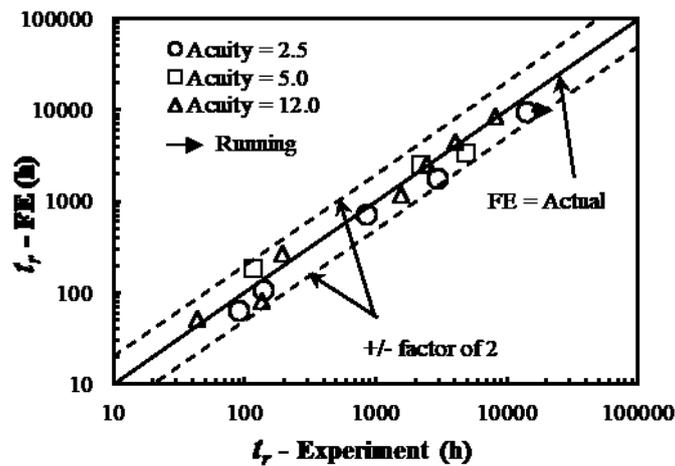
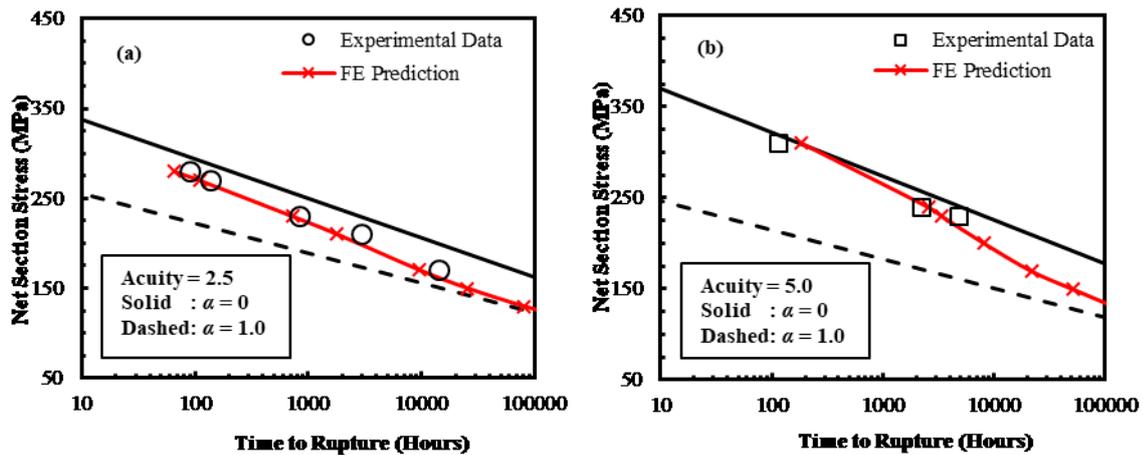


Figure 2. Comparison of rupture life between FE prediction and experimental data.



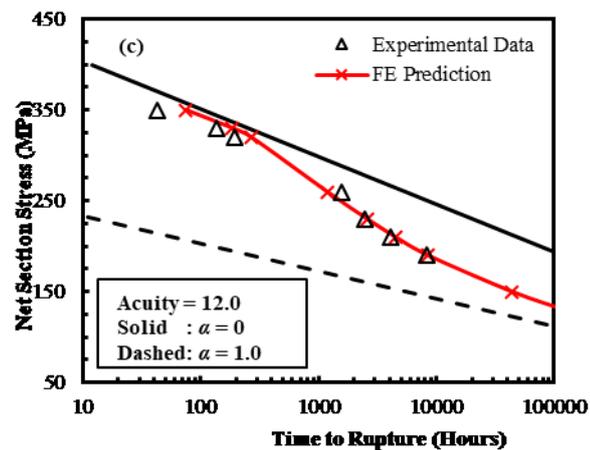


Figure 3. Creep rupture behaviour at short- to long-term time: (a) acuity = 2.5, (b) acuity = 5.0 and (c) acuity = 12.

Figure 3 compares the numerical prediction with experimental data [1] for notch acuity of 2.5, 5.0 and 12.0. Excellent prediction is shown using the employed technique for the acuity of 2.5 and 5.0. An exception for the acuity of 12.0, where the prediction is slightly overestimates the life at the high stress regime. However, it is clear that the approach employed is capable to capture a transition from von-Mises controlled at high stress to MPS-controlled at lower stress as shown in Figure 3(c). In fact, the prediction seems to agree with experimental data at a longer time. Also shown in Figure 3 is the upper/lower life curve calculated using Eqn. (9) and (10) with $\alpha = 0$ and $\alpha = 1.0$. Clearly, all the experimental data and FE prediction fall within these two extreme lines indicating the rupture is influenced by both von-Mises and MPS. It should be noted that few data for the acuity of 12.0 initially fall outside of the predicted upper/lower bounds. As all the data theoretically should be within the two lines, the F and G values used to construct the bound lines for acuity 12.0 is determined based on the upperbound of the uniaxial rupture data.

At higher stress, the creep rupture is controlled by a fixed bias between von-Mises and MPS ($0 < \alpha < 1$). As time increases, the FE results shift continuously from von-Mises to MPS controlled. The transition from von-Mises to MPS controlled rupture is only can be seen at 10 000, 3 000 and 1 000 hours for acuity 2.5, 5.0 and 12.0, respectively. Shorter transition time is observed as the notched acuity increases. It justifies that the presence of a notch promotes faster drop in creep strength and consequently shorten the time to rupture [5]. It is clearly shown that at high stress, the specimen with a sharp notch has a longer life compared to the specimen with blunt notch. However, as the stress decreases, the predicted time to rupture of blunt notch appears to be higher than other notches. The phenomenon indicates that Grade 92 steel exhibits considerable notch strengthening effect at high stress but at low stress the notch weakening effect takes place.

5. Conclusion

Numerical simulation based FE has been performed to predict the time to rupture of the notched bar with different acuity ratio. The ductility exhaustion based damage model is employed. The reduction in ductility due to the notch constraint and internal local damage is accounted during the simulation. A good agreement between simulation result and experimental data is obtained which indicates the technique and the model employed is robust and capable to predict the rupture life for different constraint levels. It is predicted that at high stress, the rupture life is controlled by the von-Mises stress while at low stress, a transition from von-Mises to MPS-controlled rupture life is clearly observed. Even though the prediction result shows excellent agreement with the experimental data, however, the study is limited to only three different notch acuity. The limitation is due to the unavailability of rupture data at long-term time of other notch geometries or acuity. When the data becomes available,

further validation of the simulation technique particularly on its capability to predict long-term behaviour should be made. In fact, the data which covers a wider range of acuity from blunt to the extreme crack-like notch must be analyzed.

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