On the Reliability Assessment of Creep Life for Grade 91 Steel

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Abstract

Reliability assessment of the long-term creep life of Grade 91 steel has been performed on a large body of creep-rupture data obtained from literature as well as from the in-house creep tests performed at IGCAR and KAERI. A “Service Condition-creep Rupture property Interference” (SCRI) model based on Z-parameter was used to simultaneously account for scatter in the creep-rupture data as well as for the fluctuations in service conditions. The magnitude of the deviation of the creep-rupture data from the master curve was obtained using optimized material constant in the Larson–Miller parameter. A probabilistic and statistical analysis on the creep-rupture data was performed. For SCRI model, a large number of random variables for $Z_S$ describing fluctuations in the service conditions and $Z_C$ defining the dispersion in the creep-rupture data were generated using Monte-Carlo simulation. It has been observed that the increased size of creep-rupture data affects the reliability of creep life. The decrease in reliability due to increased fluctuations in service temperature and stress conditions and duration of creep life has been demonstrated for Grade 91 steel.

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1. Introduction

Grade 91 steel is a favoured high temperature material for steam generator (SG) applications in fossil-fired thermal and nuclear power generating industries. Grade 91 steel developed by the addition of strong carbide/nitride forming elements such as V and Nb along with controlled addition of N [1], offers improved elevated temperatures mechanical properties than the plain 9Cr–1Mo steel [2–5]. Grade 91 steel has been chosen for all the components, i.e., tubes, shell and thick section tube plates of steam generator of sodium cooled Prototype Fast Breeder Reactor (PFBR) presently in an advanced stage of construction at Kalpakkam, India [3–5]. The steel is also a promising candidate structural materials for steam generators, intermediate heat exchangers (IHX), and primary pipes of a sodium-cooled Generation-IV reactors [6]. In order to achieve economical nuclear energy through the sodium
cooled fast reactors (SFRs) route, future SFR systems are being designed for 60 years. French Nuclear Design Code RC-MR [7] used for the design of fast reactors provides creep design curves up to $3 \times 10^5$ h, i.e., ~35 years. In order to design SFRs for 60 years, reliable life prediction and extrapolation techniques become necessary for a safe design life of 60 years.

Different time-temperature parametric (TTP) methods such as Larson–Miller parameter, Manson–Haferd parameter and Orr-Sherby-Dorn parameter are being used frequently for the extrapolation of creep life. These parametric methods, without exception, suffer from the absence of details pertaining to appropriate microstructural degradation and damage due to long-term creep exposures. Wilshire [8] introduced theta-projection method as an extrapolation technique for the prediction of long-term creep curve. Prager [9,10] proposed the MPC-Omega method for the extrapolation of creep life incorporating the concept of continuum damage mechanics. Wilshire [11,12] also proposed a new approach involving normalization of applied stress by ultimate tensile strength (UTS) in a multi-batch creep data for ferritic steels. The various prediction and extrapolation methods described above are deterministic in nature and do not involve fluctuations in operating stress and temperature conditions. In view of this, a probabilistic and statistical approach incorporating the fluctuations in the service conditions becomes necessary for reliable prediction of creep life.

Zhao et al. [13] proposed a “Service Condition-creep Rupture property Interference” (SCRI) model based on Z-parameter to predict the reliability of creep-rupture life of HK40 steel. In the SCRI model, $Z_C$ describes the experimental scatter in the creep-rupture property and $Z_s$ represents the dispersion in creep-rupture data due to fluctuations in the service stress and temperature conditions [13]. It has been shown that, the distribution of $Z$-parameters follows a normal distribution [13,14] and the probability density function of $Z_C$ can be obtained as

$$f(Z_C) = \frac{1}{S_C \sqrt{2\pi}} \exp\left(-\frac{Z_C^2}{2S_C^2}\right),$$  \hspace{1cm} (1)

where $S_C$ is the standard deviation of the creep-rupture data. The $Z_s$ component is used to describe the influence of the fluctuations in the service conditions such as temperature, stress and duration. In the SCRI model, $Z_C$ and $Z_s$ are treated as two independent random variables. The probability density function of the distribution of $Z_s$ is expressed as

$$g(Z_s) = g(T, \Delta T, \sigma, \Delta \sigma, t_s),$$  \hspace{1cm} (2)

where $T$ is the service temperature, $\sigma$ is the applied stress, $t_s$ is the service duration, $\Delta T$ is the service temperature fluctuation and $\Delta \sigma$ is the applied stress fluctuation. From the interference between $Z_s$ and $Z_C$, the failure probability as a fracture state for condition $Z_s > Z_C$ is obtained. From the failure probability corresponding to certain operating conditions and service duration, reliability, $R$ is obtained as

$$R = 1 - F,$$  \hspace{1cm} (3)

where $F$ is the cumulative failure probability and $R$ is the probability without failure for a specific service condition. Following this approach, the reliability of creep life of Grade 91 steel for reasonable size of 690 creep-rupture data has been performed, recently [14]. In the present investigation, reliability analysis has been performed on the base metal of Grade 91 steel with significantly increased size of 1072 creep-rupture data consisting of large number of long-term creep test results with global collection. The reliability of predicted creep lives for different amount of fluctuations in the operating temperature and stress conditions for durations in the range $10^4$-$10^5$ h has been presented. Using the available results, the influence of the data size affecting the reliability of creep life has been shown for the steel.

2. Creep-Rupture Data and Master Creep-Rupture Curve

In order to assess the reliability of creep life of Grade 91 steel, large body of creep-rupture data were gathered for temperature intervals of 50 °C in the temperature range 500-700 °C comprising of 1072 data points.
Creep-rupture data were obtained from different sources from Japan [15-18], Europe [20-23], USA [2], Korea Atomic Energy Research Institute (KAERI), Daejeon and Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, India (Fig. 1). In the collection of creep data, care has been taken about their reliability in terms of the chemical composition and the heat treatments conforming to ASTM standards [1]. Creep-rupture data were analyzed using Larson–Miller parameter (LMP) [24], the most commonly used parametric approach for life extrapolation as

\[ P = T \left( C + \log t_r \right), \]  

(4)

where \( T \) is the absolute temperature in Kelvin, \( t_r \) is the rupture time, \( C \) is a material constant and \( P \) is a stress functional parameter. Creep data were fitted with 3rd degree polynomial non-linear regression analysis for the plots of Larson–Miller parameter, \( P \) vs. \( \log(\text{stress}) \) using \( \log(\text{stress}) \) as a polynomial function. Detailed investigation on the applicability of various time-temperature parametric approaches for long-term creep life prediction using different order polynomials indicated that the use of 3rd order polynomial is appropriate [25]. The optimum material constant, \( C = 35 \) in the LMP was obtained displaying the highest value of \( R^2 \) for the steel. The high ‘C’ value obtained in the present investigation is in agreement with those reported for Grades 91, 92 and 122 steels [26,27]. The best polynomial fit in terms of a master creep-rupture curve representing creep-rupture data of Grade 91 steel was obtained as

\[ P = 48.9560 - 14.4976\sigma + 8.0235\sigma^2 - 2.1451\sigma^3. \]  

(5)

3. Reliability Analysis in the Framework of SCRI Approach

3.1 Statistical Distribution of Z-Parameter and Generation of Random Variables by Monte-Carlo Simulation

The scatter in the experimental creep-rupture data is conveniently defined as the Z-parameter [13] describing the magnitude of data deviation from the obtained master curve as

\[ Z_i = P_{i,\text{exp}} - P_{i,\text{mean}}, \]  

(6)

where \( Z_i \) corresponds to the deviation of experimental value \( P_{i,\text{exp}} \) from the mean value \( P_{i,\text{mean}} \) for \( i^{th} \) data \((T_i, \sigma_i, t_i)\). The values of \( P_{i,\text{mean}} \) are obtained from the master creep-rupture relation represented by eq. (5) and \( P_{i,\text{exp}} \) values are evaluated using \( C = 35 \) in Larson-Miller parameter given in eq. (4). The distribution of the Z-parameter representing the dispersion in creep-rupture data displays normal bell type distribution as shown in Fig. 2. The normal distribution of Z-parameter defining scatter in creep-rupture property is confirmed by the normal probability plot displaying good linearity. For the normal distribution, the mean value, \( \mu = -2.6396 \times 10^{-5} \) and standard deviation, \( \Sigma_{Cr} = 0.31078 \) are obtained for Grade 91 steel.

Following normal distribution of Z-parameter (Fig. 2), the probability density function for \( Z_{Cr} \) representing scatter in the experimental creep-rupture data is evaluated using eq. (1). The evaluation of the distribution of \( Z_S \) arising from the fluctuations in service condition becomes difficult using analytical method due to the fluctuations in both the operating temperature and stress. In view of this, the Monte-Carlo simulation technique is used to evaluate reliability in the SCRI model [13]. Large numbers of random variables are generated using Monte-Carlo simulation from the normal distribution of the Z-parameter. For a set of service conditions \((T_i, r_i, t_{ri})\), the values of \( Z_S \) are calculated using eq. (6). The values of \( Z_{Cr} \) are also generated randomly in a normal distribution or computed using eq. (1). The condition \( Z_S < Z_{Cr} \) defines the safe state of the material, whereas \( Z_S > Z_{Cr} \) indicates failure under the particular service condition. For total number of simulation \((N)\), the reliability (R) is obtained as

\[ R = \frac{n}{N}, \]  

(7)

where \( n \) is the number of safe states displaying \( Z_S < Z_{Cr} \) in the total number of simulation. In the present study, 30000 random variables were generated for \( Z_S \) and \( Z_{Cr} \) under certain conditions with fluctuations in the service temperatures and stresses, and reliability percentage was evaluated.
3.2 Reliability Analysis for Specific Service Conditions

Temperature and stress are the most important factors affecting the creep life of high temperature materials. Any increase in service temperature and/or stress greatly reduces the residual creep life and the reliability for the specific service duration. Therefore, it is appropriate to establish reliability in terms of specific service duration. In view of this, the variations in reliability due to excursion or fluctuations in the service temperature and stress have been evaluated for durations in the range $10^4$-$10^5$ h. As stated earlier, the deviations in the experimental creep-rupture data from the master curve are obtained using eq. (6) as

$$Z = 48.9560 - 14.4976\sigma + 8.0235\sigma^2 - 2.1451\sigma^3 - T(35 + \log t_r) \times 10^{-3}$$ (8)

The probability density function (pdf) is obtained for the mean value, $\mu = -2.6396 \times 10^{-5}$ and standard deviation, $S_{Cr} = 0.31078$. In order to account for the influence of fluctuations in the operating conditions, a service temperature, $T = 550 \, ^\circ\text{C}$ and constant stress, $\sigma = 150 \, \text{MPa}$ are conveniently chosen to assess reliability up to $10^5$ h. Following the procedure for Monte-Carlo simulation described in Section 3.1, reliability assessment has been performed using the chosen service conditions with different amount of fluctuations in the service temperature and stress. In the following, the variations in reliability due to the fluctuations in temperature and/or stress by the specific amounts are presented as examples.

The relative distribution of Z-parameters, i.e., the distribution of $Z_{Cr}$ due to scatter in creep-rupture property and $Z_S$ due to fluctuations in operating temperature, i.e., $\Delta T = 10 \, ^\circ\text{C}$ for chosen service temperature, $T = 550 \, ^\circ\text{C}$ and constant stress, $\sigma = 150 \, \text{MPa}$ is shown as probability density function (pdf) plots in Fig. 3. The distributions of $Z_{Cr}$ and $Z_S$ evaluated for temperature fluctuation, $\Delta T$ of 30 $^\circ\text{C}$ for service temperature $T = 550 \, ^\circ\text{C}$ and constant stress, $\sigma = 150 \, \text{MPa}$ are presented in Fig. 4. The distributions of $Z_{Cr}$ and $Z_S$ obtained for data set with 690 creep-rupture data points [14] are superimposed in Figs. 3 and 4. Like $Z_{Cr}$, normal distribution obtained for $Z_S$ can be clearly seen in Figs. 3 and 4. Comparative examination of Figs. 3 and 4 indicates a significant increase in the interference area specifying failure and unsafe zone for condition $Z_S > Z_{Cr}$ with increase in the temperature fluctuation from $\Delta T = 10 \, ^\circ\text{C}$ to $\Delta T = 30 \, ^\circ\text{C}$. A similar increase in the interference area indicating increased failure and unsafe zone with increase in the stress fluctuations is observed. The relative distribution of $Z_{Cr}$ for data Set-1 [14] and the present data having 1072 data points is marginally affected. Contrary to this, a shift in $Z_S$ towards right side has been observed for all temperatures and stress fluctuations with increased size of creep-rupture data (e.g., Figs. 3 and 4). This resulted in the larger interference area for conditions $Z_S > Z_{Cr}$ and decreased reliability with increase in data size.

The variations in reliability due to temperature and stress fluctuations for operating temperature, $T = 550 \, ^\circ\text{C}$ and stress, $\sigma = 150 \, \text{MPa}$ for different durations in the range $10^4$-$10^5$ h are presented in Figs. 5 and 6, respectively. A rapid decrease in reliability with increase in the temperature fluctuations in the range $\Delta T = 10 \, ^\circ\text{C}$ to $\Delta T = 30 \, ^\circ\text{C}$ for operating constant stress, $\sigma = 150 \, \text{MPa}$ can be seen (Fig. 5). More pronounced reduction in reliability due to increase in the fluctuations in temperature is obtained at longer durations. Similarly, a systematic decrease in the reliability with increase in the stress fluctuations from $\Delta \sigma = 10 \, \text{MPa}$ to $\Delta \sigma = 30 \, \text{MPa}$ for constant operating temperature, $T = 550 \, ^\circ\text{C}$ with more pronounced decrease at longer durations is evident in Fig. 6. Further, significant decrease in reliability percentage can be seen for large data size with 1072 data points in Figs. 5 and 6. The combined influence of fluctuations in both service stress and temperature on reliability is presented in Fig. 7 for the fluctuations in temperature, $\Delta T = 20 \, ^\circ\text{C}$ and stress, $\Delta \sigma = 20 \, \text{MPa}$ for operating temperature and stress conditions of $T = 550 \, ^\circ\text{C}$ and $\sigma = 150 \, \text{MPa}$, respectively. The percentage reliability obtained for similar temperature and stress fluctuations for data set comprising of 690 creep-rupture data [14] is also superimposed. Larger decrease in reliability is observed (Fig. 7), when there are fluctuations in both temperature and stress together than the condition when there is fluctuation in either temperature or stress alone (Figs. 5 and 6).

A decrease in the reliability percentage for larger data size can also be seen in Fig. 7. The influence of creep-rupture data size is reflected in the comparatively lower value of optimized material constant $C = 35$ in the present investigation with 1072 data points than $C = 38$ reported recently for 690 data points [14]. In addition to this, a noticeable decrease in the value of standard deviation, $S_{Cr} = 0.31078$ from $S_{Cr} = 0.33625$ reported for 690 data points [14] is obtained. A decrease in the value of $C$ with increased data size can arise from the fact that higher
number of long-term creep data has been included in the current investigation. The observed decrease in the standard deviation for larger creep data size clearly suggests that the master curve obtained with $C = 35$ provide improved representation of creep-rupture data than those reported for data set comprising of 690 data points [14]. However, a shift in the distributions of $Z_S$ towards $Z_{Cr}$ leads increased interference area for $Z_S > Z_{Cr}$, and decreased reliability percentage.

4. Conclusions

Reliability assessment of the creep life has been successfully performed in Grade 91 steel using large body of creep-rupture data consisting of 1072 data points in the framework of “Service Condition-creep Rupture property Interference” (SCRI) model based on Z-parameter. For SCRI model, using Monte-Carlo simulation and probabilistic and statistical analyses, the reliability of predicted creep life has been evaluated from the relative distribution of probability density function of Z-parameter, the $Z_S$ describing fluctuations in the service conditions and the $Z_{Cr}$ defining the dispersion in the creep-rupture data. It has been shown that the reliability percentage decreases systematically with increase in service temperature and stress fluctuations and creep life duration. Decreased reliability of creep life has been obtained for larger creep-rupture data size in Grade 91 steel.

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Fig. 1. Stress vs. rupture time plots at 500, 550, 600, 650 and 700 °C consisting of 1972 data points for the base metal of Grade 91 steel.

Fig. 2. Probability density plot for $Z_{C_t}$ showing distribution of Z-parameter for creep-rupture data comprising of 1072 data points in Grade 91 steel.

Fig. 3. Distribution of temperature fluctuation, $\Delta T = 10$ °C on the relative distribution of $Z_S$ and $Z_{C_t}$ showing interference area in the SCRI model for $10^5$ h. The distributions of $Z_{C_t}$ and $Z_S$ obtained for data set with 690 creep-rupture data points [14] are superimposed.

Fig. 4. Distribution of temperature fluctuation, $\Delta T = 30$ °C on the relative distribution of $Z_S$ and $Z_{C_t}$ showing increased interference area in the SCRI model for $10^5$ h. The distributions of $Z_{C_t}$ and $Z_S$ obtained for data set with 690 creep-rupture data points [14] are superimposed.
Fig. 5. Influence of increasing temperature fluctuations ($\Delta T$) in the range 0-30 °C on the reliability of creep life for various durations for operating temperature, $T = 550$ °C and stress, $\sigma = 150$ MPa. The distributions of $Z_{Cr}$ and $Z_S$ obtained for data set with 690 creep-rupture data points [14] are superimposed.

Fig. 6. Influence of increasing stress fluctuations ($\Delta \sigma$) in the range 0-30 MPa on the reliability of creep life for various durations for operating temperature, $T = 550$ °C and stress, $\sigma = 150$ MPa. The distributions of $Z_{Cr}$ and $Z_S$ obtained for data set with 690 creep-rupture data points [14] are superimposed.

Fig. 7. The influence of fluctuations in both the temperature, $\Delta T = 20$ °C and the stress, $\Delta \sigma = 20$ MPa on reliability of creep life predicted for different durations for operating temperature, $T = 550$ °C and stress, $\sigma = 150$ MPa. Reliability percentage obtained using 690 data points [14] for similar temperature and stress fluctuations for various durations are superimposed.