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Creep rupture assessment by a robust creep data interpolation using the Linear Matching Method

Daniele Barbera, Haofeng Chen*

Department of Mechanical & Aerospace Engineering, University of Strathclyde, Glasgow G1 1XJ, UK

A R T I C L E I N F O

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A B S T R A C T

The accurate assessment of creep rupture limit is an important issue for industrial components under combined action of cyclic thermal and mechanical loading. This paper proposes a new creep rupture assessment method under the Linear Matching Method framework, where the creep rupture limit is evaluated through an extended shakedown analysis using the revised yield stress, which is determined by the minimum of the yield stress of the material and the individual creep rupture stress at each integration point. Various numerical strategies have been investigated to calculate these creep rupture stresses associated with given temperatures and allowable creep rupture time. Three distinct methods: a) linear interpolation method, b) logarithm based polynomial relationship and c) the Larson–Miller parameter, are introduced to interpolate and extrapolate an accurate creep rupture stress, on the basis of discrete experimental creep rupture data. Comparisons between these methods are carried out to determine the most appropriate approach leading to the accurate solution to the creep rupture stresses for the creep rupture analysis. Two numerical examples including a classical holed plate problem and a two-pipe structure are provided to verify the applicability and efficiency of this new approach. Detailed step-by-step analyses are also performed to further confirm the accuracy of the obtained creep rupture limits, and to investigate the interaction between the different failure mechanisms. All the results demonstrate that the proposed approach is capable of providing accurate but conservative solutions.

1. Introduction

In engineering a great number of structures are subjected to the action of combined loads, especially mechanical and thermal loading. In particular fields of engineering like aerospace and nuclear among many others, creep is a remarkable phenomena. Creep rupture is identified during uni-axial testing, and is observed as a rapid strain increase in a short time period. The source of creep damage is related to the growth and coalescence of voids in the material microstructure. The assessment of this degenerative process is necessary to establish in which location and how the component will fail.

Various of creep damage models have been proposed, such as the Kachanov–Rabotnov model (Kachanov, 1999; Rabotnov, 1969), or others (Chaboche, 1984; Dyson, 2000; Hyde et al., 1996; Liu and Murakami, 1998). Approaches like these relying on detailed creep strains are able to simulate the entire damage process during creep analysis, but require numerous creep constants in the constitutive equation, which are not always available. Furthermore, the applied load is typically monotonic in these creep analyses, and greater effort is necessary when simulating a cyclic loading condition. For industrial applications, usually it is important to employ methods based upon the creep rupture data (Ainsworth, 2003) which are able to simulate a precise phenomenon with fewer constants as possible, and efficiently consider practical cyclic thermal and mechanical loading conditions.

For this consideration the Linear Matching Method (LMM) introduced an approach to simulate the creep rupture effect by extending the shakedown analysis method (Chen et al., 2003, 2006). This approach evaluates the creep rupture limit using an extended shakedown method by the introduction of a revised yield stress, which is calculated comparing the material yield stress with a creep rupture stress obtained by an analytical formulation. The assessment of creep rupture limit in this way does not need to explicitly calculate the creep strain during the component lifetime, thus avoiding difficulties from using detailed creep constitutive equation. The advantages of this approach on the basis of creep

* Corresponding author. Tel.: +44 1415482036.
E-mail addresses: daniele.barbera@strath.ac.uk (D. Barbera), haofeng.chen@strath.ac.uk (H. Chen).

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rupture data are the limited amount of material data required, and the capability to construct a complete creep rupture limit for different rupture times. The method is capable of identifying the most critical areas where the failure will occur, and also to highlight which type of failure mechanisms (plasticity failure or creep rupture) will be dominant. It is worth noting that the LMM creep rupture analysis method for cyclic load condition is also able to evaluate the monotonic loading condition as a special case, associated with an extended limit analysis. The proposed LMM creep rupture concept has been verified (Chen et al., 2003), however, it does not provide an accurate model for various alloys, where creep rupture mechanisms can be notably different, and the analytical function in Chen et al. (2006) can provides inaccurate predictions.

The aim of this paper is to develop the most efficient numerical method capable of providing the accurate creep rupture stress to replace existing analytical creep rupture stress function adopted in the LMM creep rupture analysis, by investigating various interpolation and extrapolation methods for the calculation of creep rupture stress for the entire range of temperature and creep rupture time using limited creep rupture experimental data. For this purpose, three distinct methods a) linear interpolation method, b) logarithm based polynomial relationship and c) the Larson–Miller parameters, are investigated and compared to produce the most accurate prediction. The aim of this paper is also to implement the interpolation and extrapolation methods on creep rupture data into the LMM creep rupture analysis method, and apply this new procedure to a couple of practical examples of creep rupture analysis. The first example provides a benchmarking, which analyses creep rupture limits of a holed plate subjected to a cyclic thermal load and a constant mechanical load. The second example performs creep rupture analyses of a two-pipe structure under combined action of a cyclic thermal load and a constant mechanical load, and is used to further confirm the efficiency and effectiveness of the new method, and to discuss distinct failure mechanisms associated with various creep rupture limits. For both numerical examples, step-by-step analysis is also used to verify the accuracy of the proposed creep rupture assessment method.

2. LMM approach to creep rupture analysis

The LMM approach to creep rupture analysis is performed through an extended shakedown analysis (Chen et al., 2003; Ponter et al., 2000; Ponter and Engelhardt, 2000), where the original yield stress of material in the analysis is replaced by so-called revised yield stresses at each integration points for all load instances in the finite element model. Using the strategy of extended shakedown analysis, the creep rupture limit can be assessed for both the cyclic and monotonic load conditions depending upon the number of load instances in a cycle. In the method, the revised yield stress σ_y^R is determined by the minimum of original yield stress of material σ_y and a creep rupture stress σ_C for a predefined time to creep rupture t_f. With this scheme, the creep rupture limit of a structure can be evaluated efficiently and conveniently by using the creep rupture data only, without the usage of detailed creep constitutive equations.

Apart from the time to rupture t_f, the creep rupture stress σ_C also depends on the applied temperature T. Chen et al. (2003) proposed an analytical formulation for the calculation of the creep rupture stress, which is the product of the yield stress of material and two analytical functions as shown below:

$$\sigma_c\left(x_i, t_f, T\right) = \sigma_y \cdot R\left(\frac{t_f}{t_0}\right) \cdot g\left(\frac{T}{T_0}\right) \tag{1}$$

where x_i is the position of the integration point, t_0 and T_0 are material constants, $R(t_f/t_0)$ is the function of a given time of creep rupture t_f, and $g(T/T_0)$ is the function of the applied temperature T. It is worth noting that for several of practical materials a unique equation (1) of creep rupture stress is not available. Hence a compromised scheme was provided by Chen et al. (2003) for a particular case of holed plate, where the function $R(t_f/t_0)$ was a known parameter, and therefore no detailed formulation was needed for $R(t_f/t_0)$. The function $g(T/T_0)$ that reflects the creep rupture stress dependency on temperature is formulated by:

$$g\left(\frac{T}{T_0}\right) = \frac{T_0}{T - T_0} \tag{2}$$

However, in practical applications with limited experimental creep rupture data, it would be impossible to formulate equation (1) for the analysis. To overcome this, a new numerical scheme to calculate the creep rupture stress using limited rupture experimental data is proposed in this paper and described in Section 3. Once the revised yield stress σ_y^R is obtained from the creep rupture stress for a given time to creep rupture t_f and temperature, it allows an extension of the shakedown procedure for the creep rupture analysis. In the rest of this section, the applied LMM numerical procedure (Chen et al., 2003) for the creep rupture assessment is summarised.

The material is considered isotropic, elastic-perfectly plastic. The stress history has to satisfy both the yield and the creep rupture condition. In order to define a loading history an elastic stress field $\hat{\sigma}_{ij}$ is obtained by the sum of different elastic thermal stress $\hat{\sigma}_{ij}^{\theta}$ and mechanical stress $\hat{\sigma}_{ij}^{P}$. Such elastic stress fields are associated with load parameter λ, which allows considering a wide range of loading histories:

$$\lambda\hat{\sigma}_{ij} = \lambda\hat{\sigma}_{ij}^{\theta} + \lambda\hat{\sigma}_{ij}^{P} \tag{3}$$

The method relies on a kinematic theorem (Koiter, 1960), which can be expressed by the incompressible and kinematically admissible strain rate history. This strain rate $\dot{\varepsilon}_{ij}^{c}$ is associated with a compatible strain increment $\Delta\varepsilon_{ij}^{c}$ using an integral definition:

$$\int_0^{\Delta t} \dot{\varepsilon}_{ij}^{c} dt = \Delta\dot{\varepsilon}_{ij}^{c} \tag{4}$$

A creep rupture limit multiplier can be calculated, taking into account the load history introduced:

$$\lambda_{creep} \int_V \int_0^{\Delta t} \left(\hat{\sigma}_{ij}\dot{\varepsilon}_{ij}^{c}\right) dtdV = \int_V \int_0^{\Delta t} \sigma_{ij}^{c}\dot{\varepsilon}_{ij}^{c} dtdV \tag{5}$$

For creep rupture analysis, σ_{ij}^{c} is the stress at the revised yield associated with the strain rate history $\dot{\varepsilon}_{ij}^{c}$, and $\hat{\sigma}_{ij}$ is the linear elastic stress field associated with the load history for $\sigma = 1$. Combining the associated flow rule, equation (5) can be simplified and the creep rupture limit multiplier λ_{creep} can then be calculated by the following equation:

$$\lambda_{creep} = \frac{\int_V \int_0^{\Delta t} \sigma_y^R(t) \cdot \bar{\dot{\varepsilon}}\left(\dot{\varepsilon}_{ij}^{c}\right) dtdV}{\int_V \int_0^{\Delta t} \left(\hat{\sigma}_{ij} \cdot \dot{\varepsilon}_{ij}^{c}\right) dtdV} \tag{6}$$

where $\sigma_y^R(t)$ is the revised yield stress which is determined by the minimum of the yield stress of material $\sigma_y(t)$ and the creep rupture