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Review

A review of the LICON methodology for predicting the long term creep rupture strength of materials

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ABSTRACT

In the late 1990s, an advanced iso-thermal extrapolation approach referred to as the LICON methodology was developed in a European Brite Euram project to predict the long term creep rupture behaviour of new generation steels. This methodology relies on multiaxial loading conditions to accelerate the onset of long time creep damage formation into the short time rupture regime. The LICON method therefore enables the prediction of long time uniaxial creep rupture strengths using the results from several short duration multiaxial creep crack initiation tests in conjunction with the outcome of a mechanical analysis for the adopted multiaxial specimen geometry. This paper briefly reviews the latest findings concerning application of the LICON method for different types of materials. Successful applications of the method for long time creep rupture strength predictions of advanced martensitic 9%Cr pipe steels (i.e. P91, E911 and P92), a low alloy ferritic steel (i.e. 1CrMoV) and a dissimilar metal weld (1CrMoV/Inconel 617/Inconel 625) have been successfully achieved during the last 15 years. These evaluations have well proven the applicability of the LICON concept for different types of engineering materials while at the same time emphasising the need for i) consideration of appropriate mechanical analysis tools for the assessment of the multiaxial geometry used for creep crack initiation tests dependent on the type of material/structure under investigation and ii) consideration of the complex multiaxial stress state developing within the constituent parts of weldments, even within a uniaxial testpiece.

1. Introduction

One of the main challenges in the design of high temperature components such as those used in modern power generation plant is their lifetime prediction under creep conditions. It is important to be able to accurately predict the creep response of such structures, with due consideration of fitness-for-purpose, reliability, safety and cost effectiveness, and this has been a main topic of high temperature study for many years. In ideal circumstances, creep lifetime evaluation is based on strength values derived from experimental observations from a large quantity of long duration uniaxial tests for the material of interest, ideally for a number of different heats [1]. In circumstances for which such large datasets do not exist, long time properties have to be predicted from the results of relatively short duration tests. While the latter approach can only be regarded as an interim compromise, and not as a substitute for the former approach with regards to accurate design life assessment, it is sometimes the only way to predict the long time properties of new alloys in a relatively short time scale and to thereby enable their early exploitation.

A number of approaches have been adopted for predicting long time uniaxial creep rupture strength from relatively short duration tests, e.g. extrapolating the results of high stress isothermal tests using the Larson-Miller formulation [2], iso-stress testing [3,4], applying the ‘theta projection’ concept [5,6], stress relaxation testing [7,8], etc. A review of these approaches can be found in Ref. [9]. These methods might work well for materials with stable deformation and rupture mechanisms over a wide range of temperatures and stresses. However, experience with all of these techniques consistently indicates that none are effective in predicting long time creep rupture properties when the rupture mechanism in the long time regime is different to that in the short time regime (typical for many high temperature alloys).

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In the late 1990s, an iso-thermal extrapolation approach referred to as the LICON methodology was developed in a European Brite Euram project [10,11]. The LICON methodology relies on multiaxial loading conditions to bring forward the onset of long time creep damage formation into the short time rupture regime. The LICON method employs observations from several short time creep crack initiation (CCI) tests in conjunction with the results of a mechanical analysis of the testpieces to predict the long time uniaxial creep strength of a material. A schematic representation of the LICON concept is shown in Fig. 1.

The LICON method gained attention for application to newly developed materials, for which there is little existing creep rupture data, and for their welded structures. It is worthy of mention that, in addition to long term uniaxial creep strength prediction, the LICON methodology is capable of quantifying the damaging effect of stress concentrations (with multiaxial stress states) in the creep life of structures and can be used for determining the lifetimes of components with multiaxial features [11]. It should be also noted that the LICON methodology, so far, does not take full cognizance of the long term thermal degradation of the material which occurs after long duration service, because short term multiaxial tests only accelerate stress-induced creep damage. A significant contributory factor to overall weakening is thereby missing from the predictions unless it is specifically incorporated, e.g. from iso-stress uniaxial and/or multiaxial creep data [11].

2. LICON methodology

The LICON methodology presents the creep lifetime as a function of stress and stress multiaxiality, such as [9–15]:

$$t_f = A(\overline{\sigma})^{-\nu}(H)^{-\gamma} \quad (1)$$

with $H = \sigma_1/\overline{\sigma}$, where σ_1 is the maximum principal stress and $\overline{\sigma}$ is the Mises stress, and where A, ν and γ are constants determined for the material and temperature of interest and the associated creep damage mechanism. Typically γ varies between zero for $\overline{\sigma}$-controlled rupture and ν for σ_1-controlled rupture [12,13,16].

The LICON approach is not restricted to the use of Eq. (1), and while the use of H has been demonstrated for a number of investigated materials [9–15], it is acknowledged that other multiaxiality factors and models such as those of [17] and [18] may be more appropriate for different material classes in specific temperature and stress ranges.

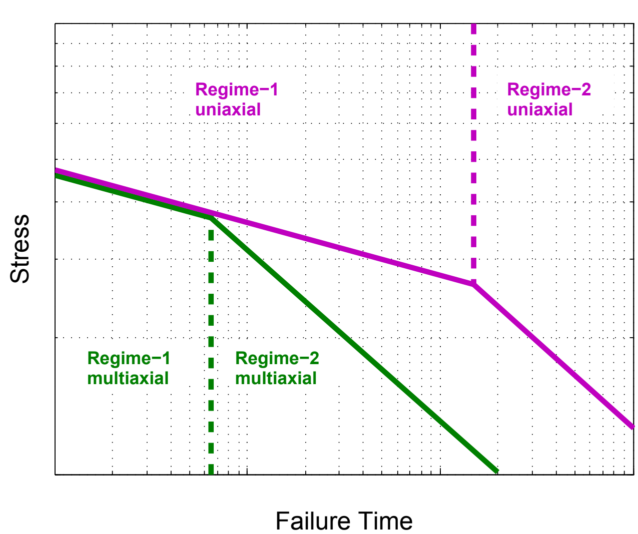

Fig. 1. Schematic representation of the LICON concept. Adopted from Refs. [11,13].

The LICON model equations characterise the failure behaviour in, at least, two mechanism regimes. In regime-1 (short term, constants with added ′), the damage mechanism for ferritic steels is typically void nucleation due to particle/matrix decohesion, and rupture is $\overline{\sigma}$-controlled (i.e. with $\gamma' \to 0$), such that:

$$t_r = A'(\sigma_0)^{-\nu'} \quad \text{uniaxial} \quad (2)$$

$$t_i = A'(\overline{\sigma})^{-\nu'} \quad \text{multiaxial} \quad (3)$$

where t_r and t_i are times to rupture and crack initiation under uniaxial and multiaxial loading conditions, respectively. Most importantly in regime-2 (long term, constants with added ″), where creep damage nucleates and develops at grain/lath boundaries for ferritic steels, rupture is mainly σ_1-controlled (i.e. with $\gamma'' \to \nu''$), such that:

$$t_r = A''(\sigma_0)^{-\nu''} \quad \text{uniaxial} \quad (4)$$

$$t_i = A''(\overline{\sigma})^{-\nu''}(H)^{-\gamma''} \quad \text{multiaxial} \quad (5)$$

Determination of the parameters A'' and ν'' for long term uniaxial creep rupture strength prediction requires i) collection of multiaxial creep data using a multiaxial testing geometry and ii) a mechanical analysis tool for determining representative $\overline{\sigma}_z$ and H_z values (where z provides a reference to the multiaxial testpiece under investigation).

According to [11], the multiaxial $t_i(\overline{\sigma})$ behaviour of a material-condition should be determined with at least 5 multiaxial creep tests with $t_i(\max) \geq 10$ kh. It should be demonstrated that the required long duration damage mechanism has been generated in at least 3 testpieces. For steels, this will be the formation of cavities on grain (and/or lath) boundaries [11].

Five multiaxial testpiece geometries were examined in the early development of the LICON methodology to accelerate the formation of creep damage in the tested materials, namely: thin walled torsion testpieces with the capability for superimposed tensile loading, notch bar testpieces, pressurized notch tube testpieces, fracture mechanics compact tension (CT) and C-type testpieces [11]. Of these, the fracture mechanics CT testpiece (e.g. with thickness of 25 mm, width of 50 mm and crack depth of 25 mm) which provides the most significant multiaxial stress state (largest H) has been considered the most suitable and most frequently used in later applications of the LICON methodology [9,12–15].

Different mechanical analysis tools can be employed for analysis of the multiaxial testpieces. The original concept for the mechanical analysis part of the LICON approach was to consider an existing reference stress solution (e.g. limit load solution [19–21]) for determination of the representative Mises stress and to use tabulated stress multiaxiality factors for the common multiaxial creep testing geometries. However, later studies revealed that more sophisticated mechanical analysis may be required and numerical approaches such as finite element analysis (FEM) should be an integral part of the approach for application to certain material-conditions [9,12–15].

For the calculated sets of $\overline{\sigma}_{CT}$ and H_{CT} corresponding to experimentally measured t_i durations for different testing conditions, a solution to Eq. (6) provides the values of A'' and ν'' to ultimately predict the long term uniaxial creep strength based on Eq. (4).

$$t_{i,x} = A''(\overline{\sigma}_{CT})^{-\nu''}(H_{CT})^{-\gamma''} \quad (6)$$