CREEP CRACK GROWTH ASSESSMENT METHODS

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ABSTRACT

This paper describes engineering methods for assessing defects in components operating at elevated temperatures where creep crack growth needs to be considered. Practical aspects such as the treatment of secondary and residual stresses and the inclusion of realistic creep laws are included. Recent finite element results for complex loading are described, as validation of the assessment methods. The British Energy R5 procedures and the European FITNET procedures, which treat creep crack growth, are briefly described.

KEY WORDS: Creep, Crack, Reference Stress

1. INTRODUCTION

Procedures for assessing cracks in components operating in the creep range were first produced about 20 years ago [1-3]. Such methods were included in the first issue of the British Energy R5 procedures. Since then, there have been developments in methods for assessing both creep and creep-fatigue crack growth [4] and these have led to updates to R5 [5]. Parts of the R5 approach have also been included in the British Standards document BS7910 [6], as described in [7], and more recently in the European FITNET procedure [8].

The R5 procedure gives methods for assessing defects in structures operating under creep-fatigue loading conditions. The information required for assessments is: the operating conditions; the nature of the defects; materials data; and structural calculations to correlate materials data with the behaviour of complex structures. This information may be used to assess whether a defect of a given size will grow to an unacceptable size in a given service life under a given loading history. A step-by-step procedure is given in R5 to perform these assessments and methods for following each step are given in detail. Reference is made to R6 [9] for calculation of the limiting defect size under short-term loadings.

This paper describes the background to creep crack growth assessment methods, starting with steady state creep crack growth under primary loading in Section 2. Then Section 3 addresses more complex loadings involving transient creep and relaxation of secondary stresses. Finite element results which have aided development of the methods are described in Section 4. Following the discussion in Section 5, the paper finally briefly summarises some existing high temperature assessment methods in Section 6.

2. BACKGROUND

The behaviour of a defect in a component operating at elevated temperature may be described in terms of three phases. The first phase is an incubation period, t_i, before any significant crack growth (usually taken as no more than 0.2mm) occurs. The second phase is one of crack growth. The third phase is creep rupture due to accumulation of creep damage in the component. This third phase eventually occurs even if a defect is not present or if a defect is present and there is no crack growth. Incubation may be expressed in terms of a critical crack tip opening displacement or, for widespread creep conditions, by a relationship of the form:

$$t_i (C^*)^\beta = \gamma \quad (1)$$

where β, γ are material constants and C^* is the steady state creep crack tip parameter. Reference stress methods [3] estimate this from

$$C^* = \sigma^p_{ref}(a)\dot{\varepsilon}^c_{ref}[\sigma^p_{ref}(a), \varepsilon^c_{ref}]R' \quad (2)$$

where σ^p_{ref} is the reference stress for the primary loading, P, and $\dot{\varepsilon}^c_{ref}$ is the creep strain rate at the current reference stress and creep strain, ε^c_{ref}. The reference stress is usually defined by

$$\sigma^p_{ref} = P\sigma_y / P_L(a, \sigma_y) \quad (3)$$

where P is the applied primary load, a is crack size and P_L is the collapse load which depends on crack size and is proportional to the yield stress σ_y. The characteristic length, R' in eqn (2) is then defined by

$$R' = (K^p / \sigma^p_{ref})^2 \quad (4)$$

where K^p is the stress intensity factor for the primary loading. As both K^p and σ^p_{ref} are directly proportional to the loading P, the value of R' is independent of the magnitude of P. However, R' does vary with crack size and, when creep and/or fatigue crack growth are being considered, both K and σ^p_{ref} should be calculated for the defect size equal to that of the original crack plus the amount of crack growth. The value of R' is also different at the surface and deepest points of a semi-elliptical surface defect due to differences in the values of K^p, for example.

Following incubation, creep crack growth rates are estimated from C* obtained from eqn (2) and data generally presented in the simple form:

$$\dot{a} = A(C^*)^q \tag{5}$$

where A and q are material constants.

In calculating creep crack growth rates from eqn (5), C^* is obtained from eqn (2) with $\dot{\varepsilon}^c_{ref}$ defined at the creep strain accumulated under the reference stress history up to time t. That is, a strain hardening rule is used to define creep strain rates under increasing stress during the crack growth stages.

The reference stress estimate of eqn (2) enables realistic creep laws rather than simple secondary creep rates to be used and this is illustrated in Section 4 by some finite element analyses. Equation (2) is for primary loading in the steady state. Estimates of C* for the more complex loadings which occur in practice are described next in Section 3.

To assess the third phase of behaviour described above, it is necessary to assess general levels of creep damage in cracked components. For constant primary loading, the stress is well known and the time, t_{CD}, for creep damage to propagate through a structure and lead to failure is taken as

$$t_{CD} = t_r[\sigma^p_{ref}(a)] \tag{6}$$

where $t_r(\sigma)$ is the rupture time at stress, σ, from conventional stress/time-to-rupture data and the reference stress is calculated for the primary loads only for the current crack size, a. Prior to crack growth the rupture time is calculated for the initial defect size, a_0. In ductile materials, the rupture time may be life limiting rather than the crack incubation and growth phases and this is illustrated in [3].

3. COMPLEX LOADING

3.1 Transient Creep for Primary Loading

Time is required for stress redistribution due to creep from the initial elastic or elastic-plastic stress field to the steady state creep field. Stress redistribution is complete and widespread creep conditions are established for times in excess of a redistribution time, t_{red}. For constant loading this may be expressed for small-scale yielding as

$$\varepsilon^c_{ref}[\sigma^p_{ref}(a), t_{red}] = \sigma^p_{ref}(a)/E \tag{7}$$

where $\varepsilon^c_{ref}[\sigma^p_{ref}(a), t]$ is the accumulated creep strain at the reference stress for time, t, and crack size, a, from uniaxial creep data.

In the period before steady state creep is established, it is necessary to allow for transient creep with the crack tip fields being described by C(t), the transient crack tip characterising parameter, which generally exceeds C* [3]. It is assumed that for times less than the redistribution time ($t<t_{red}$), eqn (5) may be generalised to

$$\dot{a} = A[C(t)]^q \tag{8}$$

The parameter C(t) may be estimated from

$$\frac{C(t)}{C^*} = \frac{(1+\varepsilon^c_{ref}/\varepsilon^e_{ref})^{1/(1-q)}}{(1+\varepsilon^c_{ref}/\varepsilon^e_{ref})^{1/(1-q)} - 1} \tag{9}$$

where ε^c_{ref} is the accumulated creep strain at time t, ε^e_{ref} is the elastic strain at the reference stress and q is the exponent in the creep crack growth law of eqn (5). If there is plasticity on initial loading, eqn (9) can be modified to allow for the initial plastic strains and this is discussed below for more general loading.

3.2 Combined Primary and Secondary Loading

For combined primary and secondary loading, if the initial response on loading is elastic, an initial reference stress, σ^0_{ref}, can be defined by

$$\sigma^0_{ref} = \sigma^p_{ref}(K^p + K^s)/K^p \tag{10}$$

where K^s is the stress intensity factor for the secondary loading. The reference stress may also be defined from the stress resultants for combined loading using an equation similar to eqn (3). This is not discussed in detail here but is particularly suitable for loadings with significant stresses not in the plane of the defect. The combined reference stress of eqn (10) may relax due to both creep straining and crack growth and the rate of change is given by

$$\frac{\dot{\sigma}_{ref}}{\sigma_{ref}} + \left[\frac{K^s}{(K^p+K^s)} \left\{ \frac{\partial K^p/\partial(a/w)}{K^p} - \frac{\partial K^s/\partial(a/w)}{K^s} \right\} - \frac{\partial \sigma^p_{ref}/\partial(a/w)}{\sigma^p_{ref}} \right] \frac{\dot{a}}{w} + \frac{E\dot{\varepsilon}^c_{ref}}{Z\sigma_{ref}} = 0 \tag{11}$$

for a crack of depth a in section width w, where Z is the elastic follow-up factor and the creep strain rate is calculated at the current combined reference stress. Evaluation of the elastic follow-up factor is discussed later in Section 5.

Equations (10, 11) enable the initial reference stress and its relaxation to be determined. Omitting algebraic details, the resulting value of the transient crack tip characterising parameter, generalised to the case of combined primary and secondary loading involving stress relaxation due to both creep and crack growth and plasticity on initial loading is

$$\frac{C(t)}{C^*}=\left(\frac{\sigma_{ref}\dot{\varepsilon}^c_{ref}}{\sigma^p_{ref}\dot{\varepsilon}^c_{ref,p}}\right)\left[\frac{(\varepsilon_{ref}/\varepsilon^0_{ref})^{1/(1-q)}}{(\varepsilon_{ref}/\varepsilon^0_{ref})^{1/(1-q)}-(\sigma^0_{ref}/E\varepsilon^0_{ref})}\right] \qquad (12)$$

where $\dot{\varepsilon}^c_{ref}$ and $\dot{\varepsilon}^c_{ref,p}$ are the creep strain rates at σ_{ref} and σ^p_{ref}, respectively, ε_{ref} is the total strain at σ_{ref}, C^* refers to the value evaluated for the primary loading only, and ε^0_{ref} is the total elastic-plastic strain corresponding to the initial value of the total reference stress σ^0_{ref}. For pure primary loading, eqn (12) can be written

$$\frac{C(t)}{C^*}=\frac{(\varepsilon^{e+p+c}_{ref}/\varepsilon^{e+p}_{ref})^{1/(1-q)}}{(\varepsilon^{e+p+c}_{ref}/\varepsilon^{e+p}_{ref})^{1/(1-q)}-(\varepsilon^{e}_{ref}/\varepsilon^{e+p}_{ref})} \qquad (13)$$

where superscripts e, e+p and e+p+c denote elastic, elastic-plastic and elastic-plastic plus creep, respectively. This generalizes eqn (9) to the case when plasticity occurs on initial loading. Plasticity tends to reduce the value of C(t) making it closer to the steady state value, C*.

For pure primary loading, it is straightforward to evaluate the strain terms in eqn (13) as the reference stress is well defined from the limit load expression of eqn (3). For more general loading, the initial strain term may be obtained from an estimate of the initial value of J, J_0. Estimates of J_0 are discussed in low temperature defect assessment procedures such as R6 [9] and FITNET [8] and these enable ε^0_{ref} to be estimated from

$$\sigma^0_{ref}\varepsilon^0_{ref}=\frac{(\sigma^p_{ref})^2}{E}\frac{(1+VK^s/K^p)^2}{f^2(L_r)} \qquad (14)$$

where $L_r = P/P_L$, both V, the parameter treating interactions between primary and secondary stress, and $f(L_r)$, the shape of the failure assessment diagram, are defined in R6 [9] and FITNET [8]. Equation (14) may be used to define σ^0_{ref} and ε^0_{ref} if the shape of the stress-strain curve is known.

4. FINITE ELEMENT ANALYSIS RESULTS

The estimates of C(t) described above are based on reference stress methods and are extensions of those developed by Ainsworth [10]. Validation of the extended methods by finite element analysis is described here.

The finite element analyses have been preformed for an external fully circumferential crack of normalised depth a/w=0.2, where a is the crack depth and w is the wall thickness, in a cylinder of internal radius R_i and external radius R_o. A small uniform primary axial stress (17.6% of the yield stress σ_y) and an axisymmetric secondary stress based on a residual stress due to girth welding were applied. The axial, σ_a, and hoop, σ_θ, residual stresses as a function of distance $r-R_i$ from the inside of the vessel wall are shown in Figure 1. It can be seen that the secondary stresses are high and relatively uniform where the crack is postulated with $\sigma_a \approx 1.4\sigma_y$ and $\sigma_\theta \approx 2.5\sigma_y$ so that the loading is dominated by the secondary stresses and there is potential for substantial stress relaxation.

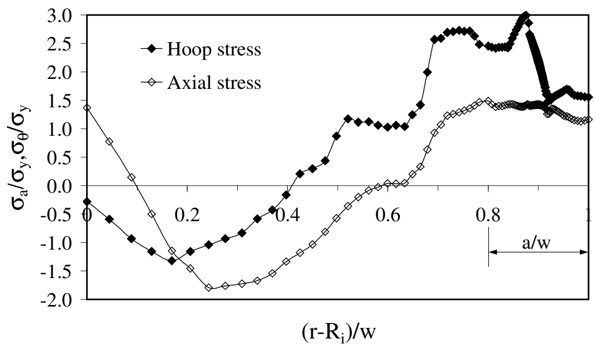

Figure 1. Normalised residual stress distributions in the uncracked body as a function of normalised distance from the inside vessel wall.

The true stress-strain curve was fitted by a piece-wise polynomial rising to a stress of about $3\sigma_y$ at a plastic strain of 25%. The creep law was typical of a Type 316H stainless steel at 550°C and was described by a primary, secondary creep law. The stress dependence in primary creep was described by a power law with stress exponent cn_1=4.18 and secondary creep was described by a power law with stress exponent cn=8.2. A creep analysis of the uncracked cylinder with residual stress acting alone led to rapid relaxation due to primary creep with both axial and hoop stresses falling to about $0.75\sigma_y$ at the outside of the cylinder after 10,000h.

The primary reference stress ($\sigma_{ref} = 0.2\sigma_y$) was obtained from eqn (3) using the limit load solution in [11] and K^p was obtained from the stress intensity factor solution in [9]. The value of K^s was obtained from an elastic analysis of the cracked cylinder with the residual stress only and $\sigma^s_{ref} (= 0.95\sigma_y)$ was obtained from an elastic-plastic finite-element analysis of the cracked cylinder with the residual stress only and a version of eqn (14) simplified to secondary stress only. This is sufficient to determine the initial reference stress, relaxation of the reference stress and hence C(t) using the equations set out in Section 3, provided an estimate of elastic follow-up factor, Z, is available. The estimate of Z is discussed in Section 5 below.

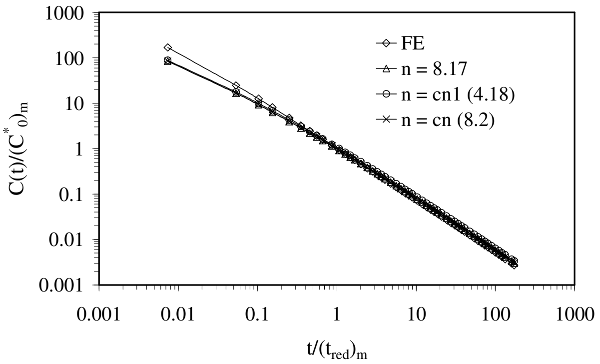

Figure 2. Comparison of C(t) estimated by eqn (12) and values obtained from finite element analysis for the residual stress acting alone for a/w=0.2.

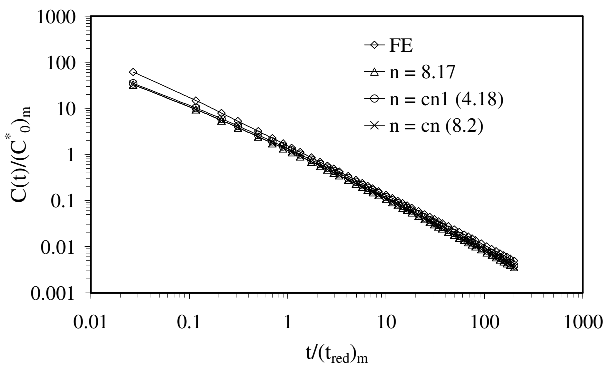

Figure 3. Comparison of C(t) estimated by eqn (12) and values obtained from finite element analysis for combined residual stress and axial stress for a/w=0.2.

Rather than the normalisation by C* in eqn (12), the finite element results for C(t) have been normalised by $(C^*_0)_m$ which is obtained from eqn (2) using the initial reference stress σ^0_{ref} instead of σ^p_{ref} and with $\dot{\varepsilon}^c_{ref}$ defined by the secondary creep strain rate at σ^0_{ref}. Changing the normalisation does not, of course, affect C(t) but it enables results to be presented for the case of residual stress acting alone, for which C*=0. Results are also presented in terms of time normalised by $(t_{red})_m$ which is obtained from eqn (7) using the stress σ^0_{ref} instead of σ^p_{ref}.

The results are shown in Figure 2 for residual stress acting alone and in Figure 3 for combined residual stress and axial tension. In plotting eqn (13), three estimates of the exponent q have been taken, related to corresponding estimates of the stress exponent n by n=q/(1-q) or equivalently q=n/(n+1). It can be seen that the estimates of eqn (13) are not sensitive to the choice of q and are close to the finite element results, although slightly underestimating the finite element values at short times. The results are discussed further in Section 5 but clearly the simplified reference stress approximation has been validated for a loading case involving major biaxial residual stress and substantial stress relaxation for a complex creep law.

5. DISCUSSION

5.1 Generalised Creep Laws

The reference stress estimate of eqn (2) was initially validated by comparison with solutions described by power-law plasticity. However, it was written in the form of eqn (2), rather than a power of stress, to enable it to be used for other creep laws. Comparison of the resulting values of C* with experimental values deduced from measured displacement rates have demonstrated its accuracy for a range of material descriptions [3]. Finite element analyses have also demonstrated accuracy for a range of creep laws [12] for primary loading cases. The finite element results reported in Section 4 confirm the accuracy of the reference stress method for complex creep laws for complex loading involving stress relaxation. It has also been shown (Figures 2, 3) that an accurate estimate of an equivalent power-law exponent (n) is not needed to obtain an accurate estimate of the creep characterising parameter.

5.2 Elastic Follow-up

To evaluate stress relaxation in eqn (11), it is necessary to have an estimate of the elastic follow-up factor Z. For the comparisons in Figures 2 and 3, Z has been estimated from the long-term stress relaxation response obtained in the finite element analyses as Z=1.7 for residual stress acting alone and Z=2.3 for combined residual and axial stresses. At shorter times, higher values of Z may be expected when the residual stresses are high and more uniform over the defective region of the cylinder. Commonly, a value of Z=3 is taken for uncracked bodies and R5 recommends that the uncracked value of Z is increased by unity to allow for the potential increased follow-up caused by the crack. This would result in a value Z=4 in the present case which would lead to significant underestimation of stress relaxation and overestimation of C(t). However, Figures 2 and 3 suggest that the long-term value of Z may lead to an overestimate of stress relaxation and an underestimate of C(t) at short times.

Finite element results have also been performed for crack sizes a/w=0.1, 0.3 and 0.4. These show that Z is larger at smaller crack sizes and is higher for combined loading than for residual stress acting alone. However, the results are not particularly sensitive to a/w suggesting that simplified estimates of Z may be possible for practical applications. This is a topic where further work is required.

5.3 Effect of Crack Growth

Crack growth has not been considered in the finite element results reported in Section 4. However, the effect of crack growth would be to lead to increased stress relaxation for two reasons. First, elastic follow-up reduces with increasing crack size as discussed in Section 5.2. Secondly, as the crack grows out of the region of high uniform residual stress there will be a significant reduction in the effect of these stresses on the crack tip loading. Indeed, it can be seen from Figure 1 that the crack tip will be in a compressive residual stress for large crack sizes. The effect of both creep and crack growth is illustrated schematically in Figure 4.

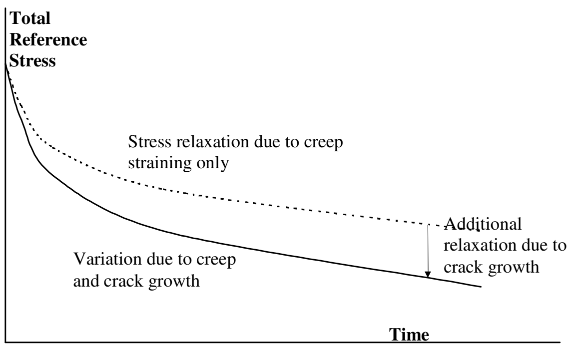

Figure 4 Schematic of residual stress relaxation due to both creep strain and crack growth

Clearly, the combined effect of creep straining and crack extension leads to significantly greater stress relaxation than the case of creep straining acting alone. The effects of crack growth are treated by eqn (11). It should be noted, however, that for cases dominated by primary loading there is an increase in reference stress with crack growth (due to the reduction of the limit load in eqn (3)) rather than stress relaxation.

6. FITNESS-FOR-SERVICE ASSESSMENT

There are now a number of procedures that address crack growth at elevated temperatures. Many of these are, however, limited to simplified loading cases or small amounts of crack growth that do not affect the loading parameters. Within Europe, two procedures that do address the more complex cases presented in Section 3 are R5 [5] and the FITNET procedure [8]. In the application of these procedures the following significant times are specified or calculated:

t_o The period over which the defective component has been subject to high temperature operation.

t_s The future assessment period.

t_i The incubation time for creep crack growth. Creep growth will only occur for times in excess of t_i.

t_{red} The redistribution time prior to the attainment of widespread creep conditions during which the initial elastic crack tip stresses relax due to the creep.

t_{CD} The time for structural failure by continuum damage mechanisms (creep rupture).

The procedures then define the steps to be followed to perform a fitness-for-service assessment. These include the following steps, which are briefly described here.

Define Service Parameters

Loadings and temperature histories are required for the total assessment time t_o+t_s. All stresses need to be categorised as primary or secondary to apply the procedures as demonstrated in Section 3.

Calculate Creep Life Fraction

For cases dominated by primary loading, the creep damage may be evaluated for the load and temperature history using the life fraction rule with the continuum damage failure time evaluated from eqn (6). Alternatively, R5 presents ductility exhaustion methods where the creep life fraction is obtained from the ratio of the creep strain to the material ductility. As the reference stress method described in Section 3 leads to an estimate of accumulated creep strain, it is straightforward to apply ductility exhaustion approaches in conjunction with the calculations of Section 3 and these are particularly suitable for cases involving significant stress relaxation.

Calculate Incubation Time

Various methods of estimating the incubation time are set out in R5 and FITNET and have recently been summarised in [13-15]. These include approaches other than the steady state estimate using eqn (1). The use of a failure assessment diagram similar to that in R6 [9] is described in detail in the FITNET document [8] for two similar diagrams [14, 15].

Calculate Redistribution Time

The requirement for the initial transient creep conditions to be complete is defined by the redistribution time of eqn (7) for primary loading with an initial elastic response. For initial elastic-plastic conditions and combined loading, the transient conditions are implicitly treated through the calculation of C(t) by eqn (12). Thus, in the general case there is no need to consider transient creep as a separate period.

Material	**Temperature (°C)**	**Upper Bound**		**Mean**	
		A	**q**	**A**	**q**
Plain C steels	482 - 538	0.015	1.0	0.006	1.0
½CrMoV, wrought and cast	500 - 600	0.06	0.80	0.006	0.80
½CrMoV, Type IV	540 - 565	0.15	0.80	0.007	0.80
½CrMoV, coarse HAZ	565	0.30	0.80	0.10	0.80
1CrMo	450-600	0.02	0.84	0.006	0.84
1CrMoV	538 - 594	0.015	0.75	0.005	0.79
2¼Cr1Mo weld metal	540 - 565	0.015	0.647	0.003	0.647
2¼Cr1Mo wrought	550 - 600	0.006	0.80	0.004	0.83
Type 304 and Type 304H	650 - 760	0.035	1.0	0.007	1.0
Type 304, service exposed	760	0.10	0.85	0.05	0.85
Type 321, wrought	650	0.02	0.90	0.005	0.90
Type 316 and 316H, wrought	500 - 550	0.023	0.81	0.005	0.81
Type 316 weld	600 - 650	0.06	0.876	0.01	0.876
Inconel 800H	800	0.08	0.90	0.025	0.90
In 939	850	0.20	1.0	0.04	1.0
Modified 9Cr	580 - 593	0.005	0.65	0.003	0.70
Aluminium alloy RR 58	150	2.5	0.85	1.5	0.85
Aluminium alloy 2519 - T851	135	0.35	0.90	0.175	0.90
Astroloy API	700	0.124	0.78	0.054	0.79

Table 1. Typical Creep crack growth data collated during the FITNET project. Constants are those in eqn (5) with $\dot{a}$ in units of m/h and C in units of MPa m/h.*

Calculate Crack Growth

The total crack growth during a loading cycle is generally given by the sum of fatigue crack growth per cycle and the creep crack growth. Fatigue crack growth rates are often described by a Paris law but at high temperature allowance for crack closure is often also required. Creep crack growth is determined as discussed in detail in Sections 2 and 3.

Collect Materials Property Data

The key materials property data for a high temperature fitness-for-service assessment are creep strain, creep rupture and creep and fatigue crack growth information. Assessments of the type described above have been performed for a range of materials and data were collated during the FITNET project as illustrated in Table 1 for creep crack growth data. More recently, long-term creep crack growth data have been obtained from tests lasting several years [16] and these indicate that data are approximately inversely proportional to material ductility as suggested by the models discussed in [3]. Thus, where materials are known to have low long-term ductility, caution must be exercised in using creep crack growth data from short-term tests in which the representative ductility is higher, possibly because the failure mechanism differs at long times.

The R5 procedures [5] address both creep-fatigue crack growth and creep-fatigue damage accumulation in uncracked components. Short-term fracture is addressed in the companion R6 document [9]. Conversely, FITNET [8] does not address creep-fatigue damage accumulation in uncracked components but covers both creep-fatigue crack growth and short-term fracture in a single procedure. Additionally, the FITNET procedure contains extensive advice on the treatment of both fatigue and corrosion. Further details of R5 and the creep part of FITNET may be obtained from the review papers [17] and [18].

7. CONCLUSIONS

Creep crack growth assessment methods have been described with particular attention paid to combined primary and secondary loading. It has been demonstrated that practical defect assessments may be performed for cases involving combined loading, creep crack growth, stress relaxation and complex creep laws. Validation of the methods has been illustrated by comparisons with finite element analyses.

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