CREEP MODULE

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Symbols

a	crack size
a_0	initial crack size
a_g	crack size after growth
a_{min}	crack size below which the crack growth rate is assumed to be constant
$\dot{a}$	crack growth rate
A	material constant (creep crack growth)
B'	material constant (cyclic crack growth)
B_n	net specimen thickness
C	material constant (cyclic crack growth)
$C(t)$	transient crack tip parameter
C^*	steady state crack tip parameter
$\overline{C}^*$	mean estimate of C^* during transient early cycles
d_c^{surf}	surface creep damage accumulated in a cycle
D_c^{surf}	total surface creep damage
E	elastic modulus
$f(L_r)$	failure assessment curve
J_0	initial value of elastic-plastic crack tip parameter for combined loading
k	factor for the weld zones
$K_{I\,id}$	stress intensity factor
$K_{I\,i}$	stress intensity factor
K_{mat}^c	creep toughness (TDFAD)
K_{max}	maximum stress intensity factor in cycle
K_{min}	minimum stress intensity factor in cycle
K^p	stress intensity factor due to primary load
K_s	factor for the effect of cyclic strain hardening or softening
K^s	stress intensity factor due to secondary loading
ℓ	material constant (cyclic crack growth)
L_r	load ratio P/P_L
L_r^{max}	cut-off on TDFAD
n	creep stress exponent
P	load
P_L	limit load
q	material constant (creep crack growth)
q_o	fraction of total load range for which crack is judged to be open
Q	material constant (cyclic crack growth)
r_p	size of the cyclic plastic zone
r_{crack}^p	cyclic plastic zone size at the crack tip
R	stress intensity factor ratio $(= K_{min}/K_{max})$
R'	length in estimate of C^*
R_K	stress intensity factor ratio (2CD)
R_σ	stress ratio (2CD)

S_y	minimum 0.2% proof stress
t_i	initiation time
t_{cyc}	time to reach steady cyclic state
t_o	service life to date
t_g	time required for the crack to propagate by an amount Δa_g
t_h	hold time at high temperature
t_m	maximum allowable time at temperature
t_r	rupture time
t_{red}	redistribution time
t_s	desired future service life
t_{CD}	time for continuum damage failure
T_{ref}	reference temperature
U_c	creep area under load-displacement curve
U_e	elastic area under load-displacement curve
U_p	plastic area under load-displacement curve
U_T	total area under load-displacement curve
V	parameter treating interactions between primary and secondary stress
Z	elastic follow-up factor
α	coefficient of thermal expansion
β, γ	material constants (creep crack initiation)
δ_i	critical crack tip opening displacement (creep crack initiation)
Δa_i	crack growth corresponding to initiation
ΔJ	range of J-integral
Δ_c	creep displacement
Δ_e	elastic displacement
Δ_p	plastic displacement
Δ_T	total displacement
$\Delta\bar{\varepsilon}_t$	total surface strain range (cyclic crack growth)
ΔK_{eff}	stress intensity factor range for which crack is open
$\dot{\varepsilon}_0$	creep strain rate at stress σ_0
$\dot{\bar{\varepsilon}}_c$	equivalent creep strain rate
ε_c	creep strain
ε_e	elastic strain
$\dot{\varepsilon}_c$	creep strain rate
$\dot{\varepsilon}_{c,ref}$	creep strain rate at stress σ_{ref}
$\dot{\varepsilon}^p_{c,ref}$	creep strain rate at stress σ^p_{ref}
$\bar{\varepsilon}_f$	creep ductility
ε^e_{ref}	elastic strain at stress σ_{ref}
ε^{e+p}_{ref}	elastic plus plastic strain at stress σ_{ref}

$\varepsilon_{ref}^{e+p+c}$	elastic plus plastic plus creep strain at stress σ_{ref}
ε_{ref}^{0}	elastic plus plastic strain at stress σ_{ref}^{0}
η	homogeneous experimental calibration factor
μ	stress exponent in power law plasticity
ν	Poisson's ratio
$\bar{\sigma}$	short-term flow stress
σ_{0}	initial stress
$\sigma_{0.2}^{c}$	0.2% creep strength
$\sigma_{1.0}^{c}$	1.0% creep strength
σ_{d}	stress at a small distance ahead of the crack tip
σ_{max}	peak equivalent welding residual stress
$\sigma_{n\,pl}$	nominal stress
σ_{ref}	reference stress
σ_{ref}^{0}	initial value of the total reference stress
$\dot{\sigma}_{ref}$	reference stress rate
$\sigma_{ref}^{cyc=1}$	reference stress for first cycle
σ_{ref}^{p}	reference stress for primary loading
$\sigma_{ref,hom}^{p}$	homogeneous cracked body reference stress
σ_{R}	creep rupture strength
σ_{y}	yield stress
σ_{u}	ultimate tensile stress

2CD	Two Criteria Diagram
CT	Compact Tension specimen
DMW	Dissimilar metal weld
TDFAD	Time Dependent Failure Assessment Diagram

8 Creep module

8.1 Introduction

The procedure in this section specifies methods for assessing defects in structures operating at high temperatures and subject to creep-fatigue loading conditions. The basic ingredients required for an assessment are: (i) the operating conditions; (ii) the nature of the defects; (iii) materials data; and (iv) structural calculations to correlate materials data tests with the behaviour of complex structures. This information is then used to assess whether a defect of a given size will grow to an unacceptable size by creep-fatigue mechanisms in a given service life under a given loading history. The procedure can readily be adapted to consider assessments of other types, such as:

(a) the loadings which give a life equal to a given service life;

(b) the initial flaw size which will just grow to the maximum acceptable size in a given service life (and hence the margin for a given flaw size);

(c) the combinations of materials properties, geometry and loadings for which crack tip behaviour has a negligible effect on lifetime.

An alternative procedure in Section 8.10.3 assesses whether or not a small, defined crack extension will occur in the required service life using a failure assessment diagram approach similar to that in Section 6. Another procedure in Section 8.10.4 uses the calculation of a stress at a small distance ahead of the crack tip, the σ_d approach, to assess whether significant crack extension occurs in the service life.

8.2 Overall Procedure

In this section, a step-by-step procedure is set out for assessing a component containing a known or postulated defect under creep-fatigue loading. Flowcharts for the procedure are given in Figure 8.1 to Figure 8.3. These address a component that is required to operate for a further period, t_s, at high temperature. Continuum damage accumulation and crack growth are addressed. The cases of insignificant creep and insignificant fatigue are included as special cases. The procedure may be applied to a component that has not yet seen operation at creep temperatures, or one that has already operated for a period, t_o, at high temperature. In the latter case, advice is given additionally on the effect of the time at which the defect is assumed to form. The steps in the procedure are listed below. Further information on performing the individual steps is given in Sections 8.3 to 8.10.

STEP 1. Establish Cause of Cracking and Characterise Initial Defect

It is first necessary to establish the cause of the cracking to ensure that the creep procedures are applicable. This is discussed in Section 8.3.

The defect type, position and size should also be identified. For defects found in service, this process may require the advice of materials and non-destructive testing experts, particularly for the case of defects in welds. Suitable sensitivity studies should be performed to address uncertainties.

The detected defect should be characterised by a suitable bounding profile amenable to analysis. Defects which are not of simple Mode I type should be resolved into Mode I orientation. Note that it may also be possible later to re-characterise a defect in the case that the initial assessment leads to an unacceptable result. Advice on defect characterisation is contained in Section 5.1. Advice on methods for detecting and measuring defects is included in Annex E and covers components operating at high temperature.

STEP 2. Define Service Conditions

It is necessary to resolve the load history into cycle types suitable for analysis. This includes both historical operation and the assumed future service conditions. Advice is contained in Section 5.2.

The service life seen to date and the desired future service life should be defined.

For the case of a component that was known to be defect-free at the start of high-temperature operation, an estimate of the time at which the defect formed should also be determined. Suitable sensitivity studies should be performed to address uncertainty in the time of defect formation.

STEP 3. Collect Materials Data

It is first necessary to define the materials relevant to the assessed feature including, in the case of weldments, the weld metal and heat-affected zone structures. Then it is necessary to collect the material properties appropriate to the type of assessment to be performed (cyclic, creep, etc) over the appropriate temperature range and in the correct cyclically-conditioned state. For example, it may be necessary to consider the effects of thermal ageing and reduced ductility due to internal oxidation products leaking to preferred fracture paths. In practice, the requirements are influenced by the outcome of the tests for significant creep or fatigue in Step 6 below. Time-independent material properties are required for the stability analyses in Steps 5 and 11, noting that fracture toughness properties may be required for creep-damaged material.

STEP 4. Perform Basic Stress Analysis

Elastic stress analyses of the uncracked feature should be performed for the extremes of the service cycles identified under Step 2 assuming homogeneous properties. The analysis should allow for any changes from the start of operation; for example, increased stress due to loss of section by wall thinning or increased temperatures due to reduction in thermal diffusivity as a result of surface scale. In the case of cyclic loading, a shakedown assessment of the uncracked feature should then be performed. It should be determined that the feature satisfies strict or global shakedown. If shakedown cannot be demonstrated, it may be necessary to employ inelastic analysis methods. If shakedown is demonstrated, the crack depth should be such that the compliance of the structure is not significantly affected. The extent of the cyclic plastic zone at the surfaces of the component should be evaluated as this may affect the method of calculating crack growth in Step 9.

STEP 5. Check Stability under Time-Independent Loads

The component should be assessed against failure by time-independent mechanisms under fault or overload conditions at the initial defect size using the fracture part of this procedure. This assessment should use the initial values of any residual stresses, not those in the shakedown state. If failure is conceded at this stage, the assumptions in the analysis should be revisited or remedial action taken. Only if sufficient margins can be justified is it permissible to continue to Step 6 to justify future service life.

STEP 6. Check Significance of Creep and Fatigue

The significance of creep should be assessed. If creep is insignificant then the assessment becomes one of cyclic loading alone and Steps 7 and 10 below are omitted. Conversely, if fatigue is judged to be insignificant, then the assessment becomes one of steady creep loading alone and further consideration of cyclic loading is not required. A further test determines if creep-fatigue interaction is significant. If it is not, simplified summation rules for combining creep and fatigue crack growth increments may be adopted. Section 8.7 contains detailed advice.

STEP 7. Calculate Rupture Life based on the Initial Defect Size

The time to continuum damage failure (creep rupture), t_{CD} , is firstly calculated based on the initial crack size from Step 1; if this is less than the required service life, then margins are not acceptable and it may not be necessary to perform crack growth calculations. The estimate of rupture life is based on a calculated limit load reference stress and, for predominately primary loading, the material's creep rupture data. For damage due to cyclic relaxation and due to the relaxation of welding residual stresses, ductility exhaustion methods are more appropriate. The detailed calculations are described in Section 8.8.

STEP 8. Calculate Initiation Time

The initiation time is the time, t_i , from the start of the assessed period of high-temperature operation prior to which no significant crack growth occurs. Depending on the cause of cracking, its location within a weldment and the type of loading it may be possible to calculate a non-zero initiation time. It is conservative to ignore this period and assume that crack growth occurs on first loading. Calculation methods are set out in Section 8.8.

The cause of cracking influences the determination of an initiation time. For example, a naturally-occurring creep defect, such as a Type IV weld defect, may not experience an initiation period prior to macroscopic crack growth, unless the initial defect has extended across the region of extensive creep damage leading to its formation and thus has its tip in essentially undamaged material.

STEP 9. Calculate Crack Size after Growth

The crack size at the end of the assessed period of operation is calculated, following the advice in Section 8.7, by integrating the appropriate creep and fatigue crack growth expressions. This integration is simplified in some cases, depending on the outcomes of the significance tests in Step 6. Changes in reference stress due to crack growth should be included in the calculations.

STEP 10. Re-Calculate Rupture Life after Crack Growth

The time to continuum damage failure should be re-calculated taking into account the increased crack size from Step 9. Crack growth calculations should not be performed in practice beyond an acceptable rupture life. It is conservative to base the estimate of rupture life on the final crack size as this neglects slower accumulation of creep damage when the crack size is smaller during growth.

STEP 11. Check Stability under Time-Independent Loads after Crack Growth

In practice, this step is carried out in conjunction with the crack size calculations of Step 9. The crack growth calculations of that step should not be performed beyond a crack size at which failure by time-independent mechanisms is conceded at fault or overload load levels using the fracture procedure.

STEP 12. Assess Significance of Results

Margins against failure are not prescribed here and are left to the user to set. The sensitivity of the results of the preceding steps to realistic variations in loads, initial flaw size and location, and material properties must, however, is assessed as part of a sensitivity study. The various modelling assumptions made can also be revisited with a view to reducing pessimisms in the analysis if unacceptable margins are determined. If this still fails to result in an acceptable assessment, the options of reducing future service conditions, or repair or replacement of the defective component should be considered. This is discussed in Section 8.9.

STEP 13. Report Results

The results of the assessment, including margins determined, and the details of the materials properties, flaw size, loads, stress analysis calculations, etc, used in the assessment should be comprehensively reported. This facilitates both verification of the particular assessment and repeatability in future assessments.

8.3 Establish Cause of Cracking

Before performing calculations, an investigation should be carried out to determine the most likely cause of cracking. At least, this should involve a combination of non-destructive testing, visual examination and metallurgical examination. If it is possible to identify the mode of cracking, this can provide qualitative information on the relative contributions of creep and fatigue to the overall process; creep crack growth is generally intergranular whereas fatigue crack growth tends to be transgranular. Also, where possible, a dimensional check should be carried out to establish whether there has been any significant distortion.

When a defect has been discovered in a component that has been in service, the conservative assumption for the calculation of continuum damage is that the crack initiated early in life. This should be assumed unless there is evidence to the contrary. Where the defect can be reliably justified to have formed after the start of high-temperature operation, then it is permissible to use an estimate of the corresponding time in the calculations of crack growth and continuum damage. The reference stress appropriate to this period is then determined on the basis of the uncracked body. Suitable sensitivity studies should be performed to address the effect of the assumption on the robustness of the assessment. Particular caution should be taken if the defect formed in service by creep mechanisms, noting the comments in the next paragraph concerning the effects of creep damage on crack growth properties.

Significant creep damage, away from the crack tip, probably indicates that there has been local over-heating or over-stressing. In these circumstances, all crack growth calculations should take account of the material in its damaged state. In addition, where cracks are discovered in material that has experienced extensive creep damage, it is essential for end-of-life assessment that material data are used which are fully representative of material in its damaged state. Data on fracture toughness and remaining creep rupture life are particularly sensitive in this respect.

Where there is evidence of environmentally assisted cracking (multiple cracking without cavitations), the methods required are discussed in Section 9.

8.4 Define Service Conditions

This procedure is applicable to components which operate for long periods at steady or steady cyclic conditions of load (stress), or displacement, and temperature. Each loading and temperature must be defined for the locations of interest. In making an assessment, it is conservative to assume that all the loading is load-controlled and ignore stress relaxation; it may also be assumed that infrequent short-term overloads will not modify the crack tip conditions significantly.

Specification of the service conditions must define the load, temperature and life seen to date. In addition to historical operation, future service conditions must also be defined. The loading must include all time independent, transient and fault loading. In many circumstances, the service load and temperature history can be broken down into a number of blocks during which stress and temperature are sensibly constant. This will simplify the analysis.

Where transient loading occurs, during either start-up or shutdown, the number of load and temperature cycles and their magnitude should be established. In defining the future life that is required from plant, conservative predictions have to be made about the likely transient conditions that will be experienced.

8.5 Collect Materials data

This section outlines the material properties data required to follow the steps in the procedure set out in Section 8.2. Further discussion is contained in Section 5.4 and sample materials data are presented in Annex M. Some of the material properties may be inter-related and it is necessary to use consistent material properties data in different steps of the procedure. This is of particular importance when material properties data are obtained from a number of different source references. Where possible, materials properties data should be obtained by following testing standards. However, standards are not available for measuring all properties for performing a comprehensive creep-fatigue crack initiation analysis and Section 8.11 includes guidance set out in, for example, codes of practice in these cases.

8.5.1 Creep Rupture Data

Creep rupture data are required to calculate the rupture life of the remaining ligament and to estimate the current continuum damage level in the ligament as the defect grows.

8.5.2 Creep Deformation Data

Creep deformation data are required for steady loadings to estimate the creep crack incubation time and subsequent creep crack growth rates using reference stress techniques. For cases with steady primary load or large elastic follow-up, forward creep data collected under constant load conditions are appropriate. For essentially strain-controlled conditions, in the absence of follow-up, stress relaxation data may be more appropriate than forward creep data. Reliable constitutive equations are needed to provide a smooth transition between these extremes. For creep-fatigue loadings, a description is required of the creep deformation of the material in the relevant cyclic condition in order to estimate creep crack growth rates during the dwell periods. Creep deformation data may also be required to calculate the time for failure by continuum damage using a ductility exhaustion approach or to estimate creep damage at the surface for use in a creep-fatigue crack growth law. Often a simple power law expression

$$\dot{\varepsilon}_c / \dot{\varepsilon}_o = \left(\sigma / \sigma_o\right)^n \tag{8.1}$$

is used to describe creep strain rate. More generally, creep deformation is described by three stages: primary, secondary and tertiary. Equation (8.1) describes the secondary stage whereas some other laws consider only an increasing strain rate after the primary stage. Rather than describing the creep strain rate, creep deformation data are often represented by isochronous stress-strain curves, see Figure 8.4, or tables giving, for example, the stress required to give a total strain of 1% after a specified time at a specified temperature. Examples of creep strain rate equations and isochronous data are contained in Annex M.

8.5.3 Creep Ductility Data

Creep ductility data may be required to calculate the time for failure by continuum damage using a ductility exhaustion approach or to estimate creep damage at the surface. In addition, creep ductility data may be used to estimate creep crack growth rates for situations in which explicit crack growth data are not available.

8.5.4 Creep Crack Initiation/Incubation Data

For situations where fatigue is insignificant, it may be possible to take account of an incubation period prior to crack extension. Creep crack incubation data may be expressed in terms of a critical crack tip opening displacement, δ_i, or, for widespread creep conditions, by a relationship of the form:

$$t_i (C^*)^\beta = \gamma \tag{8.2}$$

where t_i is the incubation time and β and γ are material constants. In situations where explicit incubation data are not available, it is possible to estimate the incubation time for widespread creep conditions using approximate expressions given later. In addition, two alternative approaches for predicting incubation times are given in Section 8.10.

8.5.5 Creep Crack Growth Data

Creep crack growth data are required to calculate crack growth under steady loading conditions or to estimate the crack extension during dwell periods for creep-fatigue conditions. Creep crack growth data are generally presented as a simple relationship of the form:

$$\dot{a} = A (C^*)^q \tag{8.3}$$

where A and q are material constants. Annex M gives some typical values of these constants for a number of materials. The constants A and q may depend on the test specimen geometry used to obtain creep crack growth data. For a conservative assessment, it is recommended that compact or deeply cracked bend specimens are chosen and that data satisfy validity criteria specified in standards. However, if use of more specific data can be justified, to allow for loss of constraint for example, alternative test specimens can be used as described in the CRETE code of practice [8.18].

8.5.6 Cyclic Crack Growth Data

The type of cyclic crack growth data required depends on the size of the defect relative to the cyclic plastic zone at the surface of the component. For small defects embedded in the cyclic plastic zone, a strain based method for calculation of crack growth is set out in Section 8.8.3 (A). This uses the strain based crack growth law termed Method II that is described in Section 8.5.6.2. For cracks larger than the cyclic plastic zone, a Paris law modified for crack closure is used. This is termed Method I and is described in Section 8.5.6.1. Depending on the application, it may not be necessary to collect both Method I and Method II data.

8.5.6.1 Method I

The cyclic component of creep-fatigue crack growth required for a Method I crack growth rate law is described by

$$\left(\frac{da}{dN}\right)_f = C\Delta K_{eff}^{l} \tag{8.4}$$

where C and l are material and temperature dependent constants. ΔK_{eff} is the stress intensity factor range for which the crack is judged to be open, as evaluated for component applications by equation (8.6) below. In situations where cyclic crack growth data have been obtained from tests with significant plasticity, it is preferable to evaluate ΔK_{eff} from experimental estimates of ΔJ. However, it will be pessimistic to use data which have been correlated with elastically calculated ΔK_{eff} values. Further information on the use of fatigue crack growth data is given in Section 7, which includes alternative expressions to equation (8.4).

8.5.6.2 Method II

The cyclic component of creep-fatigue crack growth required for a Method II crack growth rate law is described by a high strain fatigue crack growth law of the form:

$$\left(\frac{da}{dN}\right)_f = B'a^Q \qquad a_{min} \le a \le r_p \tag{8.5}$$

where $a_{min} = 0.2$ mm is the crack depth below which the crack growth rate is assumed to be constant. B' and Q depend on material, strain range and environment and can be determined experimentally. These laws apply for a total surface strain range $\Delta\overline{\varepsilon}_t$, while the defect is embedded in the cyclic plastic zone of size r_p at the surface of the component. Further information on strain based methods for fatigue crack growth assessment is contained in Section 7.

8.5.7 Other Data

In addition to the creep data described in Sections 8.5.1-8.5.6, it may be necessary to have other data to perform an assessment. These are listed below. In addition, for the alternative methods in Section 8.10, some special requirements are needed when alternative approaches are followed and these requirements are discussed in the appropriate part of Section 8.10.

8.5.7.1 Elastic and Physical Constants

Values for Young's modulus, E, Poisson's ratio, ν, and the instantaneous or mean coefficient of thermal expansion, α, are required to perform the basic stress analysis and may also be required if a detailed shakedown analysis has to be performed.

8.5.7.2 Stress-strain Data

Values for the minimum monotonic 0.2% proof stress are required to check crack stability for time-independent loadings and to perform a shakedown analysis.

Cyclic stress-strain data are required to determine the stress intensity factor range when cyclic plastic deformation occurs and to determine deformation stress-strain loops. Cyclic stress-strain data may be described by a relationship between the total stress range and the total strain range of the hysteresis loops through the use of the Ramberg-Osgood equation. For cyclically stable materials, the stress-strain hysteresis loop can be reconstituted from this equation but the process is less successful for hardening and softening materials. For situations in which strict shakedown is achieved, these data will not be required as the short-term response will be elastic. However, cyclic stress-strain data will be required for more severe loading.

The factor K_s is an experimentally derived factor which can be applied to the minimum 0.2% proof stress of the material to give a level, $K_s S_y$, which is the largest semi-stress range for which the material has stable i.e. exhibits non-ratchetting, cyclic stress-strain behaviour. K_s is therefore required to perform a shakedown analysis.

The variation of K_s with temperature for Type 316 and wrought ferritic steels is given in R5 Volume 2/3. Additional details on the derivation of K_s are given in Section A1.3 of R5 Volume 2/3.

8.5.7.3 Fracture Toughness Data

Values of the fracture toughness are required to check crack stability for time-independent loadings. In general, data relate to materials which have experienced no prior global (ligament) or local (crack tip) creep damage. It is therefore necessary to confirm that the fracture toughness values used for assessing crack stability under time independent loadings are appropriate for the material condition ahead of the crack tip.

8.6 Perform Basic Calculations

8.6.1 Stress Intensity Factors

The linear elastic stress intensity factor, K, depends on the loading and the crack size and may vary with position around a crack front. For cyclic loading, it is necessary to evaluate the stress intensity factor range and the ratio, R, of minimum K_{min} to maximum stress intensity factor, K_{max}. The value of R should be calculated from a shakedown analysis rather than a simple elastic analysis. This is because creep during a cycle tends to lead to a cyclic stress state which gives a lower value of R than the initial elastic response. The shakedown analysis only affects the value of R and not the total stress intensity factor range, as the residual stress is independent of position in the cycle.

In the absence of cyclic plasticity in the uncracked body, the effective stress intensity factor range ΔK_{eff} is defined by:

$$\Delta K_{eff} = q_o \Delta K \tag{8.6}$$

where $\Delta K = K_{max} - K_{min}$ and q_o is the fraction of the total load range for which a crack is judged to be open. This may be estimated conservatively from:

$$\begin{aligned} q_o &= 1 && R \geq 0 \\ q_o &= (1 - 0.5R)/(1 - R) && R < 0 \end{aligned} \tag{8.7}$$

where $R = K_{\min} / K_{\max}$.

8.6.2 Reference Stress

For creep crack growth evaluation, it is necessary to evaluate the reference stress at the start of the dwell. The reference stress for simple primary loading is determined by the methods of limit analysis and is defined by:

$$\sigma_{ref}^{p} = P\sigma_y / P_L(\sigma_y, \mathrm{a}) \tag{8.8}$$

In cases where cyclic loading is present the load P is evaluated from the stress, produced by the shakedown analysis, at the time in the cycle corresponding to the creep dwell. It should be noted that this is not necessarily at the peak stress in the cycle. P_L is the value of P corresponding to plastic collapse assuming a yield stress σ_y. The effect of the flaw must be included in evaluating the plastic collapse load. When creep crack growth is being considered, the relevant flaw size is the size of the original flaw plus the amount of crack growth. For the purposes of initial calculation of the time for failure by continuum damage mechanics and calculation of incubation time, the relevant flaw size is that of the original defect.

8.6.3 C* Parameter

For steady state creep, the crack tip stress and strain rate fields (and hence creep crack growth rates) may be characterised by the C^* parameter. This is the creep equivalent of the J-contour integral used to describe elastic-plastic fracture. It may be evaluated by finite element analysis but a reference stress based estimate of C^* is often used. This is

$$C^* = \sigma_{ref}^{p} \dot{\varepsilon}_c [\sigma_{ref}^{p}(a), \varepsilon_c] R' \tag{8.9}$$

Here, $\dot{\varepsilon}_c$ is the creep strain rate at the current reference stress and creep strain, ε_c, 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 incubation and growth stages. This is applicable to complex time-varying creep laws. The characteristic length, R' is defined by

$$R' = (K^p / \sigma_{ref}^{p})^2 \tag{8.10}$$

where K^p is the stress intensity factor due to primary load only. As both K^p and σ_{ref}^{p} 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 crack growth is being considered, both K and σ_{ref}^{p} should be calculated for the defect size equal to the size of the original crack plus the amount of creep 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 other than simple primary loadings, estimates of C^* are given in Section 8.10.2.

8.6.4 Redistribution Time, t_{red}

This calculation is only required when cyclic loading is insignificant.

Time is required for stress redistribution due to creep from the initial elastic state at the start of a creep dwell. The requirement for the stress redistribution to be complete and widespread creep conditions to be established may be expressed in terms of a redistribution time, t_{red}. This may be expressed conveniently in terms of the reference stress for cases of primary load only as

$$\varepsilon_c[\sigma_{ref}^{p}(a),t_{red}] = \sigma_{ref}^{p}(a)/E \tag{8.11}$$

where $\varepsilon_c[\sigma_{ref}^{p}(a),t]$ is the accumulated creep strain at the reference stress for time, t, and crack length, a, from uniaxial creep data.

Equation (8.11) applies for steady creep loading under primary stresses. When calculating crack growth under significant cyclic loading (see Section 8.7), it may be necessary to consider the early cycles before the steady cyclic state is reached. Time is required for the material response to the cyclic loading to reach a steady cyclic state or shakedown. This time, t_{cyc}, can be estimated in terms of the reference stress for the first cycle, $\sigma_{ref}^{cyc=1}$, and the reference stress under steady cyclic conditions for combined primary and secondary loading, σ_{ref}, as:

$$\varepsilon_c[\frac{(\sigma_{ref}^{cyc=1}+\sigma_{ref})}{2},t_{cyc}] = Z\frac{(\sigma_{ref}^{cyc=1}-\sigma_{ref})}{E} \tag{8.12}$$

where Z is an elastic follow-up factor, which controls the rate of stress relaxation to steady state creep. Further details of the treatment of secondary loading are given in Section 8.10.2.

8.6.5 C(t) Parameter

For times less than the redistribution time, it may be necessary to calculate the transient crack tip parameter $C(t)$. An interpolation formula for $C(t)$ during the transition between initial elastic loading and steady state secondary creep is

$$\frac{C(t)}{C^*} = \frac{(1+\varepsilon_c/\varepsilon_e)^{1/(1-q)}}{(1+\varepsilon_c/\varepsilon_e)^{1/(1-q)}-1} \tag{8.13}$$

where ε_c is the accumulated creep strain at time t, ε_e is the elastic strain and q is the exponent in the creep crack growth law of equation (8.3) with $q \simeq n/(n+1)$ where n is the exponent in equation (8.1). For times in excess of the redistribution time, $C(t)$ approaches C^*.

8.7 Check Significance of Creep and Fatigue

In many cases the complexity of a creep-fatigue crack growth assessment can be avoided by performing simple calculations to demonstrate the insignificance of creep and/or fatigue. In the event of both creep and fatigue being shown to be significant, simple tests can also be used to demonstrate insignificant creep-fatigue interactions, and thus remove the onerous requirement to generate material fatigue data incorporating the effects of creep holds.

The test for insignificant creep applies when both Method I and Method II data of Sections 8.5.6.1 and 8.5.6.2 are used. The tests for insignificant fatigue and creep-fatigue interaction only apply to Method I.

8.7.1 Insignificant Creep

The significance of creep strains should be determined for the assessed loading and temperature history. Creep may be significant for some types of loading history but not for others.

The effects of creep may be neglected if the sum of the ratios of the hold time t to the maximum allowable time t_m, at the reference temperature, T_{ref}, for the total number of cycles is less than one:

$$\sum_{j=1}^{N} \left[t/t_m(T_{ref}) \right]_j < 1 \tag{8.14}$$

The values of t_m depend on material, crack size and temperature. R5 contains curves in Figures A6.6 and A6.7 for austenitic Type 316 and Type 304 materials. For other materials, guidance on creep exemption may be taken from BS 7910. In BS 7910, t_m, for materials with creep rupture ductilities > 10%, is taken as the time required to achieve an accumulated creep strain of 0.2% at a stress level equal to the reference stress. For ductilities < 10%, t_m should be determined on the basis of creep strains with a magnitude equal to 1/50th of the creep rupture ductility. However, it should be noted that for consistency with the insignificant creep tests for uncracked structures, values of t_m should not be greater than those allowed in design codes.

8.7.2 Insignificant Fatigue

It should first be determined whether or not creep behaviour is unperturbed by cyclic behaviour. This test should be performed both for the overall structural response and for stresses local to the crack tip. Since Step 4 of the procedure of Section 8.2 requires that the crack depth is such that the compliance of the structure is not significantly affected, the test for the overall structural response may be demonstrated by showing that the elastic stress range does not exceed the sum of the steady state creep stress and the stress to cause yield at the other extreme of the cycle. Further information is contained in R5.

The test for stresses local to the crack tip may be made by demonstrating that, for the most severe fatigue cycle, the cyclic plastic zone at the crack tip is small. Under cyclic loading, the allowable elastic stress range is $2\sigma_y$ in the absence of cyclic hardening or softening, and the cyclic plastic zone size at the crack tip, $r_p^{crack} = \beta(\Delta K/2\sigma_y)^2$, where β is typically $1/2\pi$ in plane stress and $1/6\pi$ in plane strain. More generally, the cyclic plastic zone size at the crack tip should be calculated using the cyclic yield or 0.2% offset stress. This cyclic plastic zone size should be shown to be much less than the crack size or any other dimension characteristic of the structure, such as section thickness or remaining ligament ahead of the crack.

If the above tests are satisfied, cyclic loading effects on creep crack growth can be neglected. Further, fatigue is insignificant, provided that estimated fatigue crack growth does not exceed 1/10th of the estimated creep crack growth. At the start of an assessment only approximate estimates of growth are required and best-estimate data for both creep and fatigue crack growth should be used to calculate this ratio. These approximate calculations can be refined when results of a detailed assessment become available.

8.7.3 Insignificant Creep-Fatigue Interactions

When both creep and cyclic loading are shown to be significant, the significance of creep-fatigue interaction should be determined. In general, the effect of creep damage on fatigue crack growth rates has little influence on the total crack growth per cycle provided the latter includes an explicit calculation of creep crack growth. Hence, creep-fatigue interaction is insignificant and material data that allow for interactions, which lead to enhanced fatigue crack growth rates, are not required. It is adequate, therefore, in Step 9 of Section 8.2 to sum creep crack growth with continuous cycle fatigue crack growth estimates.

There are two exceptions to this general rule:

(i) In cases where the tests for insignificant cyclic loading and fatigue indicate that creep is perturbed by cyclic behaviour, but fatigue crack growth is shown to be only a small fraction of the total crack growth per cycle (i.e. fatigue crack growth does not exceed 1/10th of the creep crack growth), the enhancement of fatigue crack growth by creep damage may be large. In these circumstances the constants in equation (8.4) should be obtained from tests at hold times relevant to the service application being assessed.

(ii) In cases where cracks are propagated by fatigue through material heavily damaged by prior creep, propagation rates are likely to be increased. In these circumstances, a factor should be applied to the fatigue data, depending on the amount of prior creep damage. BS 7910 recommends that this factor should be determined experimentally, and relates heavy prior creep damage to a value of damage factor D_c greater than about 0.8.

8.8 Perform Assessment Calculations

8.8.1 Calculate Rupture Life, t_{CD}

Both stress-based and ductility-based approaches may be used for assessing creep damage. For loadings which are predominantly constant and primary, the stress is well known and it is appropriate to use stress/time-to-rupture relationships for assessment. For damage due to cyclic relaxation, the strain accumulated is limited in each cycle and ductility methods are appropriate. For predominately primary loading the time, t_{CD}, for creep damage to propagate through a structure and lead to failure is taken as

$$t_{CD} = t_r [\sigma^p_{ref}(a)] \tag{8.15}$$

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. If t_{CD} is less than the remaining assessment time then remedial action must be taken. For combined and cyclic loading, it may be necessary to evaluate t_{CD} from a ductility exhaustion approach; further details are given in Section 8.10.

8.8.2 Calculate Crack Incubation Time, t_i

The incubation time, t_i, is defined as the time during which the initial crack blunts without any significant crack extension. Incubation is defined for engineering purposes as corresponding to 0.2mm crack extension. The method for representing incubation data then depends on observed specimen response. For steady state creep conditions with an essentially constant displacement rate, the incubation time in test specimens is correlated with experimental estimates of the crack tip parameter C^* by equation (8.2). Use of the estimate of from equation (8.9) for the initial crack size a_0, then provides an estimate of t_i. More generally, incubation times can be related to measurements of a critical crack opening displacement, δ_i, which can then be used to calculate a critical reference strain as

$$\varepsilon_c [\sigma^p_{ref}(a_0), t_i] = [\delta_i / R'(a_0)]^{n/(n+1)} - \sigma^p_{ref}(a_0)/E \tag{8.16}$$

If fatigue is significant it is conservative to set the incubation time to zero. However, a creep-fatigue crack incubation time (or cycles) may be calculated using the FAD or sigma-d approaches outlined in Section 8.10.

For elliptical or semi-elliptical defects, the incubation time should be taken as the lower of the values obtained from equation (8.16) at points corresponding to the major and minor axes of the ellipse or semi-ellipse.

8.8.3 Calculate Crack Size after Growth, a_g

The extent to which crack growth calculations are required depends on the relative magnitudes of the service life to date, t_o, the desired future service life, t_s, and the incubation time, t_i; this may be summarised as follows.

- If $t_o + t_s < t_i$, the crack will not incubate and $a_g = a_0$.
- If the crack incubates during the assessment time, then it is necessary to calculate the crack size, a_g, after growth in time $t_o + t_s - t_i$.
- If the crack has incubated prior to the assessment, then it is necessary to calculate the crack size, a_g, after growth in time t_s.

The time required for the crack to propagate by an amount Δa_g is denoted t_g. There are a number of different regimes for calculations of crack growth and these are set out below.

(A) Cracks growing inside the cyclic plastic zone, r_p, at the surface of the component.

In this regime the Method II high strain creep-fatigue crack growth law should be used. This is eqn (8.5) for insignificant creep. When creep is significant, the creep-fatigue crack growth per cycle is given by:

$$\frac{da}{dN} = \left(\frac{da}{dN}\right)_f (1 - D_c^{surf})^{-2} \tag{8.17}$$

where $(da/dN)_f$ is the fatigue crack growth per cycle from eqn (8.5) and D_c^{surf} is the total surface creep damage (taking account of stress state, if necessary) accumulated up to the current time from every cycle and is:

$$D_c^{surf} = \sum_{j=1}^{N} (d_c^{surf})_j \tag{8.18}$$

where $(d_c^{surf})_j$ is the creep damage accumulated in the $\mathrm{j'th}$ cycle and the summation is carried out up to the current time. The term $(d_c^{surf})_j$ is evaluated at the surface of the uncracked component and is given by the ductility exhaustion method as

$$(d_c^{surf})_j = \int_0^{t_{h,j}} \frac{\dot{\bar{\varepsilon}}_c}{\bar{\varepsilon}_f(\dot{\bar{\varepsilon}}_c)} dt \tag{8.19}$$

where $0 \le t \le t_{h,j}$ is the $\mathrm{j'th}$ creep dwell period, $\dot{\bar{\varepsilon}}_c$ is the instantaneous equivalent creep strain rate during the dwell and $\bar{\varepsilon}_f(\dot{\bar{\varepsilon}}_c)$ is the creep ductility at that strain rate, accounting for stress state. The strain rate $\dot{\bar{\varepsilon}}_c$ is evaluated at the instantaneous stress during the dwell obtained from stress relaxation data. The relaxation data should correspond to a starting stress equal to the uncracked-body start-of-dwell stress at the surface, σ_0. In practice, many cycles will be of a similar type, in which case the summation in equation (8.16) is simplified.

When $D_c^{surf} \to 1$, equation (8.17) predicts an infinite crack growth rate. However, this should not be interpreted as predicting the failure of the component. This corresponds to the exhaustion of creep ductility at the surface of the component and the instantaneous crack depth, a, should be set to the depth of the cyclic plastic zone, r_p. If r_p is greater than the crack depth that the structure can safely tolerate under service and overload conditions then remedial action should be taken. Cracks deeper than r_p are subjected to nominally cyclic elastic deformation and the Method I growth law should be used as set out below.

(B) Crack length, a, greater than the cyclic plastic zone size, r_p, at the surface of the component.

In this regime, the Method I crack growth rate law of equation (8.4) is used and the total crack growth per cycle, da/dN, is obtained as the simple sum of the contributions due to cyclic and creep crack growth rates:

$$da/dN = (da/dN)_f + (da/dN)_c \tag{8.20}$$

The fatigue crack growth rate $(da/dN)_f$ is given by equation (8.4) with the constants modified for hold-time effects only if creep-fatigue interactions are shown to be significant in Section 8.7.3. If fatigue crack growth has been shown to be insignificant in Section 8.7.2, this term is omitted. The creep crack growth per cycle in equation (8.19) also depends on loading regime as set out in (i) - (iv), below.

(i) Steady state creep crack growth for times $t > t_{red}$, with insignificant cyclic loading

For the load controlled case and the attainment of steady state creep conditions the creep crack growth is obtained from creep crack growth data in the form of equation (8.3).

Equation (8.16) is used to estimate C^* for crack sizes between a_0 and a_g for use with equation (8.3).

The creep crack extension per cycle, $(da/dN)_c$, is evaluated as the integral of equation (8.3) over the dwell period, t_h:

$$\left(\frac{da}{dN}\right)_c = \int_0^{t_h} A(C^*)^q\,dt \tag{8.21}$$

(ii) Non-s*teady state creep crack growth, $t < t_{red}$, when cyclic loading is insignificant.*

To allow for the increased amplitude of the crack tip fields at short times, it is assumed that for times less than the redistribution time ($t<t_{red}$), equation (8.3) may be generalised to

$$\dot{a} = A[C(t)]^q \tag{8.22}$$

For situations where $t_i + t_g > t_{red}$, the effects of the redistribution period can be allowed for by using the crack growth rates of equation (8.3) multiplied by a factor of 2 for $t<t_{red}$, i.e.

$$\begin{aligned} \dot{a} &= 2A(C^*)^q \quad for\ t_i \le t < t_{red} \\ \dot{a} &= A(C^*)^q \quad for\ t \ge t_{red} \end{aligned} \tag{8.23}$$

If the total time for the assessment does not exceed t_{red}, then this simplified treatment of transient creep is not adequate and it is necessary to use the parameter $C(t)$ explicitly, from equation (8.13), in estimating creep crack growth.

The creep crack extension per cycle, $(da/dN)_c$, including transient effects is then evaluated over the dwell period, t_h, as:

$$\left(\frac{da}{dN}\right)_c = \int_0^{t_h} A[C(t)]^q \, dt \tag{8.24}$$

(iii) Early cycle creep crack growth, t < t_{cyc}, when cyclic loading is significant.

For a component outside strict shakedown a mean estimate of C^* during the transient period, $\overline{C}^*$, may be used up to t_{cyc} of equation (8.10). Where only elastic analysis is available, $\overline{C}^*$ is defined as:

$$\overline{C}^* = (\sigma_{ref}^{cyc=1} + \sigma_{ref})\,\dot{\varepsilon} R'/2 \tag{8.25}$$

where $\dot{\varepsilon}$ is evaluated as $\dot{\varepsilon}[(\sigma_{ref}^{cyc=1} + \sigma_{ref})/2]$. As crack growth is approximately linearly dependent on C^*, the crack growth during the time t_{cyc} is not particularly sensitive to the value of t_{cyc} but depends primarily on the accumulated creep strain, $Z(\sigma_{ref}^{cyc=1} - \sigma_{ref})/E$. For the early cycles, prior to structural shakedown, the creep crack extension per cycle, $(da/dN)_c$, is evaluated over the dwell period, t_h, as:

$$(da/dN)_c = \int_0^{t_h} A[\overline{C}^*]^q \, dt \tag{8.26}$$

(iv) Steady cycle creep crack growth, t > t_{cyc}, when cyclic loading is significant.

At $t \geq t_{cyc}$, equation (8.26) is replaced by equation (8.21), but C^* is calculated from the loads in the steady cycle obtained from a shakedown analysis.

8.9 Assess Significance of Results

Application of the assessment procedures will lead to one of the following results:

i) The final defect size leads to an acceptable end-of-life safety margin. In this case, a sensitivity analysis should be carried out to ensure that the safety margin is not overly sensitive to variations in the input parameters of the assessment.

ii) Failure or excessive crack growth is indicated within the required service life. In these circumstances, the assessment may be revisited with a view to reducing the assumed pessimisms. In the event that acceptable end-of-life safety margins still cannot be demonstrated, remedial action should be taken.

These scenarios are both discussed in further detail below.

8.9.1 Sensitivity Analysis

The limiting conditions for a failure assessment are described elsewhere in the FITNET procedure. The limiting state is not normally acceptable for engineering purposes and confidence in determining safe loading conditions is traditionally gained by applying safety or reserve factors in design calculations. However, the application of particular numerical factors in fracture analyses can be misleading because of the inherent but variable inter-dependence of the parameters contributing to fracture behaviour.

Confidence in assessments is gained in two stages. The use of lower bound limit load solutions, together with upper bound loads, defect sizes and stress intensity factor values, provides confidence that the failure assessment is suitably conservative. This should then be reinforced by investigating the sensitivity of the assessment point to variations of appropriate input parameters.

For example, the sensitivity analysis may consider uncertainties in the service loading conditions, the extrapolation of materials data to service conditions, the nature, size and shape of the flaw, and the calculational inputs.

For defects found in service, the sensitivity of the assessment to any assumption about whether the crack is already growing may be tested by performing assessments both with and without the incubation stage. It is recommended that, where cast-specific data are not available, an initial assessment be performed using best-estimate, mean data. The sensitivity study should include the following combinations: (i) lower bound creep crack growth rate with upper bound creep strain data, (ii) upper bound creep crack growth rate with lower bound creep strain data. It should be recognised that a sensitivity analysis which combines upper bound creep strain data, lower bound crack initiation data and upper bound creep crack growth data is likely to be overly conservative.

Confidence in an assessment is gained when it is possible to demonstrate that realistic changes in the input parameters do not lead to dramatic reductions in the end-of-life safety margin. Further confidence in the assessment and in any appropriate inspection period is gained when consideration of the end-of-life crack growth rate shows that there is not rapid crack extension leading to imminent failure. Details of the sensitivity analysis should be reported with the assessment results.

An alternative to the deterministic approach is to use probabilistic methods to directly determine failure probabilities. These methods make use of the statistical variation of the input parameters, rather than assuming that the parameters are single-valued, as in the deterministic approach. Such assessments require estimates of the statistical distributions of the variable input parameters. Advice is contained in Annex H.

8.9.2 Remedial Action

Many regulations and design standards require, or at least recommend, periodic inspection of components under loads such as internal pressure and/or high temperature operation. Often the regulations require a pressure test to be performed, verifying that pressure components are not leaking. Alternatively, regulations accept the use of some non-destructive testing, demonstrating component integrity.

Typical re-inspection periods are every ten years or lower. Inspections can be performed using some of the available methods and techniques described in Annex D. Inspection of components operating in the creep range uses these techniques to demonstrate integrity, but other techniques are also used to determine creep status, including:

- Magnetite layer measurement: the magnetite layer is indicative of the operational effective temperature. The layer is usually measured by ultrasonic testing, but sometimes destructive testing of samples extracted from selected points, confirms ultrasonic testing results. Combined with tube thickness measurements, this technique is used for creep remaining lifetime determination.
- Hardness: hardness is not a clear indicator of remaining lifetime, but it is a cheap technique and in combination with replicas can provide useful information about creep component status.
- Metallographic replicas; the analysis of replicas provides information about physical and structural damage of the component. As replicas require some surface preparation, it is usual to complement these with hardness measurements. The technique is also used to analyse detected cracks, helping to determine cracking mechanisms and crack growth, for input into remaining lifetime assessment.
- Dimensional analysis: creep deformation can be detected and surveyed by selected measurements.
- X-ray diffraction: this technique provides information on material composition, level of stress and creep status.
- Micro-specimen destructive testing: some tests are available, providing information on material properties and creep status. The most frequently used techniques are the miniature specimen creep test, the impression creep test and the small punch test.

These techniques are described in more detail in Annex D.

If failure or excessive crack growth is indicated within the required service life, then it may be possible to revisit the assessment with a view to reducing the assumed pessimisms. For example, it may be possible to obtain specific materials data that is less pessimistic than the use of bounding data. Only in the event that an acceptable safety margin still cannot be demonstrated should remedial action be taken.

The most frequent measure, when the calculated lifetime is lower than expected is to modify the re-inspection period and/or recommend the use of different inspection techniques. For example, if calculations associated with hardness measurements indicate that the remaining lifetime of a component is lower than 20000 hours, it is possible to look for cracks (magnetic particles, dye penetrant liquid, ultrasonic testing), perform metallographic replicas, dimensional analysis or magnetite layer measurements.

Remedial action may involve changing the in-service parameters (such as load, temperature or desired service life) and then using the assessment procedure either to demonstrate acceptance or to estimate at what time repair will be necessary. Alternatively, the defective component may be repaired or replaced.

The sensitivity analysis is particularly useful for indicating which materials properties may significantly influence the assessment. For example, if remedial action is required because the desired service life exceeds the rupture life there is little point in generating accurate creep crack growth data in an attempt to improve the assessment.

8.9.3 Report Results

When reporting the results of a structural integrity assessment, the information listed below should be presented.

1. LOADING CONDITIONS - e.g. service load and temperature and service life including life seen to date; conditions considered for time independent loadings, for example transient or fault loadings; categorisation of loads and stresses.

2. MATERIAL PROPERTIES - material specification; creep rupture data, incubation COD, creep strain data, creep crack growth data; time-independent assessment material data (yield stress, ultimate tensile stress and fracture toughness for material with creep damage at crack tip); elastic data (Young's modulus, Poisson's ratio); whether data obtained by direct testing or indirect means; source and validity of data.

3. DEFINITION OF FLAW - flaw location, shape and size; allowance for sizing errors; whether re-characterisation of flaw undertaken.

4. REFERENCE STRESS - source of limit load solution; yield criterion; whether local and/or global collapse considered.

5. STRESS INTENSITY FACTOR SOLUTION - source of K solution (e.g. standardised solution, finite-element analysis).

6. SIGNIFICANCE OF CREEP AND FATIGUE – results of tests for insignificant creep, fatigue and creep-fatigue interactions, if applicable.

7. TIME INDEPENDENT ASSESSMENT - form of assessment, reserve factors.

8. CYCLE DEPENDENT ASSESSMENT – Type of fatigue crack growth law; stress intensity factor range, crack closure parameter, surface strain range, creep damage; time to shake down to steady cyclic state.

9. TIME DEPENDENT ASSESSMENT - results of analysis; incubation time, redistribution time, defect size after growth, crack velocity parameter, time to rupture by continuum damage.

10. SENSITIVITY ANALYSIS - input parameters against which sensitivity studies undertaken (e.g. flaw size, material properties, etc); results of each individual study.

11. REPORTING - nature of the quality assurance to which the analysis has been subjected.

Known pessimisms incorporated in the assessment route should be listed. All departures from the procedure should be reported and separately justified. A separate statement should be made about the significance of potential failure mechanisms remote from the defective areas.

8.10 Additional Information

8.10.1 Treatment of Defects in Weldments

8.10.1.1 Introduction

This section gives the information required to apply the procedure of Section 8.2 to defects in weldments. The scope of the section is first described in Section 8.10.1.2. A particular problem with weldments is the presence of residual welding stresses. Although these relax as creep strains accumulate, they may reduce creep life by initiating crack growth at shorter times and by increasing crack growth rates. Often the effect is small, particularly for stress-relieved welded joints made from creep-ductile materials. Therefore, a simple check is made in Section 8.10.1.3 to assess whether welding residual stresses are significant. Then, a simplified, conservative assessment procedure is described in section 8.10.1.4. In some cases, the level of conservatism may be excessive and a more detailed procedure is described in Section 8.10.1.5 to remove some of this over-conservatism. It should, however, be recognised that validation for the detailed procedure is limited to specific weldment types. Finally, Section 8.10.1.6 describes some specific modes of cracking observed in high temperature weldments.

8.10.1.2 Scope

Defects in austenitic and ferritic similar metal welds and in conventional bi-material dissimilar metal welds (DMWs) can be assessed. Allowance is made for welding residual stresses where necessary as set out in Section 8.10.1.3. Both crack growth and continuum damage accumulation are addressed.

Defects which are characterised as being fully in either the ferritic or austenitic materials adjacent to a DMW should be assessed using the procedure of Section 8.2 and the appropriate homogeneous material properties.

Experience with the DMW crack growth procedures of Section 8.10.1.5 is currently limited to ferritic 2.25Cr1Mo to austenitic Type 316 pipe or tube welds made using either austenitic or nickel-based (Inconel) weld metal. The procedure may, however, be used for other geometries and material combinations provided that the required data have been obtained.

Secondary stresses are assumed to relax over a redistribution period. In some cases, the secondary stresses may have completely relaxed due to creep in service at the start of the assessment period. It is, however, conservative to treat all stresses as primary and to neglect relaxation.

Allowance for an incubation time of a pre-existing defect prior to significant crack propagation is made for similar weldments under steady loading. No such period is currently assessed, within the procedures of Section 8.10.1.5 for DMWs; it is assumed that crack growth occurs immediately upon loading. For creep-fatigue loading, it is generally assumed that there is no incubation period.

8.10.1.3 Significance of Welding Residual Stresses

Simple tests, as set out below, may be applied to the case of residual stress fields with modest elastic follow-up, $Z \le 3$. Outside this range, the residual stress should be considered significant.

Welding residual stress do not significantly affect the results of an assessment if

$$\frac{\sigma_{max}}{E} < 0.1\left[\frac{\delta_i}{R'(a_o)}\right]^{n/(n+1)} \tag{8.27}$$

where $\sigma_{\max}$ is the peak equivalent welding residual stress, and δ_i, the incubation crack opening displacement. In a non-stress-relieved weldment, $\sigma_{\max}$ may be conservatively taken as the material yield stress, but in practice, inequality (8.27) may be difficult to satisfy for cracks in non-stress-relieved weldments. Normalised through-wall as-welded residual stress profiles are given in Annex C for some geometries.

The length, R', is calculated from equation (8.10) assuming homogeneous material properties. When $\delta_i \leq R'$ (a_o), as is usually the case, it is conservative to set n/(n+1) equal to unity.

8.10.1.4 Simplified Assessment

In the simplified estimate, the time for creep rupture failure and the extent of creep crack growth are estimated. It is assumed that the crack incubation time is zero.

Bulk creep damage is assessed assuming that the weld is homogeneous with the rupture properties of the weakest region. The time to failure by continuum damage mechanisms, t_{CD}, is calculated using equation (8.15). The calculation is performed separately for each of the weldment constituents using the appropriate rupture data, but with the reference stress always defined from equation (8.8) from the homogeneous limit load. The value of t_{CD} used in the assessment is the smallest of those determined for the different regions, i.e. the lowest life obtained from equation (8.15).

In order to assess creep crack growth, C* is calculated from equation (8.16). It is assumed that the weld is homogeneous for the purposes of calculating the reference stress of equation (8.8) and the length parameter of equation (8.10). C* follows from equation (8.9) with creep strain rate data of the fastest creeping region. The extent of creep crack growth is then obtained from equation (8.21) with this value of C* and creep crack growth data for the region where the flaw is located, unless the flaw can propagate into material with a higher crack growth law.

For other than simple primary loadings, estimates of C* are given in Section 8.10.2.

8.10.1.5 Detailed Assessment

For the purposes of calculating the initiation time and creep crack growth, the reference stress, $\sigma_{\mathrm{ref}}^{\mathrm{p}}$, is calculated for the specific location of the crack. For continuum damage calculations, a reference stress is calculated for each microstructural zone. These reference stresses are different, in general, from that calculated using equation (8.8) assuming homogeneous creep properties across the joint, as used in Section 8.10.1.4.

The reference stress for a given zone is a factor k times the corresponding homogenous cracked-body reference stress, $\sigma_{\mathrm{ref,hom}}^{\mathrm{p}}$, that is

$$\sigma_{ref}^{p} = k\sigma_{ref,\mathrm{hom}}^{p} \tag{8.28}$$

where $\sigma_{\mathrm{ref,hom}}^{\mathrm{p}}$ is obtained from equation (8.8). The factor k is different for the different weld zones.

The source of different k values may be illustrated by considering a pipe under pressure and end load. For some stress states, such as pressure only, the maximum principal stress is approximately parallel to the fusion boundary (‘hoop stress control’) and is different in the different weld zones as a result of stress redistribution; this leads to k values different from unity. For cases of ‘axial-stress control’, such as under high system loads where the maximum principal stress is transverse to the fusion boundary, overall stress redistribution cannot occur and k=1 is more likely.

The reference stress for each constituent in a weldment is determined from a limit load calculation performed with the assumed yield stress of each region proportional to the creep rupture strength of the corresponding material for the service lifetime. The resulting limit load may differ from that of the homogeneous component due to the effects of the mismatch in plastic (creep) properties. The reference stress for each zone then follows from equation (8.8) but using the local yield stress and the mismatch limit load. Note that the factor k is then the ratio of the resulting reference stress to the homogeneous value. Advice on mismatch limit loads is given in Section 6 and Annex B.

In general, the factor k is loading, geometry and material dependent and accounts for the elevation in stress in strong material within the weldment or, conversely, the reduction in stress in weaker materials in the weldment. This 'weld redistribution factor' can be conveniently expressed as a function of the ratio of weld metal/parent metal minimum creep rates for the case of a pipe-pipe butt weld under internal pressure loading. Some illustrative k factors for weld metal, HAZ and parent material for different ferritic 0.5CrMoV weldment combinations are shown in Table 8.1 for a pipe with the ratio of external to internal radius, r_o/r_i = 1.52 and typical creep properties.

Table 8.1 – The influence of weld metal/parent metal minimum creep rate ratio on k factors for 0.5CrMoV weldments (*coarse microstructure; ** refined). The k factors were derived for an uncracked pipe-pipe butt weld, with ratio of outer to inner radius of 1.52, under internal pressure alone.

Weld Metal/Parent Metal Min. Creep Rate Ratio	**k Factor**		
	Parent	**Weld**	**HAZ**
1 (0.5CrMoV/0.5CrMoV)	1	1	1.37
5 (2.25Cr1Mo/0.5CrMoV)	1	0.70	1.40* 1.0**
14 (1Cr0.5Mo/0.5CrMoV)	1	0.57	1.43

The time to failure by continuum damage mechanisms, t_{CD}, should be calculated using equation (8.15). The calculations should be performed separately for each of the weldment constituents using the appropriate rupture data, and the corresponding reference stress from equation (8.28). The value of t_{CD} is the smallest of those determined for the different regions.

The time to incubate a growing creep crack, t_i, is calculated using equation (8.16). The creep strain, reference stress and incubation crack opening displacement, δ_i, are specific to the microstructural region within which the crack tip is located. However, for the case of hoop stress control, compatibility of hoop strain rate across the weld implies that ε_c in equation (8.16) can be replaced by the corresponding parent strain at the parent reference stress. When $\delta_i / R'(a_o)$ is small and the right hand side of equation (8.16) is negative, the incubation time, t_i, should be set to zero.

The creep crack growth parameter, C^*, should be estimated from equation (8.9) using the value of σ_{ref}^{p} and the creep properties appropriate to the material region within which the crack tip is located, together with the value of R' determined from equation (8.10) but assuming homogeneous material properties. For the case of hoop stress control, compatibility of hoop strain across the weld implies that $\dot{\varepsilon}_c$ in equation (8.9) for C^* can be replaced by the corresponding parent strain rate at the parent reference stress. In order to obtain crack growth rates from C*, the creep crack growth law should be specific to the microstructural region within which the crack is growing and should account for changes in growth rate with any changes in microstructure that the crack encounters. In applying transient corrections, stress redistribution is complete and widespread creep conditions are established when the redistribution time, t_{red}, defined by equation (8.11) is exceeded for the region containing the defect.

For bi-material dissimilar metal welds (DMWs), some simplifications of the above approach are possible if it is assumed that the defect occurs on the boundary between two material states. In practice, crack propagation in these DMWs is generally associated with the ferritic base to weld metal interface region. This interface region is considered here for simplicity as consisting of the ferritic base metal, the weld metal and the heat affected zone (HAZ). . For a cracked weldment, the homogeneous limit load reference stress of equation (8.8) is used with corresponding uniaxial cross-weld rupture data to assess creep rupture of the DMW. To assess creep crack growth, the stress intensity factor K used in the calculation of the length scale R' in equation (8.10) is determined assuming homogeneous elastic properties for the weld constituents. C^* is estimated by equation (8.9) using the homogeneous reference stress and the creep strain rate, $\dot{\varepsilon}_c$, evaluated for a reference material at the reference stress level. It is conservative to equate the reference material to the ferritic HAZ. This assumes that, under simple uniaxial loading, the HAZ is the region of lowest creep resistance. A creep crack growth rate expression of the form of equation (8.3) is then used for interfacial crack growth. A and q should be determined from testing creep crack growth specimens of standard geometry, such as the compact tension (CT) specimen, using conventional test procedures. The specimen should be such that the ferritic to weld interface region lies in the plane of the crack in the test specimen. Care should be taken that the starter notch meets the appropriate interface microstructure. The specimen should be extracted where possible from a full-size weldment so as to reproduce accurately the details of the ferritic HAZ microstructure. It is not necessary, however, that the specimen contains the austenitic base metal as deformation in the CT specimen, for example, is dominated by bending about the ligament ahead of the crack tip and hence by the materials adjacent to the crack. The homogeneous experimental calibration (η) factor relating C^* to the measured load and creep displacement rate should be used. This has been shown to give a close approximation between experimentally calculated and finite element values of C^* for the bi-material CT specimen under load control for a range of mismatch in creep rates.

8.10.1.6 Specific Modes of Cracking

Stress-relief cracking in ferritic weldments. Circumferential heat-affected-zone (HAZ) and transverse weld metal cracking arise during post-weld stress relief heat treatment or very early in the plant operating life. Initiation of cracking is very dependent on materials composition, weldment microstructure and residual stress; the latter two factors being critically dependent on welding and heat treatment procedures. In turn, crack growth is also dependent on microstructure and stress, both of which vary initially as a function of position and change further as a function of time and temperature as the weldment is exposed to plant conditions. The effect of multiaxial stress state on creep rupture may need to be considered.

Type IV cracking in ferritic weldments. This mode of failure involves the initiation and growth of circumferential creep cracks in the low temperature extremity of the HAZ adjacent to the untransformed parent material. It has been observed from times midway through the design life and onwards. Axial loading over and above the nominal axial stress due to internal pressure is significant in promoting this mode of cracking. The intercritically transformed region is thin making it difficult to collect materials data relevant to the intercritical region and to perform multi-material stress analysis of the weldment which includes the thin zone. The accuracy of the assessment is often limited by the uncertainty of the axial stresses occurring in pipe work.

Transverse weld metal cracking in ferritic weldments. This is a mode of cracking which has been encountered in pipe to pipe weldments subjected to predominantly internal pressure loading. Under these conditions the weldments invariably reach or exceed their design lives by which time the hoop strain accumulation initiates axial cracks, transverse to the weldments, in the more coarse-grained columnar regions of the weldments. This generally involves multiple crack initiation leading eventually to excessive deformation, bulging and the formation of secondary circumferential cracks in the weld metal, which result in eventual failure.

Austenitic weldment cracking. Solidification cracking or stress-corrosion cracking mechanisms can give rise to defects early in life or at various times throughout life, respectively, which may propagate by creep in these weldments. In the absence of such defects, the anticipated failure mode is transverse weld metal cracking. In addition stress-relief or reheat cracking similar to that described for ferritic steels above can also occur in austenitic steels. This brittle intergranular cracking occurs in the HAZ close to the fusion line as a result of the concentration onto grain boundaries of relaxation strains associated with stress relief, or the concentration of creep strains during extended service. This strain concentration is due to strengthening within the matrix of the grains resulting from fine precipitate dispersions on dislocation networks. The mechanism appears able to operate in service at temperatures as low as 500˚C, given sufficiently long times. The propensity to this type of cracking is greatest in the Nb stabilised Type 347 steel, but it is also encountered in the Ti stabilised Type 321 steel. Dependent upon operating temperature and the level of residual or applied stress a similar mechanism may also occur in Type 316 steel, particularly high carbon varieties. It is however less likely to occur in nitrogen strengthened low carbon Type 316 varieties.

Dissimilar metal weldments. Failure of these weldments occurs almost exclusively by circumferential cracking along the fusion boundary on the ferritic material side of the weldment. The stresses arising due to the differences in coefficients of thermal expansion play an important role in this mechanism of cracking, as do processes of ageing that give rise to precipitates forming along the ferritic-austenitic interface.

8.10.2 Treatment of Secondary Loading

For combined primary and secondary loading, if the initial response on loading is elastic, a total reference stress, σ_{ref}, is used instead of that defined by equation (8.8) and is

$$\sigma_{ref} = \sigma^{p}_{ref}(K^{p} + K^{s}) / K^{p} \tag{8.29}$$

where K^{p}, K^{s} are the stress intensity factors for the primary loading and the secondary loading, respectively. This total reference stress may relax due to both creep straining and crack growth and the rate of change is given by

$$\frac{\dot{\sigma}_{ref}}{\sigma_{ref}} + \left[\frac{K^{s}}{\left(K^{p}+K^{s}\right)}\left\{\frac{\partial K^{p}/\partial\left(a/w\right)}{K^{p}} - \frac{\partial K^{s}/\partial\left(a/w\right)}{K^{s}}\right\} - \frac{\partial\sigma^{p}_{ref}/\partial\left(a/w\right)}{\sigma^{p}_{ref}}\right]\frac{\dot{a}}{w} + \frac{\mathrm{E}\dot{\varepsilon}_{c}}{Z\sigma_{ref}} = 0 \tag{8.30}$$

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 total reference stress.

For elastic-plastic response on initial loading, equation (8.13) needs to allow for plastic strains and must also be generalized for combined primary and secondary loading. If it is assumed that plasticity and creep are both described by power-law equations, with creep strain given by equation (8.1) and plastic strain given by $\varepsilon_{\mathrm{p}} = \beta\sigma^{\mu}$ with $\mu = \mathrm{n}$, then an estimate of C(t) is

$$\frac{C(t)}{C^{*}} = \left(\frac{\sigma_{ref}}{\sigma^{p}_{ref}}\right)^{n+1}\left[\frac{\left(\varepsilon_{ref}/\varepsilon^{0}_{ref}\right)^{n+1}}{\left(\varepsilon_{ref}/\varepsilon^{0}_{ref}\right)^{n+1} - \left(\sigma^{0}_{ref}/\mathrm{E}\varepsilon^{0}_{ref}\right)}\right] \tag{8.31}$$

where $\varepsilon_{\mathrm{ref}}$ is the total strain at σ_{ref}, C^{*} refers to the value evaluated for the primary loading only, and the initial value of the total reference stress is $\sigma^{0}_{\mathrm{ref}}$, defined by equation (8.29) for elastic response on initial loading. In order to use equation (8.31), it is necessary to estimate $\varepsilon^{0}_{\mathrm{ref}}$, which is the total elastic-plastic strain corresponding to $\sigma^{0}_{\mathrm{ref}}$. For elastic behaviour on initial loading, this is simply $\sigma^{0}_{\mathrm{ref}}/\mathrm{E}$. Equation (8.31) may also be expressed as

$$\frac{C(t)}{C^*}=\left(\frac{\sigma_{ref}\dot{\varepsilon}_{c,ref}}{\sigma^p_{ref}\dot{\varepsilon}^p_{c,ref}}\right)\left[\frac{\left(\varepsilon_{ref}/\varepsilon^0_{ref}\right)^{1/(1-q)}}{\left(\varepsilon_{ref}/\varepsilon^0_{ref}\right)^{1/(1-q)}-\left(\sigma^0_{ref}/\mathrm{E}\varepsilon^0_{ref}\right)}\right] \tag{8.32}$$

where $\dot{\varepsilon}_{c,ref}$ and $\dot{\varepsilon}^p_{c,ref}$ are the creep strain rates at σ_{ref} and σ^p_{ref} respectively, which generalizes equation (8.13) to combined loading.

For pure primary loading, equation (8.31) can be written

$$\frac{C(t)}{C^*}=\frac{\left(\varepsilon^{e+p+c}_{ref}/\varepsilon^{e+p}_{ref}\right)^{n+1}}{\left(\varepsilon^{e+p+c}_{ref}/\varepsilon^{e+p}_{ref}\right)^{n+1}-\left(\varepsilon^{e}_{ref}/\varepsilon^{e+p}_{ref}\right)} \tag{8.33}$$

where superscripts e, e+p and e+p+c denote elastic, elastic-plastic and elastic-plastic plus creep, respectively. This generalizes equation (8.13) to the case when plasticity occurs on initial loading.

For pure primary loading, it is straightforward to evaluate the strain terms in equation (8.33) as the reference stress is well defined from the limit load expression of equation (8.8). For more general loading, the initial strain term may be obtained from an estimate of the initial value of J, J_0. By analogy with equation (8.9) this is given by

$$J_0=\sigma^0_{ref}\varepsilon^0_{ref}R' \tag{8.34}$$

The procedures of Section 6 may be used to estimate J_0 and give

$$\frac{K^p+VK^s}{\sqrt{\mathrm{E}J_0}}=f\left(L_r\right) \tag{8.35}$$

where V is the parameter treating interactions between primary and secondary stress and $f(L_r)$ is defined by the failure assessment diagram. Then,

$$J_0=\frac{\left(K^p+VK^s\right)^2}{\mathrm{E}f^2\left(L_r\right)} \tag{8.36}$$

From equation (8.34),

$$\sigma^0_{ref}\varepsilon^0_{ref}\left(K^P/\sigma^p_{ref}\right)^2=\frac{\left(K^p+VK^s\right)^2}{\mathrm{E}f^2\left(L_r\right)} \tag{8.37}$$

or

$$\sigma^0_{ref}\varepsilon^0_{ref}=\frac{\left(\sigma^p_{ref}\right)^2}{\mathrm{E}}\,\frac{\left(1+VK^s/K^p\right)^2}{f^2\left(L_r\right)} \tag{8.38}$$

This may be used to define ε^0_{ref} if the shape of the stress-strain curve is known.

8.10.3 Failure Assessment Diagram Methods

8.10.3.1 Introduction

The methods set out in Section 8.2 for assessing incubation and the early stages of creep crack growth are based on the evaluation of parameters including crack opening displacement, δ, and the crack tip parameters C^* and C(t) together with experimental data describing creep crack incubation or growth. However, for low temperature fracture assessment, the concept of a Failure Assessment Diagram (FAD) is used in Section 6 to avoid detailed calculations of crack tip parameters. In recent years, FAD approaches have been extended to the creep regime. The high temperature Time Dependent Failure Assessment Diagram (TDFAD) method has been incorporated into R5. A key requirement of TDFAD approaches is the evaluation of a time dependent creep toughness, denoted K_{mat}^{c}.

In Germany, a similar Two Criteria Diagram (2CD) Approach has been independently developed to assess creep crack incubation in ferritic steels. This approach uses crack tip and ligament damage parameters, R_K and R_σ, respectively, which are similar to the parameters K_r and L_r used in the TDFAD. The critical stress intensity factor, K_{Ii}, is used as a measure of crack initiation resistance rather than the creep toughness, K_{mat}^{c}, used in the TDFAD approach. During the past two decades relevant materials data have been obtained for various rotor and cast steels used in power plant technology and the method has been applied to the assessment of defects in components such as cast steel components.

The TDFAD and 2CD methods are described in this section. More detailed information is contained in the Bibliography, in particular in R5 [8.1] and in Ewald et al. [8.29].

8.10.3.2 Creep Crack Initiation Assessment Procedures

8.10.3.2.1 TDFAD Approach

The TDFAD is based on the FAD specified in Section 6 and involves a failure assessment curve relating the two parameters K_r and L_r, which are defined in equations (8.39) and (8.40) below, and a cut-off L_r^{max}. For the simplest case of a single primary load acting alone

$$K_r = K_{I\,id}/K_{mat}^{c} \tag{8.39}$$

where $K_{I\,id}$ is the stress intensity factor and K_{mat}^{c} is the appropriate creep toughness value, and

$$L_r = \sigma_{ref}/\sigma_{0.2}^{c} \tag{8.40}$$

where σ_{ref} is the reference stress of equation (8.8) and $\sigma_{0.2}^{c}$ is the stress corresponding to 0.2% inelastic (plastic plus creep) strain from the average isochronous stress-strain curve for the temperature and assessment time of interest, see Figure 8.4. The failure assessment diagram is then defined by the equations

$$K_r = \left[\frac{E\cdot\varepsilon_{ref}}{L_r\cdot\sigma_{0.2}^{c}} + \frac{L_r^{3}\cdot\sigma_{0.2}^{c}}{2\cdot E\cdot\varepsilon_{ref}}\right]^{-1/2} \qquad L_r \le L_r^{max} \tag{8.41}$$

$$K_r = 0 \qquad L_r > L_r^{max} \tag{8.42}$$

In equation (8.41), E is Young's modulus and ε_{ref} is the total strain from the average isochronous stress-strain curve at the reference stress $\sigma_{ref} = L_r\cdot\sigma_{0.2}^{c}$, for the appropriate time and temperature. For moderate stresses and times, valid isochronous data should be available to evaluate equation (8.41) for a range of stress levels (i.e. L_r values). At low stresses where creep strains are negligible, equation (8.41) reduces to $K_r = (1+0.5L_r^2)^{-1/2}$, which is independent of time. Even at higher stresses the shape of the TDFAD is relatively insensitive to time and this with the low stress limit enables the TDFAD to be constructed without a need for accurate data extrapolation. Thus, equation (8.41) enables the TDFAD to be plotted with K_r as a function of L_r, as shown schematically in Figure 8.5. The cut-off, L_r^{max}, is defined as

$$L_r^{max} = \sigma_R / \sigma_{0.2}^c \tag{8.43}$$

where σ_R is the rupture stress for the time and temperature of interest. However, for consistency with the methods in Section 6, the value of L_r^{max} should not exceed $\overline{\sigma}/\sigma_{0.2}$ where $\overline{\sigma}$ is the short-term flow stress and $\sigma_{0.2}$ is the conventional 0.2% proof stress. As in Section 6, $\overline{\sigma}$ may be taken as $(\sigma_{0.2}+\sigma_u)/2$ where σ_u is the ultimate tensile strength.

A central feature of the TDFAD approach is the definition of an appropriate creep toughness which, when used in conjunction with the failure assessment diagram, ensures that crack growth in the assessment period is less than a value Δa. Creep toughness values may be estimated indirectly from conventional creep crack incubation and growth data or evaluated directly from experimental load versus displacement information. This section describes the latter direct approach for evaluating creep toughness values.

Direct approaches for determining creep toughness are based on experimental load-displacement data. Consider a load-controlled creep crack growth test conducted on a standard compact tension (CT) specimen. It is assumed that the amount of crack growth in the test, Δa, is small, so that the total displacement, Δ_T, may be conveniently partitioned into elastic, plastic and creep components, denoted Δ_e, Δ_p and Δ_c, respectively, where

$$\Delta_T = \Delta_e + \Delta_p + \Delta_c \tag{8.44}$$

Similarly, the total area under the load-displacement curve, UT, may be partitioned into elastic, plastic and creep components, denoted U_e, U_p and U_c, respectively, where

$$U_T = U_e + U_p + U_c \tag{8.45}$$

Testing standards then give an expression for the experimental total J value and this may be used to give the creep toughness as

$$K_{mat}^c = \left[K^2 + \frac{E'\eta}{B_n(W-a_0)} \left(U_p + \frac{n}{n+1} U_c \right) \right]^{1/2} \tag{8.46}$$

where W is the specimen width, a_0 is the initial crack length, B_n is the net specimen thickness, $E' = E$ for plane stress and $E' = E/(1-\nu^2)$ for plane strain conditions, and

$$\eta = 2 + 0.522(1 - a_0/W) \tag{8.47}$$

for CT specimens. Values of creep toughness, K_{mat}^c, are derived from creep crack growth tests as a function of crack growth increment, Δa.

8.10.3.2.2 Two Criteria Diagram

In the Two Criteria Diagram (2CD) for creep crack initiation the nominal stress σ_{npl} describes the stress situation in the ligament, i.e. in the far-field of the creep crack and the elastic parameter K_{Iid} at time zero characterizes the crack tip situation. These loading parameters are normalised in a 2CD (Figure 8.6) by the respective time and temperature dependent values, which indicate the material resistance against crack initiation. The normalised parameters are the stress ratio

$$R_\sigma = \sigma_{n\ pl} / \sigma_R \tag{8.48}$$

for the far-field and the stress intensity factor ratio

$$R_K = K_{I\ id} / K_{Ii} \tag{8.49}$$

for the crack tip. The value σ_R is the creep rupture strength of the material and the parameter K_{Ii} characterizes the creep crack initiation of the material. This parameter has to be determined from specimens with a high ratio $K_{I\ id} / \sigma_{n\ pl}$, preferably using CT25-specimens. The 2CD distinguishes three fields of damage mode separated by lines of constant ratio R_σ / R_K. Above $R_\sigma / R_K = 2$ ligament damage is expected, below $R_\sigma / R_K = 0.5$ crack tip damage is expected and between these lines a mixed damage mode is observed. Crack initiation is only expected above a boundary line.

8.10.3.3 Comparison of Parameters

A comparison can be made between the parameters in the TDFAD and 2CD. L_r can be compared with R_σ and K_r can be compared with R_K. The first noticeable difference is that L_r lies on the abscissa of the TDFAD and R_σ lies on the ordinate of the 2CD. The reference stress, σ_{ref}, can be compared with the nominal stress, $\sigma_{n\ pl}$. The reference stress can be defined for the appropriate stress state (plane stress or plane strain) and either Tresca or von Mises yield surfaces. Non-dimensional values of reference stress for a CT-specimen for two cases are given below.

Based on Tresca for plane stress conditions

$$\sigma_{ref} \frac{B_n \cdot (W-a)}{P} = \frac{W-a}{W \cdot [\sqrt{2 + 2 \cdot (a/W)^2} - 1 - (a/W)]} \ . \tag{8.50}$$

Based on von Mises for plane strain conditions

$$\sigma_{ref} \frac{B_n (W-a)}{P} = \frac{W-a}{W \times (2/\sqrt{3})[\sqrt{2.702 + 4.599(a/W)^2} - 1 - 1.702(a/W)]} \tag{8.51}$$

In a similar way, the nominal stress $\sigma_{n\ pl}$ [12] for a CT-specimen can be expressed non dimensionally as

$$\sigma_{n\,pl} \frac{B_n \cdot (W-a)}{P} = \sqrt{\frac{B_n}{B}} \left[1 + 2\frac{W+a}{W-a}\right] . \tag{8.52}$$

The reference stresses determined according to plane stress using the Tresca criterion and according to plane strain using the von Mises criterion are compared with the nominal stress $\sigma_{n\ pl}$ in Figure 8.7. The results of plane stress (Tresca) are closest to the values of nominal stress.

K_r represents the ordinate of the R5 TDFAD and RK represents the abscissa of the 2CD. These ratios are calculated by dividing the linear elastic stress intensity factor $K_{I\ id}$ by the material incubation parameters K^{c}_{mat} and K_{Ii}, respectively. Hence, the creep toughness parameter K^{c}_{mat} has to be compared with the critical stress intensity factor K_{Ii}. A comparison between the incubation parameters is shown in Figure 8.8 and Figure 8.9 for a 1CrMoV-steel at 550 °C assuming a creep crack initiation length $\Delta a_i = 0.5$ mm. In Figure 8.8 (lin-log-diagram) the creep toughness tends to become equal to the critical stress intensity factor for long times. However this trend does not become obvious in Figure 8.9 (log-log-diagram).

The parameter $\sigma^{c}_{0.2}$ in the R5 TDFAD approach is the stress to give 0.2% inelastic (plastic plus creep) strain at the assessment time, denoted the 0.2% inelastic strength. Figure 8.10 shows the variation of $\sigma^{c}_{0.2}$ and the rupture stress σ_R with time for a 1CrMoV-steel at 550 °C. For completeness, this figure also shows the variation in the stress to give 1% inelastic strain. Figure 8.11 shows the 0.2% and 1% inelastic strength values normalised by the rupture stress σ_R. It can be seen that the ratio $\sigma^{c}_{0.2}/\sigma_R$ varies from 0.6 at 100 hours to 0.4 at 10 000 hours. The ratio $\sigma^{c}_{0.1}/\sigma_R$ tends to 0.75 for long times. This value is the basis of the value of intercept on the ordinate of the 2CD.

8.10.3.4 Comparison of the TDFAD and the Two Criteria Diagram

In this section a comparison of the R5 TDFAD and 2CD is described. As an example data for 1CrMoV-steel at 550 °C are analysed. Data from experiments with different specimen types (Compact Tension specimens, Double-Edge Notched Tension specimens, DENT) were used. The width of the specimens was up to 200 mm (CT) and 50 mm (DENT) with thickness of up to 100 mm (CT) and 60 mm (DENT). As the crack initiation criterion, a constant crack length of $\Delta ai = 0.5$ mm was used. Figure 8.12 shows an example for the prediction of creep crack initiation time with the TDFAD, a cut-off $\sigma_R/\sigma^{c}_{0.2}$ on the L_r - axis was used. The prediction of creep crack initiation time using the 2CD is shown in Figure 8.13. Both approaches have been shown to give conservative predictions of creep crack initiation ($\Delta a_i = 0.5$ mm) for 1CrMoV-specimens tested at 550 °C, Figure 8.14. Both methods tend to be most accurate for longer times with the level of conservatism of 2CD reducing with test duration. A comparison of creep crack initiation times of both approaches is shown in Figure 8.15.

In order to compare the TDFAD and 2CD results directly it is necessary to transform R_σ to L_r and R_K to K_r using the following equations

$$L_r = \frac{\sigma_{ref}}{\sigma^{c}_{0.2}} = R_\sigma \left[\frac{\sigma_{ref}}{\sigma^{c}_{0.2}} \frac{\sigma_R}{\sigma_{n\ pl}} \right] \text{ and} \qquad (8.53)$$

$$K_r = \frac{K_{I\ id}}{K^{c}_{mat}} = R_K \left[\frac{K_{I\ id}}{K^{c}_{mat}} \frac{K_{Ii}}{K_{I\ id}} \right]. \qquad (8.54)$$

To transform L_r to R_σ and K_r to R_K the following equations may be used

$$R_\sigma = \frac{\sigma_{n\ pl}}{\sigma_R} = L_r \left[\frac{\sigma_{n\ pl}}{\sigma_R} \frac{\sigma^{c}_{0.2}}{\sigma_{ref}} \right] \quad \text{and} \qquad (8.55)$$

$$R_K = \frac{K_{I\ id}}{K_{Ii}} = K_r \left[\frac{K_{I\ id}}{K_{Ii}} \frac{K^{c}_{mat}}{K_{I\ id}} \right] \qquad (8.56)$$

Equations (8.53) and (8.54) allow the TDFAD to be plotted on the 2CD in R_K - R_σ space as shown in Figure 8.16 for 1CrMoV-steel at 550 °C. Figure 8.17 shows the 2CD plotted on the TDFAD in $L_r - K_r$ space. Both examples show that the TDFAD is a function of time. The comparison is based on plane stress Tresca reference stress solutions. The cut-off values for the TDFAD are based on $\sigma_R/\sigma_{0.2}^c$ for 100 to 10 000 hours.

Further work is required to analyse the results of the different approaches in detail and then apply both approaches to assessment of incubation in structural geometries.

8.10.4 The σ_d Approach

The σ_d approach to predicting crack incubation is based upon the methodology proposed by Moulin et al. [8.10] and incorporated in the French RCC-MR procedures (Appendix A16 [8.6]). It relies on predicting the stress strain response of a defective structure at a defined distance, *d*, ahead of the crack tip. The method concedes that, for all but brittle materials, the stresses and strains obtained from a conventional elastic analysis do not take into account local plasticity at the crack tip that would potentially occur if true material response were modeled. For creep, based upon the monotonic tensile stress-strain response for a material, the method evaluates the local strain amplification due to plasticity and creep at a distance d ahead of the crack tip.

Clearly response at a point *d* ahead of a crack will depend on material properties as well as the imposed loading conditions. A key feature of the σ_d approach, therefore, is to define the critical distance, *d*, to be adopted during analysis. This is invariably achieved experimentally. For Type 316 material Appendix A16 defines the distance *d* at 50 μm.

For creep only loading, the method may be applied as follows:

1. Calculate the stress intensity factor K associated with the creep load, P. This may be accomplished using compendia of stress intensity factor solutions or using detailed numerical models.
2. In the plane of the crack calculate the Rankine equivalent stress, σ_{de} , that is the greatest elastic principal stress at a distance *d* ahead of the crack tip using, for example, Creager's simplified expression:

$$\sigma_{de} = \frac{K}{\sqrt{2\pi d}} \tag{8.57}$$

3. Using the Neuber procedure, applied together with the average material monotonic tensile curve at the assessment temperature, calculate the effective elastic-plastic stress σ_{delpl}. Calculation of the elastic-plastic stress relies on maintaining energy equivalency between the idealised elastic stress strain response and that under elastic-plastic conditions. Additional conservatism may be introduced into the calculation by enhancing the total elastic strain (ε_1) by additional plastic strain (ε_2) accumulated under the imposed primary reference stress σ_{ref}^p :

$$\varepsilon_e = \varepsilon_1 + \varepsilon_2 = \frac{\sigma_{de}}{E} + \left(\frac{\sigma_{ref}^p(a)}{A} \right)^{1/\beta} \tag{8.58}$$

   Thereafter, the effective elastic-plastic stress ahead of the crack tip, σ_{delpl}, and associated total strain, ε_T , are determined from the energy balance:

$$\left(\frac{\sigma_{de}}{E} + \varepsilon_2 \right) . \sigma_{de} = \varepsilon_T . \sigma_{delpl} \tag{8.59}$$

where ε_T and σ_{delpl} are related via the monotonic tensile curve.

$$\varepsilon_T = \frac{\sigma_{delpl}}{E} + \left(\frac{\sigma_{edlpl}}{A}\right)^{1/\beta} \tag{8.60}$$

4. Calculate the stress rupture lifetime, t_{CD}, for the material at the assessment temperature and stress σ_{delpl} based upon best estimate (mean) material properties. The rupture time t_{CD} is deemed to represent the crack incubation time t_i under creep loading conditions.
5. Under variable loading conditions, each elevated temperature dwell (t_h) period may be considered based upon the above approach with crack incubation inferred based upon the summation over all dwell periods as:

$$\sum \frac{t_{hi}}{t_{CDi}} = 1 \tag{8.61}$$

Further advice on application of the σ_d procedures, including advice for creep-fatigue loading is contained in R5 [8.1], but it should be recognized that this is still a developing area, particularly for application to materials other than austenitic stainless steels.

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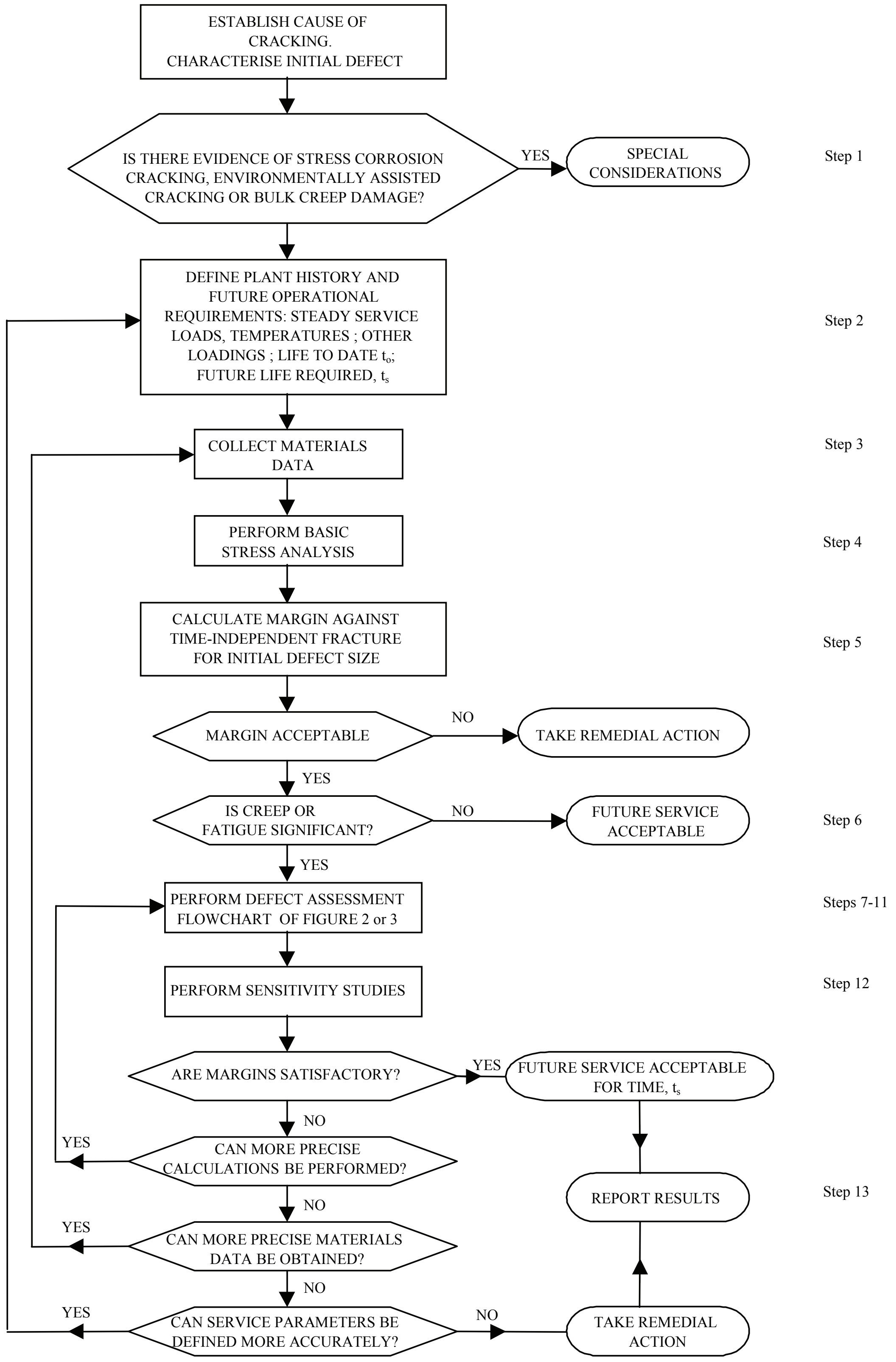

Figure 8.1 – Flowchart for Overall Creep Assessment Procedure

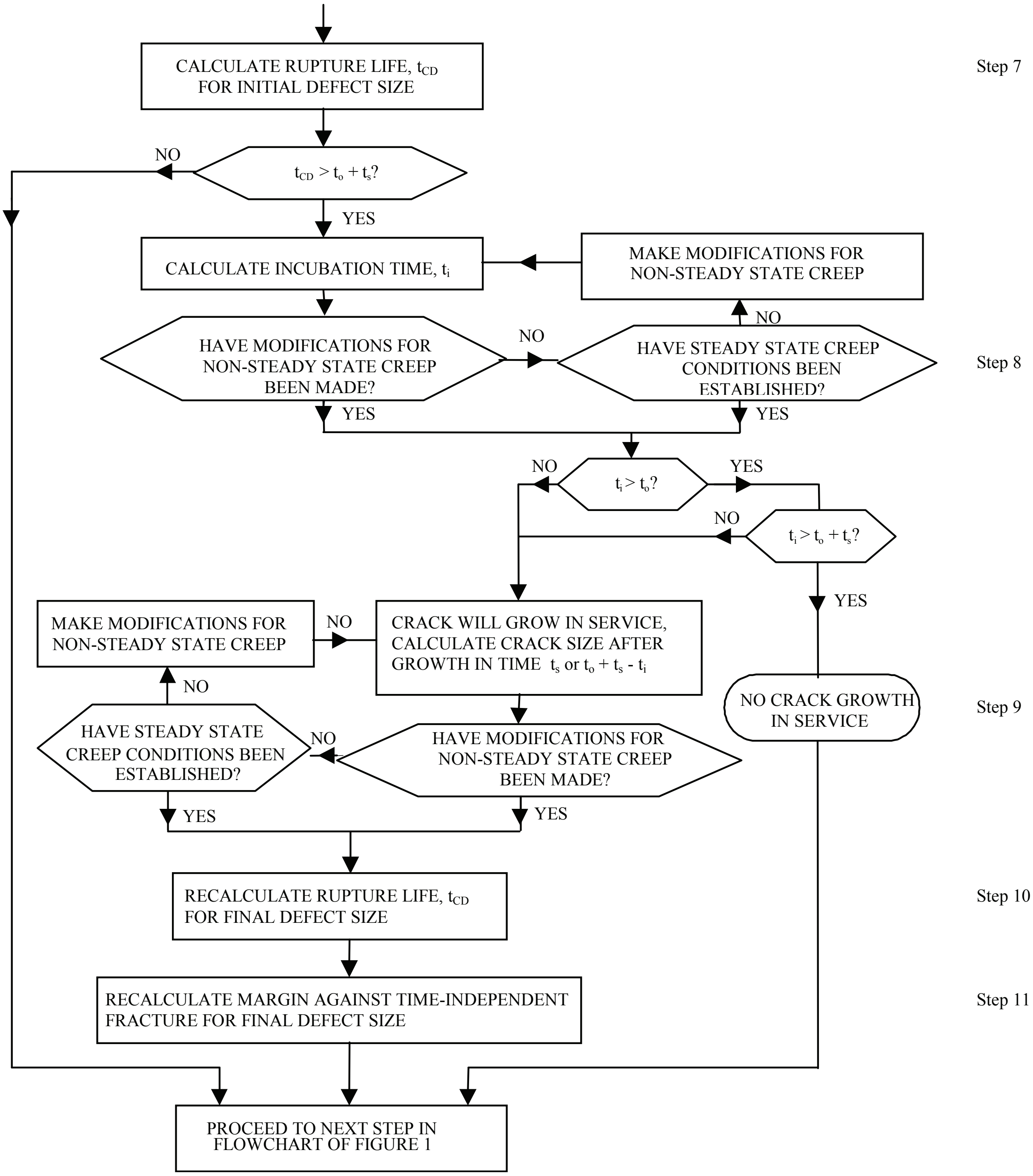

Figure 8.2 – Defect Assessment Flowchart for Insignificant Fatigue

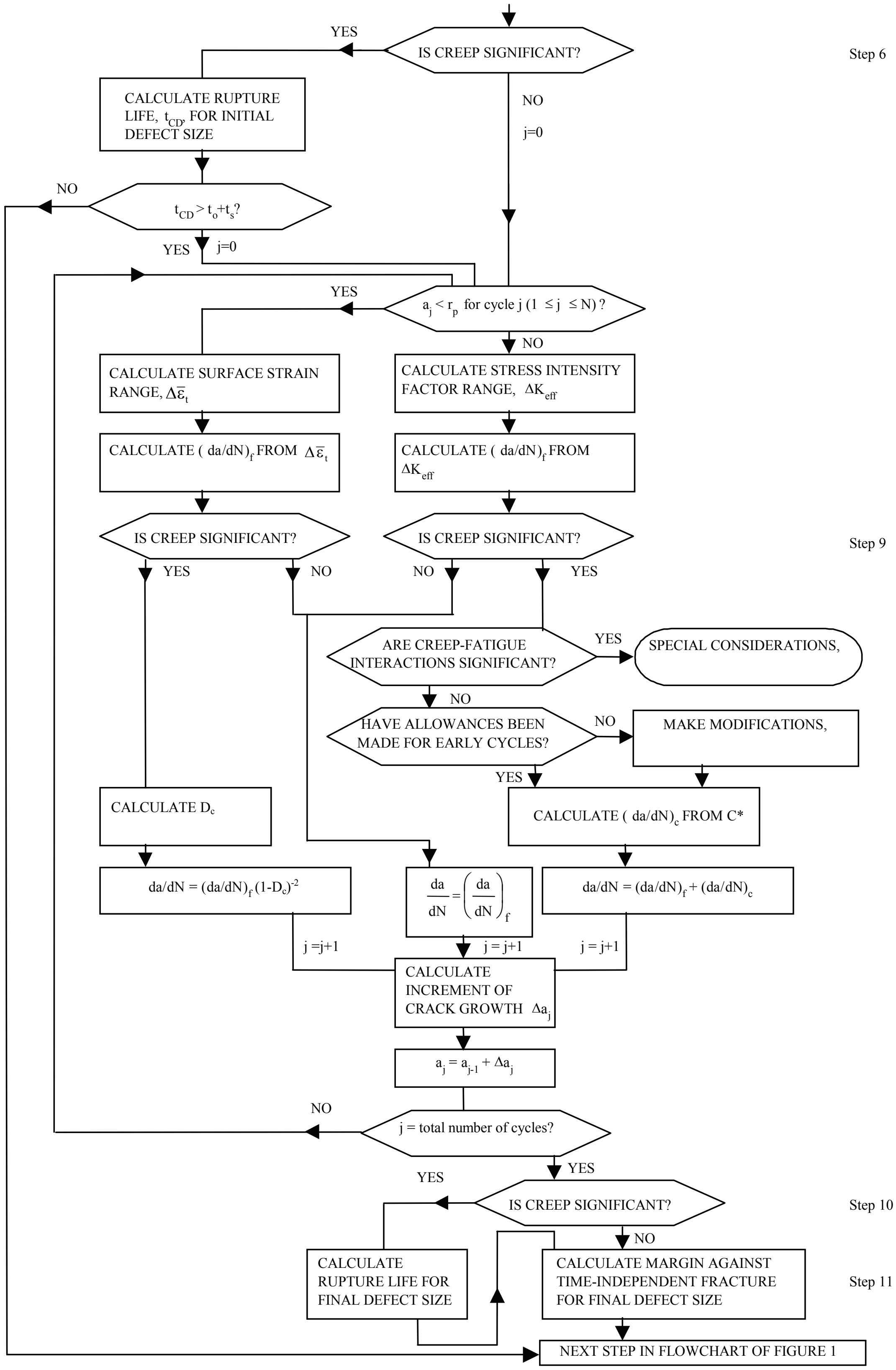

Figure 8.3 – Defect Assessment Flowchart for Significant Fatigue

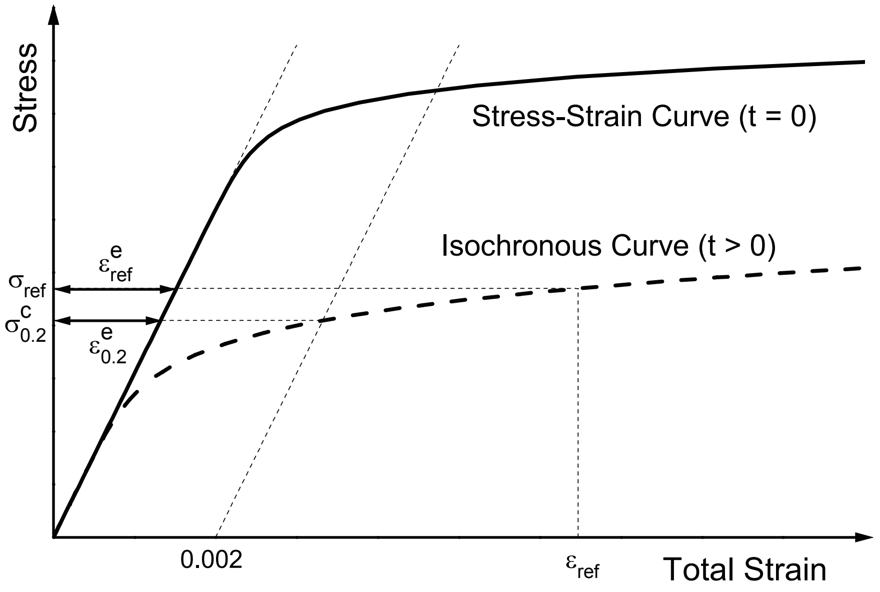

Figure 8.4 – Schematic Isochronous Stress-Strain Curves

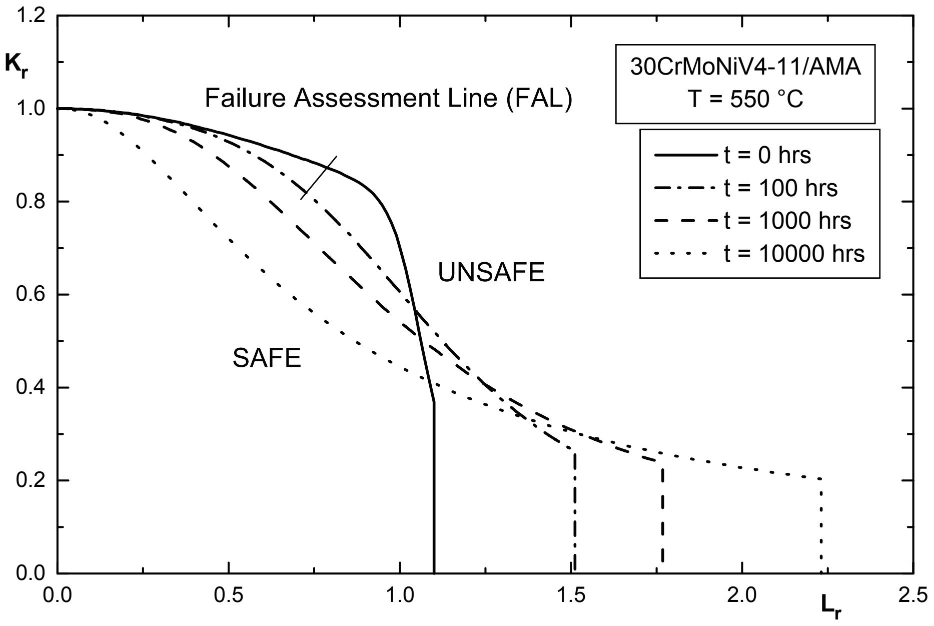

Figure 8.5 – Schematic Time Dependent Failure Assessment Diagram based on Data from a 1CrMoV-steel at 550 °C

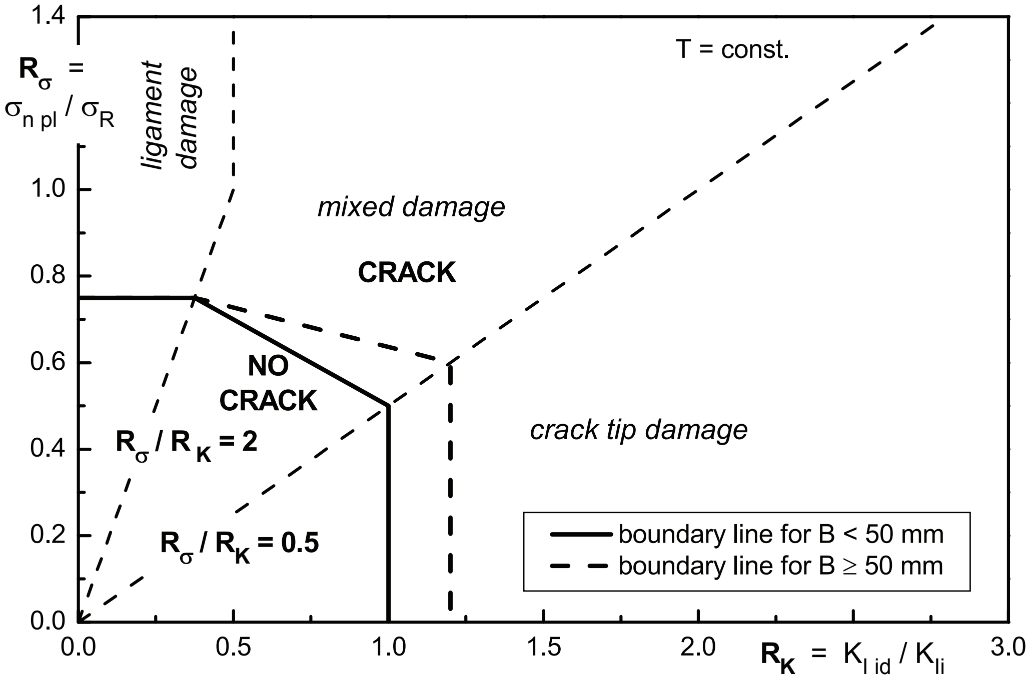

Figure 8.6 – Two Criteria Diagram for Creep Crack Initiation for Creep-Ductile Steels

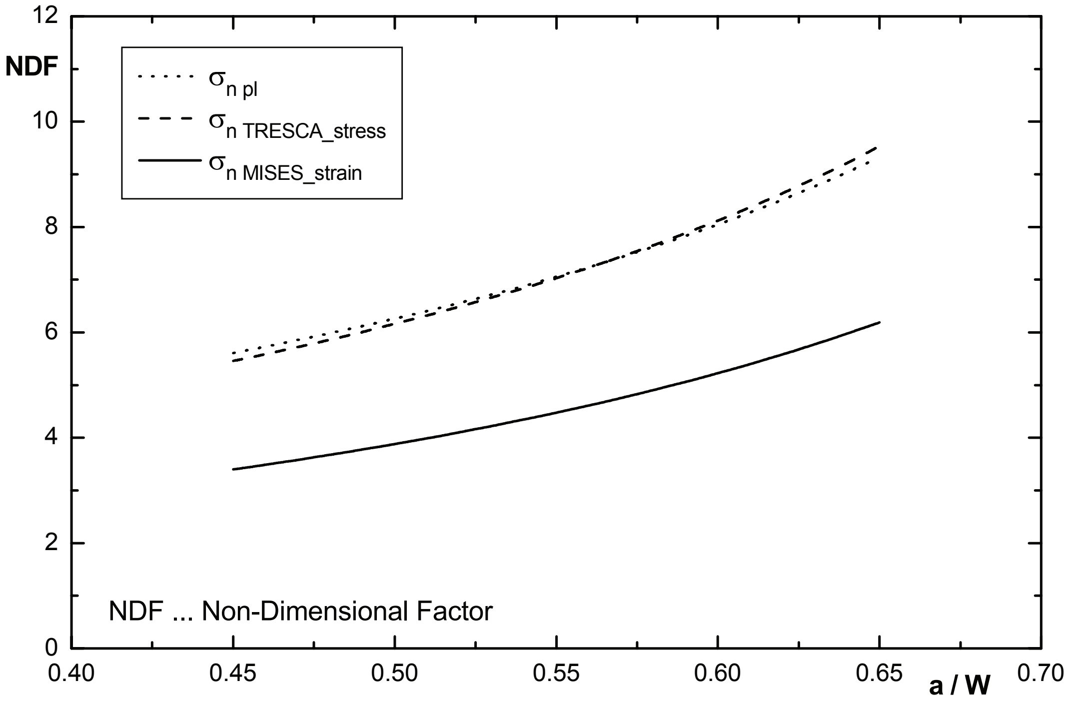

Figure 8.7 – Comparison of Reference Stress and Nominal Stress for CT-specimens

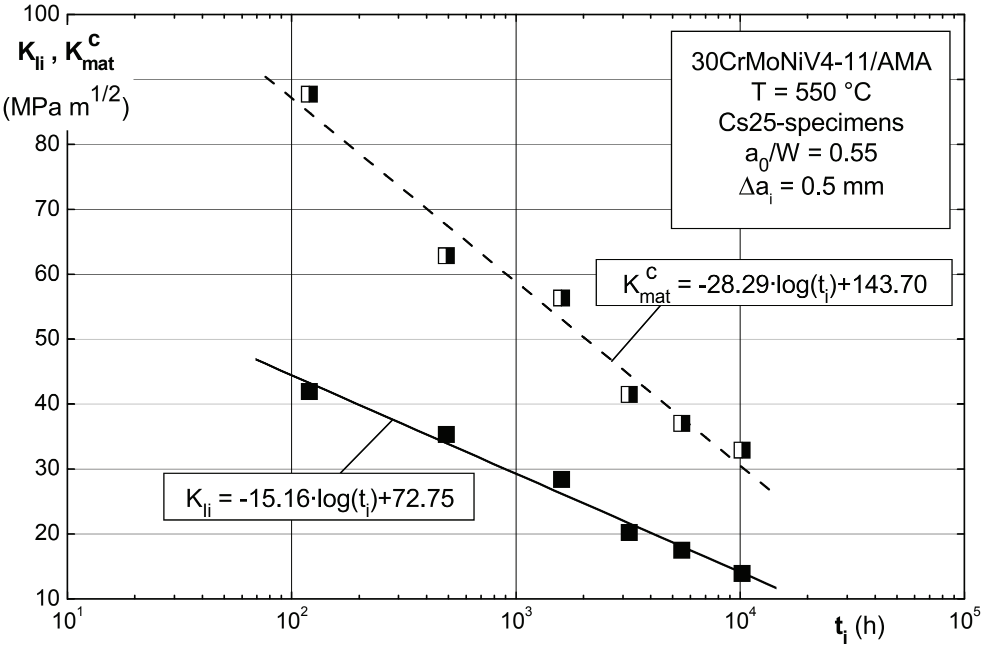

Figure 8.8 – Creep Crack Initiation Time for Cs25-specimens, 1CrMoV-steel at 550 °C

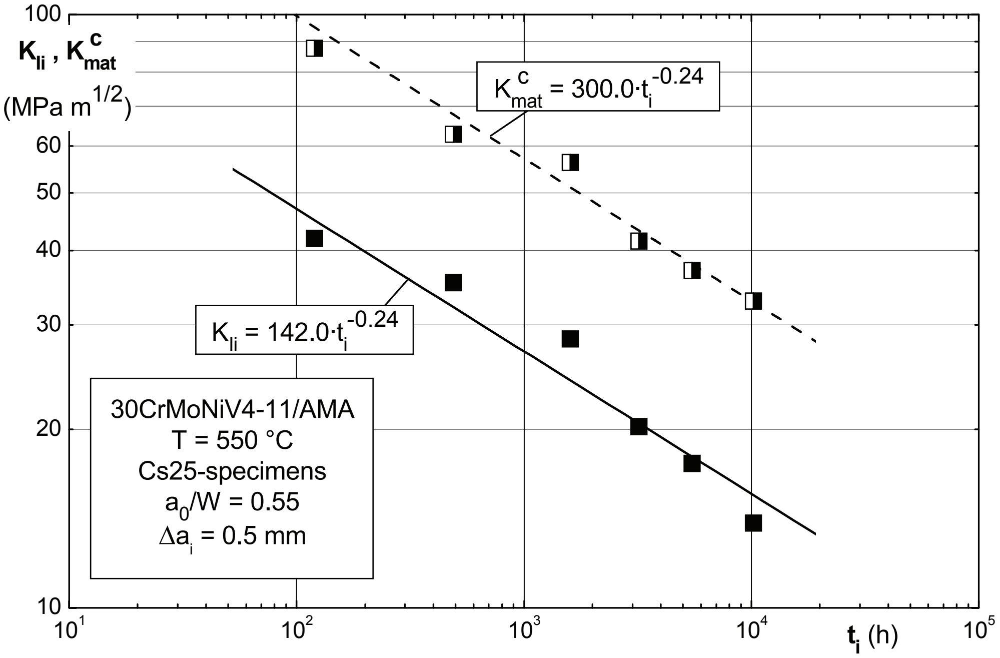

Figure 8.9 – Creep Crack Initiation Time for Cs25-specimens, 1CrMoV-steel at 550 °C

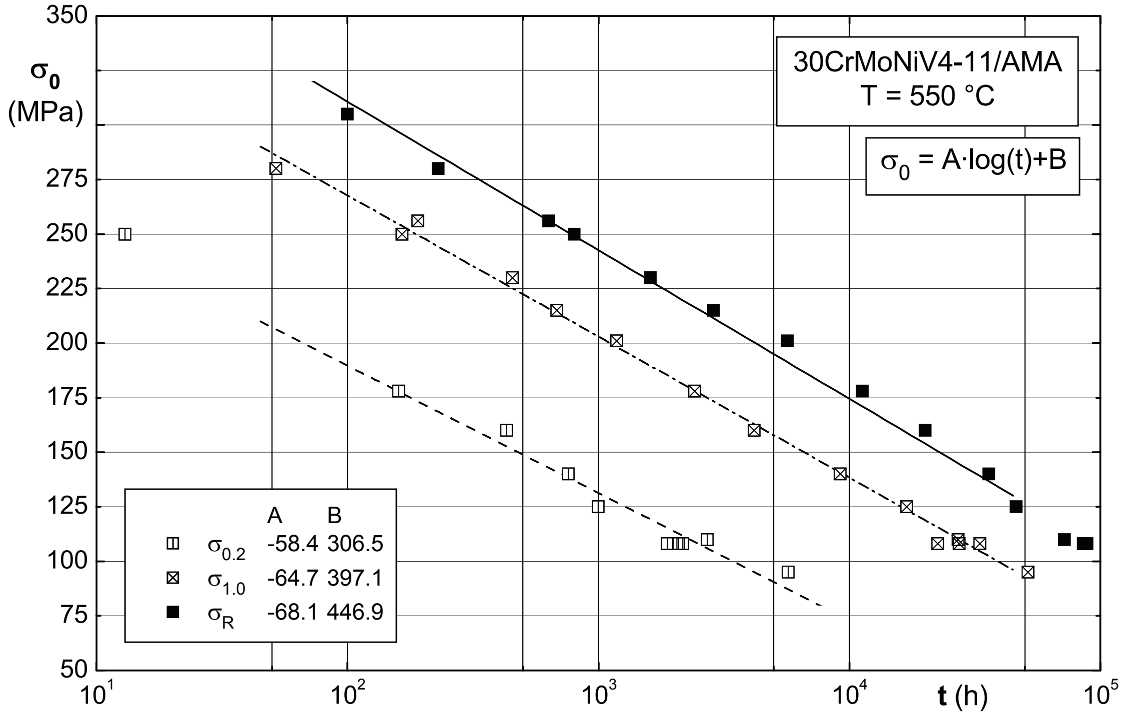

Figure 8.10 – Comparison of creep strength with rupture data for 1CrMoV-steel at 550 °C

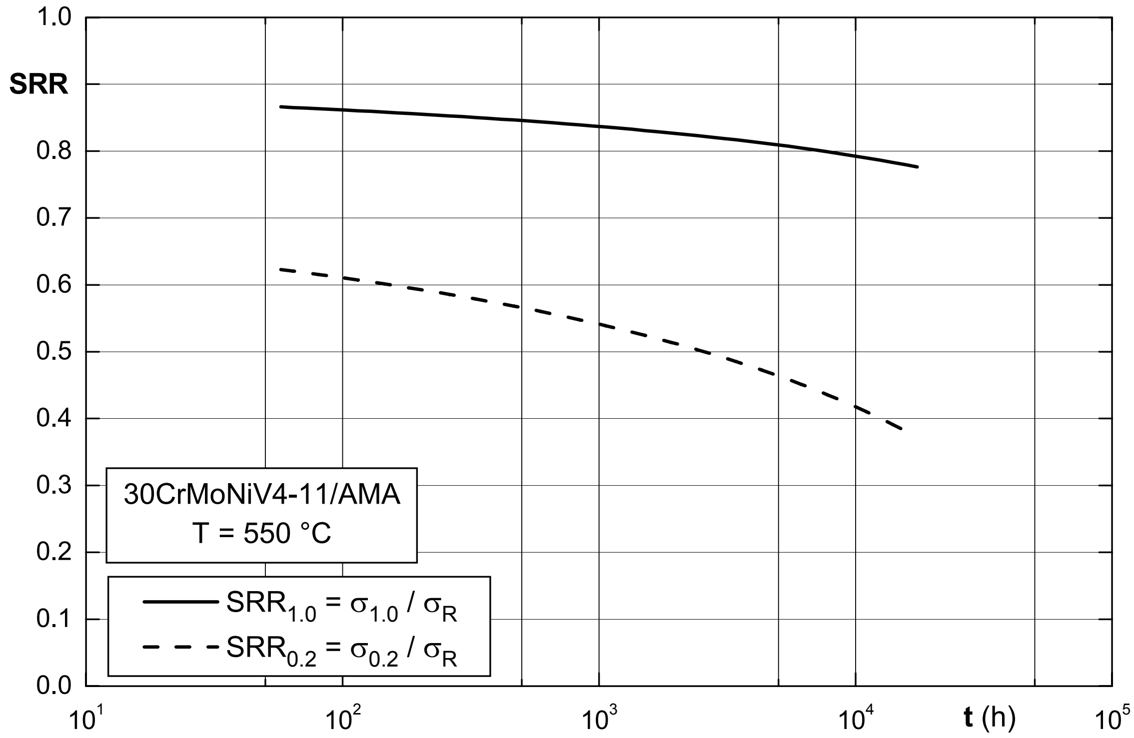

Figure 8.11 – Strength/Rupture Ratios (SRR) for 1CrMoV-steel at 550 °C

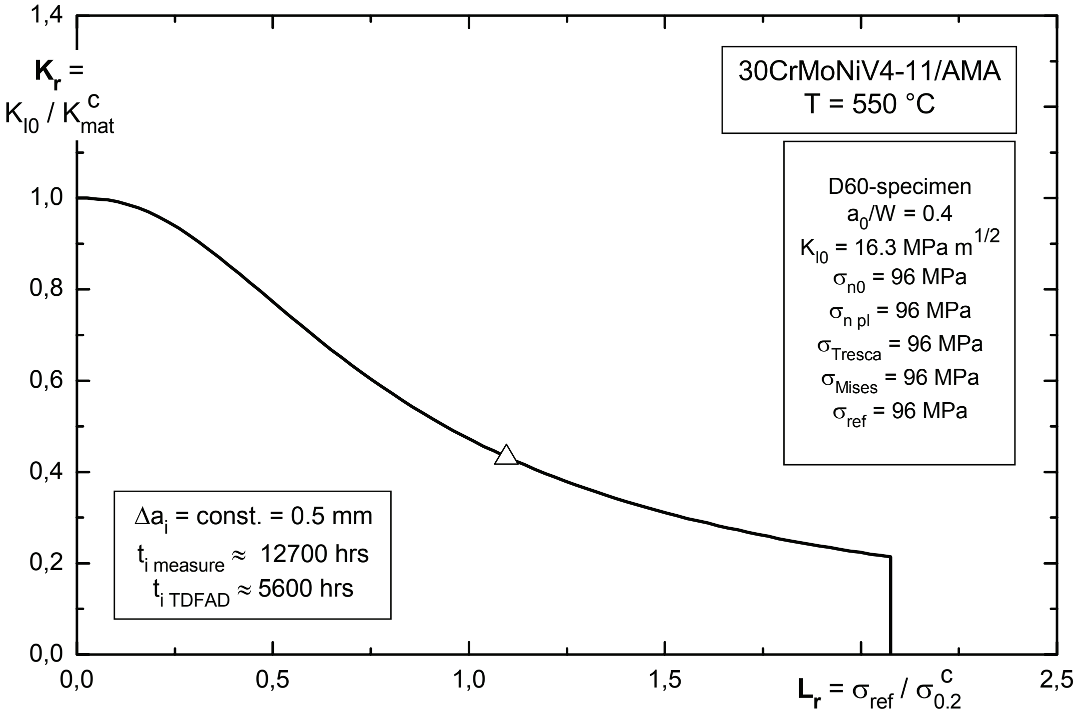

Figure 8.12 – Prediction of creep crack initiation time for Δa_i = 0.5 mm by using the TDFAD, 1CrMoV-steel at 550 °C

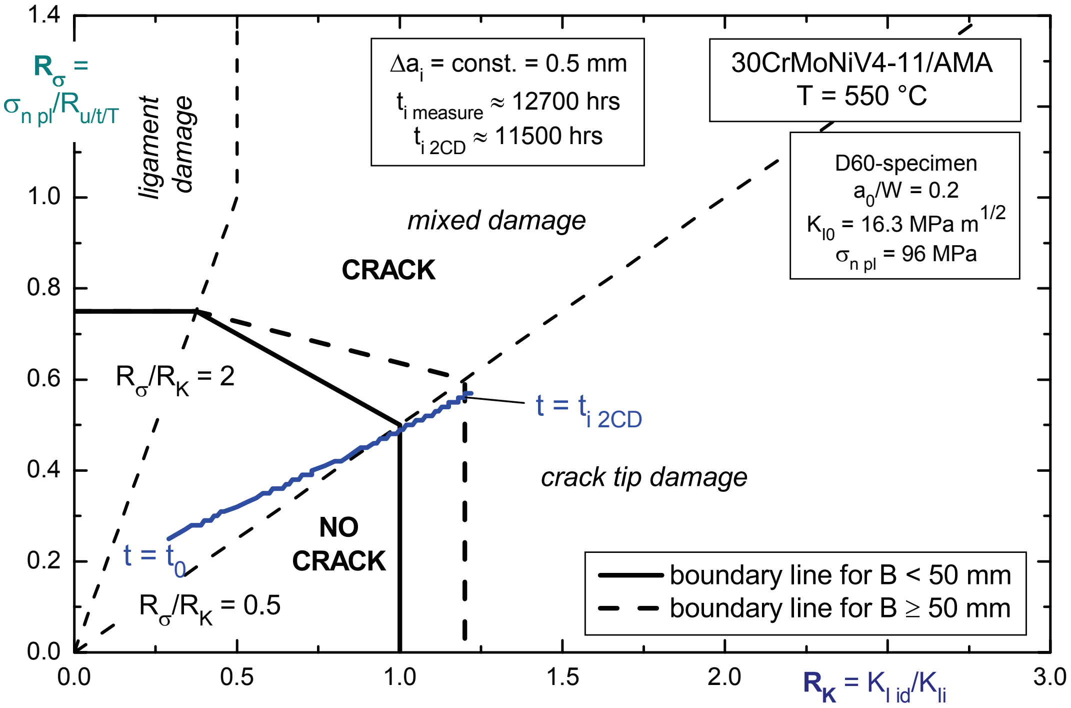

Figure 8.13 – Prediction of creep crack initiation time for Δa_i = 0.5 mm by using the 2CD, 1CrMoV-steel at 550 °C

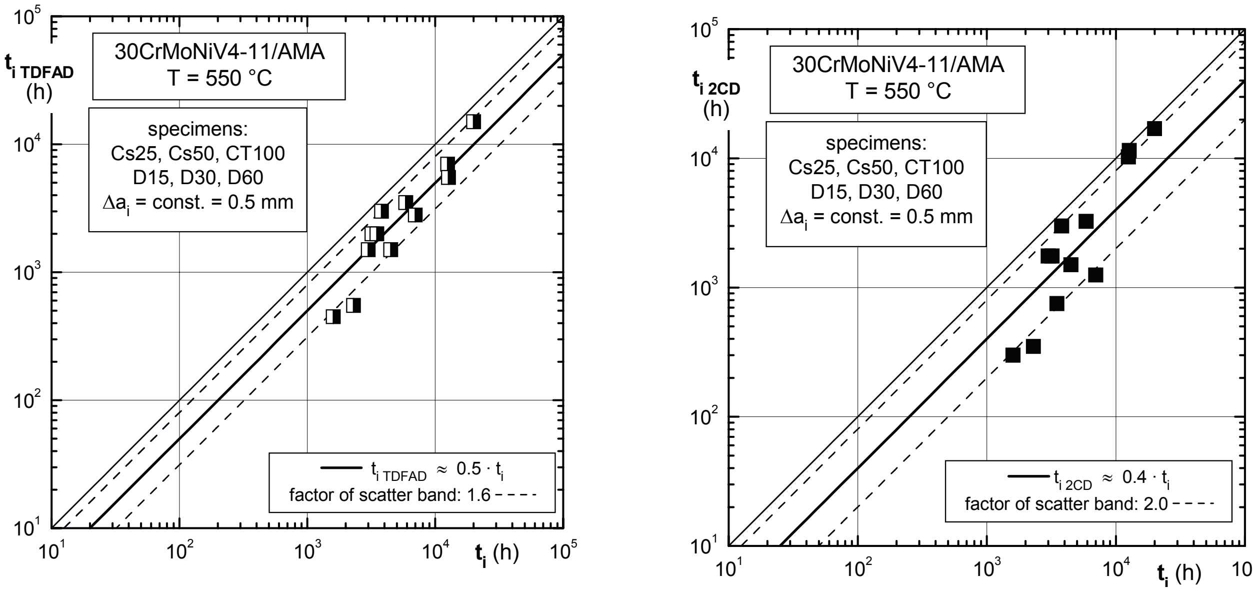

Figure 8.14 – Comparison between experimental and predicted creep crack initiation times by using TDFAD (a) and 2CD (b) on different specimen types for Δa_i = 0.5 mm, 1CrMoV-steel at 550 °C

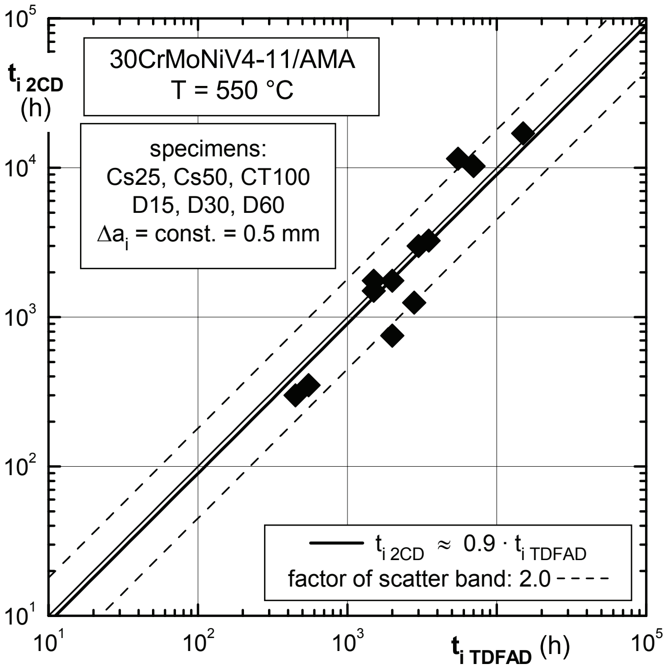

Figure 8.15 – Comparison between predicted creep crack initiation times by using TDFAD and 2CD on different specimen types for Δa_i = 0.5 mm, 1CrMoV-steel at 550 °C

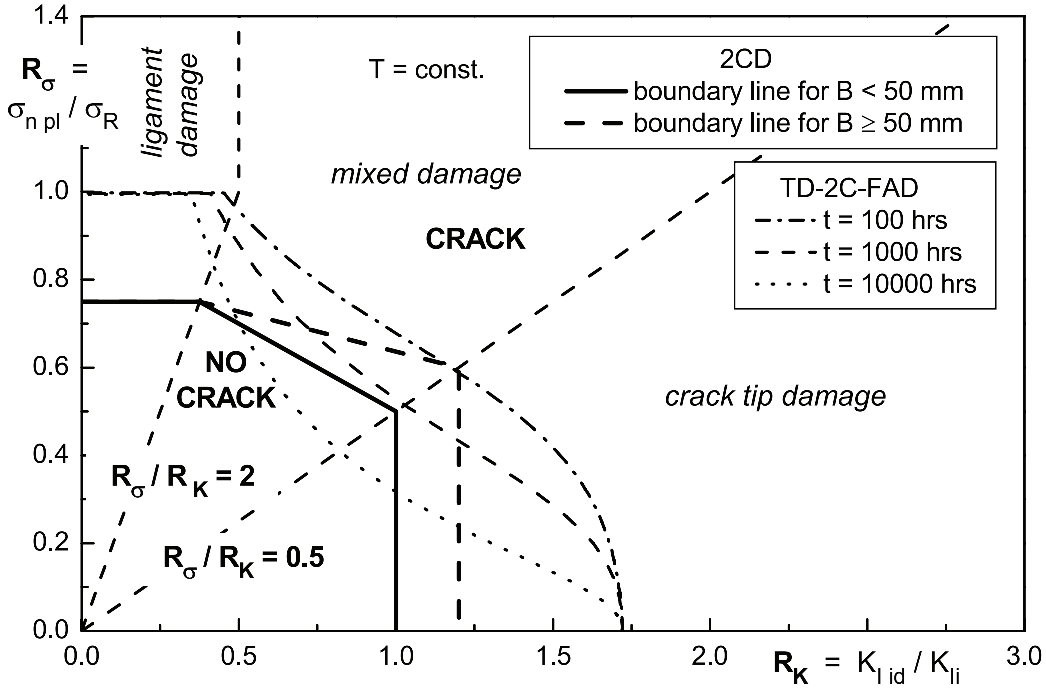

Figure 8.16 – TDFAD in terms of 2CD, schematic for 1CrMoV-steel at 550 °C

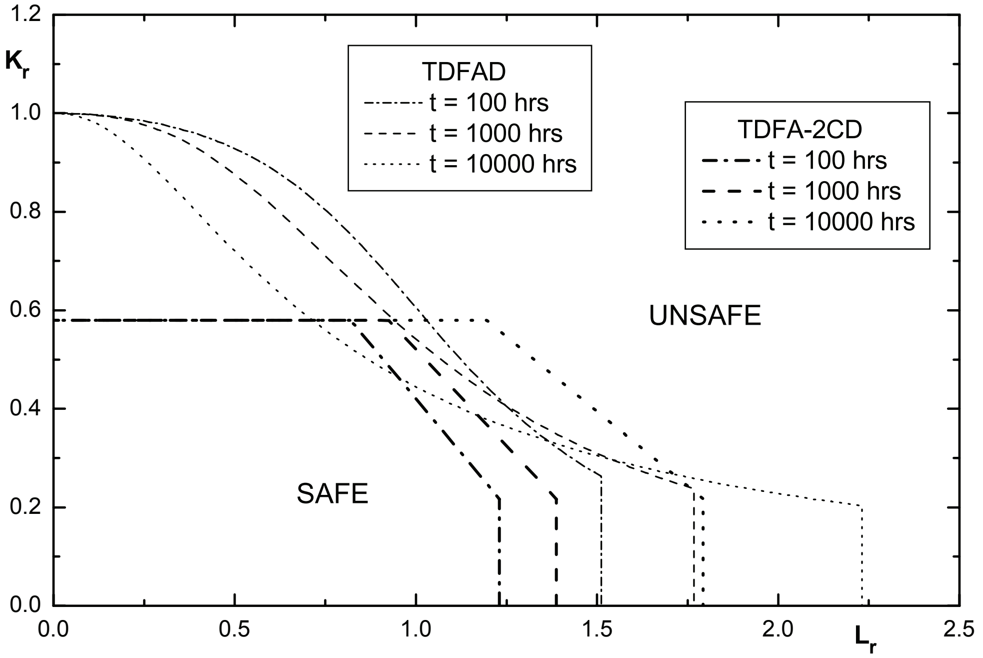

Figure 8.17 – 2CD in terms of TDFAD, schematic for 1CrMoV-steel at 550 °C