C. PROCEDURE APPLICATION (FITNET)

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- INTRODUCTION
- ANALYSIS STEPS
- MATERIALS DATA
- BASIC CALCULATIONS
- ASSESSMENT CALCULATIONS
- ASSESS SIGNIFICANCE OF RESULTS

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INTRODUCTION

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 next pages.

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 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.

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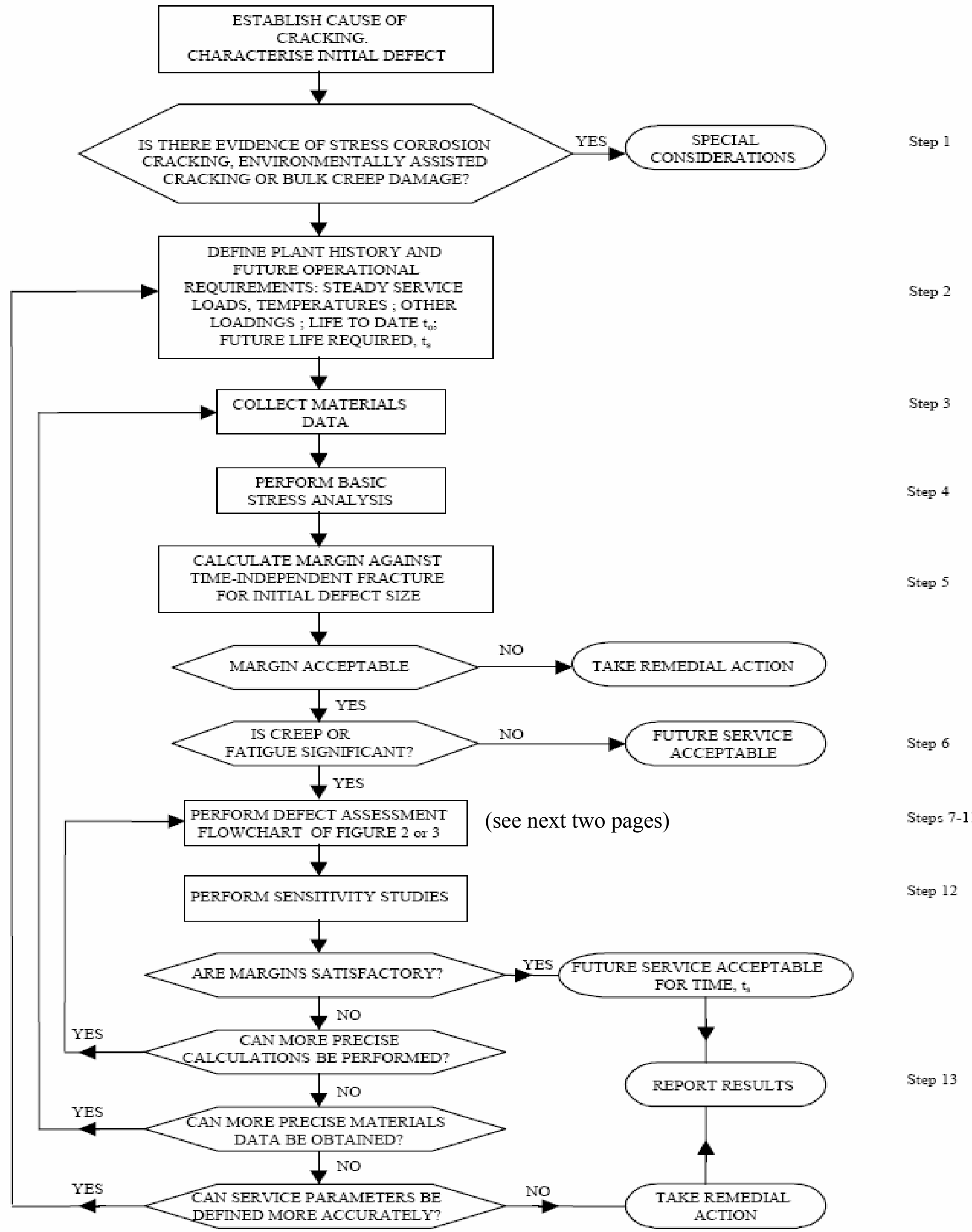
Flowchart for Overall Creep Assessment Procedure



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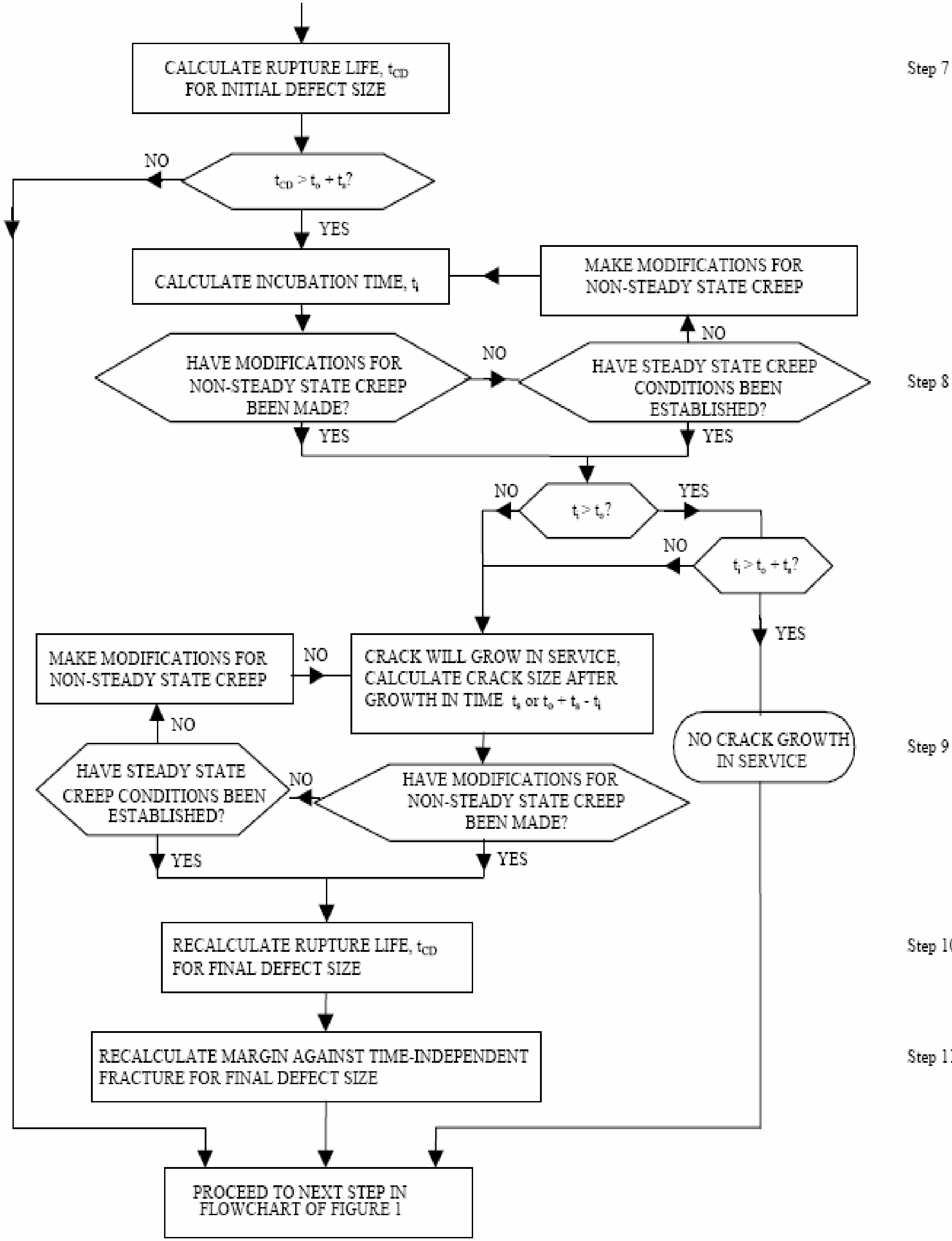
Defect Assessment Flowchart for Insignificant Fatigue



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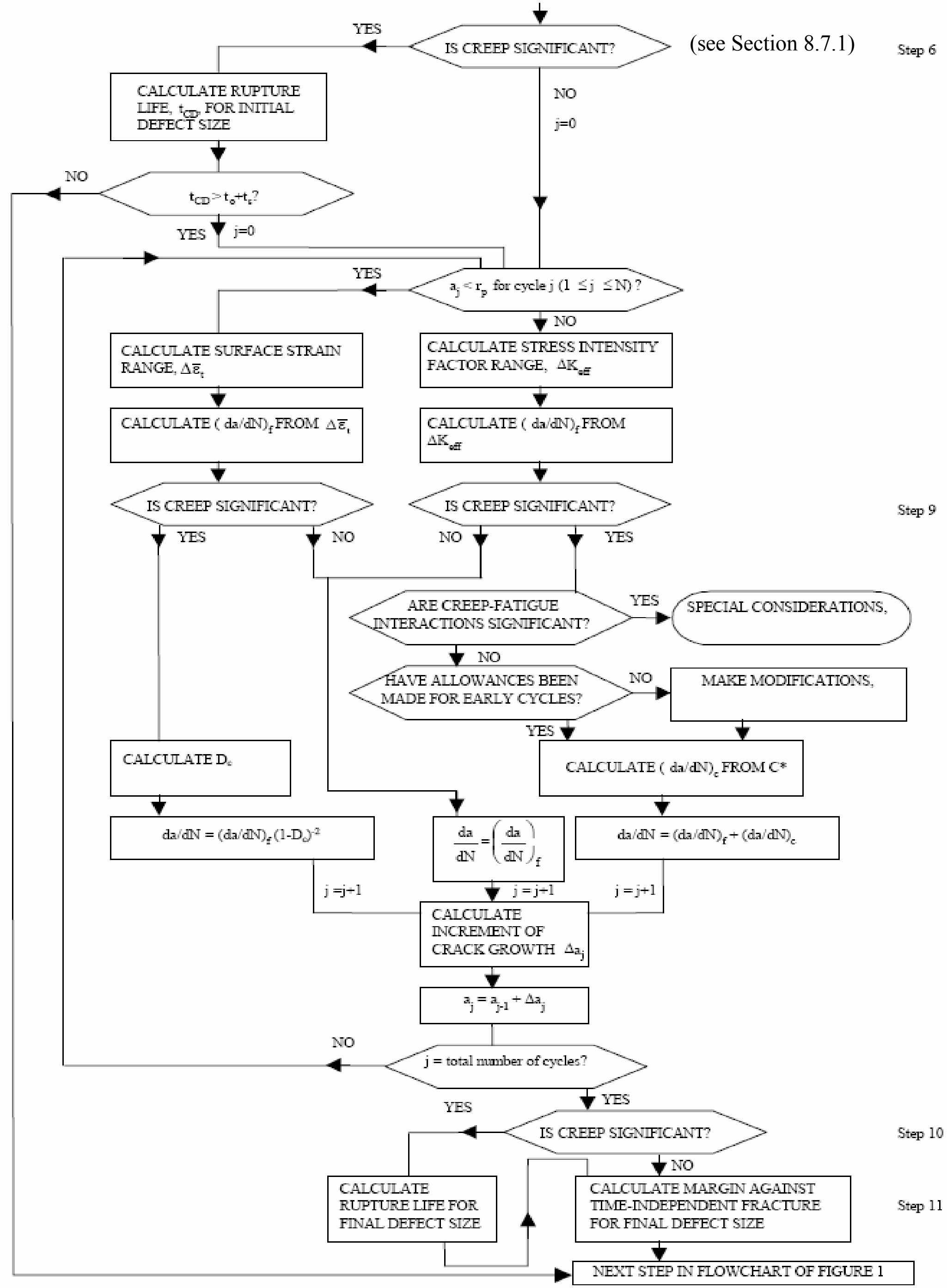
Defect Assessment Flowchart for Significant Fatigue



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ANALYSIS STEPS

STEP 1. Establish Cause of Cracking and Characterise Initial Defect (see Section 8.3)

STEP 2. Define Service Conditions (see Section 8.4)

STEP 3. Collect Materials Data (see Section 8.5)

STEP 4. Perform Basic Calculations (see Section 8.6)

STEP 5. Check Stability under Time-Independent Loads

STEP 6. Check Significance of Creep and Fatigue (see Section 8.7)

STEP 7. Calculate Rupture Life based on the Initial Defect Size (see Section 8.8.1)

STEP 8. Calculate Initiation Time (see Section 8.8.2)

STEP 9. Calculate Crack Size after Growth (see Section 8.8.3)

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ANALYSIS STEPS

STEP 10. Re-Calculate Rupture Life after Crack Growth

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

STEP 12. Assess Significance of Results (see Section 8.9)

STEP 13. Report Results (see Section 8.9.3)

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ESTABLISH CAUSE OF CRACKING (STEP 1)

STEP 1- Establish Cause of Cracking

Before performing calculations, an investigation should be carried out to determine the most likely cause of cracking.

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.

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.

For further information see Section 8.3.

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DEFINE SERVICE CONDITIONS (STEP 2)

STEP 2- Define Service Conditions

The 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.

For further information see Section 8.4.

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COLLECT MATERIALS DATA (STEP 3)

STEP 3- Collect Materials Data

Next pages outline the material properties data required to follow the steps in the procedure. Some of these 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.

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.

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COLLECT MATERIALS DATA (STEP 3)

STEP 3- Collect Materials Data (cont.)

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.

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COLLECT MATERIALS DATA (STEP 3)

STEP 3- Collect Materials Data (cont.)

Creep Deformation Data (cont.)

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

$$\frac{\dot{\varepsilon}_c}{\dot{\varepsilon}_0} = \left(\sigma / \sigma_0\right)^n$$

$\dot{\varepsilon}_c$	creep strain rate
$\dot{\varepsilon}_0$	creep strain rate at stress σ_0
σ_0	initial stress
n	exponent of stress in creep strain equation

is used to describe creep strain rate.

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COLLECT MATERIALS DATA (STEP 3)

STEP 3- Collect Materials Data (cont.)

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.

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COLLECT MATERIALS DATA (STEP 3)

STEP 3- Collect Materials Data (cont.)

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:

$$t_i \left(C^*\right)^\beta = \gamma$$

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 the procedure (see Section 8.10).

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STEP 3- Collect Materials Data (cont.)

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:

$$\frac{da}{dt} = A \cdot C^{*q}$$

where A and q are material constants. The procedure gives some typical values of these constants for a number of materials (see Annex N).

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COLLECT MATERIALS DATA (STEP 3)

STEP 3- Collect Materials Data (cont.)

Cyclic Crack Growth Data

Method I

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

$$(da/dN)_f = C\Delta K_{eff}^{l}$$

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.

In situations where cyclic crack growth data have been obtained from tests with significant plasticity, it is preferable to evaluate from experimental estimates of ΔJ . However, it will be pessimistic to use data which have been correlated with elastically calculated values.

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COLLECT MATERIALS DATA (STEP 3)

STEP 3- Collect Materials Data (cont.)

Cyclic Crack Growth Data (cont)

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

$$(da/dN)_f = B' a^Q \qquad a_{\min} \leqslant a \leqslant r_p$$

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 $\Delta\bar{\varepsilon}_t$, while the defect is embedded in the cyclic plastic zone of size r_p at the surface of the component.

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COLLECT MATERIALS DATA (STEP 3)

STEP 3- Collect Materials Data (cont.)

Other Data

In addition to the creep data described previously, it may be necessary to have other data to perform an assessment:

- Elastic and Physical Constants (see Section 8.5.7.1)
- Stress-strain Data (see Section 8.5.7.2)
- Fracture Toughness Data (see Section 8.5.7.3)

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BASIC CALCULATIONS (STEPS 4 AND 5)

STEPS 4-5- Basic Calculations

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 of minimum to maximum stress intensity factor, R.

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.

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BASIC CALCULATIONS (STEPS 4 AND 5)

STEPS 4-5- Basic Calculations

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:

$$\sigma_{ref}^{p} = P\sigma_{y} / P_{L}\left(\sigma_{y}, a\right)$$

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 .

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BASIC CALCULATIONS (STEPS 4 AND 5)

STEPS 4-5- Basic Calculations

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.

It may be evaluated by finite element analysis but a reference stress based estimate of is often used. This is

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

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.

The characteristic length, R′ is defined by: $R' = (K^p / \sigma_{ref}^p)^2$

where K^p is the stress intensity factor due to primary load only.

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BASIC CALCULATIONS (STEPS 4 AND 5)

STEPS 4-5- Basic Calculations (cont.)

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

$$\varepsilon_c[\sigma^p_{ref}(a), t_{red}] = \sigma^p_{ref}(a) / E$$

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

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BASIC CALCULATIONS (STEPS 4 AND 5)

STEPS 4-5- Basic Calculations (cont.)

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

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

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 with q~n/(n+1) where n is the exponent in the equation obtained from the creep deformation data. For times in excess of the redistribution time, C(t) approaches C*

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CHECK SIGNIFICANCE OF CREEP AND FATIGUE (STEP 6)

STEPS 6- 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.

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CHECK SIGNIFICANCE OF CREEP AND FATIGUE (STEP 6)

STEPS 6- Check Significance of Creep and Fatigue (cont.)

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:

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

For further information see Section 8.7.1

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CHECK SIGNIFICANCE OF CREEP AND FATIGUE (STEP 6)

STEPS 6- Check Significance of Creep and Fatigue (cont.)

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. For further information the Procedure refers to the R5 Procedure.

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CHECK SIGNIFICANCE OF CREEP AND FATIGUE (STEP 6)

STEPS 6- Check Significance of Creep and Fatigue (cont.)

Insignificant Fatigue (cont.)

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.

For further information see Section 8.7.2.

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CHECK SIGNIFICANCE OF CREEP AND FATIGUE (STEP 6)

STEPS 6- Check Significance of Creep and Fatigue (cont.)

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.

Two exceptions to this general rule are provided in Section 8.7.3.

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ASSESSMENT CALCULATIONS (STEPS 7 TO 11)

STEP 7- 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

$$t_{CD} = t_r\left[\sigma_{ref}^{p}(a)\right]$$

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.

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ASSESSMENT CALCULATIONS (STEPS 7 TO 11)

STEP 7- Calculate Rupture Life, t_{CD} (cont.)

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.

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ASSESSMENT CALCULATIONS (STEPS 7 TO 11)

STEP 8- Calculate Crack Incubation Time, t_i

The method for representing incubation data 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 by:

$$t_i\left(C^*\right)^{\beta} = \gamma$$

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

$$\varepsilon_c\left[\sigma_{ref}^{p}\left(a_0\right), t_i\right] = \left[\delta_i / R'\left(a_0\right)\right]^{n/(n+1)} - \sigma_{\mathrm{ref}}^{p}\left(a_0\right)/E$$

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 the Procedure (Section 8.10).

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ASSESSMENT CALCULATIONS (STEPS 7 TO 11)

STEP 9- 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_0, the desired future service life, t_s and the incubation time, t_i; this may be summarised as follows

- If $t_0+t_s<t_i$, 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 $t_0+t_s-t_i$.
- 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.

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ASSESSMENT CALCULATIONS (STEPS 7 TO 11)

STEP 9- Calculate Crack Size After Growth, a_g (cont.)

The time required for the crack to propagate by an amount Δa_g is denoted t_g. For the load controlled case and the attainment of steady state creep conditions this is obtained from creep crack growth data.

The creep crack extension per cycle, $(da/dN)_c$, is evaluated as follows:

$$\frac{da}{dN_c} = \int_0^{t_h} A(C^*)^q \, dt$$

t_h hold time at high temperature

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 for crack propagation may be generalised to

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

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ASSESSMENT CALCULATIONS (STEPS 7 TO 11)

STEP 9- Calculate Crack Size After Growth, a_g (cont.)

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 previously seen multiplied by a factor of 2 for $t<t_{red}$, i.e.

$$\dot{a} = 2A\left(C^*\right)^q \qquad \text{for } t_i \le t < t_{red}$$

$$\dot{a} = A\left(C^*\right)^q \qquad \text{for } t \ge t_{red}$$

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 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:

$$\frac{da}{dN_c} = \int_0^{t_h} A[C(t)]^q \, dt$$

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ASSESS SIGNIFICANCE OF RESULTS (STEP 12)

STEP 12- 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 in the Procedure (see Section 8.9).

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REPORT RESULTS (STEP 13)

STEP 13- Report Results

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

1.LOADING CONDITIONS
2.MATERIAL PROPERTIES
3. DEFINITION OF FLAW.
4. REFERENCE STRESS
5. STRESS INTENSITY FACTOR SOLUTION
6. SIGNIFICANCE OF CREEP AND FATIGUE.
7. TIME INDEPENDENT ASSESSMENT
8. CYCLE DEPENDENT ASSESSMENT
9. TIME DEPENDENT ASSESSMENT
10. SENSITIVITY ANALYSIS
11. REPORTING

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ADDITIONAL INFORMATION

ADDITIONAL INFORMATION

FITNET Procedure provides methodologies for the analysis of specific industrial/technical problems:

- Treatment of Defects in Weldments (see Section 8.10.1)
- Treatment of Secondary Loading (see Section 8.10.2)
- Failure Assessment Diagram Methods (see Section 8.10.3)
  - TDFAD Approach (see 8.10.3.2.1)
  - Two Criteria Diagram (see 8.10.3.2.2)
- Probabilistic Approach to Lifetime Assessment in Creep Regime (see Section 8.10.4)

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