Defect Assessment Procedures at High Temperature

Robert A. Ainsworth
Central Electricity Generating Board, Berkeley, UK

SUMMARY

Within the Central Electricity Generating Board (CEGB), a comprehensive assessment procedure for the high temperature response of structures is being produced. The procedure is referred to as R5 and is written as a series of step-by-step instructions in a number of volumes. This paper considers in detail those parts of R5 which address the behaviour of defects. The defect assessment procedures may be applied to defects found in service, postulated defects, or defects found during operation as a result of creep-fatigue loading. In the last case, a method is described for deducing from endurance data the number of cycles to initiate a crack of a specified size. Under steady loading, the creep crack tip parameter C* is used to assess crack growth. Under cyclic loading, the creep crack growth during dwell periods is still governed by C* but crack growth due to cyclic excursions must also be included. This cyclic crack growth is described by an effective stress intensity factor range. A feature of the R5 defect assessment procedures is that they are based on simplified methods and approximate reference stress methods are described which enable C* in a component to be evaluated. It is shown by comparison with theoretical calculations and experimental data that reliable estimates of C* and the associated crack growth are obtained provided realistic creep strain rate data are used in the reference stress approximation.

1. INTRODUCTION

Within the CEGB, a comprehensive assessment procedure for the high temperature response of structures is being produced. The procedure, termed R5, is written in seven volumes addressing the following areas of structural integrity:

(1) Overview,
(2) Simplified Methods of Stress Analysis,
(3) Creep-Fatigue Crack Initiation,
(4) Creep Crack Growth,
(5) Creep-Fatigue Crack Growth,
(6) Behaviour of Transition Joints,
(7) Behaviour of Similar Welds.

This paper is concerned with the defect assessment parts of R5 which are covered by volumes 3, 4 and 5. The creep crack growth procedure of volume 4 has been described elsewhere by Ainsworth et al (1987) and Ainsworth (1987) and is only briefly outlined in Section 2 below. Volumes 3 and 5 have been produced more recently and are discussed in some detail in Section 3 and 4. In particular, Section 3 describes a method for deducing from endurance data the number of cycles to initiate a defect of a specified size.

A feature of the R5 assessment methods is that they are based on simplified reference stress methods rather than detailed inelastic analysis. Reference stress methods were developed some years ago for creep analysis of non-defective structures (Penny and Marriott, 1971) and were subsequently modified to cracked structures under steady load by Goodall and Chubb (1976) and Ainsworth and Goodall (1983). More recently they have been extended to non-steady creeping structures by Ainsworth and Budden (1988a, b) and these developments and associated comparisons with experimental data are described in Section 5.

2. PROCEDURE FOR CONSTANT LOADING

Defect assessments under constant loading at high temperature require information on the operating conditions and the size and shape of flaws, and information from materials tests and structural calculations. The operating conditions are the steady service load and temperature under normal operating conditions. The initial defect size, a_0, on which an assessment is based, may be determined from in-service measurement, from past experience, from the limits of inspection methods, from the approach of Section 3 below, or from the maximum size of defect that could be present and yet not have caused failure during a proof test. As well as the size of the flaw, its shape must be characterised by a geometrically simple flaw amenable to analysis. The CEGB procedure of Ainsworth et al (1987) does not provide detailed guidance on flaw characterisation but instead suggests use of low temperature methods, as detailed in R6 (Milne et al, 1988) for example.

Accurate defect assessments require good quality materials data. The creep crack growth data required are a parameter controlling incubation, the incubation COD δ_i for example, and correlation of subsequent crack growth rates with a fracture mechanics parameter, usually C* (Ainsworth et al, 1987). In using such data it is important to establish the relevance of laboratory data to service conditions. This is achieved by ensuring satisfaction of validity limits which are given in Ainsworth et al (1987) and which are analogous to those in low temperature material testing. Validity limits are also defined in Ainsworth et al (1987) for ensuring that C* is the relevant controlling parameter. In addition to crack growth data, uniaxial creep strain and rupture data are also required to perform the calculations in an assessment. An important advantage of the reference stress methods described in Section 5, is that realistic creep laws can be used and this often leads to significant improvements in the accuracy of assessments compared with those based on minimum creep rates defined by Norton's law (Neate, 1986a).

Providing the loading and defect have been defined and materials data are available, the defect assessment procedure may be followed in a simple stepwise manner according to the flow chart of Figure 1. This is self-explanatory and is not discussed here: it has been described in detail elsewhere (Ainsworth et al, 1987; Ainsworth, 1987, 1988a). As noted in the introduction, a feature of the procedure is that calculations are performed using simplified reference stress methods and these are described in Section 5. For application of volume 4 of R5, these calculations require only an ability to calculate the elastic stress intensity factor and the limit load of the defective component. These requirements are similar to those in R6 (Milne et al, 1988) and so solutions are well established, enabling the procedure to be readily applied to a wide range of geometries. An example illustrating application of the procedure has been given by Ainsworth and Coleman (1987).

3. CREEP-FATIGUE INITIATION

Where components are subject to high surface strain ranges, due to thermal cycling for example, it may not be possible to demonstrate an adequate lifetime on the basis of endurance data. In such cases it would be unduly pessimistic to concede failure of the whole component when the lifetime of the surface material is exhausted. Instead the loading may be taken to induce a crack of a particular size, a_0 say, on the surface. The growth of this crack may then be calculated using the methods of Section 4 below. Where the applied strain range decays away from the surface, as it often does for thermal loading, it is quite likely that crack propagation slows down and the defective component is able to withstand a large number of cycles.

In volume 3 of R5, the number of cycles to initiate a crack of size a_0 is based on creep rupture data, creep ductility and continuous cycling endurance data to determine the creep-fatigue damage at the surface. The value of a_0 is chosen by the user. However, if a_0 is chosen to be small, the number of cycles to initiation will be small and crack propagation calculations will be required for most of the lifetime. Conversely, if a large value of a_0 is chosen then the assessment will be overly conservative for cases where the strain range decays away from the surface, as the initiation time is based on the accumulated damage at the surface.

The accumulated damage, D, is written as the sum of fatigue and creep components:

$$D = D_F + D_C \qquad (1)$$

The fatigue damage is deduced from the number of cycles, N_0, to grow a defect to size a_0 under continuous cycling conditions at the surface strain range, strain rate and temperature:

$$D_F = N/N_0 \qquad (2)$$

where N is the number of operational cycles. Where the size a_0 is in excess of the crack size, a_l say, corresponding to the failure condition in a laboratory test, it is conservative to set N_0 equal to the number of cycles to failure, N_l say, in that laboratory test. However, particularly for thin section applications, a_0 may be less than a_l and it is necessary to deduce N_0 from N_l. Initiation and growth of small cracks have been examined by a number of authors (for example Pineau, 1983; Skelton 1983) and N_0 may be obtained from the number of cycles, N_i, to produce a crack of size a_i and the subsequent number of cycles to grow the crack to size a_0. In volume 3 of R5, the value of a_i is taken as 20 μm which is the crack depth in austenitic steels beyond which well-defined fatigue striations can be identified (Pireau, 1983). Subsequent growth of the crack is usually expressed as

$$da/dN = Ba^Q \qquad (3)$$

where Q is a constant, and B is a function of strain range (Skelton, 1983). Pineau (1983) suggests that for very short cracks ($a_i \leqq a < a_{min}$, say) the crack growth rate is constant whereas at longer crack sizes the striation spacing is an increasing function of crack size. Thus equation (3) is taken to hold for $a \geqq a_{min}$ whereas the growth rate being constant at

$$da/dN = B\, a_{min}^Q \;, \; a < a_{min} \qquad (4)$$

ensures continuity at $a = a_{min}$.

The function B may be eliminated by integrating equations (3) and (4) with the condition that N_l is the endurance in a laboratory test with the corresponding crack size a_l. Then N_0 is obtained. For the particular case Q = 1 and with $a_0 > a_{min}$, the result is

$$N_0 = N_i + (N_l - N_i) \left[\frac{(a_{min} - a_i) + a_{min} \ln (a_0/a_{min})}{(a_{min} - a_i) + a_{min} \ln (a_l/a_{min})} \right] \qquad (5)$$

Similar results for $Q \neq 1$ or $a_0 < a_{min}$ can readily be derived. From measured crack growth rates (ie measurements of B in equations (3) and (4)) it is also possible to deduce N_i from N_l and in R5 Volume 3 the empirical relationship

$$Ni = 0.0366\ N_l^{1.306} \qquad (6)$$

is adopted for $15 < N_l < 50,000$. Beyond 50,000 cycles, N_i may be taken equal to N_l. This is slightly different from the expression proposed by Pineau (1983) but has been validated for a greater range of N_l. As the equations ensure that N_0 reduces to the total endurance when $a_0 = a_l$, the expression for N_0 is not particularly sensitive to the value of Q or the choice of a_l.

Equation (5) enables the fatigue contribution to the total damage of equation (1) to be evaluated from equation (2). The creep contribution is

$$D_C = \int_0^{t_h} \dot{\varepsilon}/\varepsilon_f(\dot{\varepsilon})dt \qquad (7)$$

where t_h is the dwell time in the cycle and ε_f is the creep ductility which is a function of strain rate $\dot{\varepsilon}$. The strain rate is evaluated by finite-element analysis of the component using a material hardening law and a suitable equation describing creep deformation. Alternatively, $\dot{\varepsilon}$ can be obtained from stress relaxation data if the stress at the start of the dwell can be estimated from the total strain range and the degree of elastic follow-up is known. Guidance on these aspects and recommended descriptions of stress relaxation data are provided in the R5 documentation.

A crack of size a_0 is assumed to be formed at the surface when the total damage of equation (1) equals unity. The assumption of linear damage summation has been examined by calculating D_C and D_F at failure in laboratory tests covering a wide range of materials, hold times and cycle types. Best estimate fatigue and stress relaxation data were used in the calculations and the results are shown in Figure 2 (Skelton, 1988). It is apparent that there is considerable scatter, particularly in the calculated creep damage, but the data show that the approach described in this section is generally conservative. If lower bound data had been used in calculating the damage fractions, as it would be in component assessments, the degree of conservatism would have been increased.

4. PROCEDURE FOR CYCLIC LOADING

The procedure of Section 2 is extended by volume 5 of R5 to cover creep-fatigue loading. The procedure as currently written deals with crack growth in thin-section austenitic components but is to be extended to cover general materials and components. As severe cyclic plasticity is usually restricted to the surface of components, where crack initiation and rapid crack propagation are covered by the methods of Section 3, crack growth under essentially elastic-creep conditions is addressed. The relevant stress conditions can then be described by means of approximate shakedown methods which are contained in volume 2 of R5 and have been outlined by Goodall and Ainsworth (1988).

In a similar manner to the summation of damage in equation (1), crack growth is taken to be the sum of fatigue and creep components:

$$da/dN = (da/dN)_F + (da/dN)_C. \qquad (8)$$

The fatigue crack growth per cycle is obtained from a Paris law:

$$da/dN = C(\Delta K_{eff})^l \qquad (9)$$

where C and l are constants deduced from laboratory test specimen data. For austenitic steels, particularly low ductility weld metals, the constants have been found to be a function of dwell time, since crack growth is expected to occur through creep-damaged material (Gladwin, Miller and Priest, 1988). ΔK_{eff} is an effective stress intensity factor range which is the fraction q_0 of the total stress intensity factor range, ΔK, for which the crack is open:

$$\Delta K_{eff} = q_0 \ \Delta K \tag{10}$$

The fraction q_0 depends on the stress ratio, and for application to components may be obtained from the simplified dependence shown in Figure 3. However, in interpreting laboratory data according to equation (9) this simplification is not needed if it is possible to deduce crack closure directly from the load-displacement record.

The creep crack growth contribution to equation (8) is assumed to be a function of C* according to

$$(da/dN)_C = \int_o^{t_h} AC^{*q} \ dt \tag{11}$$

where A and q are constants derived from test specimen data. It should be noted that C* may vary due to stress relaxation and crack growth during the dwell and these effects should be included in calculations of C* as described in Section 5 below. Experimental values of A and q for austenitic steels have been found to be similar under displacement controlled cycling and under constant load and so the data collected for application of volume 4 of R5 can also be used for application of volume 5 provided a few tests have been performed to confirm the trends.

The crack growth calculations may be performed for the number of cycles expected in service or may be extended to provide a measure of margins available. The calculations must, however, be terminated when the creep rupture life of the remaining ligament becomes unacceptably small, or the component is close to rapid ductile fracture, as depicted for steady loading in Figure 1.

5. REFERENCE STRESS METHODS

In the defect assessment procedure of R5, reference stress methods are used for three different purposes: calculation of the incubation period prior to crack growth under steady load; calculation of creep rupture life under steady load; and calculation of C* to enable calculations of crack growth under both steady and cyclic loadings. Under steady loading, the reference stress is

$$\sigma_{ref} = P \ \sigma_y / P_L(\sigma_y, a) \tag{12}$$

where P is the applied load and P_L is the load at plastic collapse assuming a rigid plastic material of yield strength σ_y. The limit load, and hence the reference stress, depend on crack length and solutions for a wide range of cracked geometries have been summarised by Miller (1988).

The reference stress methods for determination of initiation time, t_i and creep rupture life, t_{CD}, under steady load are depicted in Figure 4 and are based on the creep curve at the reference stress defined for the initial crack size, a_0. In this figure, δ_i is the critical crack opening displacement for initiation and R is a length parameter, defined by equation (16) below, which converts the COD to a critical strain. The approach for initiation is based on crack blunting under widespread creep conditions and is limited to conditions for which the creep strain satisfies

$$\varepsilon^c(\sigma_{ref}, t_i) > \sigma_{ref}/E \tag{13}$$

where E is Young's modulus. However, recent work of Ainsworth and Budden (1988a) has demonstrated that the effects of transient creep can also be analysed using reference stress techniques. In cases where inequality (13) is violated, the greater creep strain rates during the transitional period lead to increased rates of crack tip opening. This may be allowed for by replacing the critical strain in Figure 4 by

$$\varepsilon^c(\sigma_{ref}, t_i) = (\delta_i/R) - \sigma_{ref}/E \tag{14}$$

Ainsworth (1988b). When the right-hand-side of equation (14) is negative the incubation time is set equal to zero. When crack initiation is induced by creep-fatigue loading, the approach of Section 3 is used to assess the time to initiation, even when subsequent crack growth is governed by essentially load-controlled stresses.

It may be noted that application of this approach is not restricted to materials described by Norton's law and primary creep strains, which often make an important contribution to initiation, are incorporated in a straightforward manner as depicted in Figure 4.

The third use of reference stress methods is in the calculation of C*, and this applies to both steady and cyclic loadings. The approximation developed is

$$C^* = \sigma_{ref}\ \dot{\varepsilon}^c_{ref}\ R \tag{15}$$

where $\dot{\varepsilon}^c_{ref}$ is the creep strain rate corresponding to σ_{ref}, and R is a component dimension given by

$$R = K^2/\sigma^2_{ref} \tag{16}$$

where K is the elastic stress intensity factor.

For steady loading, the estimate of C* has been validated by comparison with detailed finite-element solutions and by comparison with experimental data for which C* can be deduced from displacement rate measurements. The former validation has been reported by Miller and Ainsworth (1989) who showed that equations (15,16) gave similar results to detailed solutions for Norton's law materials for a wide range of geometries, crack sizes and creep indices.

In practice, creeping materials exhibit primary, secondary and tertiary behaviour, and even under steady loading stresses change as crack growth occurs. These effects may be included in the estimate of equation (15) by interpreting $\dot{\varepsilon}^c_{ref}$ as the creep strain rate at the reference stress defined for the current crack size, and using a strain hardening rule to incorporate history effects via the accumulated creep strain under the reference stress history. These interpretations are not easily examined numerically by finite-elements and instead have been tested by comparing equation (15) with values of C* deduced from measurements on test specimens of a variety of materials. In general, equation (15) has been found to provide a good and slightly conservative prediction of experimental behaviour provided an accurate description of uniaxial creep response is used (Ainsworth et al, 1987; Neate, 1986a). The estimate of equation (15) is valid for widespread creep conditions when inequality (13) is satisfied. As in the case of initiation, the higher strain rates prior to the attainment of widespread creep may be incorporated in a simple manner, and details are contained in Ainsworth (1988b).

Under cyclic loading, equations (15,16) are again used to estimate C* but if the loading is strain controlled it is additionally necessary to allow for stress relaxation during the dwell period, t_h. (Ainsworth and Budden, 1988a) have shown that the rate of relaxation under these conditions may be estimated from

$$\dot{\sigma}_{ref} = - E\dot{\varepsilon}^{c}_{ref}/\mu \tag{17}$$

where a value $\mu = 2$ is recommended in volume 5 of R5 as being appropriate to bending situations. However, the stress drop during a dwell period is often small and the reference stress in equation (15) may be conservatively taken as the value at the start of the dwell. Of more importance in equation (15) is the reference creep strain rate which can fall significantly with time under stress relaxation conditions. R5, therefore, recommends that under strain controlled loading, the strain rate is derived from stress relaxation data obtained on material in the cyclically stabilised condition.

For cyclic loading, the validity of equations (15-17) has been examined by comparison with finite-element analysis, by comparison with experimental data for which C* can be deduced from measured of load drop rate, and by comparison of integrated estimates of crack growth with experimental measurements.

Detailed finite-element analysis of a compact tension specimen under displacement controlled loading has been reported by Ainsworth and Budden (1988a). The results show that equation (17) provides an accurate estimate of the rate at which the applied load falls. It was found that the associated values of C* fell rapidly and were conservatively predicted by equations (15,16).

For cyclic loading, it is particularly difficult to model complex material behaviour using finite-element methods and, therefore, direct comparisons with experimental data have been made in a similar manner to the comparisons described above for constant loading. In making such comparisons care has been taken to obtain stress relaxation data from material in the cyclically conditioned state rather than to use forward creep data in equation (15). A number of materials have been examined and an example for an austenitic 321 steel is shown in Figure 5 (Gladwin, Miller, Neate and Priest, 1988). It can be seen that the agreement is good and similar results have been obtained for a number of materials provided relevant creep strain rate data have been used in the C* estimation formula.

The final validation of the reference stress approach for cyclic displacement controlled loading has been of the integrated crack growth in equation (11). Ainsworth and Budden (1988b) showed that the integration could be performed in conjunction with equation (17) to derive an approximate estimate of the total crack growth in terms of the load reduction ΔP:

$$(da/dN)_C = AC_o^{*q} \left(\frac{2n}{n+1}\right)\left(\frac{\sigma^o_{ref}}{E\ \dot{\varepsilon}^o_{ref}}\right)\left(\frac{\Delta P}{P_o}\right) \tag{18}$$

where subscripts "o" indicate values at the start of the dwell period. Equation (18) is based on the assumption that the crack growth is small and does not lead to significant reductions in load due to the change in elastic compliance of the structure. This is adequate for practical applications, but the changes in crack size can be significant in laboratory tests and including this effect leads to the approximate formula

$$(da/dN)_C = \frac{\Phi_C\ (\Delta P/P_o)}{[1 + \Phi_C\ (C'/Cw)]} \tag{19}$$

where $\Phi_c = A\, C_o^{*q} \left(\frac{2n}{n+1}\right)\left(\frac{\sigma^o_{ref}}{E\, \dot{\varepsilon}^o_{ref}}\right)$, w is section thickness, C(a/w) is the elastic compliance with C' = dC/d(a/w). Clearly equation (19) reduces to equation (18) when Φ_c << W.

Equations (18) and (19) predict that the crack extension is simply related to the load drop. Experimental evidence of Neate (1986b), for example, confirms that this simple pattern is qualitatively correct (see Figure 6). In addition, the quantitative predictions of equations (18) and (19) have been examined for austenitic and ferritic steels exhibiting a range of ductilities. The results confirm that simple, yet reliable, estimate of total crack growth can be made by reference stress methods, even under complex loading conditions (Ainsworth and Budden 1988b).

6. CONCLUDING REMARKS

It has been shown that defect assessments may be made at high temperatures using simplified methods. The theoretical and experimental validation for methods which use reference stress techniques has been described. These techniques are now well developed and have been included in the CEGB's R5 methodology for high temperature structural assessment.

Acknowledgements

I am grateful to colleagues within the CEGB whose contributions to the CEGB's R5 procedures are reflected in this paper. This work was carried out at the Berkeley Nuclear Laboratories of the Research Division and the paper is published with permission of the Central Electricity Generating Board.

REFERENCES

Ainsworth, R A (1987). CEGB High Temperature Assessment Procedure for Defects under Steady Loading, Proc. I Mech E Seminar on High Temperature Crack Growth, MEP, London, pp9-15.

Ainsworth, R A (1988a). Assessment Procedures for High Temperature Crack Growth, Proc. I Mech E Seminar on Recent Advances in Design Procedures for High Temperature Plant, MEP, London, pp103-109.

Ainsworth, R A (1988b). Stress Redistribution Effects on Creep Crack Growth, Proc. Conf. Mechanics of Creep Brittle Materials, Leicester, Elsevier in press.

Ainsworth, R A and Budden, P J (1988a). Crack Tip Fields Under Non-Steady Creep Conditions, I: Estimates of the Amplitude of the Fields, CEGB Report RD/B/6005/R88.

Ainsworth, R A and Budden, P J (1988b). Crack Tip Fields Under Non-Steady Creep Conditions, II: Estimates of the Associated Crack Growth, CEGB Report RD/B/6006/R88.

Ainsworth, R A, Chell, G G, Coleman, M C, Goodall, I W, Gooch, D J, Haigh, J R, Kimmins, S T and Neate, G J (1987). CEGB Assessment Procedure for Defects in Plant Operating in the Creep Range, Fatigue Fract Engng Mater Struct, Vol 10, pp115-127.

Ainsworth, R A and Coleman, M C (1987). Example of an Application of an Assessment Procedure for Defects in Plant Operating in the Creep Range, Fatigue Fract Engng Mater Struct, Vol 10, pp129-140.

Ainsworth, R A and Goodall, I W (1983). Defect Assessments at Elevated Temperature, ASME J Pres Ves Tech, Vol 105, pp263-268.

Gladwin, D N, Miller, D A, Neate, G J and Priest, R H (1988). Creep, Fatigue and Creep-Fatigue Crack Growth Rates in Parent and Simulated HAZ Type 321 Stainless Steel, Fatigue Fract Engng Mater Struct, Vol 11, pp355-370.

Gladwin, D N, Miller, D A and Priest, R H (1988). An Examination of the Fatigue and Creep Fatigue Crack Growth Behaviour of Aged 347 Stainless Steel Weld Metal at 650°C, Materials Sci Technology, in press.

Goodall, I W and Ainsworth, R A (1988). Structural Assessment of Metal Components, Conf on Materials and Engineering Design, Institute of Metals, London.

Goodall, I W and Chubb, E J (1976). The Creep Ductile Response of Cracked Structures, Int J Fract, Vol 12, pp289-303.

Miller, A G (1988). Review of Limit Loads of Structures Containing Defects, Int J Pressure Vessels Piping, Vol 32, pp197-327.

Miller, A G and Ainsworth, R A (1989). Consistency of Numerical Results for Power-Law Hardening Materials, and the Accuracy of the Reference Stress Approximation for J, Engng Fract Mech, Vol 32, pp233-247.

Milne, I, Ainsworth, R A, Dowling, A R and Stewart, A T (1988). Assessment of the Integrity of Structures Containing Defects, Int J Pressure Vessel Piping, Vol 32, pp3-104.

Neate, G J (1986a). Creep Crack Growth in 1/2 CrMoV Steel at 838K, I: Behaviour at a Constant Load, Materials Sci Engng, Vol 82, pp59-76.

Neate, G J (1986b). Creep Crack Growth in 1/2 CrMoV Steel at 838K, II: Behaviour under Displacement Controlled Loading, Materials Sci Engng, Vol 82, pp77-84.

Penny, R K and Marriott, D L (1971). Design for Creep, Mc-Graw Hill, New York.

Pineau, A (1983). High Temperature Fatigue Behaviour of Engineering Materials in Relation to Microstructure, in Fatigue at High Temperature (ed. R P Skelton) Applied Science, London, pp305-364.

Skelton, R P (1983). Growth of Short Cracks During High Strain Fatigue and Thermal Cycling, ASTM STP 770, pp337-380.

Skelton, R P (1988). Private communication.

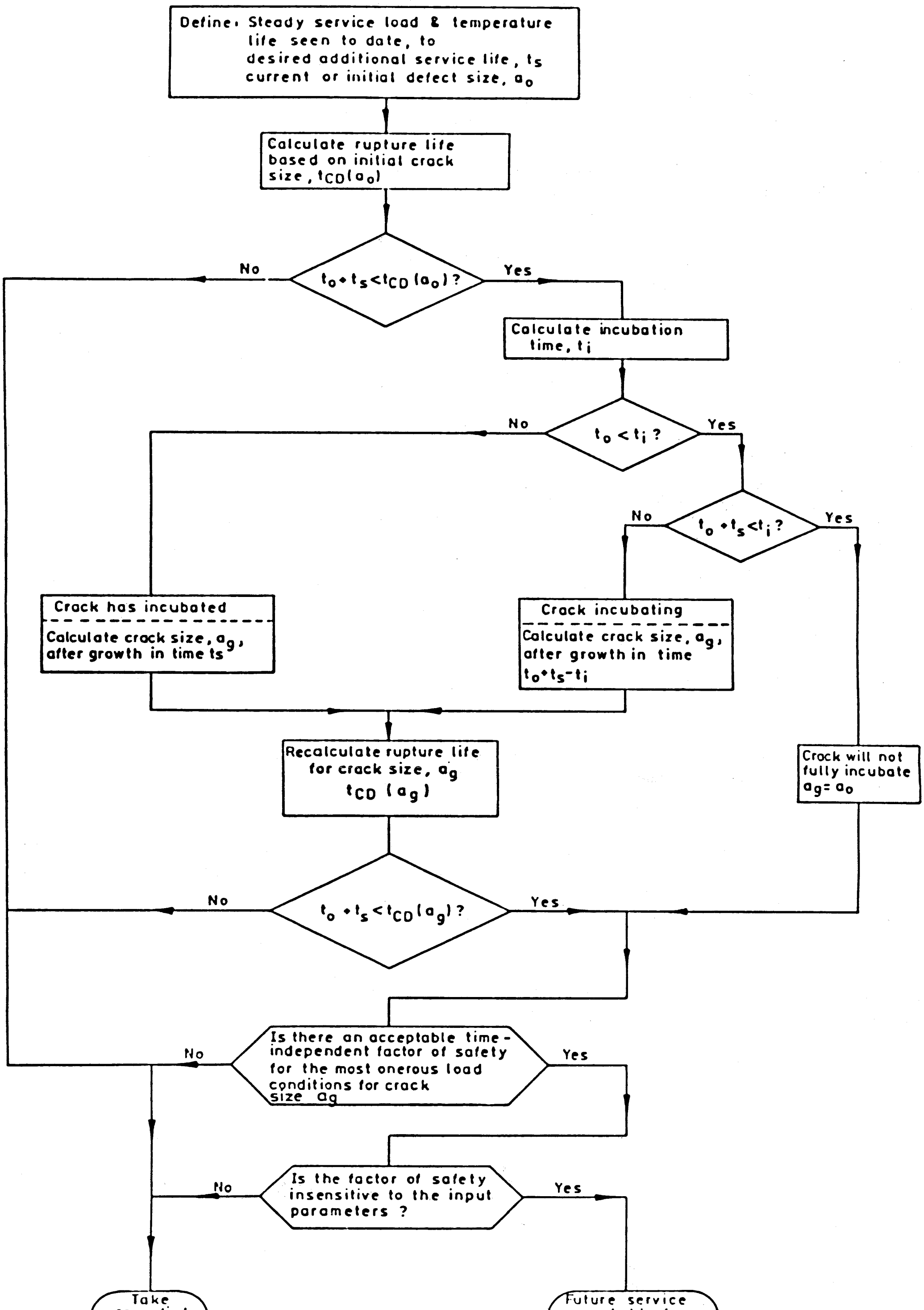

Figure 1. Flow chart for defect assessment procedure under constant loading

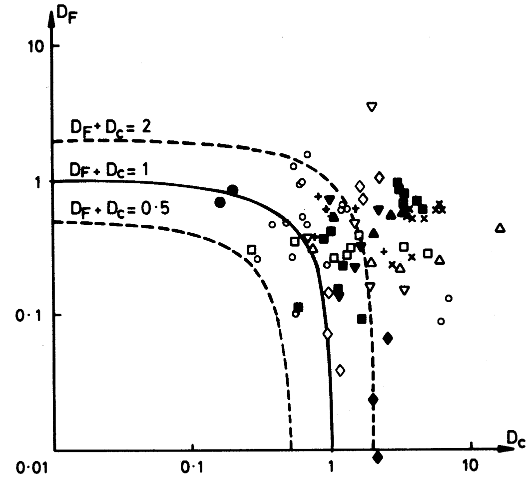

Figure 2. Comparison of linear damage summation with experimental data for a range of materials.

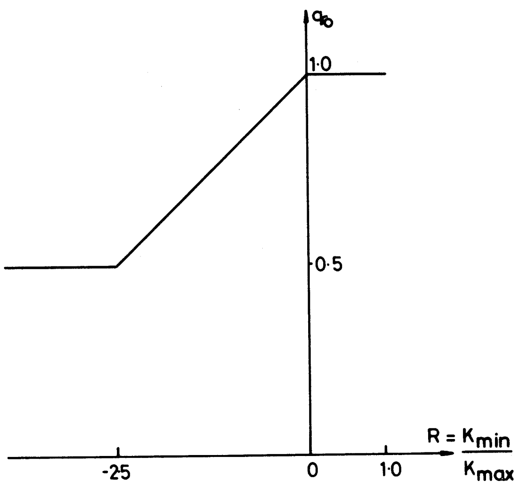

Figure 3. Definition of the parameter q_0 used to define ΔK_{eff} in equation (10).

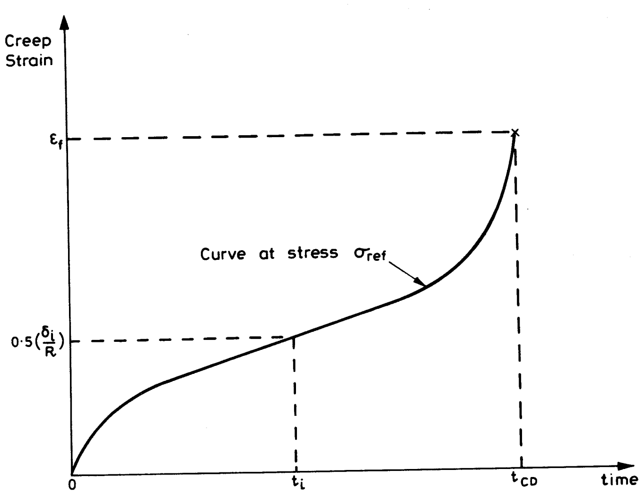

Figure 4. Illustration of the reference stress method for determination of initiation time, t_i, and creep rupture life, t_{cD}.

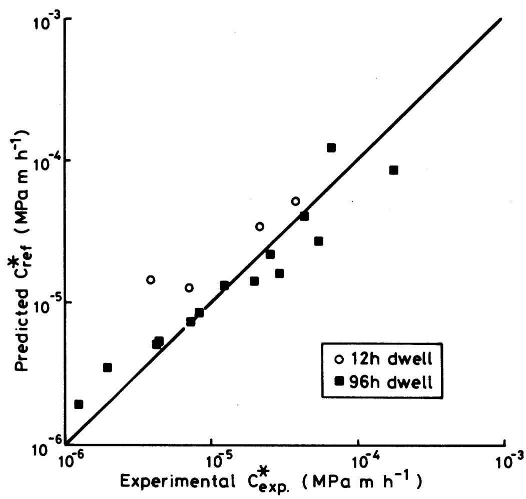

Figure 5. Comparison of value of C* predicted by equation (15), C^*_{ref}, with that deduced from experimental data, C^*_{exp}, for an austenitic 321 steel (after Gladwin et al, 1988).

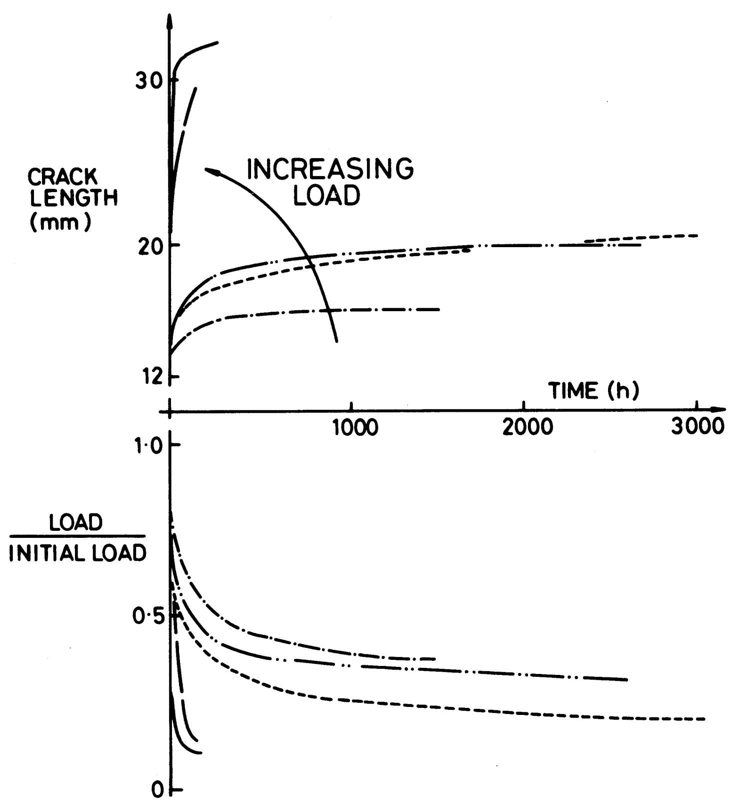

Figure 6. Experimental data illustrating the relationship between crack extension and load drop (after Neate, 1986b).