T73S03 (R5V4/5) – Session 40B – Incubation

Last Update: 2/5/16

Methods of incubation assessment, High Temperature FAD, Incubation CTOD, Sigma-d Method (only sigma-d is treated in detail)

Qu.: What is "incubation"?

Incubation is the period prior to the start of creep-fatigue crack growth.

During the incubation period the crack tip region is accumulating sufficient damage to start the crack tearing (growth).

Qu.: Is there always an incubation period?

No.

If a crack forms (initiates) by a creep-fatigue mechanism, then the growth phase is likely to follow the initiation phase without any hiatus. This is because the creep-fatigue damage at the crack tip must already be approaching unity in order for the crack to have initiated.

Incubation refers to cracks which have been formed by some other mechanism. Examples are welding defects of many different types, or defects due to the various forms of oxidation/corrosion.

One could postulate funny circumstances such as a defect which has initiated by pure fatigue, but which is then subject to predominantly creep conditions. In this case it would be appropriate to consider incubation of the creep crack growth mechanism (though this situation is rather contrived).

Qu.: What methods are there for calculating the incubation time?

Five methods are discussed in R66/R5,

- Empirical C* correlations for widespread creep;
- Correlation with rupture data for widespread creep;
- The CTOD method;
- The HTFAD method;
- The sigma-d method.

The last of these is usually the most useful and will be treated in detail here. The other methods are described briefly.

The first three methods only apply to creep, i.e., they assume fatigue is insignificant. The last two methods can be applied when there is combined creep and fatigue.

Qu.: What is the C*-correlation method?

Under widespread creep conditions (which means $C(t) \approx C^*$) the incubation time can be derived from ccg test data and fitted to an inverse power of C*. For example, for 316 steels at ~550°C R66 gives a lower bound incubation time,

$$t_i = 0.1\left(C^*\right)^{-0.61} \tag{1}$$

where the time is in hours for C* in MPa.m/hr. But steady creep is perhaps unlikely in 316ss at 550°C, in which case this would not be valid.

For similar fits for other materials see R66 Section 11.2

WARNING: R66 Section 11 uses the word "initiation" to mean "incubation".

Qu.: What is the correlation with rupture data?

This method again assumes that widespread creep conditions have been established prior to incubation. The method is taken from BS7910 (2007). The advantage of the method is that no specific incubation test data are required. The incubation time is estimated as,

$$t_i = 0.0025\left\{\frac{\sigma_{ref} \cdot t_r}{K^2}\right\}^{0.85} \tag{2}$$

Here σ_{ref} is the reference stress including the effects of the crack. Since widespread creep is assumed to prevail, I assume that this is the primary reference stress (secondary stresses having been assumed to have relaxed). t_r is the creep rupture time for stress σ_{ref} and K is the relevant primary SIF. This gives the time in hours for units MPa and MPa√m. Best estimate rupture data yields best estimate incubation time.

Qu.: What is the CTOD method of incubation assessment?

CTOD = crack tip opening displacement.

The CTOD method for estimating the incubation time under steady primary creep is described in R5V4/5 §10.4 and Appendix A2, §A2.6. Under cyclic and combined loading see R5V4/5 Appendix A3, §3.4.5. Here I have run the requirements together into one equation.

The method requires test data to supply the value of the critical CTOD for incubation, δ_i. This is the main drawback of this method because the incubation CTOD is not usually available. However, if it is, the incubation time is found by solving,

$$\varepsilon_c\left(\sigma_{ref}, t_i\right) = \varepsilon_c^0 + \left(\frac{\delta_i}{R'}\right)^q - \left(\frac{K_T}{K_P}\right)^2 \frac{\sigma_{ref}}{E} \tag{3}$$

where $R' = \left(\frac{K_P}{\sigma_{ref}}\right)^2$ and σ_{ref} and K_P refer to the primary loads and the crack size of interest, whereas K_T is the primary plus secondary SIF. In (3), ε_c^0 is the creep strain which has accumulated at the crack tip prior to the introduction of the crack. It is debatable whether this should be included in (3).

The LHS of (3) is the creep strain evaluated for the reference stress and temperature of relevance. Essentially (3) is saying that the strain (hence the crack tip blunting) required to initiate crack growth equals the quantity on the RHS. (3) applies for both widespread creep and transient creep. In the case of widespread creep (i.e., times longer than the redistribution time) it can be simplified to,

$$\varepsilon_c\left(\sigma_{ref}, t_i\right) = \varepsilon_c^0 + \frac{1}{2}\left(\frac{\delta_i}{R'}\right)^q \tag{4}$$

The parameter q which appears in (3) and (4) is the index in the ccg law. If this is not known then it can be equated to $q = \frac{n}{n+1}$ where n is the creep index.

Qu.: What is the HTFAD?

HTFAD = High Temperature Failure Assessment Diagram

The HTFAD extends the FAD approach of R6 to creep. It can be used to assess both incubation and creep crack growth. It can be used for combined primary plus secondary loads. Fatigue can also be included.

I will not attempt to do full justice to the method here, but only give a rough indication of how it works.

(i) In place of the 0.2% proof stress from short-term tensile tests we use $\sigma_{0.2}^{c}$, the stress to produce 0.2% inelastic (plastic+creep) strain at the assessment temperature and assessment time of interest;

(ii) The L_r parameter is defined as $P/P_L(\sigma_{0.2}^{c})$ where P is the primary load and $P_L(\sigma_{0.2}^{c})$ is the collapse load for the crack size of interest if the perfectly plastic yield strength were $\sigma_{0.2}^{c}$;

(iii) The HTFAD is defined as $K_r = \left\{ \frac{E\varepsilon_{ref}^{c}}{L_r \sigma_{0.2}^{c}} + \frac{L_r^3 \sigma_{0.2}^{c}}{2E\varepsilon_{ref}^{c}} \right\}^{-1/2}$ where ε_{ref}^{c} is the total reference strain from the mean isochronous creep curve at a stress of $L_r \sigma_{0.2}^{c}$ and for the time and temperature being assessed;

(iv) The "creep toughness" is defined via ccg tests by $K_{mat}^{c} = \sqrt{E' J_{ep} + E J_c}$ where J_{ep} is the usual elastic-plastic J for the specimen and J_c can be defined via the same J-integral but in which the strains are all creep strains. In practice J_c is found experimentally using $J_c = \eta\left(\frac{n}{n+1}\right)\frac{P}{B_n(w-a)}\Delta_c$, where Δ_c is the load line displacement due to creep. Hence $C^* \approx \frac{dJ_c}{dt} = \eta\left(\frac{n}{n+1}\right)\frac{P}{B_n(w-a)}\dot{\Delta}_c$ is the usual empirical formula for C^*. The creep toughness depends upon time and temperature and also upon the crack growth, Δa;

(v) If specific test data of the form required in (iv) to evaluate the creep toughness is not available then §A5.4.4 gives an alternative method which takes the crack growth law, $\dot{a} = AC^{*q}$, as the input;

(vi) K_r for primary loading is defined as K_p / K_{mat}^{c}. For combined primary plus secondary loading the definition of K_r is via a specific formula (thus avoiding the equivalent of the plasticity correction, ρ or V, in R6). This is,

$$K_r = \frac{\sqrt{K_p^2\left(E\varepsilon_{ref}^{c} / L_r \sigma_{0.2}^{c}\right) + K_S^2 + 2K_P K_S}}{K_{mat}\sqrt{E\varepsilon_{ref}^{c} / L_r \sigma_{0.2}^{c}}}$$

(vii) The (L_r, K_r) assessment point is plotted on the HTFAD. If it lies within the diagram then the crack growth is less than the value Δa assumed in the above calculations. If it lies outside then the growth is greater than Δa. Iteration until the point lies on the HTFAD yields the predicted crack growth.

(viii) An incubation assessment is carried out using the HTFAD method by setting Δa to some suitably small value, e.g., 0.2mm.

(ix) Fatigue is addressed by calculating the fatigue crack growth separately and subtracting this from the total crack growth. Thus, the creep crack growth used in the above assessment steps is interpreted as $\Delta a_{total} - \Delta a_{fatigue}$.

Note that the HTFAD has to be re-drawn for different assessment times or temperatures and will generally be more onerous (lower) for longer times or higher temperatures.

The assessment point depends upon time, temperature and also crack growth, Δa.

Qu.: What is the "sigma-d method" for incubation assessment?

The sigma-d method originates from the French code RCC-MR. The R5V4/5 version is defined in Appendix A6. The method addresses incubation by both creep and fatigue, separately or in combination.

The sigma-d method derives a characteristic stress (σ_d) at a microstructurally relevant distance d from the crack tip. Continuum data (fatigue endurance and creep rupture) are then used to assess failure under such a stress, and this is interpreted as incubation.

A major advantage of the sigma-d method is that it does not require any empirical incubation input, nor indeed any data from crack growth tests. Being based only on standard continuum data (fatigue endurance and creep rupture) makes it a far more convenient method than the methods described above.

Qu.: To what materials is the sigma-d method applicable?

The sigma-d method can be applied to both austenitic and ferritic materials. However the bulk of the validation has been for austenitic material, with various different forms of 316ss featuring most frequently.

Qu.: What is the recommended value for d?

For austenitic materials, including weldments, the recommended value to assume for the key distance d is 50 microns (0.050mm).

Validation for ferritic material is poor – but *I think* it is OK to use the method with this proviso.

The method is applicable to materials which exhibit work hardening and whose UTS at room temperature is less than 600 MPa.

Qu.: Can relaxation of secondary stresses be included in a sigma-d assessment?

Yes.

It will be simpler, and conservative, to ignore relaxation of secondary stresses. However if this seems excessively conservative (e.g., if there are yield magnitude residual stresses) then relaxation may be included. Details are given below.

Qu.: What precursor checks are necessary before a sigma-d assessment?

- The crack must be stable (as assessed using R6);
- The ligament must not rupture during the assessed period;
- The structure must be within global shakedown.
- Check if creep is insignificant. For this use the test for cracked bodies specified in Session 40A,see http://rickbradford.co.uk/T73S03TutorialNotes40A.pdf and R5V4/5 §9.1 and Figures A6.6 and A6.7 in Appendix A6.
- Check to see if fatigue is insignificant. In this context, fatigue is deemed insignificant if the fatigue crack growth rate would be less then $1/10^{th}$ of the creep crack growth rate (after incubation).

Qu: How do creep and fatigue interact in a sigma-d assessment?

Creep and fatigue interact in two ways:-

[1] If fatigue is not negligible then the procedure for finding the sigma-d stress for use in evaluating the creep damage near the crack tip differs from that if fatigue is insignificant;

[2] The creep and fatigue damage terms in the incubation assessment do not combine linearly. Instead there is a non-linear interaction diagram – R5V4/5 Figure A6.5, reproduced below.

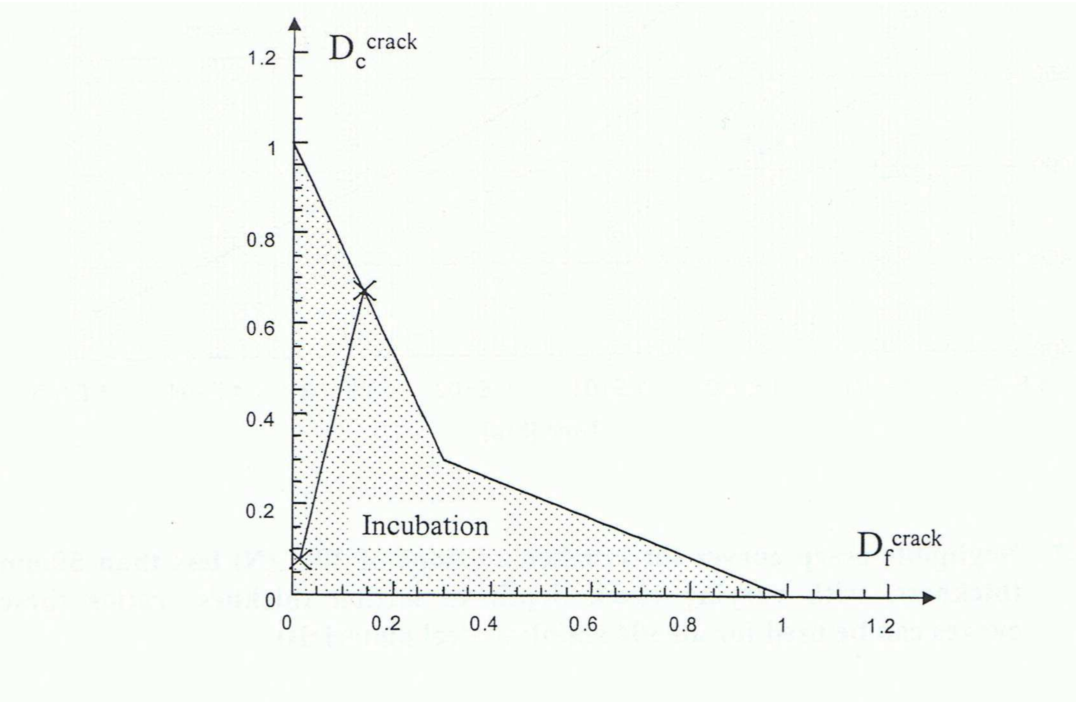

Figure A6.5 Creep-fatigue interaction diagram used for sigma-d procedure

If fatigue is insignificant then $D_f^{crack} = 0$ and the incubation criterion is simply $D_c^{crack} = 1$.

Note that the use of a non-linear interaction diagram is unusually in R5. Other parts of R5 simply add creep and fatigue terms linearly.

Qu.: What is the sigma-d procedure when fatigue is insignificant?

The procedure is in 7 steps, as follows…

(1) **Find the LEFM SIF**, K, for the total loading, i.e., primary plus secondary loads. Hence if residual stresses are present they must be included in this K. Only the normal operating loads are relevant, i.e., those which act during the creep dwell. This is because this SIF is to be used purely for finding σ_d and thence the crack tip creep damage.

(2) **Calculate the reference stress**, σ_{ref}. This is the 'ordinary' primary load reference stress as defined in R6 via the limit state. Secondary stresses do not contribute to σ_{ref}.

(3) **Obtain the mean monotonic true stress-strain curve** at the temperature of the dwell. Note it is the monotonic curve that is required here, not the cyclic curve.

$$\varepsilon = \frac{\sigma}{\overline{E}} + \left(\frac{\sigma}{A}\right)^n \qquad \text{where,} \qquad \overline{E} = \frac{3E}{2(1+\nu)} \tag{5}$$

(4) **Find the plastic strain corresponding to the reference stress** on the above monotonic stress-strain curve, i.e.,

$$\varepsilon_2 = \left(\frac{\sigma_{ref}}{A}\right)^n \tag{6}$$

(5) **Calculate the elastic stress at a distance *d*** from the crack tip, i.e.,

$$\sigma_{de} = \frac{K}{\sqrt{2\pi d}} f \tag{7}$$

In Equ.(7), f is a function of the crack tip radius and equals unity for a sharp crack [otherwise see R5V4/5 Equ.(A6.3)].

(6) From a starting point defined by the stress σ_{de} and the strain $\frac{\sigma_{de}}{\overline{E}} + \varepsilon_2$ **carry out the Neuber construction** to the mean monotonic stress-strain curve, as illustrated by Figure A6.2 (reproduced below). This defines the sigma-d stress, σ_d. Algebraically it is found by solving,

$$\left[\frac{\sigma_d}{\overline{E}} + \left(\frac{\sigma_d}{A}\right)^n\right]\sigma_d = \left(\frac{\sigma_{de}}{\overline{E}} + \varepsilon_2\right)\sigma_{de} \tag{8}$$

(7) **Evaluate the time to rupture**, t_{rup}, at stress σ_d and the relevant dwell temperature. If relaxation of secondary stresses is ignored then the creep damage term for this dwell is $D_c^{crack} = \frac{t}{t_{rup}}$. Summing such terms over all dwells gives the total D_c^{crack} over the assessed period. In the absence of significant fatigue, incubation occurs when $D_c^{crack} = 1$.

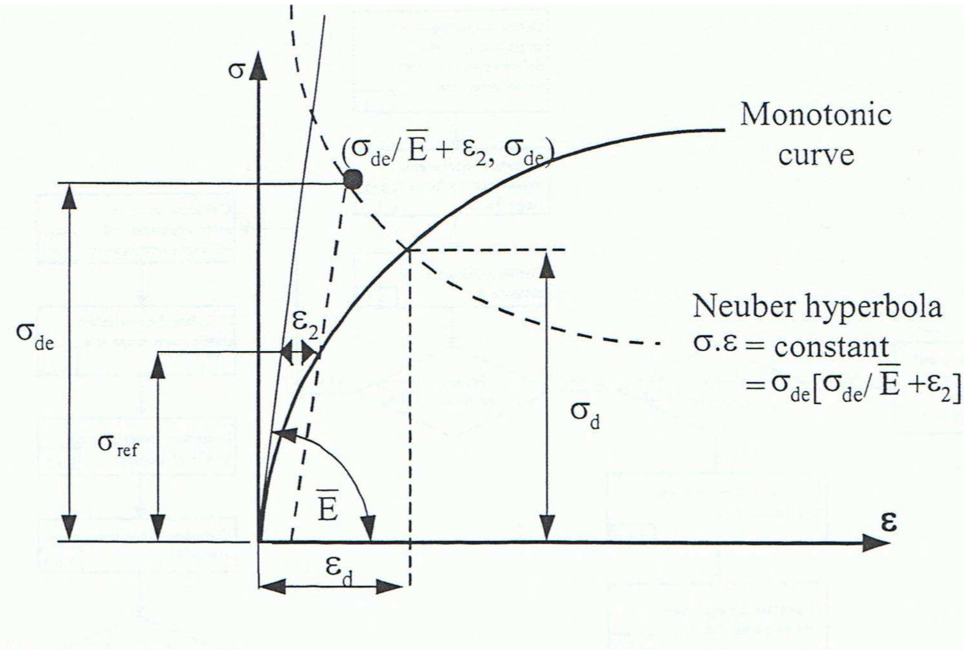

Figure A6.2 Application of Neuber's rule for creep loading

Qu.: What is the sigma-d procedure when fatigue ***is*** significant?

Not only must fatigue be included, but the way in which the creep damage is evaluated is now different. The reason is that the sigma-d stress, now written σ_{kd}, is generated by the cyclic plastic zone at the crack tip, which depends upon the load cycles. The procedure is in 19 steps, as follows…

(1) **Find the range of the LEFM SIF**, ΔK, for the total loading, i.e., primary plus secondary loads, $\Delta K = K_{\max} - K_{\min}$, where $K_{\min}$ may be negative. Constant stresses, e.g., residual stresses, will not contribute to ΔK.

(2) **Calculate the mean reference stress**, σ_{ref}^{mean}, defined as the time average of σ_{ref} (hence depending upon primary loads only). If the dwell occupies virtually all the operating time (which will commonly be the case) then this reduces to σ_{ref} under the normal operating primary loads.

(3) **Calculate the reference stress range**, $\Delta\sigma_{ref}$, defined as the algebraic difference of the reference stresses at the peak load and at the minimum load, and where the minimum reference stress is taken as negative if the loads reverse. At least, this is my interpretation of R5 Equ.(6.5) in Section A6.3.6.1.

(4) **Obtain the mean cyclic true stress-strain curve** at the temperature of the dwell. Note it is the cyclic curve that is required here, not the monotonic curve, and this differs from the procedure for insignificant fatigue.

$$\Delta\varepsilon = \frac{\Delta\sigma}{\overline{E}} + \left(\frac{\Delta\sigma}{B}\right)^{1/\beta} \quad \text{where,} \quad \overline{E} = \frac{3E}{2(1+\nu)} \tag{9}$$

I use 'B' here to distinguish the cyclic and monotonic Ramberg-Osgood fits.

(5) **Find the plastic strain range corresponding to the reference stress range** on the above cyclic stress-strain curve, i.e.,

$$\Delta\varepsilon_2 = \left(\frac{\Delta\sigma_{ref}}{B}\right)^{1/\beta} \tag{10}$$

(6) **Calculate the elastic stress range at a distance *d*** from the crack tip, i.e.,

$$\Delta\sigma_{de} = \frac{\Delta K}{\sqrt{2\pi d}} f \tag{11}$$

In Equ.(11), f is the same function of the crack tip radius as previously and equals unity for a sharp crack [otherwise see R5V4/5 Equ.(A6.8)].

(7) From a starting point defined by the stress range $\Delta\sigma_{de}$ and the strain range $\frac{\Delta\sigma_{de}}{\overline{E}} + \Delta\varepsilon_2$ **carry out the Neuber construction** to the mean cyclic stress-strain curve, as illustrated by Figure A6.3 (reproduced below).

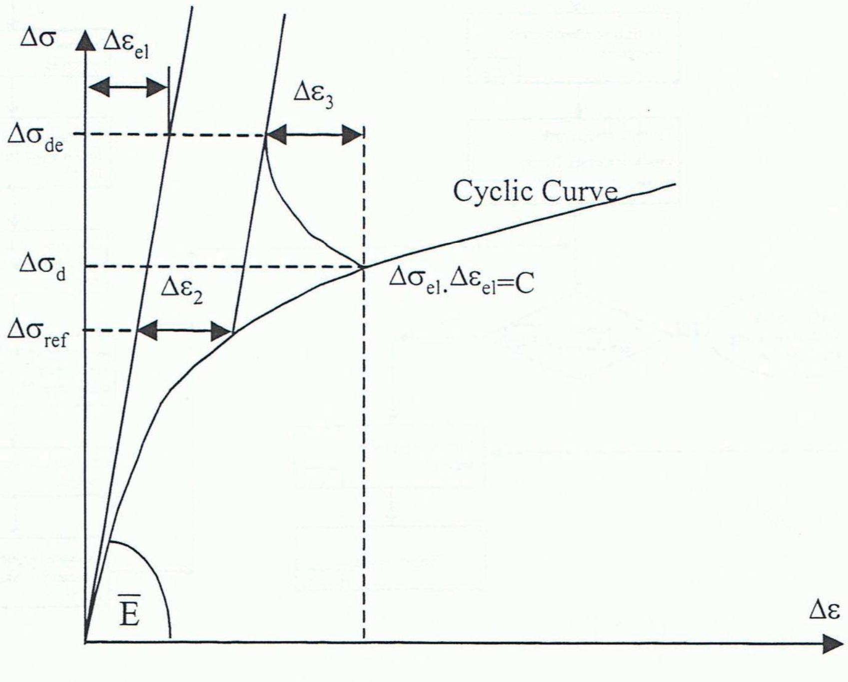

Figure A6.3 Application of Neuber's rule for fatigue loading

This defines the elastic-plastic stress range, $\Delta\sigma_d$. Algebraically it is found by solving,

$$\left[\frac{\Delta\sigma_d}{\overline{E}} + \left(\frac{\Delta\sigma_d}{B}\right)^{1/\beta}\right]\Delta\sigma_d = \left(\frac{\Delta\sigma_{de}}{\overline{E}} + \Delta\varepsilon_2\right)\Delta\sigma_{de} \tag{12}$$

The corresponding elastic-plastic strain range is,

$$\Delta\varepsilon_d = \frac{\Delta\sigma_d}{\overline{E}} + \left(\frac{\Delta\sigma_d}{B}\right)^{1/\beta} \equiv \Delta\varepsilon_{el} + \Delta\varepsilon_2 + \Delta\varepsilon_3 \tag{13}$$

(8) **Evaluate the volumetric correction** to the strain range, $\Delta\varepsilon_{vol}$, using the same procedure as in R5V2/3 §7.4.2.

(9) **Check whether creep is significant**. If not, go to step (16).

(10) **Find the "fatigue stress range"**, $\Delta\sigma^*$, defined as the stress range which gives a strain range of $\Delta\varepsilon_d + \Delta\varepsilon_{vol}$ on the cyclic stress-strain curve, i.e., it is the solution to,

$$\frac{\Delta\sigma^*}{\overline{E}} + \left(\frac{\Delta\sigma^*}{B}\right)^{1/\beta} = \Delta\varepsilon_d + \Delta\varepsilon_{vol} \tag{14}$$

So $\Delta\sigma^*$ is just a small correction to $\Delta\sigma_d$ due to the volumetric correction to the strain range.

(11) **Define the strain** ε_p as that which corresponds to a stress of σ_{ref}^{mean} on the *modified* uniaxial stress-strain curve, i.e., noting the factor of 2…

$$\varepsilon_p = \frac{\sigma_{ref}^{mean}}{\overline{E}} + \left(\frac{2\sigma_{ref}^{mean}}{B}\right)^{1/\beta} \tag{15}$$

(12) **Define the strain** ε_s as that which corresponds to a stress of $0.5\Delta\sigma^*$ on the *modified* uniaxial stress-strain curve, i.e.,

$$\varepsilon_s = \frac{0.5\Delta\sigma^*}{\overline{E}} + \left(\frac{\Delta\sigma^*}{B}\right)^{1/\beta} = \Delta\varepsilon_d + \Delta\varepsilon_{vol} - \frac{0.5\Delta\sigma^*}{\overline{E}} \tag{16}$$

The strains ε_p and ε_s are illustrated by Figure A6.4 (reproduced below).

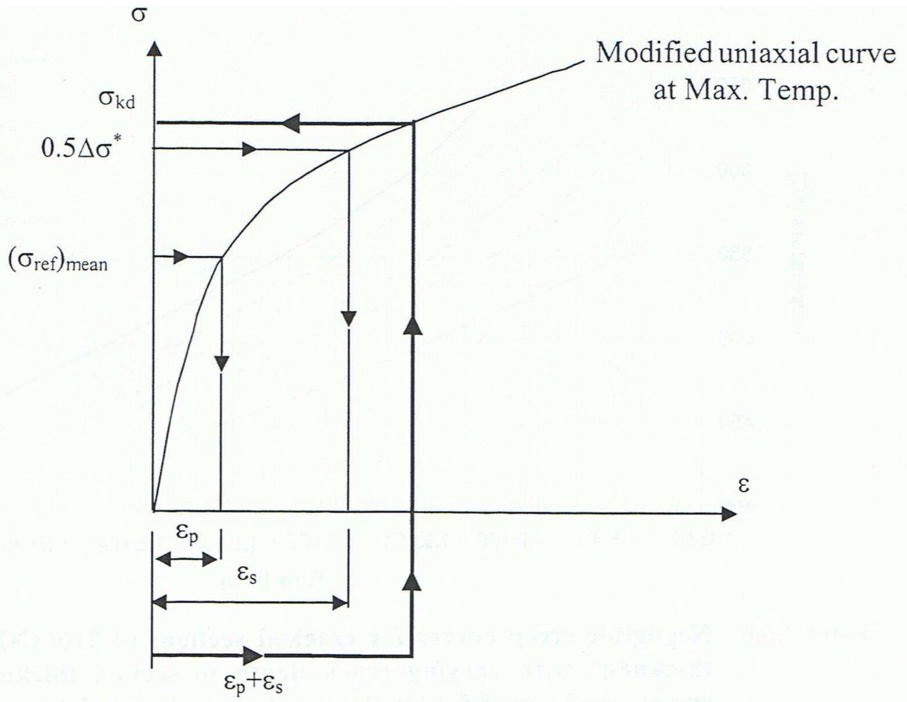

Figure A6.4 **Evaluation of stress at start of dwell, σ_{kd} (ε_p and ε_s are strains on the modified uniaxial stress-strain curve corresponding to stresses $(\sigma_{ref})_{mean}$ and $0.5\Delta\sigma^*$ respectively)**

(13) **Find the start of dwell stress,** σ_{kd}, as that stress which gives a strain of $\varepsilon_p + \varepsilon_s$ on the *modified* uniaxial stress-strain curve, as illustrated on Fig.A6.4 and defined algebraically by,

$$\frac{\sigma_{kd}}{\overline{E}} + \left(\frac{2\sigma_{kd}}{B}\right)^{1/\beta} = \varepsilon_p + \varepsilon_s \qquad (17)$$

(14) **Evaluate the time to rupture,** t_{rup}, at stress σ_{kd} and the relevant dwell temperature. If relaxation of secondary stresses is ignored then the creep damage term for this cycle, with a dwell time *t*, is $D_c^{crack} = \dfrac{t}{t_{rup}}$. Summing such terms over all cycles/dwells gives the total D_c^{crack} over the assessed period.

(15) **Evaluate the increment of creep strain,** $\Delta\varepsilon_{cr}$, using mean forward creep deformation data at the relevant dwell temperature and at a stress of σ_{kd}. Note that the use of mean deformation data does not imply the use of mean rupture data - see below.

(16) **The total fatigue strain range** is defined by,

$$\Delta\varepsilon_t = \Delta\varepsilon_d + \Delta\varepsilon_{vol} + \Delta\varepsilon_{cr} \qquad (18)$$

(17) **Determine a "design" fatigue endurance curve** by reducing a best estimate, continuous cycling, endurance curve by a factor of 2 on strain or by a factor of 20 on cycles, whichever is more restrictive for the application. Note that this differs from the usual R5 approach, which would use a fitted lower bound endurance curve, because the sigma-d procedure has been lifted from RCC-MR and it is desirable to maintain consistency so that the validation is not undermined.

(18) Enter the "design" fatigue curve at a strain range of $\Delta\varepsilon_t/1.5$ to obtain an allowable number of cycles, N. **Define the fatigue crack incubation usage factor** as $D_f^{crack} = \frac{n}{N}$ where *n* is the assessed number of plant cycles. If there are several types of cycle, the total fatigue usage is the sum of those evaluated separately.

(19) **The point** $\left(D_f^{crack}, D_c^{crack}\right)$ **is plotted on the interaction diagram**, Fig.A6.5. If the point lies outside the line then incubation is conceded and the crack must be assumed to be growing by creep/fatigue.

Qu.: Should mean or lower bound creep rupture times be used?

The use of mean data should be interpreted as producing a best estimate of incubation time. For a lower bound incubation time, lower bound rupture should be used. See R5 §A6.3.5.7 and §A6.4.11.

My reading of the validation data is that the use of mean data will produce an incubation time which is somewhat conservative compared to experimental mean incubation times, but certainly does not bound all experimental data. The use of lower bound rupture will bound all experimental incubation data, and implicitly includes additional allowance for service ageing. Consequently a robust case for "no growth" will need to use the lower bound rupture – but it may be possible to argue some intermediate rupture assumption on a case by case basis.

Qu.: Should parent or weld stress-strain curves be used?

Obviously if you are assessing a region well away from any weld, then parent stress-strain curves should be used.

However, if the assessment addresses any part of a weldment (the weld material itself or the HAZ) then “equivalent” material stress-strain curves should be used. R5V4/5 recommends that the R6 mismatch procedure be used. This will result in stress-strain curves which are intermediate between parent and weld material.

Qu.: What are the rules for relaxation of secondary stresses?

The methodology for relaxation is,

- Relaxation must not reduce the stress to below the value of σ_d calculated for the primary loads alone (σ_d^P);
- Hence I suggest that the relaxation equation should be a version of that of R5V4/5 Appendix A3, Equ.(A3.20), but modified to impose the above limit, i.e.,

$$\frac{d\sigma_d}{dt} = -\frac{E}{Z}\left\{\dot{\varepsilon}_c(\sigma_d, \varepsilon_c) - \dot{\varepsilon}_c\left(\sigma_d^P, \varepsilon_c\right)\right\} \quad (19)$$

- The elastic follow-up factor used should be $Z = 4$ (see A.6.4.13)

In line with current R5 recommendations, the relaxation equation is written assuming strain hardening. However this may be replaced by any hardening behaviour as considered appropriate.

I believe the intent of R5 is that, if fatigue is significant, relaxation may be assumed over a single dwell between cycles only. This is because it is assumed that stresses at the start of the subsequent dwell are re-set by the load cycle.

Qu.: How does relaxation differ if fatigue is insignificant?

My reading of R5V4/5 A.6.4.13 is: if fatigue is insignificant, then relaxation is effectively continuous over the whole of plant life. Plant cycles may interrupt the relaxation, but the relaxation is deemed to continue from the same stress upon returning to load (creep is unperturbed by cyclic loading).

However, if fatigue is significant, then the above procedure implicitly assumes that the start-of-dwell stress is reset to σ_{kd} on every cycle. Thus, Equ.(19) is integrated over the dwell period starting from σ_{kd} for every cycle. The end-of-dwell stress will not necessarily be the same for all cycles, though, because…

Qu.: Is creep hardening continuous between cycles?

On successive dwells it will be conservative to assume that creep hardening is continuous between cycles. This is because creep damage is being evaluated as a time-fraction using rupture data. Consequently, because continuous hardening causes a reducing strain rate and hence reducing relaxation, the stress will remain higher than if primary creep were reset on each cycle.

This differs from an R5V2/3 assessment, where ductility exhaustion is used, for which continuous hardening is less onerous than assuming primary creep is reset on each cycle.

Qu.: How is D_c^{crack} found when there is relaxation?

Each dwell is considered as divided into a (large) number of periods of duration t_i. Integration of Equ.(18) gives the stress at the start of each of these periods to be σ_{di} where σ_{d1} is the start-of-dwell stress. The creep rupture life at these stresses, and at the relevant temperature, is written $t_{rup,i}$. Hence,

$$D_c^{crack} = \sum_i \frac{t_i}{t_{rup,i}} \tag{20}$$

When fatigue is insignificant, and assuming there is only one relevant operating creep condition, a single sum like (20) can cover the whole of plant life.

When fatigue is significant, and hence $\sigma_{d1} \equiv \sigma_{kd}$, there will be a distinct sum like (20) for each dwell. The corresponding $D_{c,j}^{crack}$ for the j^{th} dwell will differ due to creep hardening between cycles and the total is $D_c^{crack} = \sum_j D_{c,j}^{crack}$ where j runs over the plant cycles. If primary creep were reset on every cycle (which would probably be non-conservative) then all the $D_{c,j}^{crack}$ would be equal and $D_c^{crack} = ND_{c,j}^{crack}$ where N is the number of plant cycles.

Background

Manus O'Donnell, "Developments in the Sigma-d Method for the Assessment of Creep Crack Incubation", E/REP/BDBB/0075/AGR/05 (April 2005).