T73S03 Tutorial Session 44B – Safe Lives and CCG at Low Temperature

Last Update 1/8/16

Integrability of $da/dt = A.C(t)^q$; Derivation of K-based formula for crack growth when $t << t_{red}$; Paradox of apparent temperature independence: process zone and real temperature dependence (RAA report); "Safe Lives" methodology – IMAN#5.

Low Temperature Creep Crack Growth

Qu.: Is creep crack growth sensitive to temperature?

Yes, of course it is.

Qu.: Where does the temperature sensitivity of $AC(t)^q$ lie?

The point I wish to make here is that the empirical parameters A and q are quite insensitive to temperature. R66 tends to give a single value for these parameters to cover a broad temperature range. Over this same temperature range the strain rate would vary by orders of magnitude. So the temperature dependence of $AC(t)^q$ lies entirely in $C(t)$, whose temperature dependence in turn derives almost entirely from the creep strain rate.

Hold that thought.

Qu.: To what does $AC(t)^q$ reduce when the temperature is low?

When temperature is sufficiently low the creep strains will be small and the redistribution time becomes very long. Consequently $\tau = t/t_{red} = \varepsilon_c/\varepsilon_{ep}$ is very small, $\tau << 1$. In addition primary creep will prevail for very long times at low temperature, so we can assume a primary creep expression such as,

$$\varepsilon_c = C_1 t^{C_2}\sigma^n \quad \text{and} \quad \dot{\varepsilon}_c = C_1 C_2 t^{C_2 - 1}\sigma^n \tag{1}$$

Using an approximation $\frac{K_{TOT}}{\sigma_{ref}} \approx \frac{K^{PR}}{\sigma_{ref}^{PR}}$ the estimation formula for $C(t)$ becomes,

$$C(t) = f(\tau)\frac{\dot{\varepsilon}_{c,ref}}{\sigma_{ref}} K_{TOT}^2 \tag{2}$$

where all the quantities in (2) are primary-plus-secondary. Now if we ignore plasticity, for $\tau << 1$ we have,

$$f(\tau) = \frac{(1+\tau)^{n+1}}{(1+\tau)^{n+1} - 1} \to \frac{1}{(1+n)\tau} = \frac{\varepsilon_e}{(1+n)\varepsilon_c} \tag{3}$$

So (2) becomes,

$$C(t) = \frac{\varepsilon_e}{(1+n)\varepsilon_c}\frac{\dot{\varepsilon}_{c,ref}}{\sigma_{ref}} K_{TOT}^2 = \frac{\dot{\varepsilon}_{c,ref}}{\varepsilon_{c,ref}}\frac{K_{TOT}^2}{(1+n)E} \tag{4}$$

But from (1) we have $\frac{\dot{\varepsilon}_{c,ref}}{\varepsilon_{c,ref}} = \frac{C_2}{t}$ so,

$$C(t) = \frac{C_2 K_{TOT}^2}{(1+n)Et} = \frac{C_2}{(1+n)t} J_{el} \quad (5)$$

So the crack growth rate becomes,

$$\frac{da}{dt} = AC(t)^q = A\left(\frac{C_2 K_{TOT}^2}{(1+n)E}\right)^q t^{-q} \quad (6)$$

Note that this is only true for an original sin defect because we have assumed both initiation and the start of primary creep at $t = 0$.

Because $C(t)$ is divergent at $t = 0$, so is the crack growth rate.

Qu.: Does the divergent crack growth rate cause infinite growth?

No.

The growth rate, (6), is integrable because $q < 1$.

If we consider only small amounts of crack growth so that the SIF is roughly constant then integration of (6) gives,

$$\Delta a = \frac{A}{1-q}\left(\frac{C_2 K_{TOT}^2}{(1+n)E}\right)^q \Delta t^{1-q} \quad (7)$$

Using $n = q/(1-q)$ this becomes,

$$\Delta a = \frac{AC_2^q}{(1-q)^{1-q}}\left(\frac{K_{TOT}^2}{E}\right)^q \Delta t^{1-q} \quad (8)$$

For example if $q = 0.89$ and $C_2 = 0.4$ then we get,

$$\Delta a = 0.56A\left(\frac{K_{TOT}^2}{E}\right)^{0.89} \Delta t^{0.11} \quad (9)$$

Qu.: When is (8) valid?

The assumptions we made to derive (8) are,

[1] $\tau << 1$ (which also implies that secondary stresses do not relax significantly);

[2] Original sin with no incubation;

[3] No plasticity;

[4] Any combination of primary and secondary stresses provided that $\frac{K_{TOT}}{\sigma_{ref}} \approx \frac{K^{PR}}{\sigma_{ref}^{PR}}$;

[5] Small amounts of crack growth so that K_{TOT} does not change much.

To ensure [1] it is sufficient that the temperature be sufficiently low.

Within its range of applicability, Equ.(8) is a very simple and quick way to estimate crack growth. It is an explicit function of time, thus avoiding the need for numerical integration

Qu.: So where has the temperature dependence gone?

The paradox I wish to bring to your attention is that Equ.(8) is apparently temperature independent. Recall that A and q appear to be temperature insensitive. But now the former temperature dependence of the ccg rate which came via the strain rate has cancelled from (8) – other than the very mild temperature dependence of C_2.

But the derivation of Equ.(8) should hold good as long as the temperature is sufficiently low (assuming the other conditions above are relevant). This appears to imply that ccg rates remain constant below a certain temperature.

Qu.: Surely that cannot be true?

No, quite.

Qu.: What went wrong?

The basis of the above derivation is that the crack tip fields are HRR controlled. Only then do we have a basis for assuming that $C(t)$ controls ccg. We have already seen one way that this assumption might break down – when the crack growth is too fast ($\lambda > 0.5$) so that the HRR fields are replaced by the Hu-Riedel fields.

What we have not considered so far is the possibility that the extent of the region in which the fields are HRR controlled is just too small to be relevant. In practice there is some process zone of finite size within which the damage mechanisms leading to cracking occur. Typically this will be the nucleation and growth of cavities on the grain boundaries, ultimately linking to form microcracks. The process zone is thus typically around a grain in size. But if the HRR fields dominate only over a region much smaller than this, then they will not control the crack growth process. In fact, if the temperature (or stress) is low enough, the region in which there are significant creep strains might be small compared with the process zone size. In this case there will be no crack growth. We'll return to this shortly, after a brief reprise…

Qu.: What is the criterion for insignificant creep in R5V4/5?

Warning: The criterion for insignificant creep is different for cracked and uncracked structures

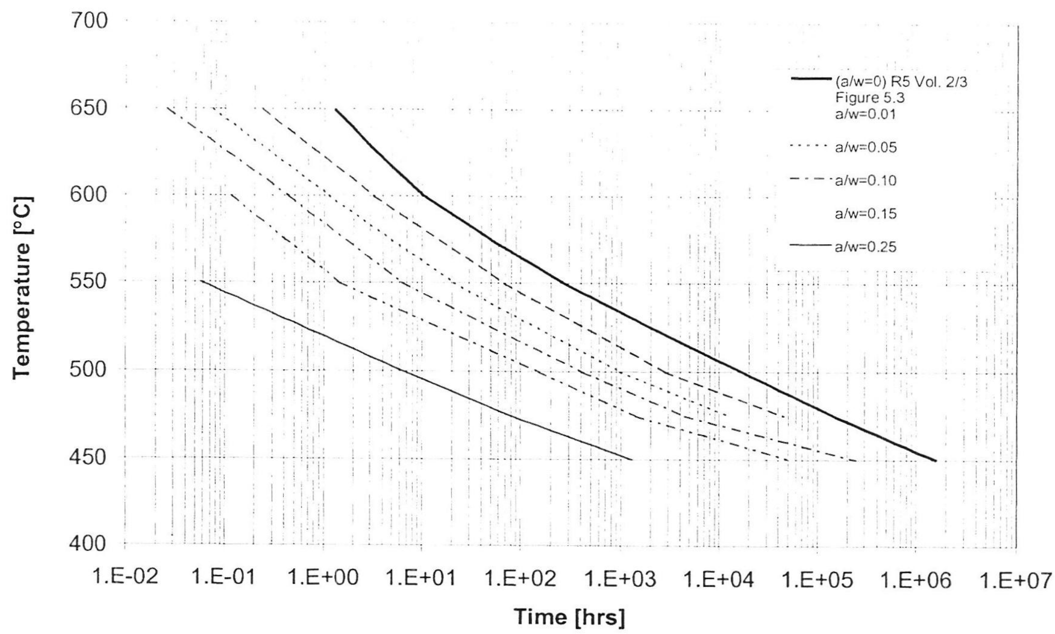
For cracked structures, the test for insignificant creep is defined in R5V4/5 §9.1 and Figures A6.6 and A6.7 in Appendix A6.

For cracked structures, the (in)significance of creep depends upon the crack depth. The criterion is that creep is insignificant for a period of time t_m defined as the time to accumulate a strain equal to 1/50th of the creep ductility (capped at 10%) at the relevant ***reference*** stress and operating/assessment temperature. (In addition, t_m is limited to the LOIC time for the uncracked structure). The use of the reference stress in the definition of t_m is what causes the crack size dependence.

Unlike the uncracked LOIC, t_m depends upon the loading of the structure. However, for 304ss and 316ss, Figures A6.6 and A6.7 in R5V4/5 Appendix A6 give load independent versions (essentially generalisations of LOIC to the cracked case). The 316 curve is given as Figure 1 below.

For example, for 316 the uncracked LOIC for 250,000 hours is ~470^{o}C, whereas for a structure with a 10% crack it drops to ~450^{o}C, and may be roughly 420^{o}C for a 25% crack.

Figure 1 Insignificant Creep for Cracked 316 Sections



e A6.6 **Negligible creep curves for cracked sections of 316L(N) less than 50mm thickness, with varying crack depth to section thickness ratios (these curves can be used for all 316 stainless steel materials)**

Hence: You can still get creep crack growth below the uncracked LOIC

Qu.: So, at least we know that ccg is zero below the cracked LOIC given above?

Yes. - or, at least, negligible.

Qu.: Do we have to use Equ.(8) at 1°C above the cracked LOIC?

No – because crack growth may not have initiated – especially since $\tau << 1$.

Qu.: What is a more reasonable approach?

If creep strain rates are very low, so that $\tau << 1$, then it may be that crack incubation never occurs. (Note that creep initiated cracks are unlikely in this case). So one of the crack incubation methodologies in R5 can be tried, see http://rickbradford.co.uk/T73S03TutorialNotes40B.pdf.

Bob Ainsworth, Ref.[1], discussed this problem prior to the current version of R5 being issued (hence prior to the inclusion of the sigma-d incubation methodology). He discussed an alternative approach based on incubation not occurring until the creep zone reached the process zone size. For the process zone he suggested the grain size, typically 50 microns in austenitic materials. For the creep zone size he gave the following expression,

$$r_{cr} = \frac{1}{2p\pi}\left(\frac{K}{\sigma_y^{eff}}\right)^2 \qquad (10)$$

where, $$\sigma_y^{eff} = \left(\frac{C(t)}{B(t)K^2} \right)^{\frac{1}{n-1}} \tag{11}$$

and $p = 1$ for plane stress but $p = 3$ in plane strain. σ_y^{eff} plays the part of an effective yield strength, with (10) being the usual formula for 'plastic' (here creep) zone size. The creep deformation law here has been taken to be $\dot{\varepsilon}_c = B(t)\sigma^n$, for example we might have $B(t) = C_1 C_2 t^{C_2 - 1}$ to be consistent with (1). This estimate of the creep zone is based on a definition requiring the Mises creep strain and elastic strain to be equal.

The term $C(t)/B(t)$ in (11) is divergent at $t = 0$ (at least if there is no plasticity) so that the effective 'yield' strength is divergent and the creep zone is vanishingly small at very early times. With any reasonable definition the creep zone must be zero initially.

At longer times, as $C(t) \to C^*$, the effective 'yield' strength becomes equal to the reference stress.

Using (10,11) a time can be found at which $r_{cr} = 50$ microns (say), which is the incubation time.

Safe Life Assessments

Qu.: What is meant by a "safe life assessment"?

The terminology is unfortunate because virtually any assessment could be called a 'safe life assessment'. However this phrase has come to mean something very specific. It refers to assessments in which a crack-like defect is postulated even though no such defect has been found. In fact, in typical cases, the components in question will have been inspected recently with no crack-like defects being reported. Postulating a defect is therefore very pessimistic and is generally only required for the higher nuclear safety duty items under the auspices of Ref.[2]. The safe life assessment consists of conservatively assessing crack growth from the assumed initial defect to failure, thus deriving a minimum safe life.

Qu.: What are the "higher nuclear safety duty" items?

The higher nuclear safety duty items are those designated in the safety case as HI, IOGF or IOF. These acronyms stand for,

- HI High Integrity
- IOGF Incredibility of Guillotine Failure
- IOF Incredibility of Failure

These nuclear safety classes are all higher than that of plant whose failure is deemed tolerable on either a frequent or an infrequent basis. In the simplest terms the distinction is that,

- "Frequent" tolerability of failure items have two diverse and independent lines of protection (by which is meant reactor shutdown and post-trip cooling in the event of the item failing);
- "Infrequent" tolerability of failure items have one line of protection (i.e., if the item fails, safe shutdown is still anticipated);
- IOF items have no independent line of protection.

IOF is the highest nuclear safety class.

For IOGF items gross failure must be incredible, but leaks are tolerable.

HI is a form of "IOF-light" in which a partial line of protection can be argued.

In practice IOGF and HI require the same rigour in their structural integrity assessments, but can be less onerous than that of full IOF.

The main difference between assessments of F/IF plant and IOGF/HI/IOF plant is that only the latter require cracks to be postulated when none are known or anticipated, Ref.[2].

Qu.: Are safe life assessments mandatory for HI/IOGF/IOF Items?

No, but almost.

All IOGF/HI/IOF plant will be covered by item-specific safety cases. The requirements are defined by the safety case.

However, it is generally the case that safe life assessments are regarded as an essential part of IOGF/HI/IOF safety cases. This is the default position.

Safe life assessments are a requirement of the Guidelines on structural integrity based safety cases, Ref.[2] – so a mandatory requirement is avoided only because these are *guidelines*.

Qu.: What is a safe life assessment?

A 'Safe Life Assessment' is a structural integrity assessment which assumes the presence of a crack-like defect. The assumption of defectiveness is usually,

- unrelated to any specific mechanism of crack formation;
- despite inspection providing evidence of a defect-free state, and;
- for the purpose of providing an additional safety case leg for IOF, IOGF or HI plant, [Ref.1].

The 'Safe Life' is the time for the postulated starter crack to grow to its limiting size by creep / fatigue (or for net section rupture to occur, if earlier).

The limiting size will probably be determined by an R6 crack stability assessment under the relevant fault condition, or by creep rupture.

Qu.: Are safe life assessments always creeping assessments?

No.

They may be creeping or non-creeping. However, because the purpose of this tutorial is R5V4/5 we are only considering creeping safe life assessments here. In practice it is the creeping safe life assessments which present difficulties – because of potentially rapid creep crack growth (theoretically, at least). Below the creep regime the operative mechanisms are usually fatigue and/or corrosion mechanisms (e.g., SCC). Neither fatigue nor corrosion are usually a problem in our IOGF/HI/IOF plant. Nevertheless, non-creeping safe life assessments are commonly required and carried out.

Items which have an active corrosion-driven cracking mechanism would present a problem in carrying out a safe life assessment, bur really such items should not be regarded as IOGF/HI/IOF.

Qu.: Are safe life assessments helpful for lifetime considerations?

No.

The term 'Safe Life Assessment' is employed for assessments of nuclear safety. As such, the advice includes implicit margins/reserve factors. Amongst these pessimisms is the overriding pessimism of assuming a crack-like defect where none is known. Safe life derived lifetimes are not, therefore, directly related to anticipated or accounting lives.

Qu.: Where is the formal procedure for safe life assessments?

I believe the only formal statement of procedural requirements is in my much-loved report E/REP/BDGBB/0100/AGR/06, Ref.[3]. However this is augmented by the informal IMAN#5, Ref.[4] – but IMANs are informal, unverified, documents which cannot be referenced in issued reports. Nevertheless, the IMANs provide a useful aide-memoir and a source of reference which can be quoted. The key elements of the procedure from these two sources are summarised below.

Qu.: Limitations on applicable scope of safe life assessments

- This advice below does <u>not</u> apply to structural assessments of known defects or defects which are actually *predicted* to occur by a known, active, degradation mechanism.
- In particular, this advice does <u>not</u> apply to austenitic weldments which entered service in the as-welded (non-stress-relieved) state and where such weldments may be subject to reheat cracking.

In these cases, predictions of defect size, location and time of occurrence will be specific to the mechanism in question (and hence the advice on these issues below will not apply).

Qu.: Thickness to employ

Safe life assessments come in two varieties,

- those done to derive a lifetime (e.g., to derive a required re-inspection interval) and based on measured thicknesses, or,
- those done to determine a minimum acceptable thickness assuming some desired lifetime.

The safe life procedure is the same. What differs is which quantity is assumed and which derived: thickness versus life.

Qu.: What size of defect is assessed?

Because safe life assessments are usually applied only to IOGF/HI/IOF items there will usually have been an inspection. The defect which is assumed will usually be the largest defect that could have escaped detection at this inspection. This will normally be expressed as a length and a depth, thus requiring an assessment of a semi-elliptic crack.

Note that this crack size relates to the time of inspection. The defect may have initiated at some earlier time and have been growing, reaching the NDT tolerance size at (or just after) the inspection time. This possibility is very important to the outcome of the assessment (see later).

Qu.: What position/orientation of defect is assessed?

Safe life assessments are required to provide an additional leg to the safety case and to cover the unforeseen. Consequently the postulated defect need not conform to any known cracking mechanism. This means that the defect could be in any weldment zone and in any orientation. In particular this means that longitudinal and transverse defects should both be assessed. However, it may be reasonable for the length of transverse defects to be confined to the extent of the weld and HAZ.

Qu.: What loading conditions are used for the creep assessments?

Creep rupture and creep crack growth calculations should employ actual operating conditions. Hence, use,

- creep effective temperatures for past operation,
- best estimate future temperatures,
- actual operating pressures,
- best estimate system loads, etc.

Qu.: What loading conditions are used for the fatigue assessment?

Fatigue crack growth calculations shall employ stress ranges derived from the peaks/troughs of recorded operating conditions. Recorded conditions are those plant events with a history of occurrence, e.g. as in CLA records.

Qu.: What loading conditions are used for the critical crack size assessment?

The guidance in Refs.[3] and [4] is,

- For IOGF/HI plant, R6 crack stability assessments should employ the most onerous frequent fault condition (i.e., with return frequency exceeding 10^{-3} p.a.), or normal operation if worse. This excludes seismic events which are regarded as infrequent.

- For IOF plant, R6 crack stability assessments should employ either the worst credible fault ($\geq 10^{-7}$ p.a.), or the most onerous fault of frequency $\geq 10^{-5}$ p.a., depending upon whether or not there is a significant degradation mechanism (see Refs.1, 4). In either case this will include seismic loading.

Qu.: What methodology should be used for the ccg assessment?

Use R5V4/5.

Qu.: Is the crack growth rate sensitive to the assumed initiation time?

Yes.

Where times are short compared with the redistribution time, the C(t) methodology adopted in these procedures means that the current creep crack growth rate is not uniquely defined by the current crack size, strain rate and load, but also depends upon the time at which the defect is postulated to have initiated.

The assumed initiation time is therefore a key factor in estimating the current crack growth rate.

Qu.: So when is the hypothetical defect assumed to have initiated?

Since the defect assumed in safe Life assessments is purely hypothetical, and need not even be related to any feasible cracking mechanism, the issue of initiation time is rather a conundrum.

The procedures for safe life assessments recommend that the defect is assumed to have initiated at 95% of the life at the last inspection (i.e. 5% of the total operating period prior to the last inspection). This is known as the “95% Rule”.

Qu.: Should an incubation allowance be included?

No.

At one time IMAN#5 was misleading on this point (*need to check if it still is*).

The defect is assumed to start growing at the 95% time.

Specifically, at a time t after formation of the crack, the growth rate is $A.C(t)^q$, with $t=0$ defined at the time of crack formation. The crack is taken to be of such a depth (a_0) at formation that it subsequently grows to the NDT tolerance size (a_{insp}) at the time of the last inspection (t_{insp}). That is,

$$a_{insp} = a_0 + \Delta a_f + \int_0^{t_{insp}} AC(\tau)^q \, d\tau \qquad (12)$$

Strain rates should be evaluated taking into account the strain accumulated since start of life, i.e., including the uncracked body strains prior to crack formation. Δa_f is the fatigue crack growth over the period from the 95% time to the inspection time. (Strictly the fatigue and creep crack growths should be calculated within the same time-stepping routine, rather than separately as implied by equ.12).

Qu.: Why is the 95% Rule reasonable?

Because $C(t)$ reduces as time increases, so does the crack growth rate. Since a specific crack depth at the inspection time is required, it follows that the crack growth rate immediately after the inspection will be faster the more recently the crack initiated. Assuming an original sin defect is non-conservative.

On the other hand, assuming initiation immediately upon start-up following the last inspection is highly improbable. Cracks are postulated in safe life assessments in order to cover the unexpected. The origin of these postulated cracks is not, in general, related to any particular mechanism. In these circumstances it is equally probable that a service-initiated crack could have formed at any time between start of life and the last inspection. An upper 95% confidence level crack growth rate is therefore judged to result from assuming that the crack forms after 95% of the prior operating period.

The 95% Rule is regarded as a reasonable, pragmatic approach with a level of conservatism commensurate with other input data assumptions, e.g. materials properties.

Qu.: Is the 95% Rule always used?

No, there can be exceptions. In some cases there may be physical events which might be postulated to give rise to the cracks, such as remaking a weld, or carrying out a heat treatment, or the occurrence of some abnormal loading. It may be reasonable to associate the crack formation with these events, i.e., at these times. In such cases the above “95% Rule” is redundant.

Qu.: Can safe life assessments be done for transition joints?

Yes, assuming you have the required material data.

IMAN#5 includes some advice on mismatch SIF estimation (though this may have been superseded by now).

References

[1] R.A.Ainsworth, "Short Term Creep Crack Growth at Lower Temperatures", EPD/GEN/REP/0030/96.

[2] BEG/SPEC/DAO/011, "Guidance on Structural Integrity Related Safety Cases"

[3] R.A.W.Bradfiord, "Methodology for Calculating Minimum Acceptable Thicknesses for AGR Outage Referrals and Databases", E/REP/BDGBB/0100/AGR/06.

[4] IMAN#5, Methodology for Safe Life Assessments. The IMANs can be found at G:\Engineering\SISB\Ltasks\SAG\Standards\IMANs.

[5] R A Ainsworth, D W Dean and P J Budden, "Creep and Creep-Fatigue Crack Growth for Combined Loading: Extension of the Advice in R5 Volume 4/5 Appendix A3", E/REP/BDBB/0059/GEN/04, Rev.004. The advice from this report was included in R5V4/5 in 2012.