T73S06 (Creep Rupture) - Session 27

Relates to Knowledge & Skills items 5.1, 5.2, 5.3, 5.4(3.4), 5.5

Last Update 26/11/14

Limitations of assessing primary stress creep rupture alone; When can influence of secondary stresses on rupture be ignored?; Provisions within R5V7; Provisions within R5V2/3 in brief: (a)cyclically enhanced creep, concept of 'core stress'; (b)checks of significance of cyclic effects or creep-fatigue; (c)damage due to relaxation of secondary stresses; The Bree diagram and code approaches; reheat cracking in ferritics, austenitics.

Qu.: Why mention secondary stresses? The subject is "creep rupture" and I thought this only depended on primary stresses?

"Creep rupture" means failure of the gross section as a whole due to creep. The analogy with plastic collapse is not entirely appropriate. Pure plastic collapse is a mechanism in which the degree of strain developed is not relevant, i.e., the material is assumed highly ductile. If we assumed in like fashion that a material has very high creep ductility, then only primary stresses will contribute to creep rupture.

However, unfortunately our materials do not always have high creep ductility. In general, the gross ligament damage due to secondary stresses will therefore also need to be taken into account in a rupture assessment.

Of course, there are the usual questions regarding how to classify loads. Some loads are really of intermediate character but are generally classed as primary for assessment purposes (e.g. pipework system loads). For such loads the usual primary rupture reference stress approach is applicable, though conservative. But for genuinely secondary loads other provisions are required – to either include them quantitatively in the rupture assessment or to justify their neglect.

Ferritic Weldments: What provisions are made within R5 Volume 7 to ensure that secondary stresses do not undermine the creep rupture assessment?

Recall that R5V7 applies to the assessment of ferritic similar metal welds under steady creep, addressing both rupture and crack growth. Cyclic effects, e.g., fatigue, are not addressed.

Qu.: Which Sections of R5V7 are relevant?

The advice on the influence of secondary stresses to a creep rupture assessment of ferritic weldments is given predominantly in R5 V7 Appendix A4, Section A4.3.

Qu.: When can the influence of secondary stresses be ignored (in R5V7)?

There are two escape clauses in R5V7 which sanction ignoring secondary stress effects on rupture. The first, in Section A4.1, clause (i), essentially says that if,

- A PWHT was carried out, and,
- A small "HAZ mixing" microstructural parameter applies, $\alpha \leq 1.5$,

then the effects of secondary stress on rupture can be ignored. However, R5 User Query 125 implies that a ductility exhaustion assessment may be omitted for rather larger α, at least 2, and perhaps 4 or 5 according to judgment. It is therefore rather ill defined when a ductility exhaustion assessment is needed.

I have some personal misgivings about this rather sweeping advice. One is that recent experience on plant with coarse HAZ cracking has cast some doubt on the “mixed HAZ” approach within R5. (This is my opinion, and not a formal company position). Also, this general guidance appears to regard welding residual stress as the only relevant secondary stress. This need not be so. If your assessment includes some other secondary stress, then this clause appears to provide no grounds for ignoring it. In this case the second provision with R5V7 is more appropriate.

Qu.: What is the other provision in R5V7 justifying ignoring secondary stresses?

Within the ductility exhaustion part of Appendix A4 (Section A4.3), the effects of secondary loading are justified as negligible if A4 Equ.(A4.8) is obeyed.

R5V7 Equ.(A4.8):
$$\frac{k\sigma_{ref}}{E}\left(\frac{K_{TOT}}{K_P}\right)^2 < 0.1\varepsilon_f$$

Here $K_{TOT} = K_P + K_S$, the latter being the primary and secondary SIFs respectively. My rough interpretation of this equation is that the creep strain attributable to the secondary stresses should not exceed 10% of the creep ductility. Strictly, the LHS of Equ.(A4.8) is the elastic strain due to the combined primary and secondary stresses. However, this can be interpreted as a bound on the creep strain due to secondary stresses provided that the elastic follow-up (Z) is not too great.

The guidance based on Equ.(A4.8) is certainly an improvement on the more sweeping advice in Section 4.1. However, I still have a couple of personal observations:-

[1] The creep ductility in Equ.(A4.8) is presumably the *uniaxial* creep ductility. If triaxial effects are substantial, as in reheat cracking situations, then the creep ductility might be almost a factor of 10 smaller than the uniaxial ductility. In such a case, the guidance based on Equ.(A4.8) would permit the secondary stresses to be ignored as regards creep rupture, whilst at the same time reheat cracking might actually occur. This is an acceptable state of affairs so long as crack initiation is regarded as a separate mechanism and is addressed elsewhere in the assessment.

[2] Wouldn’t Equ.(A4.8) have been more accurate if a Z-dependent relaxation strain had been used? I suspect so, but Equ.(A4.8) does have the merit of simplicity. Relevant to this is the following observation…

Qu.: I cannot see elastic follow-up (Z) mentioned in R5V7. Why is this?

This is a nice brain-teaser. Elsewhere in R5, Z features prominently. Why not in V7?

The answer is that R5V7 does not address the *relaxation* of secondary stresses - at least, not properly!. I don’t think R5V7 makes this clear. It is obliged to address relaxation when assessing rupture including secondary stresses, but does so via an expression like Equ.(A4.8) which implicitly assumes a certain follow-up behaviour (essentially Neuber). Again, this is not made clear in the document.

What R5V7 does do is make allowance for the *redistribution* of secondary stresses. Recall the crucial difference between *relaxation* and *redistribution*. Relaxation involves the reduction over time of the load-resultants (net force and moment) associated with the load in question. Redistribution, on the other hand, addresses only how the stresses across a section re-arrange themselves, with large stresses diminishing and small stresses increasing, but subject to fixed load resultants.

The fact that R5V7 ignores relaxation is the reason why its C(t) formulation is much simpler than that of R5V4/5 – but that's a later topic.

Qu.: The expression $\frac{\mathrm{k}\sigma_{\mathrm{ref}}}{\mathrm{E}}\left(\frac{\mathrm{K}_{\mathrm{TOT}}}{\mathrm{K}_{\mathrm{P}}}\right)^2$ occurs a lot in R5V7. What is it?

This was mentioned above. $\frac{\mathrm{k}\sigma_{\mathrm{ref}}}{\mathrm{E}}\left(\frac{\mathrm{K}_{\mathrm{TOT}}}{\mathrm{K}_{\mathrm{P}}}\right)^2$ is the total elastic 'reference' strain, including both the primary and secondary stress contributions. The reason why the quadratic term $\left(\frac{K_{TOT}}{K_P}\right)^2$ occurs in this expression, rather than $\left(\frac{K_{TOT}}{K_P}\right)$ is not obvious, is it? The derivation will be dealt with in the T73S03 Sessions on C(t) and crack growth.

Qu.: When required, how does R5V7 include secondary stresses in rupture?

…in short, by using ductility exhaustion – see Sections A4.3 and A4.3.2.

Recall that R5V7 is restricted to steady state creep. Cyclic loads are not assessed. Consequently there is no creep-fatigue to worry about, i.e., no cyclic re-priming of the dwell stress and no cyclic enhancement of creep strain accumulation. If R5V7 is applicable, the creep strains arise due to forward creep (primary loads) and due to monotonic relaxation of secondary stresses only.

R5V7 employs the same simple approximation for the creep strain due to the relaxing stresses as used in Equ.(A4.8) discussed above. It implicitly assumes that the creep strain due to the secondary stresses cannot exceed $\frac{k\sigma_{ref}}{E}\left(\frac{K_{TOT}}{K_P}\right)^2$. There is an allowance for elastic follow-up implicit in this. For example, ignoring crack growth, the time to rupture, t_{rup}, based on ductility exhaustion is,

R5V7 Equ.(A4.9):
$$\varepsilon_c\left(\sigma_{ref}, t_{rup}\right) + \frac{k\sigma_{ref}}{E}\left(\frac{K_{TOT}}{K_P}\right)^2 = \varepsilon_f$$

The first term in (A4.9) is just the primary reference creep strain. The secondary term, as discussed above, is an approximate bound for the secondary creep strain.

If the body is uncracked, the SIFs in (A4.9) are simply evaluated for a very small crack.

Note that (A4.9) implicitly assumes that relaxation is complete by the assessed rupture time. For our CMV pipework this is probably a safe bet.

Qu.: Are the two methods of rupture assessment consistent?

The two methods of rupture assessment are, (i)based on stress/time-to-rupture data when secondary stresses can be ignored, or, (ii)based on ductility exhaustion if secondary stresses need to be included. Case (i) will apply if $\frac{\mathrm{k}\sigma_{\mathrm{ref}}}{\mathrm{E}}\left(\frac{\mathrm{K}_{\mathrm{TOT}}}{\mathrm{K}_{\mathrm{P}}}\right)^2$ is 9% of the creep ductility, but case (ii) will apply if it is 11%. Ideally the assessment results should be virtually the same. However, since (i) and (ii) use different materials data, consistency is certainly not guaranteed – and I would not expect it in practice.

The source of inconsistency, however, is not R5 but the manner in which creep data is analysed. The combination of deformation and ductility data should produce the same prediction for the time to rupture as the use of stress/time-to-rupture data – but generally it does not because of the way in which the raw creep test data has been analysed.

Qu.: Do the creep rupture procedures of R5V7 apply to both cracked and uncracked structures?

Yes

In practice I suspect that ductility exhaustion assessment to R5V7 Section A4.3 is generally ignored – even when it is strictly required. But this is bad practice.

What provisions are made within R5 Volume 2/3 to enable secondary stresses to be incorporated within a creep rupture assessment?

Qu.: What does R5V2/3 assess?

R5V2/3 is primarily about the assessment of crack initiation by creep-fatigue. However, there are many precursor checks that the assessor is obliged to make in order for the crack initiation part of the assessment to be valid. Creep rupture of the gross ligament is just one of these checks. Creep rupture under primary loading is addressed in R5V2/3 Sections 6.5 and A5.2.2.

R5V2/3 is primarily about creep-fatigue. The creep-fatigue mechanism involves the cyclic re-priming of the creep dwell stress, due to the effects of plasticity when load cycling. This dwell stress is subject to partial relaxation which repeats on each cycle, thus accumulating creep damage. The fact that relaxation occurs means that the stresses in question are at least partly secondary. Consequently, the effects of secondary stresses on crack initiation (i.e., upon local damage accumulation) are accounted for by the procedure. But this is not our concern here. We are interested in creep rupture of the gross ligament – not local damage accumulation at a point leading to crack initiation.

So what about the effects of secondary stresses on gross section rupture? First you must ask yourself what secondary stresses you might mean. Because cyclic loading is the particular focus of attention in R5V2/3, in general any initial secondary stresses will be modified by the shakedown residual stresses. These are the residual stresses which arise due to the elastic-plastic load cycling. Consequently, in the context of R5V2/3, the effect of secondary stresses on creep rupture can be re-interpreted as the effect of cyclic loading on creep rupture.

This is referred to as “cyclically enhanced creep”.

Qu.: What Sections of R5V2/3 are relevant to this issue?

R5V2/3 Sections 7.2.1 and 7.5 and Appendix A9.

Qu.: But I thought that the cyclic accumulation of strain was called "ratcheting" and was dealt with via the shakedown assessment?

Shakedown concerns the elastic-plastic behaviour of the structure. If ratcheting occurs, the ratchet strains are plastic strains.

In contrast, cyclically enhanced creep concerns the accumulation of creep strains on each cycle. It is, roughly speaking, the creep equivalent of what ratcheting is to plasticity. Cyclically enhanced creep is effectively creep-ratcheting.

Qu.: What does R5V2/3 Section 7.2.1 tell us?

R5V2/3 Section 7.2.1 defines the shakedown reference stress, $\bar{\sigma}_{ref}^{S}$, and the corresponding temperature. The shakedown reference stress is found as follows,

- The steady cyclic stress field, $\tilde{\sigma}_S(x,t)$, is first estimated in some way. This is the stress field at any time t during the load cycle, after the stress-strain hysteresis cycle has shaken down to its steady cycle. It can be obtained from the elastic stress field at the time by adding the shakedown residual field, $\tilde{\sigma}_S(x,t) = \tilde{\sigma}_{el}(x,t) + \tilde{\rho}(x)$. It is sufficient to use the *linearised* elastic stresses for this purpose, and doing so will make the shakedown reference stress estimate less pessimistic.
- For each dwell period in the creep regime, the time to rupture at stress $\tilde{\sigma}_S(x,t)$ is found. The point and condition which minimises the rupture time is identified. The Mises equivalent stress formed from $\tilde{\sigma}_S(x,t)$ at this point and time is the shakedown reference stress, $\bar{\sigma}_{ref}^{S}$.

Qu.: What does R5V2/3 Section 7.5 tell us?

R5V2/3 Section 7.5 provides the procedure for calculating a gross ligament creep usage factor (called W) which includes the effects of cyclically enhanced creep. Two alternative methods are provided. Either,

[1] Use the shakedown reference stress, $\bar{\sigma}_{ref}^{S}$, and corresponding temperature, from Section 7.2.1 in the stress/time-to-rupture curve. This provides a conservative estimate of W, defined via the Robinson rule if necessary. However, it may be overly conservative. Or,

[2] A less conservative method is provided in Section 7.5.3. However it is strictly only valid for a constant primary load plus secondary loads which produce a predominantly bending stress distribution. The method works by defining a "core stress", σ_{core}, in terms of the primary and secondary stresses, and then using this core stress in the stress/time-to-rupture curve.

Note that $\bar{\sigma}_{ref}^{S}$ or σ_{core} are both supposed to be representative of the gross ligament, and hence indicative of rupture. Hence the terminology "core stress". In reality, though, they are based on the stress at a specific point, or an approximation thereto, namely at the extremity of the elastic core.

Also note that $\bar{\sigma}_{ref}^{S}$ or σ_{core} are implicitly assumed not to relax during the dwells.

Qu.: How is σ_{core} found in R5V2/3 Section 7.5

The method follows a venerable (1968) analysis by Bree (see R5V2/3 Appendix A9). This same Bree analysis is the basis for similar procedures in design codes (e.g. ASME). The restriction to a constant primary load plus a secondary stress with a bending stress distribution results from the particular geometry and loading analysed by Bree.

[*In my 2010 version of these notes I stated that it was about time someone produced further studies for other geometries and loadings to underwrite broader applicability. Actually there are others in the literature, and I am working on other solutions, so this is an area which may change in R5 over the next few years. This is highly desirable since the current Section 7.5.3 route is very restrictive*].

The primary loading is represented in the procedure of Section 7.5.3 by the ordinary primary reference stress, σ_{ref}, as used in the creep rupture assessment under primary load. Note that the rupture reference stress is *not* used.

The secondary loading is represented by the maximum *range* of *linearised elastic* secondary stress, ΔQ, for the relevant structural section. Note that it is the *range* of secondary stress which is relevant since a constant secondary stress could be 'removed' by an appropriate choice of shakedown residual stress. The linearised value is used because this is more representative of the core, i.e., excluding local stress raisers.

The core stress is then found in terms of the normalised primary and secondary stress parameters, X and Y,

$$X = \frac{\sigma_{ref}}{S_y} \qquad\qquad Y = \frac{\Delta Q}{S_y}$$

The imminent revision of R5V2/3 (due 2014) will replace the current advice with,

For $Y \le 1 - X$ $\quad\sigma_{core} = XS_y$ (Region E)

For $1 - X < Y < \dfrac{1}{1-X}$ $\quad\sigma_{core} = \{Y - 2\sqrt{Y(1-X)} + 1\}S_y$ (Region S1)

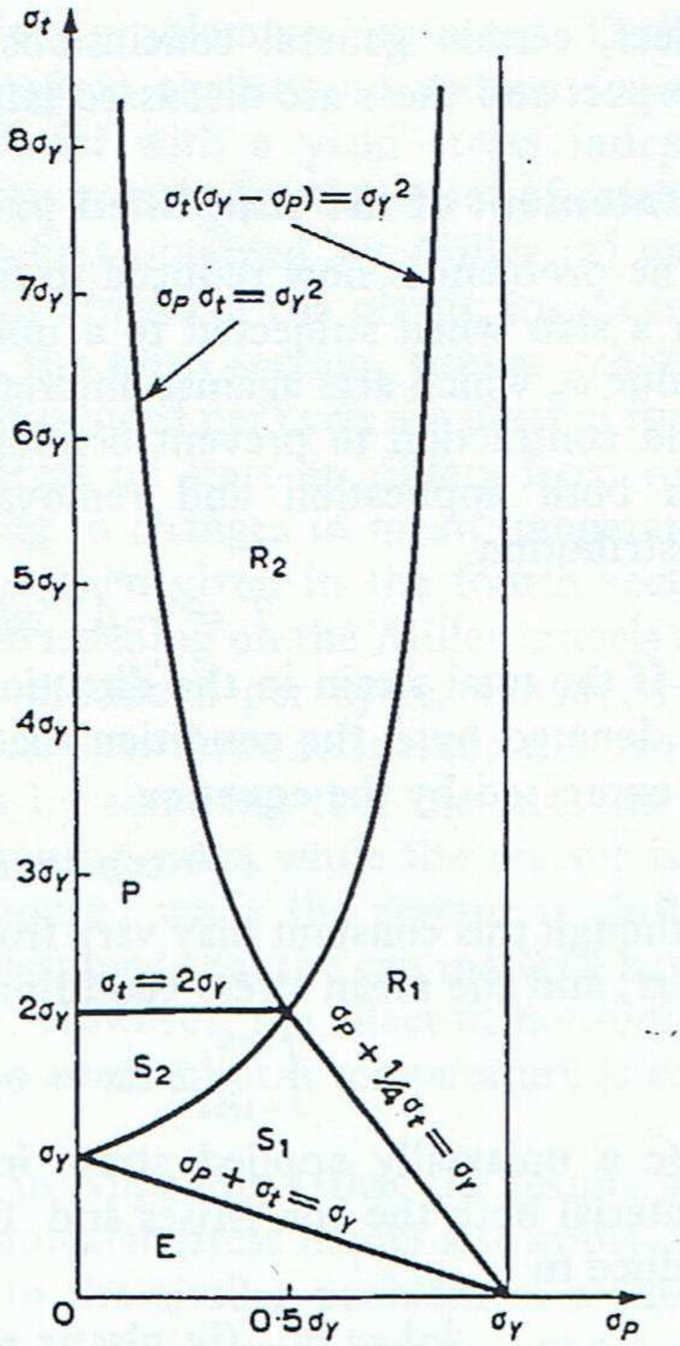
For $Y \ge \dfrac{1}{1-X}$ $\quad\sigma_{core} = XYS_y$ (Region S2 and P)

where S_y is the 0.2% proof strength at the shakedown reference temperature. R5 currently implies that this S_y should be the *lower bound* 0.2% proof strength, but I suspect a best estimate value would be more appropriate (seek expert advice).

The above equations are derived from the famous Bree Diagram, shown in Figure 1 below. The "regions" referred to above relate to this diagram.

The Bree diagram is worth studying carefully since it illustrates the archetypal shakedown/ratcheting behaviour of a structure under combined primary and secondary loads. This version of the diagram was derived for uniaxial stressing with a constant primary membrane stress and a cycling secondary bending stress. The original Bree paper, Ref.1, is rather terse. I have recently re-derived the diagram in gory detail, see my web site http://rickbradford.co.uk/BreeDiagram.html. The mathematics is trivial, but the steps needs care to get the logic right.

Figure 1 The Bree Diagram



Stress régime	Can behaviour
R_1 and R_2	Ratchetting
S_1 and S_2	Shakedown after first half-cycle
P	Plastic cycling
E	Elastic

Qu.: Does cyclically enhanced creep interact with creep rupture?

No.

The creep usage fraction based on cyclically enhanced creep, W, defined using the above core stress or the shakedown reference stress is logically completely separate from the usage fraction, U, based on the usual primary rupture reference stress. Both assessments are required, but there is no interaction between them. The requirement is $W < 1$ and $U < 1$.

Qu.: Are initial secondary stresses irrelevant in R5V2/3 if cyclically enhanced creep effects are negligible?

Yes and no.

If cyclically enhanced creep effects are negligible then any initial (applied) secondary stresses would indeed be irrelevant in R5V2/3 as regards gross section failure, i.e., creep rupture. So they would be irrelevant for the purposes of this session. If you are concerned about it, then R5V7 Equ.(A4.9) could be used to include an allowance for secondary stress effects on rupture.

However, R5V2/3 does require the creep damage due to relaxation of secondary stresses to be included in the crack initiation assessment. Even if the stress-strain cycle is elastic, so that there is no re-priming of the dwell stress, there will at least be damage due to the monotonic relaxation of the initial secondary stress field [see R5V2/3 Figure A3.5(b) and Section A4.6.1.3]. But this damage is local, relating to a point in the structure, not to the gross section. As such it is part of the crack initiation assessment and does not relate to creep rupture.

Nevertheless this can be a serious degradation mechanism…..

Qu.: What is “reheat cracking”?

This is not a creep rupture issue but is included for interest...

When the secondary stresses in question are welding residual stresses, the damage mechanism which results in creep cracking due to their relaxation is called “reheat cracking”. The assessment of monotonic creep relaxation via the ductility exhaustion approach is a reheat crack initiation assessment. The crucial factors which lead to reheat cracking are,

- Lack of PWHT resulting in yield magnitude residual stresses at the start of service;
- Poor uniaxial creep ductility;
- High stress triaxiality (large hydrostatic stress);

These factors are attained due to, or are exacerbated by,

- The fact that welding residual stresses by their nature tend to have high levels of triaxiality;
- Stress raising features such as notches or severe weld toes;
- Operation in a ductility-dip temperature range (e.g., 500^{o}C-550^{o}C for 316H);
- Elastic follow-up;
- Large service stresses;

Large service stresses have been known to be implicated in plant instances of reheat cracking, especially those cases which result in leaks (HPB/HNB reheat outlet penetrations' shop welds 1). However, deep reheat cracks can arise in thick sections due to welding residual stresses alone (HYA/HRA superheater headers - and, more recently, the spine welds 12.3).

A large programme of reheat crack initiation assessments were carried out in the period 1995-1998, covering a wide range of BE austenitic plant (mostly 316H). This led to rules of thumb for predicting when reheat cracking was likely (Ref.2). This will be discussed in a later session under T73S04.

Qu.: Is reheat cracking just a problem for austenitics?

No.

Reheat cracking assessments within BE have become synonymous with austenitic steels in recent years (that is, the last 25 years!). But this is only because the design codes (still) permit thick section austenitic weldments to enter service un-stress-relieved. The very high welding residual stresses and their associated high levels of triaxiality are responsible for the subsequent formation of reheat cracks in austenitic materials in service.

In contrast, the design codes require that thick section ferritic weldments be adequately heat treated. Because of this, reheat cracking has not been a threat in ferritic components in BE for many years. But be aware that this is the result of good practice as regards PWHT, not because ferritics are intrinsically immune from reheat cracking. In the days before PWHT became *de rigueur* for ferritics (the early 1970s) the CEGB (our glorious forebear) had quite a headache in this area. But this was before even my time (just).

References

1) Bree, J.Strain Analysis (1967) **2**, 226-238
(See also http://rickbradford.co.uk/BreeDiagram.html)

2) R.A.W.Bradford, "Finite Element Modelling of Reheat Cracking Initiation in Austenitic Weldments", Institute of Mechanical Engineers Conference Transactions, International Conference on "Assuring It's Safe", 18-19 May 1998, Heriot-Watt University, Edinburgh, UK, paper C535/023/98, pp 287-295.

(See also B.L.Baikie, R.A.W.Bradford, R.Hales, D.A.Miller, M.W.Spindler and R.A.Stevens, "Reheat Cracking in Austenitic Stainless Steels – Current Status of Understanding", EPD/AGR/REP/0346/97 (November 1997); and,

R.A.W.Bradford, "A Summary of Residual Stress Analyses and Crack Initiation Models Completed To-Date under the Generic Reheat Cracking Programme", EPD/AGR/REP/0328/97 (October 1997).