T73S03: CFCG - Session 45 – R5V4/5 Appendix A4 (Weldments)

Last Update: 10/8/16

Ferritic weldment zones & relevance in cfcg; Significance of residual stresses: criteria in, (a)R5V4/5 App.4 and (b)R5 V7; Features of cfcg specific to a TJ or graded TJ; Procedures for ligament rupture assessment, (a)for steady creep, (b)when cyclic loading is significant and/or under combined secondary and primary loading, (c)for TJs;

Qu.: Where is the methodology for cfcg in weldments?

- For similar metal, low alloy ferritic weldments under steady loading the methodology is given in R5V7. This was covered in session 43, here, http://rickbradford.co.uk/T73S03TutorialNotes43.pdf
- For austenitics welds or transition joints, or if there are load cycling effects, then the methodology is in R5V4/5 Appendix A4.

Qu.: What might you do first?

If applicable (i.e., the crack has not formed by a creep mechanism) always consider doing an incubation assessment. Methods are discussed in, http://rickbradford.co.uk/T73S03TutorialNotes40B.pdf

Qu.: What is the R5V7 methodology for ccg again?

The main features of an R5V7 assessment of a similar weld in low alloy ferritic material with no load cycling effects are:-

$$C(t) = f(\tau) \cdot C^*, \qquad (1a)$$

where,

$$f(\tau) = \frac{(1+\tau)^{1+n}}{\left[(1+\tau)^{1+n} - 1\right]}, \qquad (1b)$$

$$C^* = k \frac{\dot{\varepsilon}_c^{PR}}{\sigma_{ref}^{PR}} K_{PR}^2 \qquad (2)$$

$$\tau = \left(\frac{K_{PR}}{K_{TOT}}\right)^2 \frac{E\varepsilon_c^{PR}}{k\sigma_{ref}^{PR}} \qquad (3)$$

σ_{ref}^{PR} the primary reference stress for the homogeneous body (i.e., as if the weld were not there).

$\dot{\varepsilon}_c^{PR}$ the creep strain rate corresponding to σ_{ref}^{PR}.

K_{PR} the SIF in steady creep operation due to the primary loads alone.

k the weldment zone off-loading factor for the zone being assessed. See http://rickbradford.co.uk/T73S06TutorialNotes26.pdf for definition.

The off-loading factor *k* is ***not*** used to factor the stress when determining the strain rate used in (2). The weldment zone used to calculate the strain rate is as follows,

- For hoop dominance the parent creep deformation should always be used (whatever weldment zone is being assessed), but the k factor relevant to the zone in question should be used in Equs.(2) and (3);

- For axial dominance the creep deformation appropriate to the weldment zone being assessed should be used (but *k* is, of course, 1 for all zones).

Mixed HAZ
$$\dot{a}_M = \frac{1+\alpha}{\alpha + (\dot{a}_C / \dot{a}_R)} \dot{a}_C \qquad (4)$$

Additionally, must check:-

(i) That the crack remains stable via an R6 assessment;

(ii) That the ligament does not rupture, by integration of the time-fraction rupture damage corresponding to the (time dependent) reference stress;

(iii) The dimensionless crack velocity remains sufficiently small, i.e.,

$$\lambda = \frac{\dot{a}(\sigma_{ref})^2}{EC(t)} < \frac{1}{2} \qquad (5)$$

Qu.: Where is the advice regarding insignificant residual stress?

R5V4/5 App.A4, §4.3.3 and R5V7 App.A4 are complementary.

- R5V4/5 App.A4, §4.3.3 gives a criterion for welding residual stresses being negligible as regards their effect on creep crack growth - see below;
- R5V7 App.A4 Equ.(A4.8) gives a criterion for welding residual stresses being negligible as regards their effect on gross ligament creep rupture.

Qu.: What is the R5V4/5 App.A4 test for the significance of residual stresses?

R5V4/5 App.A4, §4.3.3 gives the following criterion for insignificant welding residual stresses (or, more generally, the insignificance of any secondary loads),

$$\frac{\overline{\sigma}_{\max}^{secondary}}{E} < 0.1\left(\frac{\delta_i}{R'}\right)^{\frac{n}{n+1}}, \qquad R' = \left(\frac{K_{PR}}{\sigma_{ref}^{PR}}\right)^2 \qquad (6)$$

Here δ_i is the incubation CTOD. This property may be hard to obtain. Easier to obtain is the creep toughness, which is usually reported in ccg test reports. It may be possible to estimate δ_i from the creep toughness. I'm guessing but I'd expect a relationship of the form $\delta_i = J_c / m\sigma_{0.2}$ where J_c is the creep toughness at initiation ($\Delta a = 0.2mm$); $\sigma_{0.2}$ is the stress to cause 0.2% creep strain by the initiation time, at the test temperature; *m* is the dimensionless HRR parameter relating CTOD to *J*, usually around 3 or so (but *n* dependent). There is an ASTM formula which permits the CTOD to be found from test data. It includes a polynomial fit for the *m* parameter.

If criterion (6) is obeyed then residual stresses (or any other secondary stresses) can be neglected in the calculation of creep crack growth.

Qu.: What are the R5V7 tests for the significance of residual stresses?

The R5V7 criterion relates to the assessment of gross ligament creep rupture only. It relates to low alloy ferritic similar metal weldments only. The effect of residual stresses on rupture may be ignored if EITHER of the following apply,

- A stress relief heat treatment to an appropriate procedure was carried out, leading to a high degree of HAZ refinement (microstructural parameter $\alpha \le 1.5$); OR,
- $\frac{k\sigma_{ref}^{PR}}{E}\left(\frac{K_{TOT}}{K_{PR}}\right)^2 < 0.1\varepsilon_f$.

For "appropriate" PWHT procedures see R5V7 App.A2, though conformance to a modern design code is sufficient.

Here ε_f is the creep ductility. R5V7 is not explicit about this but I advise that ε_f be interpreted as the creep ductility relevant to the state of stress, i.e., allowing for triaxiality. But note that this should be some measure of the gross ligament constraint, not a local surface value.

If ***either*** of these criteria is obeyed then residual stresses can be ignored in the calculation of gross ligament creep rupture. However this does ***not*** sanction ignoring residual stresses in the calculation of creep crack growth. For this see the R5V4/5 criterion, above.

R5 is not explicit about the applicability of the above criteria to austenitic welds. I advise that the second of the above criteria is applicable. Design codes still do not generally require PWHT for austenitic materials, so the first criterion is not well defined. However, a full solution heat treatment (probably at $\ge 1050^o C$) is usually taken to render the residual stresses negligible.

Qu.: What methodology should be used for ccg with residual stresses?

If criterion (6) is not obeyed then residual stresses must be included in the calculation of creep crack growth, using either,

- R5V7 for similar metal low alloy ferritic welds with negligible load cycling effects, or,
- R5V4/5

In practice the more complicated procedure of R5V4/5 is sometimes used even for low alloy ferritic welds with negligible load cycling effects. This is because it allows for incomplete stress relaxation and can give a different result from R5V7.

The R5V4/5 cfcg methodology under combined primary and secondary loading has been described in, http://rickbradford.co.uk/T73S03TutorialNotes43.pdf and http://rickbradford.co.uk/T73S03TutorialNotes44A.pdf.

Qu.: Are residual stresses included in assessments of graded joints?

No – due to their method of manufacture (see R5V4/5 App.A2 §A4.5).

Qu.: To what TJs is R5V4/5 App.A4 Applicable at present?

The procedures of R5V4/5 App.A4 for transition joints can, in principle, be applied to any TJs. However experience has been limited to,

- 2.25%Cr1%Mo to 316ss via an austenitic or nickel-based (inconel) filler, and,
- Graded TJs, i.e., Jessop-Savilles.

Most notably this excludes the UTJs in AGR boilers, which all involve 9%Cr1%Mo ferritic (and, uniquely in the case of HPB/HNB, a ferritic consumable to a nickel alloy parent). Consequently we have not done ccg assessments for the HPB/HNB UTJs, despite pressure to do so (at least this was so as of 2011). However ccg assessments of the HYA/HAR boiler spine TJs have been done, despite these being 9%Cr1%Mo/316 and hence not strictly covered by R5.

Creep crack growth assessments of 2.25%Cr1%Mo/316 TJs have been done for DNB HRH weld 8s, HYA/HAR MS TJs and HPB/HNB ????

Qu.: Where are the cracks assumed to occur in TJs?

In principle the cracks could be in any zone. But in practice the experience has been that cracking occurs at,

- The ferritic to weld interface region for conventional TJs;
- The region of a graded TJ where the Cr level is ~5%.

Qu.: What reference stress should be used for rupture assessment of a TJ?

I read R5V4/5 App.A4, §A4.4 to mean that you should use the larger of the usual homogeneous primary reference stress and the TJ specific reference stress given in R5V6 App.A2.

Qu.: What rupture data should be used for rupture assessment of a TJ?

Cross-weld data from representative TJ tests should be used.

I believe that rupture data is within R66 for the TJ types listed above. As always, check the R66 User Queries and local experts for the latest information. Do not trust R5 as regards TJ materials data.

Qu.: What methodologies should be used for rupture?

If secondary loads are insignificant according to the criterion of R5V4/5 App.A4, §4.3.3, above, then the time-fraction based definition of creep damage can be used, based on creep rupture data: $D_c = \int \frac{dt}{t_{rup}}$.

Otherwise a ductility exhaustion definition of creep damage should be used. In R5V7 App.A4, §A4.3.2, this is expressed as the usual strain-ratio damage for the primary part plus a flat allowance for the secondary stresses,

(My paraphrasing) $$D_c = \int \frac{d\varepsilon_c^{PR}}{\varepsilon_f} + \frac{k\sigma_{ref}^{PR}}{E\varepsilon_f}\left(\frac{K_{TOT}}{K_{PR}}\right)^2$$

(Implicitly this appears to assume Z = 1 for the secondary loads, but on the other hand it also assumes full relaxation). However, I suggest that a less conservative method would be the usual ductility exhaustion approach in which the stress relaxes over time, i.e.,

$$D_c = \int \frac{d\varepsilon_c^{tot}}{\varepsilon_f}$$

I advise that ε_f be interpreted as the creep ductility relevant to the state of stress, i.e., allowing for triaxiality, though R5V7 is not explicit.

Qu.: What reference stress should be used for ccg assessment of a TJ?

Use the homogeneous reference stress (not R5V6) – see R5V4/5 App.A4, §A4.4.1.1. This can be re-interpreted to apply for combined primary plus secondary loading for use in the R5V4/5 App.A2/A3 methodology, if required.

Qu.: What is the "reference material" for a conventional TJ?

The "reference material" is the material within which the crack occurs. This is assumed to be 2.25%Cr1%Mo ferritic **HAZ**.

Qu.: What is the deformation behaviour of 2.25%Cr1%Mo ferritic HAZ?

Always seek expert advice. Obviously you could start with R66 and the R66 User Queries before doing so.

R5V4/5 App.A4, §4.4.2.2 contains a methodology for determining 2.25%Cr1%Mo HAZ deformation from 2.25%Cr1%Mo parent deformation assuming the latter is expressed in terms of a rupture strength. This is,

- Determine the rupture strength of the TJ from cross-weld tests on representative TJs;
- Insert this rupture strength in the parent deformation equation.

I do not know whether this is still the best advice – seek guidance.

In particular do not assume that the parent deformation equation given in R5V4/5 App.A4, §4.4.2.2 is correct. R66 has been updated since R5 was last issued (in 2012). In fact R5 is generically treacherous as regards TJ materials data (much of that appearing in R5V6 is out of date).

Qu.: What is the ccg law for 2.25%Cr1%Mo ferritic HAZ in a TJ?

Ideally ccg data should be obtained from specimens with cracking within the ferritic HAZ of interest. However, R5V4/5 App.A4 §A4.4.2.3 suggests that the $\dot{a} - C^*$ relation for the parent ferritic material is likely to be representative. Hence, R5V4/5 App.A4 §A4.4.2.3 recommends use of the upper bound ccg law for the ferritic parent in the absence of specific HAZ data.

Qu.: What deformation behaviour should be used for Jessop-Saville joints?

R5V4/5 App.A4 §A4.5.5.3 gives specific advice for the deformation properties of the ~5%Cr region, which is the reference zone most likely to crack. However I advise that you always check with local experts regarding the current advice – having first familiarised yourself with the latest guidance in R66 and the R66 User Queries database.

My reading of R5V4/5 App.A4 §A4.5.5.3 is that you should use the faster strain rate calculated for the ~5%Cr region and the 2.25%Cr1%Mo ferritic parent.

Qu.: What creep crack growth law should be used for Jessop-Saville joints?

According to R5V4/5 App.A4 §A4.5.5.4 the mean and upper bound ccg laws for the 2.25%Cr1%Mo ferritic parent should be used to assess Jessop-Saville graded joints – including the assessment of the reference ~5%Cr region.

Qu.: How are stresses due to mismatched coefficient of expansion assessed?

This is the key problem for TJs. R5 contains virtually no advice on how to include the α -mismatch stresses in crack growth assessments. In principle you should treat the α -mismatch stresses in the same manner as any other secondary stress. The problems are,

- What are the magnitudes of the α -mismatch stresses?
- What is the corresponding SIF?
- How do they contribute to the reference stress?

Some observations on these issues are, in turn…

Qu.: What are the magnitudes of the α -mismatch stresses?

R5 Volume 6 App.3 Equ.A3.4 estimates the 'peak' elastic mismatch stress as $1.5E\Delta\alpha\Delta T$. In the context of creep crack growth, precedent in assessments to-date has been to assume zero stress conditions at the PWHT temperature, and therefore to measure ΔT as the difference from the PWHT temperature. Hence, for the assessment of creep crack growth, ΔT has been identified with $T_{PWHT} - T_{OP}$. In regard to the use of the formula $1.5E\Delta\alpha\Delta T$ we note;

- The 'peak' mismatch stress may be restricted by yielding, e.g. to the mean shear yield stress;
- Strictly there is no *peak* stress, because the shear distribution is singular at the surfaces;
- The factor of 1.5 in the formula contains implicit allowance for material factors.

Qu.: What is the α -mismatch SIF?

IMAN 5 contains some advice on the SIF due to the α -mismatch stresses. However this was never formally validated, and may be out of date by now. But it's a start. If you have to do a TJ ccg assessment I strongly advise that you study other recent assessments.

Qu.: How do the α -mismatch stresses contribute to the reference stress?

The load-resultant based reference stress formulation of Ainsworth, Dean and Budden, Ref.1, Equ.11 is *probably* not applicable in the presence of significant α -mismatch stresses. This is because these stresses are self-equilibrating through the thickness and hence correspond to zero load resultants. I say "probably" because there may be some way of fiddling it. For TJs you are largely on your own to as regards the procedure to employ – other than paying attention to precedent.

It is most likely that you will opt for a K-based reference stress formulation, e.g., R5V4/5 App.A3, Equ.A3.11. (Would the R5V7 approach be applicable? It has the advantage of requiring only the combined load SIF and the primary reference stress).

The K-based reference stress formulation of R5V4/5 App.A3, Equ.A3.11 is OK provided that the out-of-plane secondary stresses are not large. The out-of-plane α-mismatch stresses will not be large, so this is OK. Also, all our TJs are stress relieved, so the original welding residual stresses will not provide a large out of plane stress either. You might have a problem if there is a large out of plane thermal stress, but this is unusual.

Qu.: Are α-mismatch stresses relevant for graded TJs?

Yes and no. R5V4/5 Appendix A4, §A.4.5.6 advises, "*In considering thermal loads, the less severe mismatch in thermal coefficient of expansion, α, within a graded joint compared with a conventional bi-material DMW is beneficial. Thus, at constant temperature, without the severe step change in α present in a conventional DMW, reduced thermally-induced stresses may be expected. It is considered, at present, that there is no requirement to consider the effect of changes in α on K for cracks in the 5-6%Cr region under isothermal loading. However, as part of a sensitivity study, it is suggested that a step change in α at the crack plane equal to half the difference between the austenitic and ferritic values is assumed. In the calculation of stresses induced by thermal and/or α gradients, an appropriate variation of thermal expansion coefficient [A4.18-A4.19] over the length of the graded region should be assumed.*"

Qu.: How does significant cyclic loading affect the cfcg assessments of TJs?

I suggest you read R5V4/5 App.A4 §A4.6. There is little or no validation of crack growth methodology in TJs with significant ccg and significant fcg. The advice appears to be broadly to use the usual methodologies but with stress-strain and fcg properties for the most onerous zone.

In particular §A4.6 states, "*The treatment of stresses due to the mismatch in coefficient of thermal expansion across the cracked interface following cyclic excursions, however, requires further development. It is conservative to assume that these stresses are regenerated each cycle.*"

References

[1] 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.