T73S04 (R5V2/3): Tutorial Session 37
Crack Initiation in Weldments: Appendix A4

Last Update: 5/6/15 latest mods in green text

Relates to Knowledge & Skills items 1.38 to 1.46

R5V2/3 methodology for weldments; The revised Appendix A4 (2014); Definition and usage of FSRF, WSEF and WER; Methodology or for dressed & undressed weldments; Use of WSEF in cycle construction & dwell stress estimation; Factoring by local strength, limitations of R5 for inhomogeneous bodies; What point to assess?; The contribution of monotonic relaxation damage (e.g., residual stresses)

Qu.: What are the scope limitations of R5V2/3 Appendix A4?

- Only similar metal joints are covered, not transition joints.
- High cycle fatigue (say $N > 10^6$) is not covered.
- Both dressed and undressed weldments are covered

Qu.: How do the precursor assessments differ for a weldment?

The same precursor assessments are required for weldments as for a parent feature. These are,

- Primary stress limits - to be satisfied for both parent and weld strengths;
- The linearised stress range limit - to be satisfied for both parent and weld strengths;
- Creep rupture – taking account of redistribution effects where appropriate (the χ factor effect and the little k factors as per R5 Volume 7). R5V2/3 Appendix A5 should be followed for determining the rupture reference stress for a multi-material structure. This is effectively an algorithm for redistribution. Assessment should consider the rupture strength of all weldment zones;
- Satisfaction of the shakedown criterion;
- Assessment against excessive cyclically enhanced creep – §A4.7 advises that a core stress be calculated as in R5V2/3 §7.5 using parent properties, but the resulting core stress should be used to evaluate the creep damage term W for the most onerous of the weldment zones.

Qu.: Is the parent assessment bounding?

Before assessing crack initiation in the weldment to Appendix A4, the assessment should be carried out as if it were parent, i.e., for the weldment geometry, and hence the same nominal stresses, but using the parent procedure of the main text of R5V2/3.

Qu.: Are the criteria of §6.6.2 for insignificant cyclic loading applicable?

No. For weldments an assessment of fatigue damage is always necessary if the loading cycles.

Qu.: How are welding residual stress effects assessed?

Recall that reheat cracking, i.e., cracking due to the creep relaxation of welding residual stresses, can occur even when the structure remains elastic during service load cycles. Consequently the creep damage accumulated during residual stress relaxation must be included in the overall assessment. This is discussed in §4.5.2 & §4.6.1.3 of R5V2/3 Appendix A4.

If the structure cycles elastically then this is synonymous with a reheat cracking assessment (see §4.6.1.3).

If there is a hysteresis cycle, so that the creep-fatigue mechanism is active, then the damage due to residual stress relaxation is potentially additive to the cyclic creep-fatigue damage. But note that the cyclic plasticity may 'wash out' the initial welding residual stresses – in which case the two sources of damage will not really be additive, or perhaps only additive for a few cycles whilst the steady cyclic state is established.

In §A4.6.1.3 this is addressed by requiring the assessor to estimate the time, t_{cyc}, required for all traces of the initial welding residual stresses to be washed out (my words). The damage due to monotonic relaxation, i.e., the reheat cracking part of the damage, is then calculated by integrating the relaxation damage increments only up to time t_{cyc}. This damage is added to the hysteresis cycle based creep-fatigue damage calculated as described below.

But §A4.6.1.3 would have you estimate t_{cyc} by considering unperturbed monotonic relaxation down to the steady cyclic stress. Personally I believe this is unduly conservative since it fails to recognise that the first plastic loading cycle due to service loadings will tend to erase the initial welding residual stresses. There is a case, therefore, for defining t_{cyc} as the operating time up to the first significant plastic loading cycle.

Qu.: What weldment types are recognised in R5 V2/3 App.A4?

It is necessary to classify your weld into one of the following types (see R5V2/3 Appendix A4 for the full definitions, below are simplified definitions),

Type 1: A full penetration butt weld joining two plates which are nominally parallel and of equal thickness at the joint.

Type 2: A full penetration fillet weld or a full penetration T-butt weld joining two plates which are nominally perpendicular and may be of different thicknesses.

Type 3: A fillet or T-butt weld joining two plates which are not restricted in nominal direction and may be of different thickness. The weld may be of partial or zero penetration.

In the case of Types 1 and 2, any backing strips must have been removed.

This weld categorisation is intended to apply to welds whose main loading direction is transverse to the weld.

However, the assessment of welds which are parallel to the main loading direction is not precluded but the assessor should read the advice in §A4.11 (Status Notes). Note that a circumferential butt weld in a pipe whose stress is dominated by pressure loading will be in this category. *For austenitic welds does this just bring you back to Table 4.1? Rather confusing.*

The above weld types are illustrated in Fig.A4.2 of the procedure, reproduced below.

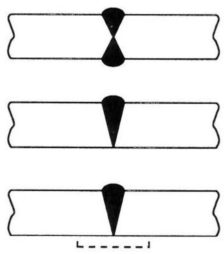
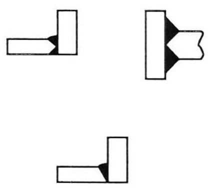
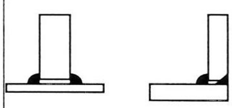
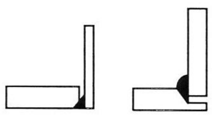
WELD TYPE	EXAMPLES	RCC-MR DEFINITIONS OF TYPES OF WELDED JOINTS				
1		I.1	Butt welding	full penetration	two sides accessible	Back welding.
		I.2	Butt welding	full penetration	two sides accessible	Gaseous back protection with or without insert.
		I.3	Butt welding	full penetration	two sides accessible	On temporary backing strip, can be inspected after removal of strip
		II.1	Butt welding	full penetration	back side inaccessible	Gaseous protection with or without insert.
2		III.1	Fillet or T	full penetration	two sides accessible	Back weld or back machining.
		III.2	Fillet or T	full penetration	back side inaccessible	Gaseous back protection
3		V	Fillet or T	partial penetration or no penetration	straight edges or single opening preparation	double bead
		VI	Fillet or T butt welding	partial penetration	single opening preparation	single bead
		VII	Fillet or T	no penetration	straight edge penetration	single bead

Figure A4.2 Classification of weld types (weld is transverse to main loading direction)

Qu.: Are Fatigue Strength Reduction Factors (FSRFs) Used in R5 V2/3 App.A4?

Not any more, no. Not since the 2014 Revision 002 of R5V2/3 Issue 3.

(For ferritic weldments, the interim procedure uses WSEFs which are numerically equal to the previous FSRFs – but this is only because better WSEFs have not yet been evaluated. The principle is that FSRFs are not required).

Qu.: So what has replaced the FSRFs?

The reduction in fatigue strength due to the weldment is now incorporated in two separate factors, the WSEF and the WER.

Qu.: What are the WSEF and the WER?

They are,

- WSEF = Weld Strain Enhancement Factor
- WER = Weld Endurance Reduction

Qu.: What difference does this make?

Previously the FSRF was used to factor the strain range before entering the ***parent*** fatigue endurance curve, thus providing the endurance for the weldment.

In the revised procedure, the WSEF is used to factor the strain range. The factored strain range is then used with either the weld material fatigue endurance or the parent fatigue endurance reduced by the WER. The smaller of these two options is used if the assessment point is in weld material, otherwise the parent endurance reduced by the WER should be used.

The logic of the revised procedure is that the WSEF contains the geometrical effects on the fatigue endurance, whereas the WER accounts for the material effects.

Qu.: What about lower bound versus best estimate endurance?

Those familiar with the old procedure will recall that some FSRFs were defined so that the use of mean parent endurance data resulted in a lower bound endurance for the weldment. This potentially confusing convention has been changed in the revised procedure. Now you simply use a lower bound input if you want a lower bound output, and the best estimate input if you want the best estimate output. The WSEF is the same in either case.

Qu.: What WSEFs should we use?

These are given in the procedure, Tables A4.1, A4.2, reproduced below.

Table 1

WSEFs to be applied to austenitic weldments for thicknesses less than 25mm*

R5 TYPES	RCC-MR TYPES	WSEF
1	I.1, I.2, I.3, II.1	1.16
2	III.1, III.2	1.23
3	V, VI, VII	1.66

*For weldments with an undressed weld toe present and nominal plate thicknesses greater than 25mm and up to 150mm, the above WSEFs should be multiplied by $(t/25)^{0.25}$; however, in recently issued design advice#, it is noted that the factor of $(t/25)^{0.25}$ relates to fatigue cracking from the toe of a weld and, therefore, is not required for weldments without this type of detail (i.e., dressed welds); also, for a weldment with a weld toe present, the thickness adjustment is only necessary when assessing the weld toe location itself.

#CEN Standard on Unfired Pressure Vessels, EN 13445, Part 3 Section 18, para. 18.10.6.1 [A4.8].

Table 2

WSEFs to be applied to ferritic weldments for thicknesses less than 25mm*

R5 TYPES	RCC-MR TYPES	WSEF
1	I.1, I.2, I.3, II.1	1.5
2	III.1, III.2	2.5
3	V, VI, VII	3.2

**Same footnote as Table 1.*

Qu.: Special provisions for Type 3 weldments

Some points worth noting for these more problematic geomnetries...

- (From §A4.6): "In general, for Type 3 weldments, the WSEFs reflect the presence of the crevice on crack initiation. However, it may be possible to argue for locations which are unaffected by the crevice, for example the weld cap, that the WSEFs for Type 2 weldments in Tables A4.1 and A4.2 would be applicable."
- (From §A4.3): For Type 3 weldments, "undue mesh refinement in the region of the singular point at the crevice tip should be avoided; a midside node element at the crevice location with dimensions of one-eighth to one-quarter of the section thickness is considered adequate".
- It is not necessary to consider the unfused land (crevice) of a Type 3 weldment to be crack-like, an uncracked assessment to R5V2/3 may be carried out on the above basis. However, an alternative approach to the assessment of the region near the crevice tip would be to use the sigma-d procedure within R5V4/5 (see R5V2/3 Appendix A4, §A4.11.6).

Qu.: So how is the WER determined?

The WER is defined as the ratio of the number of fatigue endurance cycles with and without the nucleation cycles included. In practice, the WER is not determined explicitly but is incorporated into an assessment by lowering the *parent* material fatigue endurance fatigue curve by removing the nucleation cycles. Explicitly the procedure is,

- Evaluate the *parent* endurance of the specimen at the strain range of interest (which will already include factoring by the WSEF). This will usually mean the lower bound endurance. Call this N_L cycles;
- Define the cycles to nucleation, N_i, from $\ln N_i = \ln N_L - 8.06 N_L^{-0.28}$; (1)
- Define the cycles left for growth from 0.02mm to failure of the test specimen (at crack size a_L, typically 6 to 10mm) as $N_g = N_L - N_i$;
- Choose an initiation crack size for your assessment, a_0, greater than 0.02mm;
- The number of cycles to grow the crack from 0.02mm to a_0 is N'_g cycles. This is given by $N'_g = MN_g$ where the fraction M is,
    - For $a_0 < 0.2mm$ $$M = \frac{a_0 - 0.02}{0.2\ln(a_l / 0.2) + 0.18} \quad (2a)$$
    - For $a_0 > 0.2mm$ $$M = \frac{0.2\ln(a_0 / 0.2) + 0.18}{0.2\ln(a_L / 0.2) + 0.18} \quad (2b)$$
- In an assessment of parent material, the fatigue endurance would be set to $N_i + N'_g$, but for the weldment the nucleation part is omitted and the endurance is set to only N'_g assuming that parent endurance data was used initially to find N_L.

Although you don't need it explicitly, the WER is thus $\frac{N_i + N'_g}{N'_g}$.

Qu.: Is the WER used with weld endurance data?

No.

If the assessment point is within weld material, and if weld endurance data is available (and this will usually mean lower bound endurance) then the WER is not required. The endurance must still be corrected for the initiation size effect. So the adjusted endurance must be calculated, as above, but this will be based upon a value for N_L obtained from the weld endurance. Since the nucleation phase is assumed not to exist for the weldment, the size-corrected endurance is just MN_L.

However, if weld endurance is not available, or if the assessment point is not within the weld material, then the WER process defined above should be employed, using the parent endurance.

Qu.: What is the most important difference from a parent R5V2/3 assessment?

The most important difference between the weldment assessment procedure in Appendix A4 and the parent methodology is the use of the WSEF and the WER.

In respect of fatigue damage, the effect of the WSEF and the WER together is intended to reproduce the effect of the old FSRF (roughly).

The more important difference from the parent methodology is that the WSEF is also used as a "strain concentration factor" when constructing the hysteresis loop. As a result the dwell stress is generally increased compared with a parent assessment. Hence the creep damage can be substantially larger for the weldment.

Note that only the WSEF, but not the WER, is used in the hysteresis loop construction.

Qu.: How does the old Appendix 4 procedure differ from the new one?

They differ in a great many respects. However, the most significant is that…

For undressed weldments, the old procedure used the FSRF in the construction of the hysteresis loop, whereas the revised procedure uses the (smaller) WSEF. The old procedure tended to produce excessively conservative creep damage for undressed weldments. The new procedure is not so unreasonably conservative.

On the other hand, for dressed weldments, the old procedure did not apply any factor to the strain range in the construction of the hysteresis loop, whereas the revised procedure uses the same WSEF as for an undressed weld. However, because the revised procedure uses the linearised stress it is not clear whether the revised procedure will be more or less onerous for dressed weldments.

For undressed weldments the new procedure is likely to be less onerous than the old procedure. For dressed weldments the new procedure may be either more or less onerous than the old procedure.

Qu.: What sort of finite element analysis is required?

- For the purposes of these Notes, the weldment will be assumed as modelled as a single, linear elastic, material, i.e., homogeneous elastic parent behaviour. This forms the "default" route through the Appendix A4 procedure;
- (Appendix A4 also has provision for inelastic analysis and/or inhomogeneous analysis. These cases are beyond the scope of these Notes);
- For dressed weldments, geometric modelling should be an accurate representation of the weld profile;
- In the case of undressed weldments, the nominal geometry of the weldment, but not the fine details of the weld profile, should be modelled. Undue mesh refinement in the region of surface singular points should be avoided.

Qu.: Level of mesh refinement required?

This is left vague in the procedure, but I would suggest the advice given for the Type 3 weld crevice might also be applicable to, say, a weld toe region, namely the use of mid-side node elements dimensions of one-eighth to one-quarter of the section thickness.

Qu.: Elastic versus Plastic Analysis?

The elastic-plastic analysis option is beyond the scope of these notes. Input from a purely elastic analysis is assumed here. The hysteresis cycle will therefore be constructed as defined in R5V2/3 Appendices A4 and A7. This is the process to be spelt out in full detail below.

Appendix A4 does include provision for elastic-plastic analysis, but this is not discussed here.

Qu.: Homogeneous versus multi-material analysis?

Appendix A4 includes provision for multi-material analysis, but this is not discussed here. Here we assume stresses derived from a homogeneous analysis.

Qu.: What stress-strain data is used in the hysteresis cycle construction?

A key feature of the hysteresis cycle construction methodology is that it is based on parent stress-strain data. Weldment properties enter through the WSEF and the WER. The weld cyclic stress-strain data are not used in the construction of the hysteresis cycle, e.g., in calculating the strain range for fatigue purposes, but a correction to the dwell stress is used based on the ratio of the weld to parent cyclic strengths (see below).

Qu.: What stresses are used as input to the procedure?

The combined primary and secondary stresses are necessary. For the purposes of these Notes, these will be elastic stresses.

However, a difference from the parent procedure is that the linearised stress only is used. The peak (F-)stresses are excluded. The rationale behind this is that the local stress elevation effects are included in the WSEF.

Qu.: Additional weld toe SCF

The new Appendix A4 procedure advises that, for Type 2 and 3 weldments, a stress concentration factor (SCF) is applied to the elastic stress range prior to Neuberising, etc. It is only required if the weld cap angle exceeds 30^o for undressed welds, or 39^o for dressed welds. Its value is,

$$\mathrm{SCF} = \sqrt{\theta/\psi} \quad \text{and} \quad \begin{array}{ll} \psi = 39^o & \text{for dressed welds} \\ \psi = 30^o & \text{for undressed welds} \end{array}$$

No such SCF is required for Type 1 welds. (At least, that's my reading of App.A4, though it is not entirely clear). The weld toe angle in question relates to the attachment side of the weld.

Note: this SCF is applied to the elastic stress range. In contrast, the WSEF is applied to the elastic-plastic strain range.

Qu.: Is the weldment procedure always more severe than the parent procedure?

As noted above, Appendix A4 requires the weldment geometry to be assessed as a parent feature as well as a weldment - so the result cannot be less onerous than for parent.

Qu.: How does the WSEF determine the dwell stress for creep?

The gory details of the full hysteresis loop construction are given below. However the key points may be lost in the detail, so the over-view is,

(a) Firstly, for whichever portion of the hysteresis loop you are considering, the strain range is calculated as for parent material;

(b) This is then factored by the WSEF to get the strain range for the weldment;

(c) This factored strain range is no longer compatible with the initial (parent) stress range. So the stress range corresponding to this factored strain range is found (using the ***parent*** cyclic stress-strain curve);

(d) This new stress range is used to construct the hysteresis loop for the weldment, using essentially the same process on both sides of the loop. Hence this includes constructing the dwell stress. The WSEF therefore affects the calculated dwell stress, often markedly.

(e) BUT, for an assessment point within weld material, the procedure calls for the dwell stress evaluated as above to be factored by the ratio of the weld to parent cyclic strengths, if this makes it bigger. (I don't like this bit);

(f) Continue to use the parent values of $K_S S_y$ to "symmetrise" the cycle, or to act as the "bottom stop" of the cycle, as appropriate.

Note that it is the strain range, not the stress range, which is directly factored by the WSEF. The stress range is generally not increased by as large a factor as WSEF, due to the power-law relation, $\Delta\varepsilon_p \propto \Delta\sigma^n$, between plastic strain range and stress range.

Qu.: What stress-strain properties are used in the hysteresis loop construction?

Parent stress-strain properties are used. Weldment properties enter only via the WSEF and also in step (e).

Qu.: Are parent or weld/HAZ properties used to calculate the creep relaxation?

There is a subtlety here in that the creep relaxation / creep strain may need to be calculated in two different ways depending upon usage.

As regards the calculation of strain range for evaluating the fatigue damage, parent creep relaxation or integration of parent deformation should be used to calculate the stress relaxation and associated creep strain increment (this is specified in §A4.6.1.2(iv)).

But, as regards the calculation of creep damage, the creep deformation or creep relaxation behaviour of the material zone which produces the greatest creep strain should be used. This is specified near the bottom of page 2/3.A4.9 and again in A4.11.3. This is obviously conservative.

My own opinion on the latter requirement is that it is rather simplistic. It is probably OK for dominant transverse loading - which, to be fair, is stipulated in the definition of the weldment Types - but for dominant longitudinal loading there is already a precedent in R5, namely in Volume 7, to assume strain compatibility and hence the use of parent creep deformation/relaxation data would be valid.

Qu.: Is parent or weld/HAZ ductility used to calculate the creep damage?

The creep ductility appropriate to the location of the assessment point should be used, i.e., weld, HAZ or parent. Hence creep damage might be found from the ratio of a creep strain evaluated using parent creep properties to a ductility for weld or HAZ.

Qu.: Is stress modified ductility (SMD) applicable?

At present, no. This is due to lack of validation for SMD in the context of weldments, especially its performance in predicting reheat cracking. It is possible that SMD may be validated for use with weldments at some future date, but not as of 2015.

Qu.: What is step (e)?

For assessments points within weld material, and if the weld over-matches the parent, the dwell stress is factored up by the ratio of the weld to parent cyclic strengths at the relevant strain range.

This can produce a very pessimistic assessment. The physical realism of this procedure can be challenged since, for a stronger weld, the strains will often tend to accumulate preferentially in the parent. So, rather than the weld being more prone to cracking, it may be less so.

The factoring-up of the dwell stress for a weld location by the ratio of weld:parent strength is probably overly conservative (my opinion), but is required in the procedure

Qu.: What point should be chosen for assessment?

I suppose the most onerous point should be chosen. This may be the weld due to the above factoring. However, you may have reasons for confining attention to HAZ or parent.

Note, though, that reheat cracking damage due to welding residual stresses will be greatest sub-surface (due to triaxiality). So the choice of assessment point is generally far from clear. You may need to assess several points.

Qu.: How are dressed and undressed welds treated differently?

In the old Appendix A4 (before Rev 002 of Issue 3), dressed and undressed weldments were treated very differently. For dressed welds the peak stresses were included but no FSRF was used in the hysteresis cycle construction of the dwell stress and hence the creep damage. For undressed weldments the linearised stresses were used, but the FSRF was included in the hysteresis cycle construction. Both dressed and undressed welds would have employed an FSRF in the fatigue assessment.

In the revised procedure of R5V2/3 Issue 3 Rev 002 there is very little difference between the treatment of dressed and undressed weldments. Both use the linearised stresses and both include the WSEF in the cycle construction and the WER in the fatigue endurance. For thicker sections, dressed weldments may have a smaller WSEF due to the absence of the thickness correction (see the footnote to Table 1). Also the SCF for dressed welds may be slightly smaller. However, these differences are slight.

There is unease at present that the procedure *should* treat undressed weldments significantly more onerously than dressed weldments, but does not do so. It is not clear yet how this may be resolved in future revisions.

Qu.: Mentor Guide question 1.46

A number of Mentor Guide questions were written with the old weldments procedure in mind. They can all still be answered in the new context, but Qu.1.46 might be better worded as,

Discuss recent developments in the methodology for initiation assessments of weldments, specifically how a weldment assessment to R5V2/3 Issue 3 Appendix A4 and to R5V2./3 Issue 3 Revision 1 Appendix A4 might be expected to differ.

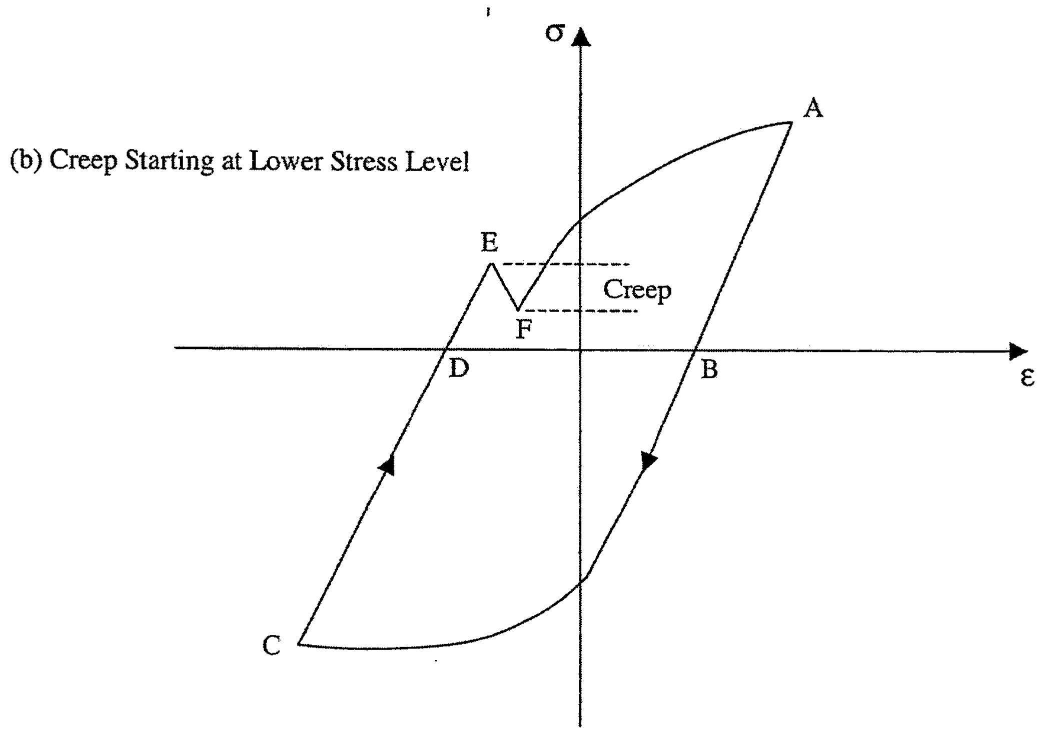
Table 3: Summary of Changes Between Old and New Weldments Procedure (assuming elastic stresses are input to the procedure)

Feature	Old Procedure	Revised Procedure
Parent	Peak stress, no FSRF	Peak stress, no WSEF nor WER – i.e., no change
Dressed Weld	Peak stress, no FSRF in hysteresis construction (i.e., in creep damage), but FSRF included in fatigue	Linearised stress, include WSEF in hysteresis construction (hence creep damage), apply WER in fatigue. No thickness correction of WSEF. FEA based on actual weld profile. Weld cap SCF may be applicable depending on profile. May be more or less onerous than old procedure. Must also apply parent procedure which might be more onerous.
Undressed Weld	Linearised stress, include FSRF in hysteresis construction and hence creep damage as well as in fatigue	Linearised stress, include WSEF in hysteresis construction (hence creep damage), apply WER in fatigue. Thickness correction of WSEF. Weld cap SCF may be applicable depending on weld toe angle. FEA based on gross geometry only. Less onerous than old procedure due to WSEF < FSRF (for austenitics at least).

Qu.: What is the detailed hysteresis loop construction procedure for weldments?

The following sequence of steps is a reprise of the hysteresis loop construction methodology which was presented in Session 33 for homogeneous parent material, but now modified for weldments in accord with the revised procedure. The differences between the parent and weldments procedure are relatively few and are highlighted thus. The same hysteresis loop as used in Session 33 will be used again to illustrate the process, Figure 1,

Figure 1: Cycle Type Assumed in theses Notes



General

Throughout: use parent cyclic stress-strain and strength properties unless otherwise stated.

The elastic stresses used should be the linearised values, not the linearised-plus-peak stresses as would be used for a parent feature.

Qu.: How is the half-cycle without creep (ABC) constructed?

We follow the procedure of R5V2/3 Appendix A7, Section A.7.5.3.1. The relevant elastic Mises stress range is that between the cycle peaks, i.e. between A and C, denoted $\Delta\sigma_{el}^{ABC}$. The ***unmodified parent*** Ramberg-Osgood expression is used to represent the cyclic strain range in terms of the cyclic stress range. Hence the elastic-plastic strain and stress ranges are found from the Neuber construction as follows,

$$\Delta\sigma_{ep}^{ABC}\Delta\varepsilon_{ep,ABC}^{parent} = \frac{\left(\Delta\sigma_{el}^{AC}\right)^2}{\overline{E}}, \text{ where, } \Delta\varepsilon_{ep,ABC}^{parent} = \frac{\Delta\sigma_{ep}^{ABC}}{\overline{E}} + \left(\frac{\Delta\sigma_{ep}^{ABC}}{A}\right)^{1/\beta} \qquad (3)$$

This is consistent with R5V2/3 Appendix A7, Equations (A7.13) and (A7.14) in the case that $\sigma_D = 0$ and $\sigma_N = \Delta\sigma_{ep}^{ABC}$.

The volumetric strain range correction, $\Delta\varepsilon_{vol}$, is then found following R5V2/3 Section 7.4.2, Equations (7.13-16).

So far this is identical to the process for a parent feature. The parent stress and strain ranges are next corrected so as to apply for the weldment. A WSEF (Weld Strain Enhancement Factor) is chosen appropriate for the type of weld and the precise assessment location within the weldment. The elastic-plastic strain range for the weldment is thus found from,

$$\Delta\varepsilon_{ep,ABC}^{weld} = WSEF\left(\Delta\varepsilon_{ep,ABC}^{parent} + \Delta\varepsilon_{vol}\right) \tag{4}$$

The insertion of the WSEF in (4) is the only change to the homogeneous (parent) procedure defined in session 33. However this enhanced strain range requires that the elastic-plastic stress range for the weldment is also adjusted so as to be compatible with it. The elastic-plastic stress range for the weldment is thus found by solving,

$$\frac{\Delta\sigma_{ep,ABC}^{weld}}{\bar{E}} + \left(\frac{\Delta\sigma_{ep,ABC}^{weld}}{A}\right)^{1/\beta} = \Delta\varepsilon_{ep,ABC}^{weld} \tag{5}$$

Note that the ***parent*** Ramberg-Osgood parameters continue to be used in (5) despite the fact that the quantities involved are the *weldment* stress and strain ranges.

Qu.: How is the reverse stress datum, σ_D, found?

The procedure follows R5V2/3 Appendix A7, Section A7.5.3.2. The values of K_sS_y are evaluated at the hot and cold ends of the cycle. If the weldment elastic-plastic stress range for half-cycle ABC exceeds the K_sS_y 'range' then the cycle is positioned so as to extrude beyond K_sS_y equally at each end of the cycle. In other words, if $\Delta\sigma_{ep,ABC}^{weld} > (K_sS_y)_{top} + (K_sS_y)_{bottom}$, then the reverse stress datum is,

$$\sigma_D = \frac{\Delta\sigma_{ep,ABC}^{weld}}{2} + \frac{(K_sS_y)_{bottom} - (K_sS_y)_{top}}{2} \tag{6}$$

On the other hand, if $\Delta\sigma_{ep,ABC}^{weld} \le (K_sS_y)_{top} + (K_sS_y)_{bottom}$, then the reverse stress datum is defined by the cycle bottom end reaching the shakedown limit,

$$\sigma_D = (K_sS_y)_{bottom} \tag{7}$$

The only difference from the parent procedure is that $\Delta\sigma_{ep,ABC}^{weld}$ replaces the parent stress range $\Delta\sigma_{ep}^{ABC}$. Parent properties are used to define K_sS_y.

The initial estimate of the forward stress datum is thus $\tilde{\sigma}_F = \Delta\sigma_{ep,ABC}^{weld} - \sigma_D$.

Qu.: How is the partial half-cycle before dwell (CDE) constructed?

Here we follow the procedure of R5V2/3 Appendix A7, Section A.7.5.4. The relevant elastic Mises stress range is that between the bottom end of the hysteresis loop and normal operation, denoted $\Delta\sigma_{el}^{CE}$. The ***modified parent*** Ramberg-Osgood expression with A replaced by A/2 is used to approximate the monotonic stress-strain relation. Hence the partial elastic-plastic strain range and the normal operating stress are initially estimated from the Neuber construction for parent material by solving the following equation for σ_N^{no},

$$(\sigma_D + \sigma_N^{no})\Delta\varepsilon_{ep,CDE}^{parent} = \frac{(\Delta\sigma_{el}^{CE})^2}{\overline{E}}, \text{ where, } \Delta\varepsilon_{ep,CDE}^{parent} = \frac{\sigma_D + \sigma_N^{no}}{\overline{E}} + \left(\frac{2\sigma_N^{no}}{A}\right)^{1/\beta} \qquad (8)$$

This is consistent with R5V2/3 Appendix A7, Equations (A7.13) and (A7.14). Note that the reverse stress datum, σ_D, follows from (6) or (7) above.

The volumetric strain range correction, $\Delta\varepsilon_{vol}$, is then found following R5V2/3 Section 7.4.2, Equations (7.13-16).

The parent stress and strain ranges are next corrected so as to apply for the weldment, applying the appropriate WSEF. The elastic-plastic strain range for the weldment is thus found from,

$$\Delta\varepsilon_{ep,CDE}^{weld} = WSEF(\Delta\varepsilon_{ep,CDE}^{parent} + \Delta\varepsilon_{vol}) \qquad (9)$$

The insertion of the WSEF in (9) is the only change to the homogeneous (parent) procedure defined in session 33. However it requires that the elastic-plastic stress range for the weldment is also adjusted so as to be compatible with this strain range. The corresponding elastic-plastic stress for the weldment in normal operation, σ_0, is thus found by solving,

$$\frac{\sigma_D + \sigma_0}{\overline{E}} + \left(\frac{2\sigma_0}{A}\right)^{1/\beta} = \Delta\varepsilon_{ep,CDE}^{weld} \qquad (10)$$

Note that the *parent* Ramberg-Osgood parameters continue to be used in (10) despite the fact that the quantities involved are the *weldment* stresses and strain range.

Qu.: What dwell stress is used to evaluate creep damage? (Construct EF)

If the assessment location is in parent material, and σ_0 exceeds the rupture reference stress, σ_{ref}^{rup}, then σ_0 is the start-of-dwell stress from which creep damage is calculated, allowing for relaxation.

However, if $\sigma_0 < \sigma_{ref}^{rup}$, then σ_{ref}^{rup} is the constant primary dwell stress from which creep damage is calculated with no relaxation.

When the assessed location lies in weld material which over-matches the parent in cyclic strength, R5V2/3 Appendix A4, Section A4.6.1.2 calls for σ_0 to be increased by a factor equal to the ratio of the cyclic strengths of the weld and parent at the relevant strain range, i.e., $\Delta\sigma_{\Delta\varepsilon}^{weld} / \Delta\sigma_{\Delta\varepsilon}^{parent}$. This factored stress is used as the start-of-dwell stress from which creep damage is calculated providing that it exceeds the rupture reference stress, σ_{ref}^{rup}. However, if $\frac{\Delta\sigma_{\Delta\varepsilon}^{weld}}{\Delta\sigma_{\Delta\varepsilon}^{parent}}\sigma_0$ is less than the rupture reference stress, then σ_{ref}^{rup} is the constant primary stress from which creep damage is calculated with no relaxation. If $\Delta\sigma_{\Delta\varepsilon}^{weld} / \Delta\sigma_{\Delta\varepsilon}^{parent} < 1$ then no adjustment of the dwell stress applies.

Often, assessments of EDF Energy plant turn out to be creep dominated, so that the above estimate of the dwell stress, the appropriately factored σ_0, is the most important outcome of the procedure.

The creep relaxation (if any) and creep damage associated with part EF of the hysteresis cycle is calculated using ductility exhaustion as per Session 34. Relaxation is based on parent creep properties for the purpose of estimating the fatiguing strain range, but the creep deformation/relaxation behaviour of the material zone which produces the greatest creep strain is assumed for the purposes of creep damage. The creep ductility employed is that for the weldment zone wherein the assessment point lies.

Qu.: How is the half-cycle including creep (CDEFA) constructed?

The purpose of this final step in the hysteresis loop construction is to provide a second estimate of the elastic-plastic strain range for the whole cycle, i.e., as an alternative to $\Delta\varepsilon_{ep,ABC}^{weld}$, so that the larger of the two can be used for assessing fatigue damage. It also provides an alternative estimate of the elastic-plastic stress peak at point A (also referred to as the 'forward stress datum', σ_F).

Neuber Construction

Here we follow the procedure of R5V2/3 Appendix A7, Section A.7.5.6.2, noting that the creep dwell decreases the stress range (and increases the strain range), see Figure 1. The relevant elastic Mises stress range is that between the extreme ends of the cycle, i.e. between points C and A, less the stress drop during the creep dwell. Hence we use,

$$\Delta\sigma_{el}^{CA} = \Delta\sigma_{el}^{AC} - \Delta\sigma_c \qquad (11)$$

where $\Delta\sigma_{el}^{AC}$ is the same elastic stress range as used in the first step (construction of ABC) and the stress relaxation, $\Delta\sigma_c$, is found as part of the creep damage calculation. The ***modified parent*** Ramberg-Osgood expression, with A replaced by A/2, is used to approximate the shape of hysteresis loop. Hence the elastic-plastic strain range and the peak trip stress are initially estimated from the Neuber construction for parent material by solving the following for σ'_F,

$$(\sigma_D + \sigma'_F)\Delta\varepsilon_{ep,CEA}^{parent} = \frac{\left(\Delta\sigma_{el}^{CA}\right)^2}{\bar{E}}, \quad \text{where,} \quad \Delta\varepsilon_{ep,CEA}^{parent} = \frac{\sigma_D + \sigma'_F}{\bar{E}} + \left(\frac{2\sigma'_F}{A}\right)^{1/\beta} \qquad (12)$$

This is consistent with R5V2/3 Appendix A7, Equations (A7.13) and (A7.14) for $\sigma_N = \sigma'_F$. Note that the reverse stress datum, σ_D, follows from (6) or (7) above.

The volumetric strain range correction, $\Delta\varepsilon_{vol}$, is then found following R5V2/3 Section 7.4.2, Equations (7.13-16).

The parent stress and strain range are next corrected so as to apply for the weldment, using an appropriate WSEF. The elastic-plastic strain range for the weldment is found from,

$$\Delta\varepsilon_{ep,CEA}^{weld} = WSEF\left(\Delta\varepsilon_{ep,CEA}^{parent} + \Delta\varepsilon_{vol}\right) \qquad (13)$$

The corresponding elastic-plastic stress for the weldment at the top of the hysteresis loop (point A), otherwise known as the 'forward stress datum', σ_F, is thus found by solving,

$$\frac{\sigma_D + \sigma_F}{\overline{E}} + \left(\frac{2\sigma_F}{A}\right)^{1/\beta} = \Delta\varepsilon_{ep,CEA}^{weld} \tag{14}$$

Note that σ_F relates to the weldment, whereas σ'_F is merely a precursor quantity defined via parent behaviour, (12). The two estimates of the forward stress datum, $\tilde{\sigma}_F$ and σ_F, should not be too different, though they are unlikely to be identical.

Qu.: What is the final strain range for fatigue damage estimation?

The strain range for the LHS of the hysteresis loop should be augmented by the creep strain, $\Delta\tilde{\varepsilon}_{ep,CEA}^{weld} = \Delta\varepsilon_{ep,CEA}^{weld} + \Delta\varepsilon_c$.

Finally, the strain range to be used for the assessment of fatigue damage is the larger of the strain ranges evaluated for the RHS and LHS of the hysteresis loop, i.e., the larger of $\Delta\tilde{\varepsilon}_{ep,CEA}^{weld}$ and $\Delta\varepsilon_{\mathrm{ep,ABC}}^{\mathrm{weld}}$.