T73S04 Session 34: Relaxation & Elastic Follow-Up

Last Update: 5/4/2015

Relates to Knowledge & Skills items 1.22, 1.28, 1.29, 1.30, 1.31

Evaluation of relaxation: integration of forward creep and limitations of Feltham type expressions; Limitation of relaxation to rupture reference stress; Watch out for 'upwards relaxation'; Defn of creep damage (again); Methods for estimating Z; Effective Z for combined pure primary and pure secondary; How sensitive is D_c to Z? Plastic Z implicit in Neuber construction - assumption implicit in using Neuber for hysteresis loop construction;

Qu.: What is meant by "forward creep"

"Forward creep" just means creep under a constant load, or constant stress, just like a standard creep test. So the term "forward creep" is used to refer to the use of standard creep strain rate data or equations.

Qu.: What is "relaxation"?

If the load applied is not entirely primary, then the load will reduce (relax) as creep strain accumulates. Relaxation is the reduction of stress due to creep (or, in some contexts, due to plasticity).

Qu.: What is "redistribution"?

If the stress across a structural section is not uniform, the initial stress distribution will change due to creep. The stress in regions of high stress will tend to reduce, off-loading onto regions of lower stress. This is redistribution. This will happen even if the ***load*** is primary. So redistribution will happen in general, if the initial stress is non-uniform, even if the load remains constant.

However, if the loading is partly secondary, redistribution and relaxation will happen simultaneously in general.

In this session we are concerned only with relaxation, not redistribution. In applications of R5V2/3, redistribution is not *explicitly* considered. However, redistribution is actually *implicit* in the R5V2/3 procedure in the following features

- The reference stress solution employed,
- The elastic follow-up factor, Z, employed, and,
- The Neuber construction.

Qu.: Are there data in R66 specifically for creep relaxation?

Yes – the whole of Section 4 of R66 is on relaxation.

The data is formulated in terms of a Feltham type expression, in which the stress drop is written as,

$$\Delta\sigma = a\ln(bt+1)$$

The coefficients *a* and *b* are expressed in terms of three other parameters A'', B'', σ_i,

$$a = \sigma_0 B''$$

$$b = \frac{EA''}{\sigma_0 B''}\exp\left\{\frac{\sigma_0 - \sigma_i}{\sigma_0 B''}\right\}$$

where σ_0 is the start-of-dwell stress. The parameter σ_i is called the "back stress".

Qu.: So R66 Section 4 is what we should use for relaxation?

Well possibly sometimes…but in general, no.

Qu.: Why not?

The main reason that Section 4 relaxation data is not generally used in R5V2/3 assessments is due to the severely limited range of its validity.

This was clarified by Mike Spindler in an email dated 15th February 2007 and attached below as Appendix A. R66 Section 4 was updated in Rev.009 (issued in July 2011) so I would hope that Mike's advice of 2007 has been incorporated – but I haven't checked. Always check the R66 User Queries for updated advice.

The Section 4 relaxation data was derived for the most part from very high temperature, very high stress tests of very short duration (often only a day or two). Clearly it is questionable how indicative such short term data can be for dwell times which, in our plant, are generally in the order of thousands of hours. Mike's email gives some interim advice to avoid serious (non-conservative) errors by using R66 Section 4 data. This consists of restrictive limits on the applicable temperatures, stresses, dwell times and internal stresses.

Unfortunately the limits on temperature and stress are very restrictive and will generally make use of the Section 4 data inapplicable. However, if your assessment is within Mike's limits (and any other restrictions within R66 Section 4) then you can use this relaxation data – but note the other issues below…

Qu.: What other problems are there with R66 Section 4 relaxation data?

There are two other issues with the Feltham-type formulation used in R66 Section 4.

<u>Creep Hardening</u>

The first issue is apparently a benefit of using Feltham expressions in that R66 Section 4 says "*it is not necessary to consider whether the process is controlled by a strain hardening or a time hardening formulation*". However, in truth, the relaxation behaviour *must* depend upon the hardening behaviour if the material is in primary creep. This is because the conditions are changing (namely the stress is decreasing). However the assumption that the parameters A'', B'', σ_i are constant effectively means that the material is assumed to be in secondary creep (due to R66 Equ.4.3).

Another way of looking at this is to say that R66 Section 4 assumes a specific hardening behaviour by virtue of the back stress, σ_i, being assumed constant. The back stress is really a product of the dislocation behaviour and hence evolves as creep proceeds. Inserting some varying back stress formulation, say by specifying $\partial\sigma_i / \partial t$, would introduce a different hardening behaviour.

<u>Elastic Follow-Up</u>

The other issue with the Feltham formulation is that in R66 Section 4 no mention is made of elastic follow-up, Z. This is rectified in R5V2/3 Appendix A11 which advises that the Feltham expression be replaced with,

$$\Delta\sigma = a \ln\left(\frac{bt}{Z} + 1\right)$$

However I suspect that this is valid only for secondary creep. Since this assumption is implicit in the formulation of R66 Section 4 anyway (see above) perhaps this is ok? But I suspect that in primary creep, with a deformation law $\dot{\varepsilon}^c = C \cdot t^m \cdot \sigma^n$, or equivalently, $\dot{\varepsilon}^c = \tilde{C} \cdot (\varepsilon^c)^{\tilde{m}} \cdot \sigma^{\tilde{n}}$, where $\tilde{m} = \frac{m}{m+1}$ and $-1 < m < 0$, that time should really be scaled by $t \to t / Z^{\frac{1}{m+1}}$, so that one should use,

$$\Delta\sigma = a \ln\left(\frac{bt}{Z^{\frac{1}{1+m}}} + 1 \right)$$

Note that this modification leads to reduced relaxation and hence reduced creep damage.

Note that for the RCC-MR formulation, $\varepsilon^c = C_1 t^{C_2} \sigma^{n_1}$, $m = C_2 - 1$.

Qu.: How should we calculate relaxation when R66 Section 4 is inapplicable?

…by integration of forward creep.

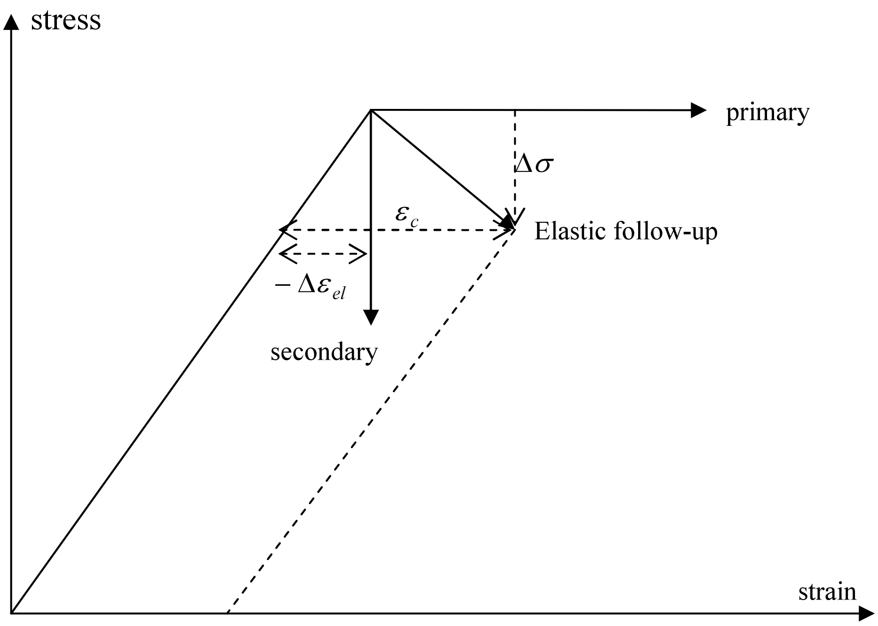
Qu.: How is relaxation calculated from a forward creep law?

Remember session 24 and the associated homework? We'll go over it again below.

Qu.: How is the elastic follow-up factor, Z, defined?

This has also been addressed before, in session 31. A reminder…

Figure 1: Definition of Z



Z is the factor by which the creep strain increment exceeds the elastic strain decrease. Algebraically this is simply,

$$\varepsilon_c = -Z\Delta\varepsilon_{el} = -Z\frac{\Delta\sigma}{E} \tag{1}$$

Qu.: How does this change for 3D states of stress?

It becomes,

$$\bar{\varepsilon}_c = -Z\frac{\Delta\bar{\sigma}}{\bar{E}} \tag{2}$$

This involves the Mises equivalent stress drop and Mises equivalent creep strain increment, and $\bar{E} = \frac{3E}{2(1+\nu)}$.

Qu.: How is the stress relaxation calculated from a forward creep law?

Assume a primary forward creep law of the form,

$$\dot{\varepsilon}^c = C \cdot t^m \cdot \sigma^n \tag{3}$$

(where $-1 < m < 0$). If time hardening is assumed the resulting relaxation against time is given by,

$$\sigma = \left\{ \sigma_0^{-(n-1)} + \frac{1}{Z}\left(\frac{n-1}{m+1}\right) CEt^{m+1} \right\}^{-\frac{1}{n-1}} \tag{4}$$

for an arbitrary elastic follow-up factor, Z.

Equ.(4) follows by integration of (3) together with (1), with the implicit assumption that Z is a constant.

For 3D states of stress replace $\sigma \to \bar{\sigma}$ and $E \to \bar{E}$.

Qu.: Is there a corresponding relaxation equation for strain hardening?

The same forward creep law can be expressed in terms of strain rather than time as,

$$\dot{\varepsilon}^c = \tilde{C} \cdot \left(\varepsilon^c\right)^{\tilde{m}} \cdot \sigma^{\tilde{n}} \tag{5}$$

where, $$\tilde{C} = \left[(m+1)^m C\right]^{\frac{1}{m+1}}, \quad \tilde{m} = \frac{m}{m+1} \text{ and } \tilde{n} = \frac{n}{m+1} \tag{6}$$

Substituting for the creep strain from (1), the stress relaxation is given implicitly by,

$$\int_{\sigma_0}^{\sigma} \sigma^{-\tilde{n}} (\sigma_0 - \sigma)^{-\tilde{m}} \, d\sigma = C\left(\frac{Z}{E}\right)^{\tilde{m}-1} t \tag{7}$$

I suspect this integral can only be done in closed form when $\tilde{n}$ and $\tilde{m}$ are integers, so I don't think there is a nice formula for strain hardening comparable to (4) for time hardening. (I'm happy to be proved wrong if someone can do the integral). Even when $\tilde{n}$ and $\tilde{m}$ are integers I suspect it would be hard to invert (7) to get stress as an explicit function of time.

So, in conclusion: for strain hardening use numerical integration.

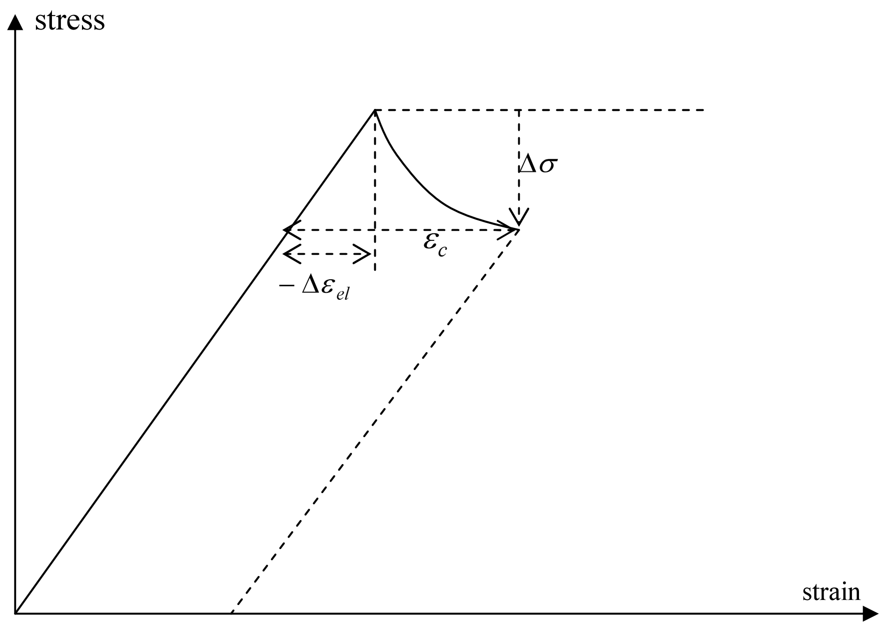
Qu.: Is Z really constant?

No.

Z is not really constant.

If it were, the relaxation trajectory on a stress-strain plot would be a straight line – just as shown on Figure 1. But of course it is not – it is a 'hyperbolic' shape…

Figure 2 A more realistic relaxation curve



It is clear from Figure 2 that defining $Z = \varepsilon_c / |\Delta\varepsilon_{el}|$ means that Z increases as relaxation progresses.

Qu.: So do we use varying Z in practice?

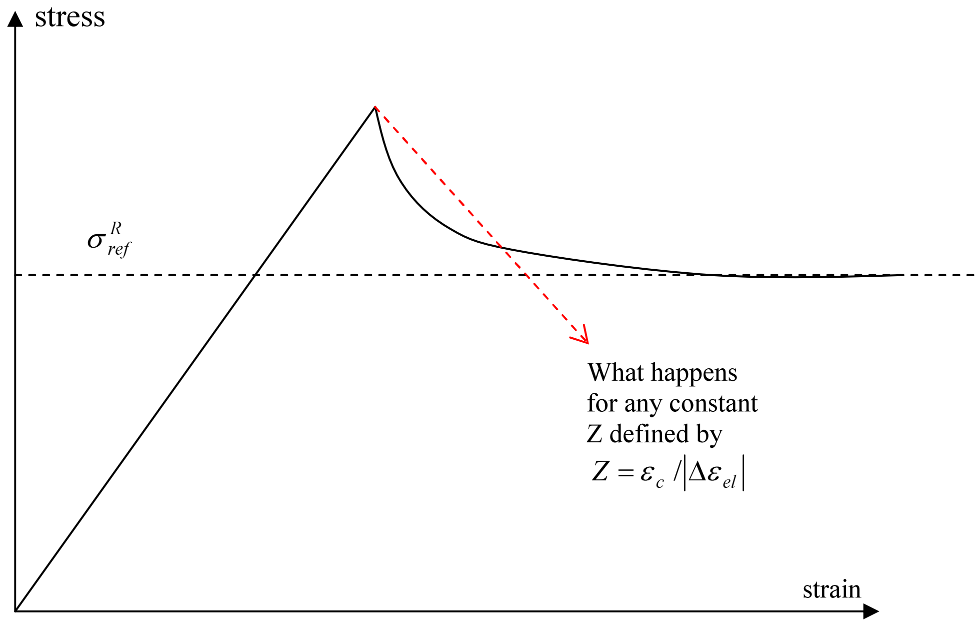
Yes and no.

I don't think people generally attempt to allow for some explicit variation in Z. However there is one very important instance where the curvature of the stress-strain trajectory during relaxation is incorporated. This is in respect of ensuring that the stress cannot relax below the primary stress level

Qu.: How is the primary stress level built into relaxation?

Relaxation cannot proceed indefinitely. The stress cannot drop below the primary stress. More precisely, the rupture reference stress is the lower bound (asymptote) of the relaxation curve…

Figure 3 The relaxed stress cannot drop below the primary stress



As illustrated above by the red line, if Z is defined by $Z = \varepsilon_c / |\Delta\varepsilon_{el}|$, then any constant, finite Z will eventually lead to relaxation dropping below the primary stress – which is not allowed.

Qu.: How is the σ_{ref}^{R} asymptote imposed algebraically?

The definition $Z = \bar{\varepsilon}_c / |\Delta\bar{\varepsilon}_{el}|$ can be re-written as,

$$\frac{Z}{\bar{E}} \cdot \frac{d\bar{\sigma}}{dt} = -\dot{\bar{\varepsilon}}_c(\varepsilon_c, \bar{\sigma}, T) \tag{8}$$

To ensure that the stress cannot relax below the primary stress (σ_{ref}^{R}) we must ensure that $\frac{d\bar{\sigma}}{dt}$ becomes zero when $\bar{\sigma} \to \sigma_{ref}^{R}$. This is accomplished by replacing (8) by,

$$\frac{Z'}{\bar{E}} \cdot \frac{d\bar{\sigma}}{dt} = -\left(\dot{\bar{\varepsilon}}_c(\varepsilon_c, \bar{\sigma}, T) - \dot{\bar{\varepsilon}}_c(\varepsilon_c, \sigma_{ref}^{R}, T)\right) \tag{9}$$

This equation, when integrated, will produce a relaxation curve like that of Figure 3, as desired.

Qu.: Can Z' in (9) be taken as a constant?

Yes, Z' in (9) can be taken as a constant whilst still achieving a relaxation curve which does not go below σ_{ref}^{R}, like Figure 3.

Qu.: But doesn't that contradict what was said before?

No. The follow-up factor Z' is no longer defined by $Z = \varepsilon_c / |\Delta\varepsilon_{el}|$, hence the 'dash' to distinguish Z' from Z.

It is clear that Z' is different from Z since integration of (9) gives,

$$Z' = \frac{\left|\bar{\varepsilon}_c - \tilde{\varepsilon}^R_{c,ref}\right|}{\Delta\varepsilon_{el}} < Z \qquad (10)$$

So Z' is always less than Z, but they are equal if the creep strain due to the primary stress is negligible.

Note that the term $\tilde{\varepsilon}^R_{c,ref}$ in (10) is ***not*** simply the forward creep strain at stress σ^R_{ref} as you might be tempted to think. This is because the strain at which the primary strain rate is integrated is not that which would arise due to primary loading alone, but the total strain based on the total (relaxing) stress.

(10) shows how a constant Z' can be consistent with Figure 3 which requires an increasing value of Z. It is because,

$$Z = \frac{\bar{\varepsilon}_c}{\bar{\varepsilon}_c - \tilde{\bar{\varepsilon}}^R_{c,ref}} \cdot Z' \qquad (11)$$

So a constant Z' implies an increasing Z as relaxation progresses.

You will not find this distinction between Z' and Z explained in R5.

Qu.: So what elastic follow-up factor should we actually use?

Numerical values are discussed below.

Because the follow-up factor is generally held constant during the integration, I suggest that they are interpreted as being Z'. This is conservative because in general the numerical value used will have been derived from the definition for Z, i.e., (1). So the suggested interpretation is conservative because (10) ensures that Z' should really be smaller. The advantage of this interpretation is that the relaxation equation (9) can be used which ensures that the stress does not drop below the primary rupture reference stress – and this is the essential requirement.

Qu.: Can the dwell stress *increase* during a creep dwell?

This sounds crazy at first, but actually the dwell stress at the assessment point can increase during the creep dwell. Of course this cannot happen if the situation is truly relaxation. It can happen only if the hysteresis cycle leads to the assessment point having a lower stress than elsewhere on the same structural cross-section. Redistribution of the stresses then occurs over the section and can lead to an increase in stress at the assessment point as stress is shed from the higher stressed positions.

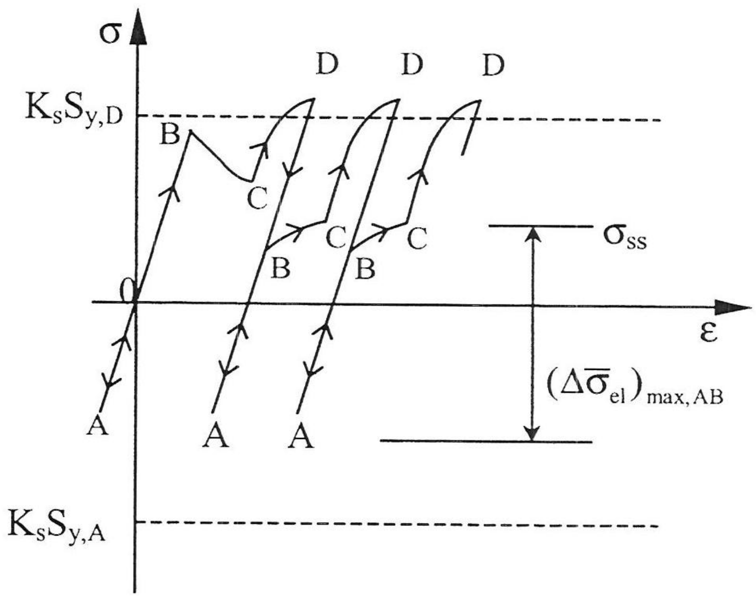
One case in which this behaviour clearly must occur is when the hysteresis cycle construction results in a dwell stress which is less than the rupture reference stress (based on the primary loads alone). Such cases are illustrated in R5V2/3 Appendix A3, Figure A3.6b and A3.6d (see Figure 4 below).

Qu.: How are such cases assessed?

It would be difficult to calculate just how fast the stress at the assessment point increases due to redistribution, since this depends upon the integrated response of the whole section. Consequently, if the hysteresis cycle construction results in a dwell stress less than σ^R_{ref} the required procedure is to assume a constant stress of σ^R_{ref} throughout the whole duration of the dwell. This is simple and conservative.

Note that this does not mean that the hysteresis cycle construction is wrong in deriving $\sigma_0 < \sigma_{ref}^R$. This is perfectly possible. It merely means that calculating how the dwell stress increases is too hard and it is simpler to assume the maximum asymptotic value, $\sigma_0 \to \sigma_{ref}^R$.

Figure 4
From R5V2/3 Fig.A3.6b: Illustration of stress increase during creep dwell
In this Figure $\sigma_{SS} \equiv \sigma_{ref}^R$



Qu.: What methods are available to estimate Z?

R5V2/3 gives three methods for estimating Z, both in Section 7.3 (in brief) and in Appendix A8 in detail. The methods are:-

Option 1

Assume the dwell stress is all primary and just use forward creep at constant stress. This is equivalent to $Z = \infty$. This is usually extremely conservative, but is fine if you get away with it.

Option 2

This method says that you can use $Z = 3$ as long as the structure is isothermal and the primary stresses are small (so that the linearised Mises primary stress does not exceed 20% of the stress after relaxation).

Personally I have a difficulty with this rather sweeping advice. I've seen many FE analyses which produced Z values larger than 3, sometimes a lot larger.

Even if there is little "gross" elastic follow-up, at a local stress concentration, such as a weld toe or a radius feature, Z can be far larger. Examples of this can be seen in the FE models produced under the austenitic reheat cracking programme in 1996/97 – see Appendix B of EPD/AGR/REP/0328/97. There are many examples in that report of Z values in the range ~4 to ~8, due to local SCFs. This is despite the loading being dominated by welding residual stresses which are often assumed to have little follow-up.

This observation is pertinent because some of the items analysed in EPD/AGR/REP/0328/97 did actually suffer from reheat cracking (e.g., the hot reheat penetrations' shop welds 1 at HPB/HNB, which are the models called R4C3 and 20/23 within Appendix B of EPD/AGR/REP/0328/97). These welds had a genuine local SCF caused by the forging geometry and the fact that the steam tubes were over-thick. Successful 'prediction' of the reheat cracking is probably dependent upon the large Z values.

However, even without any local SCF a structure may have a large degree of elastic follow-up. This is common in piping systems where displacement controlled loads can be very long range. The evaluation of Z can be avoided by taking such loads as primary, but this may give you assessment problems.

Option 3

"Do it yourself" – probably using FEA.

Qu.: What is Z for a pure primary load plus a pure secondary load (with Z = 1)?

Elastic follow-up factors, Z, are most often required when the applied load is intermediate in character between primary and secondary. An example is a displacement applied at a finite distance from the location of interest. However, another situation in which Z may be required is when two loads are applied to the structure, one being a pure primary load (which alone would have $Z \to \infty$) and a pure secondary load with no follow-up (which alone would have Z = 1). What is the effective Z for both loads applied together?

Assuming we use the definition of Z given by Equ.(1), $\varepsilon_c = -Z\Delta\varepsilon_{el}$, there is no unique answer. If we wait long enough for the secondary stress to have fully relaxed, there will only be the primary stress left and hence $Z \to \infty$ as $t \to \infty$. On the other hand, at the start of the relaxation Z will be little bigger than unity. The relaxation curve starts off dropping almost vertically and turns to become asymptotic to the primary stress. Thus, Z starts off little bigger than 1 and increases without limit. So how is our question meaningful? The question can be made meaningful by specifying that we want Z at the time when the secondary stress is ~99% relaxed. This can happen quite quickly if the primary stress is large enough. This Z will be denoted $Z_{99\%}$.

A two-bar model in http://rickbradford.co.uk/ZforPrimaryPlusSecondaryLoads.pdf suggests that $Z_{99\%} = \frac{1}{1-\xi}$ where $\xi = \left(\frac{\sigma_P}{\sigma_P + \sigma_S}\right)^2$ and σ_P and σ_S are the elastic stresses at the point of interest for the primary and secondary loads applied alone.

Figure 5

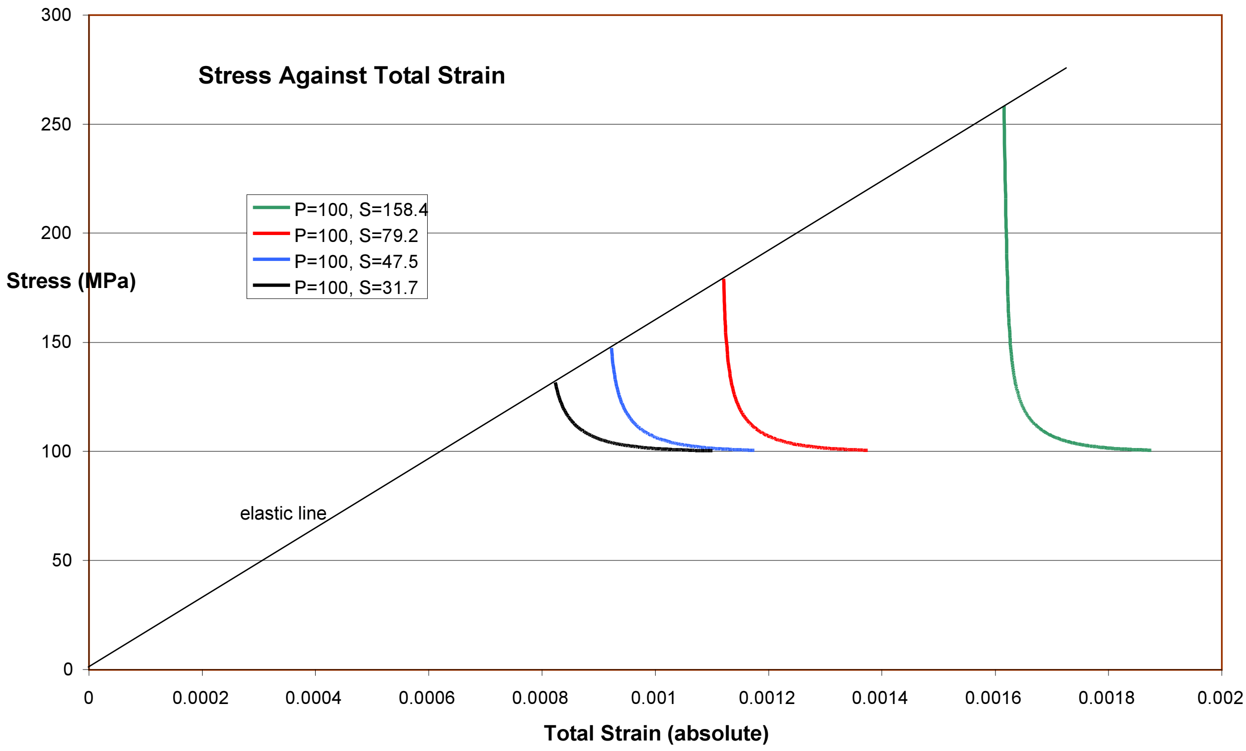
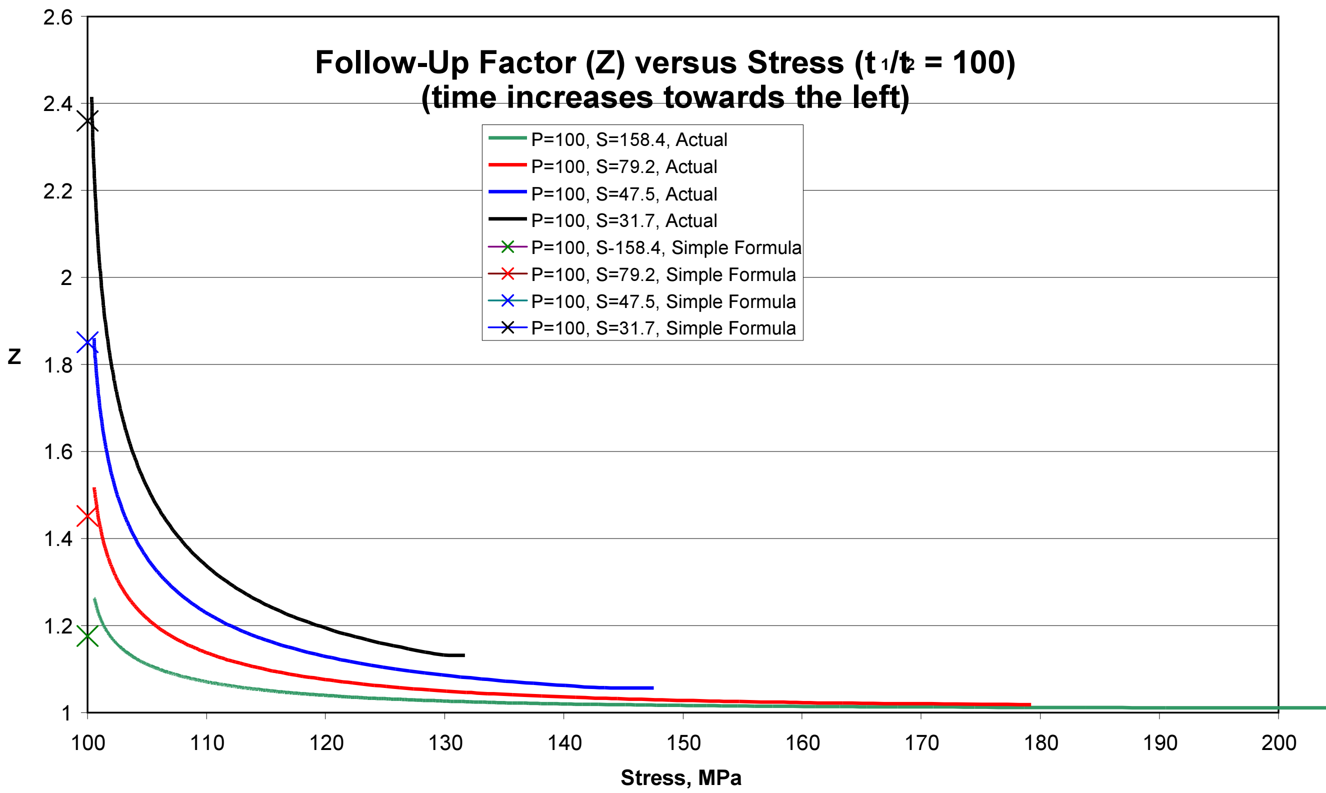


Figure 6



Qu.: How valid is the use of the Neuber construction?

There is great emphasis in R5 on using the correct follow-up factor, Z, to calculate the creep strain due to the creep dwell. But elastic follow-up is not mentioned in R5 in respect of the plastic behaviour. Instead, the elastic-plastic behaviour is approximated by the Neuber construction, whatever the degree of elastic follow-up might be.

But actually the R5 procedure for hysteresis cycle construction implicitly involves an assumption regarding the value of Z in plasticity. The Neuber construction is equivalent to a follow-up factor in plasticity of,

$$Z = \frac{2-x}{1-x} \tag{12}$$

where $x = \frac{|\Delta\sigma|}{\sigma_{el}}$, and $|\Delta\sigma| = \sigma_{el} - \sigma_{ep}$ is the amount by which the stress is reduced by plasticity, so that *x* is the fractional stress reduction due to plasticity. So Z ~ 2 for very small plastic corrections to the stress (benign loadings), but Z is unboundedly large for large reductions to the elastic stress (the more usual case in 'challenging' applications). So, it is some comfort that the implicit Z is reasonably - or even unreasonably - large, and hence likely to be conservative.

Real structures do not necessarily behave as per the Neuber construction, as FEA will generally reveal. Neuber really applies for stress-strain fields local to notches. So Neuber may not be terribly accurate if your geometry is not notch-like at all.

There is an interesting discussion point here: why should Z be different in plasticity and creep? The R5 V2/3 procedure implicitly assumes they are different. Is this reasonable?

Qu.: What is the exact definition of creep damage in R5V2/3?

The ductility exhaustion definition of creep damage is, roughly, $D_c \approx \frac{\varepsilon_c}{\varepsilon_f}$. However this is only approximate. This is because the full expression must involve an integral over varying conditions, because the creep ductility varies with strain rate and with stress state – both of which will change over time. So the correct expression is,

$$D_c = \int_0^t \frac{\dot{\bar{\varepsilon}}_c dt}{\bar{\varepsilon}_f\left(\dot{\bar{\varepsilon}}_c, \sigma_{ij}\right)} \tag{13}$$

If the multi-axial creep ductility is expressed as a stress-state dependent fraction, *S*, of the uniaxial creep ductility, then,

$$\bar{\varepsilon}_f\left(\dot{\bar{\varepsilon}}_c, \sigma_{ij}\right) = S\left(\sigma_{ij}\right)\bar{\varepsilon}_{f,uni}\left(\dot{\bar{\varepsilon}}_c\right) \tag{14}$$

In which case (8) becomes,

$$D_c = \int_0^t \frac{\dot{\bar{\varepsilon}}_c dt}{S\left(\sigma_{ij}\right)\bar{\varepsilon}_{f,uni}\left(\dot{\bar{\varepsilon}}_c\right)} \tag{15}$$

The difference between (10) and (8) is merely that the stress state and strain rate dependencies of the ductility have been assumed separable.

Qu.: What advice is there on S, the stress state factor?

R5V2/3 Appendix A1, Section A1.11.1.2 advises how to account for multiaxial effects on creep ductility, at least for some materials. (Consult the experts, or the References [1-5], for the materials for which this advice applies).

Biaxial Stressing

If one principal stress is virtually zero, and $\sigma_1 > \sigma_2$ are the other principal stresses, the multiaxial Mises ductility, $\bar{\varepsilon}_f$, is,

$$\sigma_2 < 0.5\sigma_1: \qquad S = \frac{\bar{\varepsilon}_f}{\varepsilon_{f,uni}} = \left(1 - \frac{\sigma_2}{\sigma_1}\right) \tag{16a}$$

$$\sigma_2 > 0.5\sigma_1: \qquad S = \frac{\bar{\varepsilon}_f}{\varepsilon_{f,uni}} = 0.5 \tag{16b}$$

So biaxial stressing does not decrease the ductility by more than a factor of 2. Note that (5a) implies that the ductility is enhanced by a compressive σ_2 .

Triaxial Stressing

For certain austenitic materials, models of cavity nucleation and growth have suggested that multiaxial ductility varies with stress state according to,

$$\frac{\bar{\varepsilon}_f}{\varepsilon_{f,uni}} = \exp\left\{ p\left(1 - \frac{\sigma_1}{\bar{\sigma}}\right) + q\left(\frac{1}{2} - \frac{3\sigma_H}{2\bar{\sigma}}\right)\right\} \tag{17}$$

where $\bar{\sigma}, \sigma_1, \sigma_H$ are the Mises, maximum principal, and hydrostatic stresses respectively. Consequently (6) depends upon all three principal stresses.

R5V2/3 Appendix A1, Section A1.11.1.2 includes two sets of values for the parameters p and q. The more onerous values, $p = 2.38$ and $q = 1.04$, were derived from tests on 304 stainless steel. However, these values for the parameters have been widely used for 316H in the reheat cracking temperature range (e.g., Refs.[6-8]).

A great deal of work has been done over the last 10-15 years on 316H and Eshhete, for example using notched bar specimens, to obtain data on creep ductility in triaxial states and determine the values of p and q. Consult the experts for the latest position.

Qu.: How sensitive is creep damage to Z?

Suppose that the creep ductility were strain rate insensitive. The sensitivity of the creep damage to Z would then just be the sensitivity of the creep strain to Z. When there is no primary stress it may be tempting to imagine that the creep strain per dwell is proportional to Z because of the definition $\varepsilon_c = -Z\Delta\varepsilon_{el} = -Z\dfrac{\Delta\sigma}{E}$. But the larger Z the smaller the relaxation, $\Delta\sigma$, due to (say) Equ.(8) or (9).

An illustration is shown below for 316ss at 525°C using RCC-MR deformation rates and assuming time hardening (so that Equ.(4) applies). The graphs show the factor by which Z increases the creep strain per dwell (and hence the damage per dwell) plotted against Z. The different curves are for different dwell times. The different graphs are at different lives (first cycle, after 1 year and after 10 years). The factor of increase is significantly less than Z, especially after the first few cycles.

Figure 7a

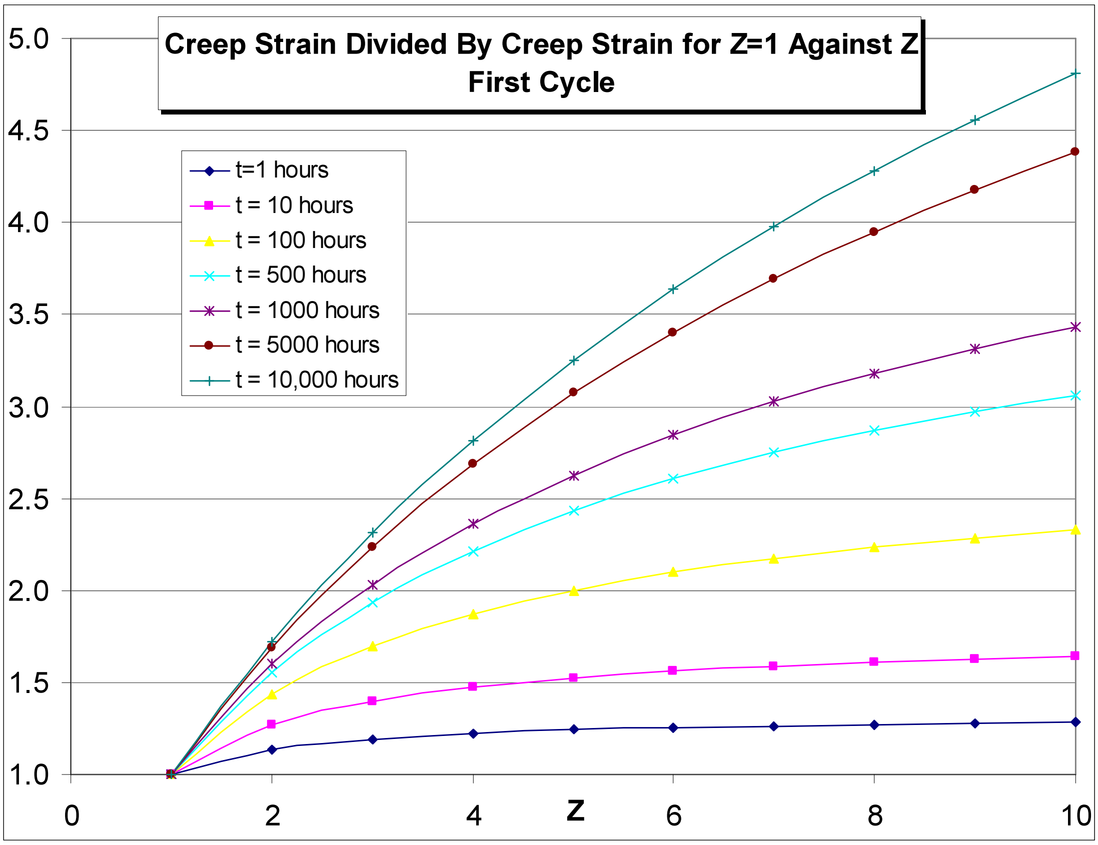


Figure 7b

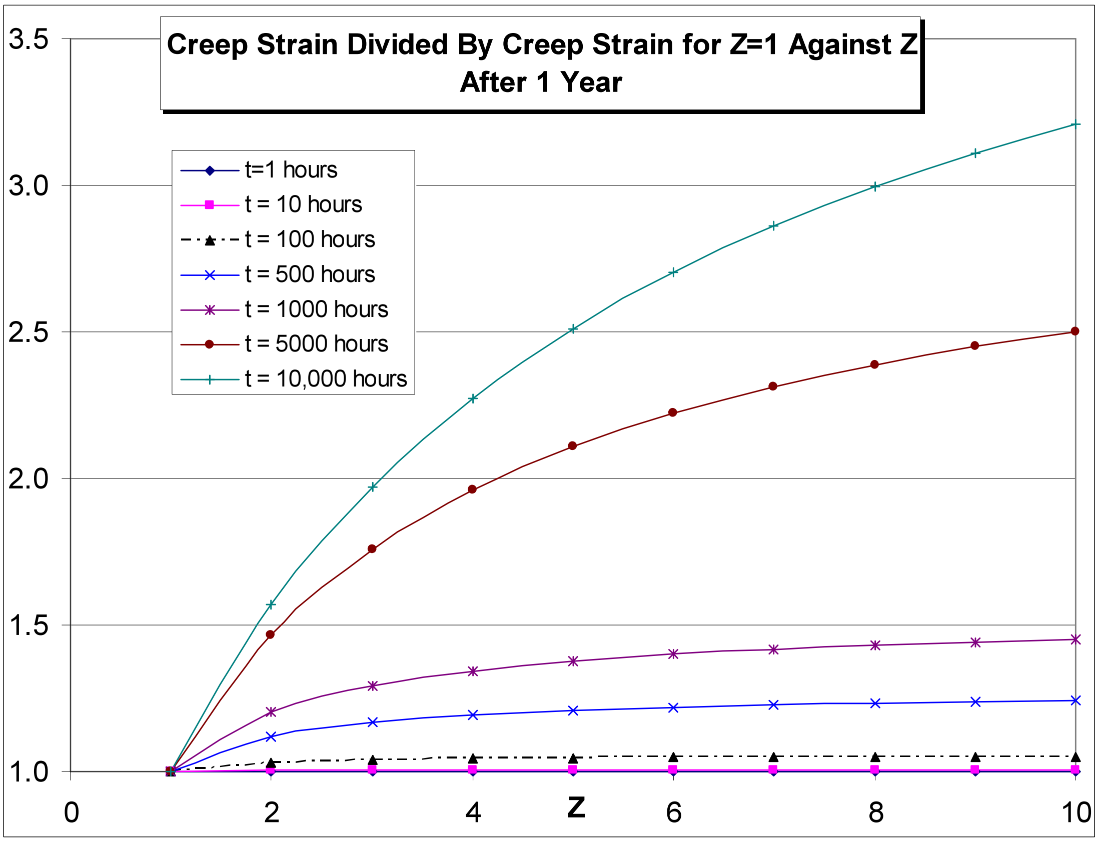
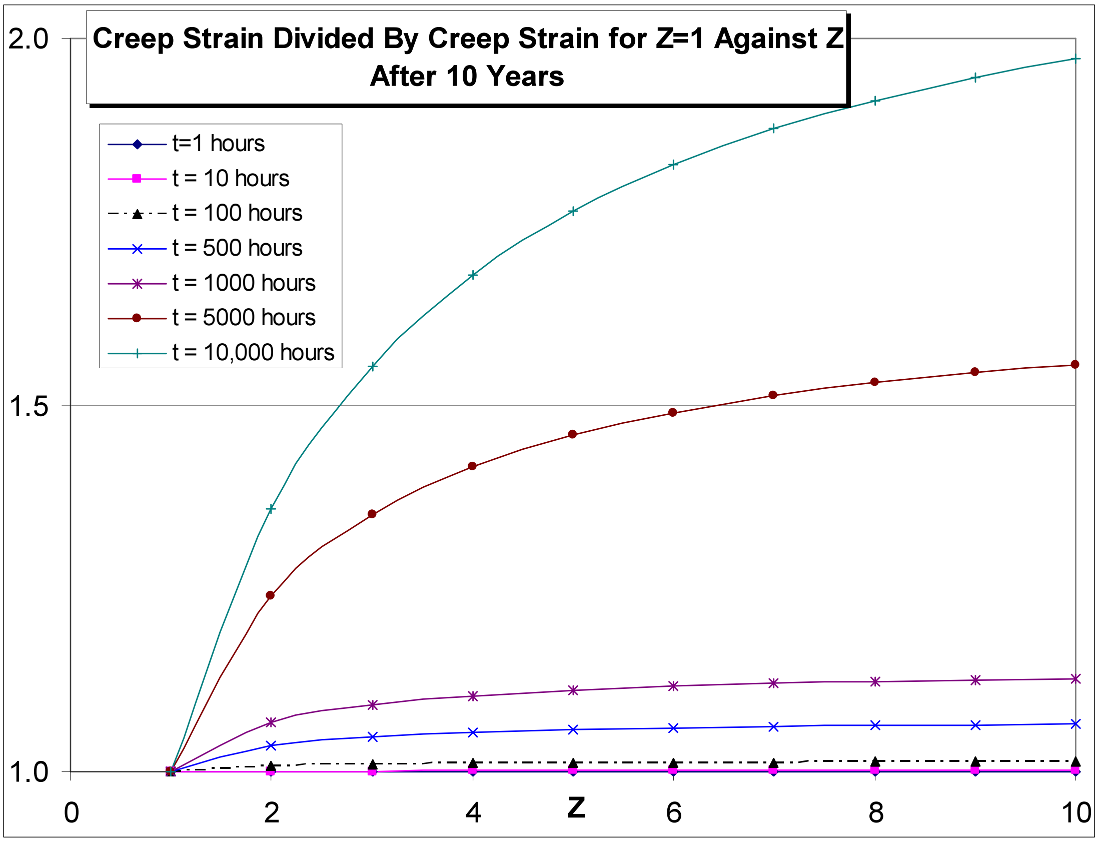


Figure 7c



Creep Strain Divided By Creep Strain for Z=1 Against Z
After 10 Years
t=1 hours
t = 10 hours
t = 100 hours
t = 500 hours
t = 1000 hours
t = 5000 hours
t = 10,000 hours
2.0
1.5
1.0
0
2
4
Z
6
8
10

Appendix A – Email from Mike Spindler on R66 Section 4 (Relaxation Data)

From: **Spindler Mike**
Sent: 15 February 2007 14:54
To: DL ENG ETB AT; DL ENG ETB SAG; Hamm Chris; Richards Ian; Lonsdale Dave; Kirk Charlie
Subject: CR 00356600 INTERNAL STRESS VALUES IN SECTION 4 OF R66 ARE NOT REALISTIC

This email is being sent out in response to a CAP assignment 0035660007 "Produce advice on use of R66 stress data before data recommendations can be revised."

CR 0035660007

It is expected that the stress relaxation data in Section 4 of the AGR Materials Data Handbook R66 would give a realistic estimate of stress relaxation behaviour, as is required for an R5 assessment.

It has been found that many of the internal stress values that are given in Section 4 of R66 are not physically realistic. In particular it has been found that many of the values of the internal stress are too high, which could lead to non-conservative assessments of creep damage using R5 Volume 2/3.

It is judged that the reason why these internal stresses are not physically correct is that the data from which they were empirically derived were from short term tests (tens of hours), which do not represent the dwell times experienced by AGR components (thousands of hours).

In order to prevent the data from being use in a non-conservative manner it has been decided to offer some interim advice regarding the validity ranges of the stress relaxation data in R66 Section 4. This advice is restricted to those materials for which internal stress values are given in R66. The current issue of R66 does not give validity limits for either the range of temperatures for which the data are applicable or for the dwell times. In addition, in some case limits on initial stress are missing.

In each case the limits on temperature are suggested to be ±25°C, which is in line with standard practice for creep rupture data. Nevertheless, expert advice must be obtained in order to adjust the coefficients to anything other than the main temperature. It is suggested that dwell times are limited to 100 times the maximum duration of the test dwells. It should be noted that this is very much longer than the usually allowable extrapolation for creep rupture data of three times. Nevertheless, for stress relaxation data where the effects of tertiary creep are not significant it is judged that 100 times extrapolation might be reasonable. However, it should be noted that there is no validation for this judgment.

Suggested interim values have been given in the Table below:

		Validity Ranges		
Material	Internal Stress MPa	Temp °C	Initial Stress MPa	Dwell Times hours
2¼Cr1Mo	35	570±25	100-200	≤1600
1CMV Rotor	200.4	550±25	312-461	≤1600
Cast 304 (mean)	57	650±25	114-200	≤2400
Cast 304 (bounding)	45	650±25	114-200	≤2400
Cast 304 aged (mean)	54.8	650±25	130-150	≤2400
Cast 304 aged (bounding)	40	650±25	130-150	≤2400
Type 321	51	650±25	160-200	≤1200
304 weld	160	570±25	243-290	≤4400
304 aged weld	CONSULT EXPERT ADVICE			
347 Weld	84	650±25	190-250	≤1200
316 Weld	124	650±25	190-250	≤2400

The R66 data should not be used outside of these validity ranges without the agreement of a suitable expert.

I hope this is useful

Mike Spindler
x3733