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RCC-MRx and R5 Creep-Fatigue Initiation Predictions Applied to the Evasion Tests

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ABSTRACT

This paper provides a brief overview of the Evasion Tests (cyclic loading in sodium at high temperature) and uses these results to undertake a code evaluation comparison using two high temperature design/assessment methods, namely RCC-MRx [1] and R5 [2]. The analysis was performed to support Work Package 5 within the European Energy Research Alliance – Joint Program on Nuclear Materials (EERA JPNM) project "DESIGNLIFE60+", which had the aim to support the demonstration of GEN IV reactor lifetimes. It also formed part of the EASICS project, considering design code selection for application to Advanced Modular Reactors (small Gen IV reactors) in the UK.

INTRODUCTION

This paper aims to provide a summary of the results coming from a comparison analysis performed when applying internationally recognised methods to determine creep fatigue initiation endurance. This includes an overview of the calculations performed (adopting the elastic stress routes) using available high temperature design codes, namely RCC-MRx [1] and R5 [2], the assessment procedures for the high temperature response of structures (noting that R5 is a lifetime assessment procedure, not a design code) when applied to the "Evasion Tests" (see description below). It is worth noting that further comparison cases have been considered but the focus of this paper is the Evasion Test comparison.

The intent of the comparison is to examine the differences in the assessment codes/procedures when applied to the Evasion Test. It is known that the RCC-MRx [1] and R5 [2] approaches are relatively similar in terms of creep-fatigue initiation assessments. That these are similar is not surprising as they share similar underlying methodologies. However, there are also some subtle differences that may become important within an assessment. The potential mix of scenarios that is required for the Evasion Tests is considered useful as this includes the effect of the weld, both in terms of enhancement to strain range and modification to material properties, which can be included and excluded from the assessment. The mix of cases considered also allows the influence of thermally induced secondary stresses and a mixture of creep dwell locations (at the peak of the loading or at intermediate stresses) to be considered. Overall, the mixture of cases is considered to provide a useful basis for the comparison of R5 and RCC-MRx creep-fatigue initiation calculations. A full review of all the contributing effects is not possible within this paper; consequently only example results are presented herein alongside the main high-level findings.

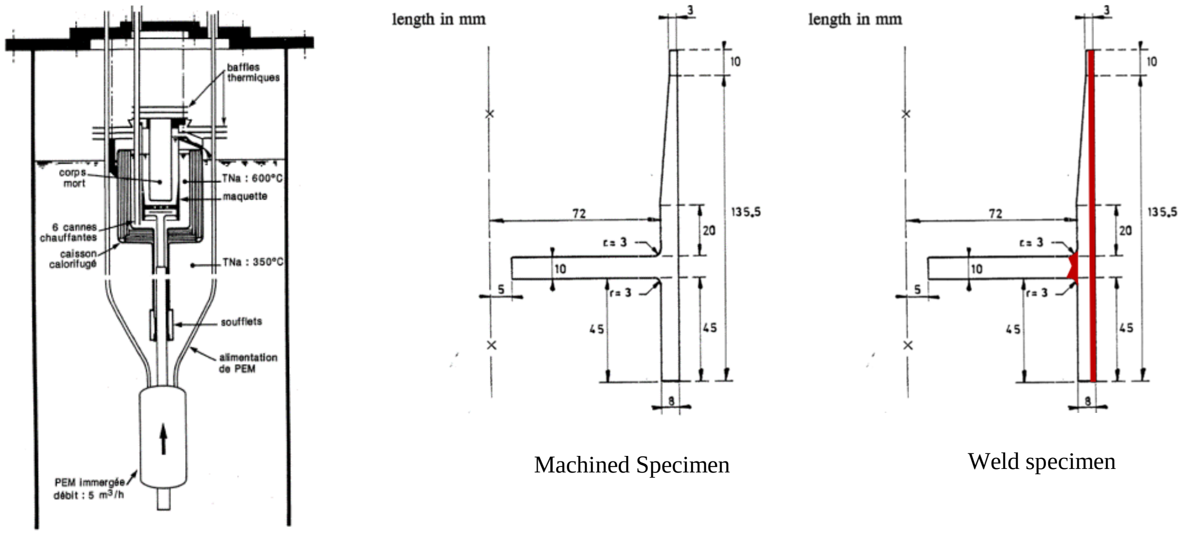
The paper is split to consider an overview of the Evasion Tests in the following section, a review of the assessment methods thereafter, followed by comparison results, interpretation and, latterly, the general observations.

Evasion Tests

Creep-fatigue tests were performed by CEA Cadarache (in the 1980's) in a sodium cooled loop operating at 600°C with two mock-ups representative of a plate-to-shell weld junction of a liquid-metal fast breeder reactor component. A short summary of the tests is included below (information provided in [3] as well as through private correspondence).

- *Overview*: These tests are from 316L(N) mock-ups of a plate-to-shell junction of a section of a sodium cooled reactor coolant flow-loop (shown in Figure 1). These were subject to thermal cyclic loading at elevated temperatures. Two mock-ups were tested, one machined and one welded (longitudinal seam weld in addition to the fillet weld for the plate).

- *Geometry*: The Evasion mock-ups are axisymmetric with the general dimensions in Figure 1. Welds were located on the plate to cylinder joint (x2 fillet welds) and one longitudinal seam weld. These were dressed and free of defect as shown by non-destructive examination.
- *Loading*: The mock-ups were subject to thermal shock loading only. The internal surface of the mock-up was subject to two thermal shock levels:
    - Transient A - 600°C down to 350°C (and back to 600°C) with a dwell time of 6 hours.
    - Transient B - 600°C down to 200°C (and back to 600°C) with a dwell time of 1 hour.
    - The outer surface remained at 600°C.
- *Material*: The tubes are made from 316L(N) and the welds from OKR3U filler material (19Cr12Ni2Mo).
- *Temperature*: The tests were at two thermal shock loads from 600°C; down to 350°C and 200°C.
- *Environment*: Sodium coolant.
- *Output*: The tests provided a number of cycles for a defect to initiate. After 1500 cycles of Transient A no defects were found (thus providing a further point to compare against). After a further 1000 cycles of Transient B some defects were found as detailed below, with a difference between the mock-up which included the weld and that which was machined.
    - Trans-granular cracks (fatigue) were observed in the two fillet radii of the machined mock-up. These were approximately 0.6 mm deep.
    - Trans-granular cracks (fatigue) were observed in the two fillet weld radii and an inter-granular crack (creep) in the longitudinal weld of the welded mock-up. The fatigue cracks were approximately 0.9 mm deep. The longitudinal weld defect was approximately 28 mm long and 4 mm deep.



Machined Specimen

Weld specimen

Schematic of the Component and Flow

Dimensions of the Evasion Mock-Up Tests

Figure 1. Schematic of the Evasion Test

The Evasion Tests are therefore well-defined tests, which include a collection of null and positive results, for different cycles and weld conditions. The Evasion Tests are purely secondary in nature (i.e. only thermal stress cycles), and the R5 and RCC-MRx approaches are capable of assessing such conditions. These tests therefore provide a useful experimental dataset by which to compare the methods available.

For the assessments below, the input data (stress and materials data) has been supplied by CEA. Here, finite element stress analyses were used to define the stresses and the materials data was taken from RCC-MRx. Here suitable mean and lower bound data were also considered as well as primary and secondary creep laws. Where data was required for the R5 Assessment beyond that included in RCC-MRx, best judgement was used to base the values on similar materials. As such, the comparisons are consistent in the inputs considered, allowing the comparison to highlight the differences in the assessment methods and assumptions made therein.

OVERVIEW OF ASSESSMENT APPROACHES

RCC-MRx Methodology

The approach in RCC-MRx uses a calculated total strain range, modified to account for all possible cycle types, to estimate a fatigue usage factor (V), and the creep rupture usage factor (W) (see Equations 1 and 2 below). For combined creep-fatigue loading an interaction diagram is used, where a point within the diagram bound indicates that a crack has not initiated, whereas a point outside may have initiated. For 316 stainless steel materials, the RCC-MRx interaction diagram is given in Figure 2.

$$\mathrm{V} = \sum_{j} \left(\frac{n_j}{N_j}\right) \tag{1}$$

Here n_j is the number of cycles of type j and N_j is the allowable number of cycles (of type j), where the value of N_j is determined by the calculated total strain range.

$$\mathrm{W} = \sum_{k} \left(\frac{t_k}{T_k}\right) \tag{2}$$

Here t_k is the creep time of cycle type k and T_k is the allowable time for that condition to cause creep rupture. Here the curves can be calculated from the creep rupture curves, S_r, with an enhanced stress level (as $\sigma_k/0.9$); any stress relaxation therefore means this term should be integrated over the hold period (the calculation of σ_k is detailed below).

Figure A3.2S.55: fatigue-creep interaction diagram

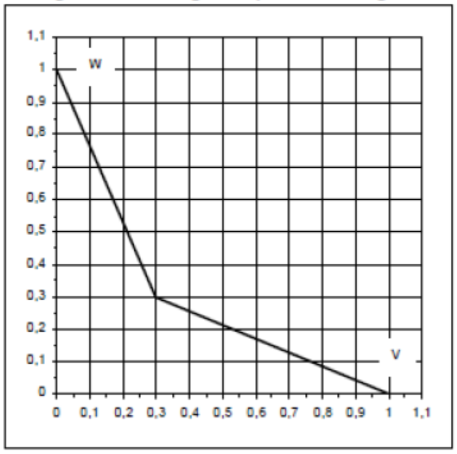


Figure 2. Creep-Fatigue Interaction Diagram from RCC-MRx [1]

A number of steps are taken to calculate the V and W terms. These are not detailed extensively below but a summary of the steps required is included:

- Calculate the elastic stress and strain range (Section RB 3224.45). The elastic stress range is calculated from the times corresponding to the maximum and minimum equivalent stresses. The elastic stress range is given by a von-Mises equivalent stress.
- Calculation of the elastic, plastic and creep strains (Section RB 3261.1123). The total strain range used in the fatigue assessment considers four different contributing terms in a fatigue assessment. These are noted as $\overline{\Delta\varepsilon_1}$ through to $\overline{\Delta\varepsilon_4}$. Also necessary is the additional strain calculated from creep, $\overline{\Delta\varepsilon_{fl}}$ such that $\overline{\Delta\varepsilon} = \overline{\Delta\varepsilon_1} + \overline{\Delta\varepsilon_2} + \overline{\Delta\varepsilon_3} + \overline{\Delta\varepsilon_4} + \overline{\Delta\varepsilon_{fl}}$. The component terms are detailed from the following:
    - $\overline{\Delta\varepsilon_1}$ provides the elastic strain range.
    - $\overline{\Delta\varepsilon_2}$ provides an enhancement from the primary stress range by calculating a primary stress range and finding the additional plastic strain corresponding to the intercept on the cyclic stress-strain curve.

  - $\overline{\Delta\varepsilon_3}$ provides the plasticity enhancement from the initial elastic stress. This follows a Neuber construction, where $\overline{\Delta\sigma}.\overline{\Delta\varepsilon} = constant$, to move from a point given by $\overline{\Delta\varepsilon_1} + \overline{\Delta\varepsilon_2} : \Delta\sigma_{el}$ to the strain which intercepts the cyclic stress-strain curve.
  - $\overline{\Delta\varepsilon_4}$ provides the plastic increase from triaxiality.
  - $\overline{\Delta\varepsilon_{fl}}$ provides the additional creep strain over each cycle. The strain is calculated by considering the different contributions from primary and secondary stresses and the effect of symmetrisation (given by a coefficient in RCC-MRx). For secondary stresses it is possible to account for the stress relaxation seen. Where the creep rate relationship is known, the total creep strain per cycle can then be calculated as:

$$\overline{\Delta\varepsilon_{fl}} = \int_0^{T^*} \dot{\varepsilon}(\sigma_k)\, dt \tag{3}$$

    Here σ_k is the dwell stress (note that there are different options to calculate this) and T^* is the time over which the creep strain accumulates (either the hold point time or the time within the hold point where the temperature is large enough to induce strains). It is worth noting that the instantaneous relaxation of the stress included in this calculation can also be modified to account for elastic follow-up, Z. Here RCC-MRx suggests taking Z as 3 unless a lower value can be justified.

- Weld Enhancement. When assessing a weld, the strain range is multiplied by a weld enhancement factor of 1.25 for stainless steels. The creep rupture curves, S_r, used to evaluate the creep damage W with equation 2 are reduced by a factor $J_r \leq 1$ depending on the creep time and temperature.

R5 Methodology

The approach in R5 uses a similar approach to that in RCC-MRx, where there is a fatigue usage factor as well as a creep damage per cycle calculated. The fatigue usage factor is given by Equation (1), but termed D_f. The creep damage term is, however, different to that in Equation (2), as this is based on the creep ductility (noting when the creep dwell stress does not relax the use of creep rupture is permitted). The total creep damage, D_c, is calculated as;

$$D_c = \sum_j n_j d_{cj} \tag{4}$$

where d_{cj} is the damage per cycle of type j, where d_c is given by;

$$d_c = \int_0^{t_h} \frac{\dot{\bar{\varepsilon}}_c}{\bar{\varepsilon}_f} dt \tag{5}$$

where t_h is the duration of the creep dwell, $\dot{\bar{\varepsilon}}_c$ is the instantaneous equivalent creep rate during the dwell and $\bar{\varepsilon}_f$ is the appropriate creep ductility (which should account for all factors affecting the ductility including aspects such as creep strain rate, stress magnitude, multi-axial stress state and temperature). It is noted that for the Evasion Tests, the ductility was assumed to be approximately constant for a given condition meaning the above equation simplifies to the accumulated creep strain in the cycle normalised to the creep ductility. It is also highlighted that Section 11.14 in R5 Volume 2/3 suggests that compressive dwells give no creep damage and, as such, provide D_c=0. There is still a need to include the additional strain range from the compressive creep in the calculation of D_f. For combined creep-fatigue loading the total damage factor, D, is simply $D = D_f + D_c$ and initiation of a defect (defined by the user but typically up to 10% of section thickness) is assumed when D>1.

As detailed for RCC-MRx above, a number of steps are taken to calculate the D_f and D_c terms. These are not detailed extensively below but a summary of the steps required for both a Simplified and more Complex methodology are included:

- Calculate the elastic stress and strain range. The elastic stress range is calculated in the same way as in RCC-MRx.
- Simplified Method for Calculating the Strain Range - When creep effects can be neglected or when the creep dwell is at the hysteresis loop tip (and the elastic follow-up is assumed to be low) Section 7.4.2

allows a simplified method to be used (as such, it is noted here that this method can be applied for these tests). It is, however, recognised that the approach may lead to overly conservative results and a further method has also been applied here (see below).

  - For this simplified method, the elastic stress range is increased by the additional stress from the creep dwell (here, although the dwell is compressive, it is enhancing the strain range and is, therefore, added to the range). This additional creep strain should be calculated as a worst case scenario by adopting an elastic follow-up factor, Z, of 1 for all conditions.
  - The total stress range is then calculated from the cyclic stress-strain curve where the corresponding elastic-plastic stress range, $\Delta\sigma$, is obtained from applying a Neuber correlation (Similar to RCC-MRx).
  - A volumetric correction is also calculated to account for the increased incompressibility of the material. Here, it is noted that the approach does differ slightly to that in RCC-MRx.
  - The total strain range used to determine the fatigue usage factor is then given by the elastic-plastic strain range plus the volumetric stain range.

- Complex Method for Calculating the Strain Range - For more complex scenarios, such as where the creep dwell is not at the peaks of the hysteresis curve, or when a less conservative result is desired a more detailed approach is included to define the strain range. For cases where the creep is insignificant, the approach is similar to the RCC-MRx approach such that this is just the summation of the elastic strain range, plastic strain range and volumetric strain. However, for the cases that include creep strains it is necessary to add the creep strain to the hysteresis loop construction.
  - Calculate the datum stress. Approaches to calculate the offset stress (termed datum stress) that is used to position the hysteresis loop are provided. If the load is sufficient to cause plasticity at both ends of the hysteresis loop, this is defined from the symmetrisation procedure, to provide equal extrusions above the materials yield stress both above and below the extremes of the hysteresis curve (if not, the datum is described by the minimum stress seen from where yielding is seen).
  - The approach in R5 then looks to split the hysteresis loop to the portion including and excluding the creep dwell (and the worse adopted for the strain range):
    - Half Excluding the Creep Dwell. This is calculated relatively simply as the elastic-plastic strain range plus the volumetric correction.
    - Half Including the Creep Dwell. Depending on the contribution of the creep (i.e. if it is tensile or compressive) the effect of creep on the stress range is considered when calculating the elastic-plastic strain range. The additional creep strain is also calculated and added (or subtracted depending on its position) to the elastic-plastic and volumetric strain range to provide the total strain range.

- Assessing Welds. When assessing a weld, the strain range (excluding the creep strain) is multiplied by a weld strain enhancement factor (WSEF) of 1.23 (Type 2) for the fillet weld and 1.16 for the seam weld (assumed to be Type 1). However, this is not applied to all components in the same way. For the simple approach, the application of a WSEF is not strictly applicable (as the creep strain is inherently included) but user interpretation has been applied to provide a similar response.
- Creep Strain Calculation. The approach to calculating the creep strain is similar to that in RCC-MRx. A value of Z is, however, not suggested but possible methods to estimate this are detailed in Appendix A8 of R5 Volume 2/3.

The start of dwell stress is clearly important in these calculations. The approach in the Complex Method automatically calculates the dwell stress as part of the hysteresis loop construction (as it also allows for intermediate dwells). The approach to calculate the dwell stress for the Simplified Method is less clear. Here, the dwell stress was calculated from a Neuber correction of the elastic peak stress value. It is noted that this approach is not part of R5 but uses the author's judgement to remain consistent with the complex method.

Comparison of Approaches

A summary of the approaches and the main differences is included in Table 1 below. As noted, two approaches within R5 have been applied but Table 1 is specific to the Complex Method. The simplified approach is not included in the above comparison explicitly as it shares many of the same characteristics as listed for R5 generally. For RCC-MRx, it is known that options for the inclusion of intermediate dwells are now included and reduced damage from compressive dwells are being considered in the next edition of the code (planned in 2022).

Table 1: Summary of main similarities and differences of the R5 and RCC-MRx assessment methods

	RCC-MRx	**R5**
Elastic stress/strain inputs	Stress range at the assessment location (not linearised).	Stress range at the assessment location (can be linearised).
Elastic stress/strain range	von-Mises equivalent range	von-Mises equivalent range
Elastic-plastic strain	Neuber construction	Neuber construction
Creep dwell position	At peak stress in basic approach (options for including intermediate dwells are available).	Any position (intermediate dwells allowed).
Creep strain	Relaxation equations	Relaxation equations or integrated forward creep equations.
Creep damage	Time fraction	Ductility exhaustion, in creep-fatigue assessment, no damage from compressive dwells. Time fracture in creep rupture assessment.
Fatigue	Fatigue curve	Fatigue curve
Weld Fatigue Properties	Modified WSEF	Modified for the potential presence of micro-defects.
Weld Creep Properties	Multiplication terms to rupture life provided.	Based on material specific ductility.
Weld Strain Enhancement Factors (WSEF)	WSEF of 1.25 for stainless steels. Some additional enhancements depending on inspect-ability of the weld.	Weld type specific WSEF (for Type I, II and III welds) of 1.16, 1.23 and 1.66 for stainless steels.
Weld Creep Enhancement Factors (WCEF)	WCEF $J_r \leq 1$ as a function of creep time and temperature	Creep damage calculated with enhanced stress including WSEF.

ASSESSMENT COMPARISON

Strain Range Calculation

The strain range calculations from the elastic input were performed for the Inside and Outside locations, respectively, when assuming both a primary and secondary creep strain response. This includes the elastic strain range, elastic-plastic strain range, creep strain, volumetric correction and total strain range. As detailed above, it is noted that each of these terms is applied in slightly different ways in each of the approaches considered and, as such some of these specific terms required additional calculation for the comparison here. This may mean that some of the parameters are not easily comparable and these comparisons should be taken with some caution; however, the influence on the final strain range can be seen clearly. For instance, the creep strain shown for the R5 Simplified approach is simply that which equates to the initial stress drop. However, the R5 Simplified approach calculates a combined inelastic strain, so it is not easy to separate the creep and plastic strain contribution to strain range. As such it is difficult to provide a direct estimate of the creep strain influence.

In these results the value of Z has been set to values of 1, 3 and 5 in the creep parts (noting this doesn't influence the Simple R5 prediction where Z = 1 is adopted). Some example results can also be seen plotted in Figure 3 for the inside location and Figure 4 for the outside location. Although not detailed here, an example of considering the option within RCC-MRx to consider the creep dwell away from the peak position would be to alter the RCC-MRx result for Z=3 in Cycle A, Figure 3, from 0.919 total strain range to 0.76, making this very similar to the Complex R5 approach.

An example of the equivalent results when considering a secondary creep strain response can be seen in Figure 5 for the equivalent case to Figure 3. For the RCC-MRx relation, only the creep strain and total strain range should change. In the R5 calculations the creep strain does not directly influence the elastic-plastic strain for the complex case, whereas the creep stress drop is included to the elastic strain range in the simplified approach, which then influences all other aspects. The effect of including the weld enhancement of WSEF factors on the results are shown for the primary creep law cases in Figure 6 (for the fillet radius equivalent case to Figure 3).

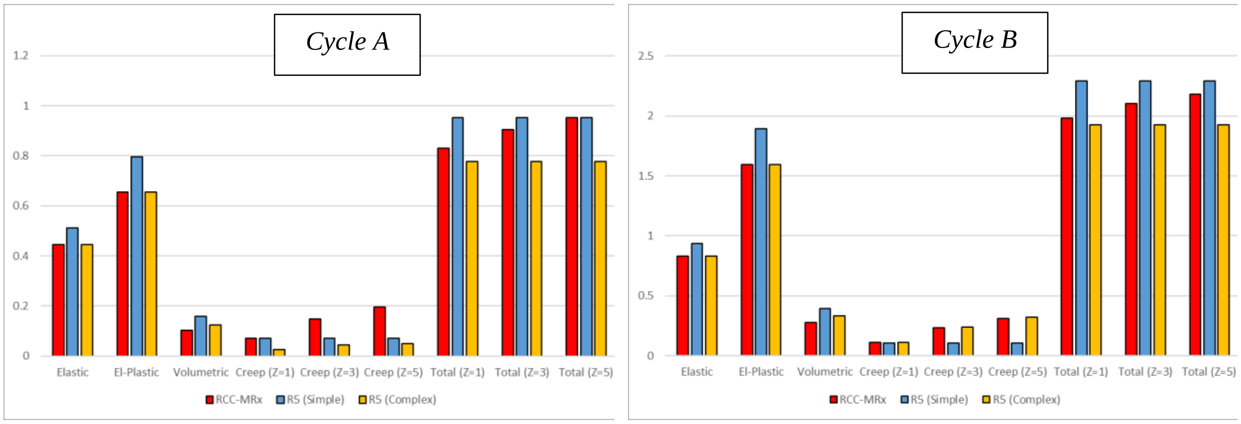


Figure 3. Calculated Strain Range Contributions for RCC-MRx (red), R5 Simple (blue) and R5 Complex (orange) at the Inside Surface with a Primary Creep Law and No Weld Correction.

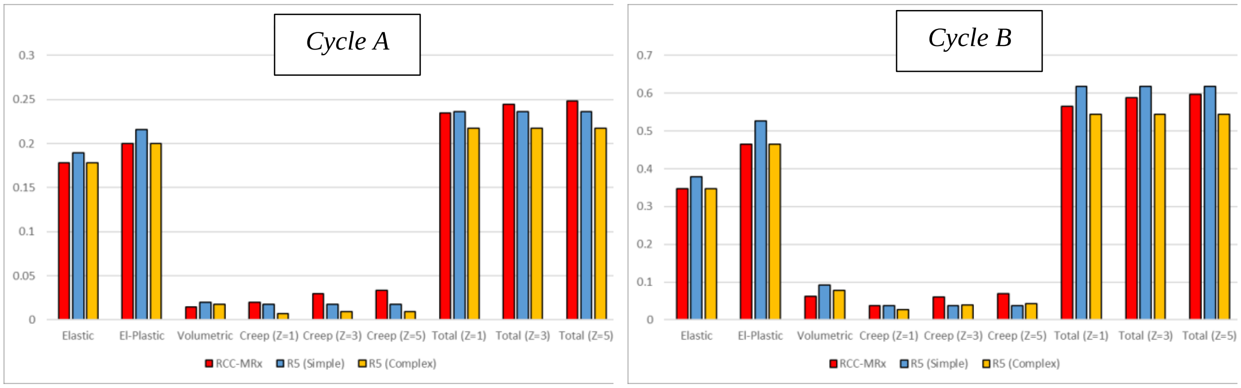


Figure 4. Calculated Strain Range Contributions for RCC-MRx (red), R5 Simple (blue) and R5 Complex (orange) at the Outside Surface with a Primary Creep Law and No Weld Correction.

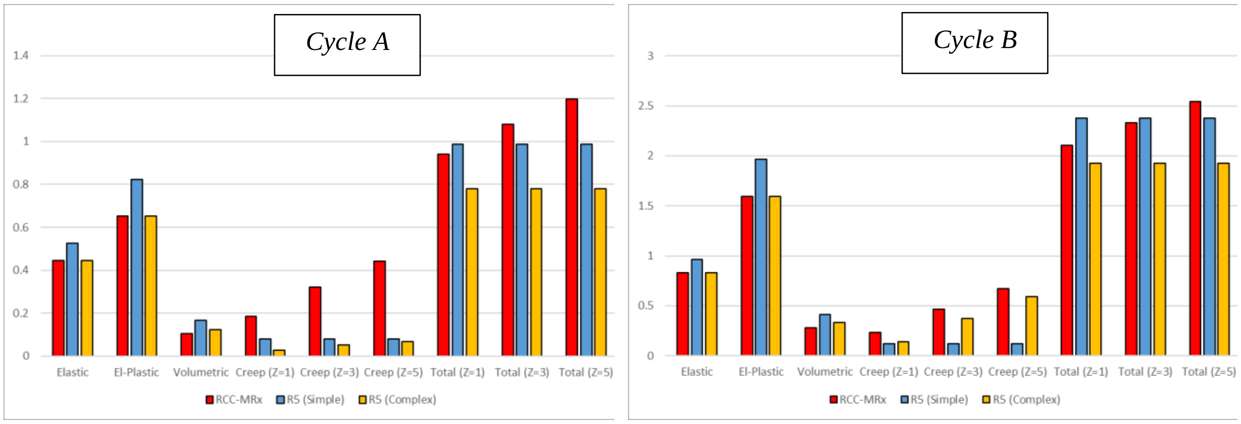


Figure 5. Calculated Strain Range Contributions for RCC-MRx (red), R5 Simple (blue) and R5 Complex (orange) at the Inside Surface with a Secondary Creep Law and No Weld Correction.

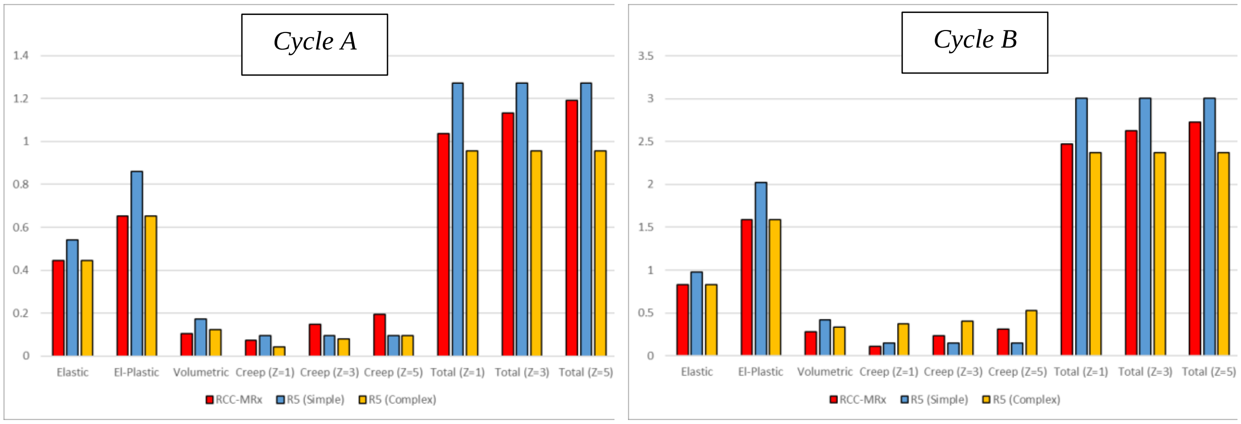


Figure 6. Calculated Strain Range Contributions for RCC-MRx (red), R5 Simple (blue) and R5 Complex (orange) at the Inside Surface with a Primary Creep Law with a Weld Correction (WSEF = 1.25 in RCC-MRx, WSEF = 1.23 in R5).

Hysteresis Loop Construction

An example of the calculated hysteresis loops for the primary creep law for the Inside Location under Cycle A can be seen in Figure 7 below (with Z=3). In these curves the location of the dwell is positioned to where the codes would include them, not necessarily to where it is during the test (basic analysis with RCC-MRx considers the dwell at the peak stress, optional intermediated dwells were not considered here). The clearest difference for these loops is the impact the amount of creep strain has on the strain range. The effect of symmetrisation can also be seen where the centre of the hysteresis loop is positioned to a stress, which may not be zero, that could then act to increase or decrease the stresses (and therefore the creep dwell stress) seen.

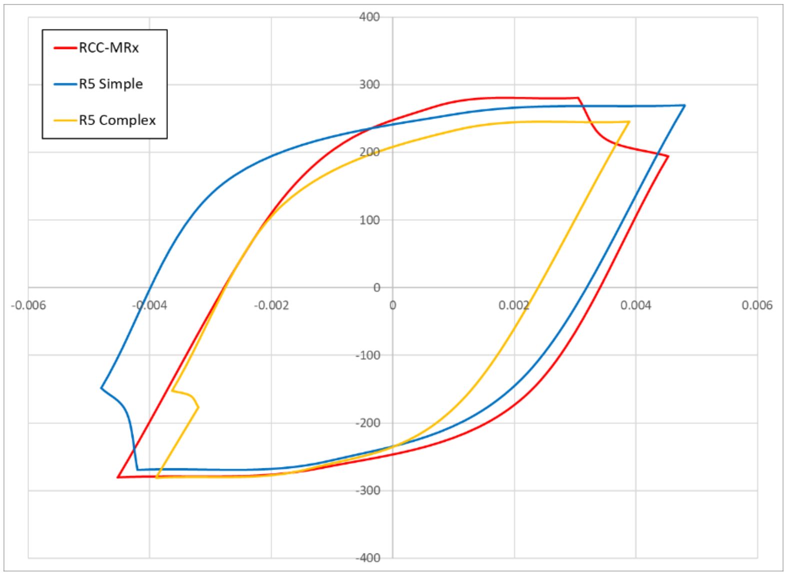


Figure 7. Hysteresis Curves for the Inside Location with Cycle A with a Primary Creep Law (Z=3 for RCC-MRx and R5 Complex, noting Z is set to 1 for the R5 Simple Case)

Damage Prediction

The predicted cycles to failure for each location has been evaluated with the different methods, values of Z, consideration of welds, and different mean and lower bound (design) curves. An example set of results for the primary creep law, with a mean fatigue curve when considering both the machined specimen (i.e. parent properties, no weld) and a case including the weld enhancement can be seen in Table 2 below. This provides an overview of the predicted number of cycles to failure for each transient type (for Cycle A and, then Cycle B after following the prior damage in Cycle A). Also shown is the creep and fatigue. The colours applied to the cycles to failure are also meant to indicate how well the results match the experimental observations for that case (where red is a conservative prediction, orange is within 250 cycles of observations and green is either matching or exceeding the observations (noting it is not possible to know when initiation exactly occurred). In the table, “*MRx*” denotes RCC-MRx, “*R5 S*” is the Simplified R5 approach and “*R5 C*” is the Complex R5 approach. Additional results denoted new MRx were obtained with the optional rules for intermediate dwells and reduced damage from compressive dwells, which will be introduced in the next edition of the code.

Table 2: Example Damage Predictions for Parent and Weld Cases with a Primary Creep Law

	Total Creep Damage						Total Fatigue Damage						Approximate Cycles to Failure					
Cycle	A			B			A			B			A			B		
Z =	1	3	5	1	3	5	1	3	5	1	3	5	1	3	5	1	3	5
Inside Surface (Parent)																		
MRx	0.86	3.73	6.67	11.03	>99	>99	0.71	0.94	1.09	3.54	3.96	4.24	596	253	161	0	0	0
new MRx	0.02	0.04	0.06	0.09	0.46	0.89	0.50	0.51	0.53	3.54	3.96	4.24	2789	2479	2280	123	78	54
R5 S	0.00	0.00	0.00	0.00	0.00	0.00	0.98	0.98	0.98	4.29	4.29	4.29	1524	1524	1524	4	4	4
R5 C	0.00	0.00	0.00	0.00	0.00	0.00	0.51	0.51	0.51	3.07	3.07	3.07	2957	2957	2957	161	161	161
Outside Surface (Parent)																		
MRx	0.08	0.15	0.19	0.13	0.34	0.45	0.00	0.00	0.00	0.10	0.12	0.13	19810	9724	7931	2460	1343	1067
new MRx	0.06	0.13	0.15	0.13	0.34	0.45	0.00	0.00	0.00	0.10	0.12	0.13	23300	11917	9908	2490	1388	1117
R5 S	0.44	0.44	0.44	0.69	0.69	0.69	0.00	0.00	0.00	0.14	0.14	0.14	3431	3431	3431	678	678	678
R5 C	0.25	0.30	0.32	0.59	0.87	0.98	0.00	0.00	0.00	0.08	0.08	0.08	6055	4922	4650	1133	734	642
Inside Surface (Weld)																		
MRx	6.23	22.12	35.54	16.94	>99	>99	1.37	1.72	1.93	5.19	5.72	6.06	159	57	37	0	0	0
new MRx	0.21	0.47	0.61	0.65	2.54	4.30	1.02	1.04	1.07	5.19	5.72	6.06	994	701	602	0	0	0
R5 S	0.00	0.00	0.00	0.00	0.00	0.00	1.90	1.90	1.90	6.27	6.27	6.27	790	790	790	0	0	0
R5 C	0.00	0.00	0.00	0.00	0.00	0.00	1.11	1.26	1.35	5.62	5.69	6.00	1345	1191	1114	0	0	0
Outside Surface (Weld)																		
MRx	0.79	1.49	1.78	0.99	2.27	2.94	0.00	0.00	0.00	0.27	0.31	0.32	1889	1006	842	128	0	0
new MRx	0.69	1.25	1.47	0.99	2.27	2.94	0.00	0.00	0.00	0.27	0.31	0.32	2181	1200	1021	194	0	0
R5 S	1.79	1.79	1.79	2.70	2.70	2.70	0.00	0.00	0.00	0.31	0.31	0.31	839	839	839	0	0	0
R5 C	1.00	1.33	1.43	2.17	3.53	4.11	0.00	0.00	0.00	0.19	0.23	0.25	1494	1125	1048	0	0	0

INTERPRETATION

Use of the Evasion Tests

The use of the Evasion Tests is useful in so much as they are well defined tests, which include a collection of null and positive results, for different cycles and weld conditions. Conversely, the cycles applied are significant in nature and do not meet the R5 pre-requisites (and likewise would not meet the RCC-MRx design criteria). This means that the approaches being applied here are unlikely to be applicable to these conditions and the varying results are not too surprising. However, it is argued that as the stresses are secondary in nature the effect of such high stresses, and the potential for ratcheting, are likely to be less significant.

General Observations

The different approaches are generally based on the same underlying methodology; to calculate a fatigue damage and a creep damage term. Here, the elastic input strain ranges are essentially the same. It also follows that the estimates of elastic-plastic strain ranges are similar for the RCC-MRx and R5 approaches (they essentially follow the same procedure). It was also noted that the creep strain calculations in RCC-MRx and R5 are similar when the start of dwell stress is in the same or a similar position (i.e. when this is at a stress peak). However, some small differences in the approaches can make a noticeable difference in the results even for these cases. For instance, the approach to symmetrisation and positioning of the creep dwell was seen to have an impact.

The volumetric strain is not too significant for any case considered. With the R5 simple approach, this is higher but is related to the initial elastic strain range being higher (when including the creep strain). However, there are some subtle differences in the values, even when the initial elastic strain and elastic-plastic stress are similar as there are differences in how this value is calculated. It is understood that this is a result of the R5 approach applying a full Neuber approach in calculating the secant stress whereas the RCC-MRx approach assumes pure displacement here (i.e. no increase in strain). As such, these differences are understandable and not thought to be of any significant concern.

The effect of primary creep versus secondary creep on the strain range is present and has a slight impact on the total strain range. The approaches generally exhibit an increase in the strain range for all cases when secondary creep is considered. The effect of changing the elastic follow-up, Z, on the results is clearly seen to change the predicted cycles to failure. Here the lower the value of Z the lower the damage per cycle and the longer before a crack is predicted. For the cases here, it is not sufficient to reduce Z to 1 and be able to reproduce the experimental observations, although this does seem to provide reasonable results for the mean material properties for a parent only case. Using lower-bound properties clearly provides significantly conservative lifetime predictions.

The different weld modification factors applied has a significant impact on the results as would be expected. With R5 providing different strain range enhancement factors (either 1.23 or 1.16 for the cases considered here) being applied to the two different weld types considered, whereas a single value is applied within RCC-MRx (1.25). The values applied in RCC-MRx and R5 are therefore similar for the fillet weld location considered here.

The effect of using the weld material properties and weld strain range modifications provides a conservative result in all cases. As noted below, there are aspects of the procedures which are inherently pessimistic and, when applied here, mean any additional consideration of weld enhancement or lower bound/design based properties are not representative (or at least overly conservative).

Conservatism

The general results conservatively predict the time to defect initiation when compared to the test observations. For the machined test specimen the predicted number of cycles to failure (note this is estimated by summing the total damage, which is not strictly correct for RCC-MRx, but serves as a useful way to compare here) is not unrealistically conservative (for a lower value of Z) and is generally close to the 1500 cycles seen without a defect. However, the impact of including the weld introduces more conservatism such that the results were seen to be very conservative.

Although not presented here, when the Neuber correction was removed from the assessment, i.e. assume displacement control, and Z=1 for the creep relaxation, more of the results are comparable to the experimental observations. This is seen where most of the assessment cases survive without a defect initiating for Cycle A and indicate that a defect will to initiate during in Cycle B. The results also indicate that, in general, the mean material properties with a Z=1 are closest for the different methods (but can overestimate the result). It is also noted that, here, a lower bound or design prediction would remain conservative to the experimental results. It is recognised that the Neuber plasticity correction assumes a relatively large amount of elastic follow-up due to plasticity, which should be conservative in most situations (note pre-requisite checks minimising the primary stresses is essential for this). Therefore it is not surprising that in this situation, when loading is due to thermal shock, that the Neuber plasticity correction over-predicts the amount of elastic follow-up due to plasticity. Therefore assuming no elastic follow-up due to plasticity (i.e. displacement control) or creep (i.e. Z=1) may be more representative for these tests, as the results suggest.

The approach in R5 to not include compressive creep damage appears to be reasonable from the results presented here. This is re-enforced by the observations of fatigue dominated cracks on the inside surface and creep dominated cracks on the external surface (with the weld). Following R5 methodology and Evasion results, the RCC-MRx rules will be modified in the next edition of the code (end of 2022) to take into account the improvements highlighted in this comparison.

Ease of Application

The RCC-MRx and Simplified R5 approaches are the simplest to apply. The Complex R5 approach is, however, more advanced than the other approaches but was seen to be less conservative and more representative, but can be more complex to apply.

CONCLUSIONS

This paper includes sensitivity studies such as assessing mean and lower bound properties and weld data compared to parent. Some of the more significant observations from the work were:

- The use of the Evasion Tests is useful in so much as they are well-defined tests that include a collection of null and positive results, for different cycles and weld conditions.
- The thermal shocks applied are significant and do not meet the R5 or RCC-MRx validity bounds. However, the methods still provide an appropriately conservative result.
- The different approaches adopt the same underlying principles. As such, the estimates of elastic-plastic strain ranges are similar for the RCC-MRx and R5, as are the creep strain calculations and approach to calculate creep strain.
- Some small differences in the approaches can make a noticeable difference in the results:
  - The approach to hysteresis loop positioning/symmetrisation provides some small difference in the peak stress and strain range.
  - R5 allows intermediate creep dwells whereas the basic RCC-MRx approach adopted here positioned this by default to the peak stress, which can significantly enhance the creep strain contribution. It is noted that there is a further approach, where intermediate dwells can be considered.
  - R5 does not include compressive creep damage; this appears to be reasonable here. It is understood that RCC-MRx 2022 will include this feature for elastic analysis.
  - RCC-MRx uses time exhaustion rule to predict failure, including safety margins, while R5 uses ductility exhaustion rule.
- Both methods are appropriately conservative and gave robust results for the creep and creep fatigue evaluations. The proposed changes to RCC-MRx also appear to be reasonable and provide results that are similar to those from R5.

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