A COMPARISON OF CREEP-FATIGUE ASSESSMENT AND MODELLING METHODS FOR GEN-IV NUCLEAR REACTOR STRUCTURAL COMPONENTS

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GEN-IV nuclear reactors – creep-fatigue

- In GEN-IV concepts the temperatures for several components are in the range where creep-fatigue interaction becomes an important issue.
- The ferritic-martensitic P91 steel and the austenitic stainless steel of the 316 type are candidate materials for several components of the GEN-IV nuclear reactors.
- ASTRID: French 1500 MW SFR prototype due to enter operation after 2020.
  - In line with the plan for a commercial GEN-IV reactor to be put in operation after 2040.

Overview of damage modes in a SFR (ASTRID)

- **Primary Vessel:**
  - T_{nom} : 395°C
  - Damage modes: Ratchetting, buckling, fatigue

- **ACS:**
  - T_{nom} : 545°C
  - Damage modes: Creep-fatigue, thermal stripping

- **Hot secondary circuit:**
  - T_{nom} : 525°C
  - Damage modes: Creep-fatigue, buckling

- **Steam Generator:**
  - T_{nom} : 525°C (Na) – 490°C (steam)
  - Damage modes: Excessive deformation, Ratchetting, creep-fatigue, Buckling
  - Tubes: corrosion and buckling

- **IHX:**
  - T_{nom} : 395-545°C
  - Damage modes: Ratchetting, buckling
  - Creep-fatigue

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Scope of study

- Creep-fatigue tests performed at VTT and test results from open literature for P91 steel and 316 stainless steel were evaluated using life fraction rule (with time fraction approach).
  - Test parameters: $\Delta \varepsilon = 0.36-1.00\%$, $T=550-600^\circ C$, $t_h=0-60\text{min}$
- Two different approaches were used: time fraction (TF) approach for "test result evaluation" without safety factors and TF approach for "design" according to the guidelines and safety margins described in the RCC-MRx code.
- The number of cycles to failure in creep-fatigue tests was predicted using life fraction rule approach and a creep-fatigue model recently developed at VTT (the $\Phi$-model).
Life fraction rule – time fraction approach

- Life fraction rule is a creep-fatigue assessment method utilized in nuclear codes (such as RCC-MRx, ASME III NH...).
- Unity for creep fraction ($D_c$) is time to rupture at defined temperature with specified stress.
- Unity for fatigue fraction ($D_f$) is the pure fatigue test result or curve point at defined temperature with equal strain range.
- For design purposes the allowable combined creep and fatigue damage for P91 steel in the RCC-MRx code is (0.3, 0.3) interaction locus.
- Allowable number of cycles ($N_f$) can be defined (in design) or number of cycles can be predicted (in test result evaluation) with following equations:

$$N_f = \begin{cases} \frac{D_c}{(1 - D_t)d_c + D_c d_f} & \text{if } d_c/d_c \geq D_t/D_c \\ \frac{D_f}{(1 - D_c)d_f + D_f d_c} & \text{if } d_c/d_c < D_t/D_c \end{cases}$$

where $d_c$ is the creep component of a single cycle and $d_f$ is the fatigue component of a single cycle.
Life fraction rule – time fraction approach

- Two different evaluation methods for life fraction was used for P91 steel: time fraction (TF) approach for "test result evaluation" and TF approach for "design" (RCC-MRx).
- Because SS 316 used in this study did not meet the requirements set for nuclear grade, only TF for "test result evaluation" was performed for that grade.
Determination of total strain range (Δε) for fatigue component $D_f$

**TF for "test result evaluation"**
- Published or measured value of the total strain range ($N_f/2$ cycle).

**TF for "design"**
- According to RCC-MRx: Section III - Tome 1 - Subsection B: RB 3000 – Design: RB 3262.1123: Elastic analysis + Amplification due to plasticity and creep ($N_f/2$ cycle).

\[
\Delta \varepsilon = \Delta \varepsilon_{el+pl} + \Delta \varepsilon_{fl}
\]
Calculating the total fatigue component $D_f$

**TF for "test result evaluation"

- Fatigue limit produced by the Manson-Coffin model fitted to public domain data.

\[ N_f = \left( \frac{\Delta \varepsilon - C_1}{C_2} \right)^\frac{1}{C_2} \]

**TF for "design"

- Fatigue limit according to RCC-MRx: Section III – Tome 1 – Subsection Z – Appendix A3.18AS: Properties Groups for products and parts in alloy steel grade X10CrMoVNB9-1 normalised - tempered or quenched – tempered: A3.18AS.47 – Fatigue curves.

<table>
<thead>
<tr>
<th>Number of cycles $N$</th>
<th>$20^\circ C$</th>
<th>$370\text{ - }450^\circ C$</th>
<th>$500^\circ C$</th>
<th>$525^\circ C$</th>
<th>$550^\circ C$</th>
<th>$600^\circ C$</th>
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<tbody>
<tr>
<td>20</td>
<td>3.57</td>
<td>3.3</td>
<td>3.06</td>
<td>2.78</td>
<td>2.1</td>
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<tr>
<td>40</td>
<td>2.04</td>
<td>1.65</td>
<td>1.7</td>
<td>1.53</td>
<td>1.17</td>
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<td>100</td>
<td>1.192</td>
<td>1.08</td>
<td>0.997</td>
<td>0.932</td>
<td>0.86</td>
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<tr>
<td>200</td>
<td>0.91</td>
<td>0.773</td>
<td>0.727</td>
<td>0.688</td>
<td>0.643</td>
<td>0.543</td>
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<tr>
<td>400</td>
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<td>0.577</td>
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<td>0.519</td>
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<td>$10^6$</td>
<td>0.547</td>
<td>0.48</td>
<td>0.46</td>
<td>0.442</td>
<td>0.421</td>
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<tr>
<td>$2 \times 10^6$</td>
<td>0.469</td>
<td>0.408</td>
<td>0.39</td>
<td>0.374</td>
<td>0.355</td>
<td>0.312</td>
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<tr>
<td>$4 \times 10^6$</td>
<td>0.396</td>
<td>0.346</td>
<td>0.33</td>
<td>0.316</td>
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<td>0.263</td>
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<tr>
<td>$10^6$</td>
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<td>0.278</td>
<td>0.265</td>
<td>0.254</td>
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<tr>
<td>$2 \times 10^6$</td>
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<td>0.235</td>
<td>0.225</td>
<td>0.216</td>
<td>0.206</td>
<td>0.182</td>
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<tr>
<td>$4 \times 10^6$</td>
<td>0.229</td>
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<td>0.168</td>
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<tr>
<td>$4 \times 10^6$</td>
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<td>0.126</td>
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<td>$5 \times 10^6$</td>
<td>0.128</td>
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<td>0.116</td>
<td>0.113</td>
<td>0.109</td>
<td>0.101</td>
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<tr>
<td>$10^6$</td>
<td>0.122</td>
<td>0.113</td>
<td>0.11</td>
<td>0.108</td>
<td>0.104</td>
<td>0.096</td>
</tr>
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</table>
Calculating the total creep component $D_c$

TF for "test result evaluation”

- The stress level at $N_f/2$ cycle taking the measured or published values of stress relaxation into account.
- The creep limit according to RCC-MRx: Appendix A3.18AS.53b: Average values of the creep rupture stress.

TF for "design”

- The stress level at $N_f/2$ cycle and the stress relaxation according to RCC-MRx: Section III - Tome 1 - Subsection B: RB 3000 – Design: RB 3262.1123 and A3.AS18.54: Creep strain rules.
- The creep limit according to RCC-MRx: Appendix A3.18AS.53a: Minimum values of the creep rupture stress.
The data points resided quite near the (0.3, 0.3) interaction locus using the TF for “test result evaluation” approach with CF tests with hold periods from 0 to 60 min (fatigue dominated).

- Will this hold true also for tests with significantly longer hold periods (creep dominated)?
- The data points exceeded the (0.3, 0.3) interaction locus by orders of magnitude using the TF for “design” approach (RCC-MRx).
- This procedure is not appropriate for evaluating these kind of tests?
A conservative evaluation was also performed so that the stress relaxation was not taken into account.

The stress relaxation has strong impact on the creep component $D_c$ for tests with relatively high stress levels and considerable relaxation.

For test with lower stress levels and stress relaxation the effect on $D_c$ is not so significant.
Creep-fatigue life modelling: the $\Phi$-model

- A creep-fatigue model by VTT, which predicts the creep-fatigue life as a function of temperature, strain range and hold period.
- The model utilizes UTS and creep rupture strength of the material in question.

Measured $\Phi$: $\sigma_{\text{ref}}$ is the stress level with which the time to rupture (in creep) equals the sum of hold periods in CF-test.

$$\Phi = \sigma_{\text{ref}} / \sigma_{\text{UTS}}$$

Modelled $\Phi$: The parameters $c_1$-$c_4$ are fitted so that the measured $\Phi$ equals modelled $\Phi$ using as large data set as possible.

The "creep-fatigue time" can then be calculated with the modelled $\Phi$:

$$t_{\text{CP}}(\Delta \varepsilon, t_h, T) = -\frac{\ln(\Phi(\Delta \varepsilon, t_h, T))}{k} \cdot \exp\left(\frac{Q}{R \cdot T}\right)$$

And cycles to failure:

$$N_f(\Delta \varepsilon, t_h, T) = \frac{t_{\text{CP}}(\Delta \varepsilon, t_h, T)}{t_h}$$

Where $t_h$ is the duration of creep-fatigue hold period.
Creep-fatigue life modelling: the $\Phi$-model

- The $\Phi$-model predicted the number of cycles to failure with a scatter factor of 2.94 for multi-heat data set consisting of 53 data points (P91).

$\text{LOG}(N_f)$ is the logarithmic value of number of cycles to failure.

$$Z = 10^{2.5\sqrt{\frac{\sum(\text{LOG}(N_{pred})-\text{LOG}(N_{meas}))^2}{n-1}}}$$

Comparizon: the Φ-model vs. TF for test result evaluation

- P91 material from two different heats.
- The Φ-model predicted the number of cycles to failure with a scatter factor of 2.29.
- The TF for "test result evaluation" predicted the number of cycles to failure with a scatter factor of 4.06.
Conclusions (1/2)

- Using the TF approach for "test result evaluation" the data points resided near the (0.3/0.3) interaction locus in the life fraction rule plot, for both P91 and 316L with short hold periods (0-60min).
  - Will this hold true also for tests with significantly longer hold periods (creep dominated)?
- All evaluated P91 creep-fatigue test results using the RCC-MRx procedure resided well above the interaction locus of (0.3/0.3) in the life fraction rule plot.
  - Creep-fatigue test with significantly longer hold periods may be more suitable for evaluating the procedure and safety margins of the RCC-MRx code.
Conclusions (2/2)

- For the P91 data set that included sufficient relaxation data for the time fraction approach assessment, the Φ-model successfully predicted the number of cycles to failure with a scatter factor of 2.29. The same data set predicted with the time fraction approach gave a scatter factor of 4.06.

- For the larger combined multi-heat P91 data set (53 data points) the Φ-model predicted the creep-fatigue life within a scatter factor of 2.94 at 99% confidence.
Acknowledgements

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Thank you for your attention!

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