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High Temperature Creep-Fatigue Structural Design Criteria for EUROFER 97 and its Weld Joints

Final Report
TW6-TTMS-005, D3

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Institut für Materialforschung
Programm Kernfusion
Association Forschungszentrum Kalrsruhe / EURATOM

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Hochtemperatur-Auslegungsregeln für Kriech-Ermüdung von EUROFER 97 und seine Schweißverbindungen

Zusammenfassung

Die Hochtemperaturregeln für Kriech-Ermüdung, die im Rahmen von TW5-TTMS-005 (D7) für die Bewertung von aus EUROFER 97 als Basismaterial gefertigten Bauteilen formuliert wurden, wurden zur Bewertung von EUROFER 97-Schweißverbindungen erweitert. Dabei wurden im Wesentlichen die Richtlinien des ASME Codes für die Betrachtung von Schweißverbindungen befolgt. Zur Verifikation der erweiterten Regeln wird darüber hinaus ein umfangreiches Versuchsprogramm vorgeschlagen.

Abstract

The high temperature creep-fatigue design rules, which had been formulated within TW5-TTMS-005 (D7) for the assessment of components built from EUROFER 97 base metal, have been extended for the assessment of EUROFER 97 welding joints. Thereby the guide-lines of the ASME Code for the consideration of welds are followed. For the verification of the extended rules a comprehensive test program is recommended in addition.

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1 Introduction

The reduced activation ferritic martensitic (RAFM) steel EUROFER 97 developed recently in the framework of EURATOM Fusion Technology programme is a potential candidate as a structural material for in-vessel components of future fusion power plants [1]. During planed operation structural materials of in-vessel plasma facing components, blanket and divertor, are subjected to cyclic thermo-mechanical loading and high irradiation doses which yield different types of lifetime limiting failure mechanisms: ratchetting, creep, fatigue and radiation induced loss in ductility and toughness.

Within our activities in the EFDA Technology Work programme with the reference TTMS-005 “Rules for Design, Fabrication and Inspection” structural design criteria for components built from EUROFER 97 will be developed and qualified. Our investigations are focused on high temperature rules, particularly those for preventing creep, fatigue and creep/fatigue interaction, not yet considered and implemented in the current ITER Structural Design Criteria for In-Vessel Components (SDC-IC) [2]. Therefore we developed and formulated high temperature creep-fatigue design rules for the assessment of components built from EUROFER 97 on the base of the current design codes well established for nuclear applications: ASME Boiler and Pressure Vessels Code and the French RCC-MR code [3]. These rules have been extended within the task reported here to assess EUROFER 97 welding joints (TIG, EB, laser diffusion welds) foreseen in the current designs of blanket and divertor. The extension has been done mainly following the guidelines of the ASME Boiler and Pressure Vessels Code, code case N-47-29 for the consideration of welds.

In this report, the creep-fatigue evaluation rules for EUROFER 97 and its welds are presented as they can be recommended on the base of the knowledge gathered so far. Since further verifications are still required they maintain thitherto their draft status. However, to establish the rules verification experiments, particularly on welds, are recommended as an outlook.

2 Creep-fatigue evaluation rules for EUROFER 97 and its Welds

2.1 Damage equation

To accept a design subjected to service loadings yielding creep and fatigue damage, including hold time and strain rate effects, the linear summation of fatigue and creep damage shall not exceed the allowable total creep-fatigue damage D' satisfying the following relation:

$$\sum_{j=1}^{p}\left(\frac{n}{N_d}\right)_j+\sum_{k=1}^{q}\left(\frac{\Delta t}{T_d}\right)_k\leq D' \qquad (2.1)$$

where

p = number of different cycle types required to define the cyclic strain history for the specified service life. Each cycle type is uniquely defined by its equivalent mechanical strain range $\Delta\varepsilon$ and the maximum material temperature occurring during the cycle.

$(n)_{\mathrm{j}}$ = number of applied repetitions of cycle type j.

$(N_d)_{\mathrm{j}}$ = number of design allowable cycles for cycle type j determined from one of the design fatigue curves corresponding to the maximum material temperature occurring during the cycle. The design fatigue curves were determined from completely reversed loading conditions at strain rates greater than, or equal to those noted on the curves.

q = number of time intervals (each with a unique stress-temperature combination) needed to represent the specified elevated temperature service life at the point of interest for the creep damage calculation.

$(T_d)_{\mathrm{k}}$ = allowable time duration determined from stress-to-rupture curves for a given stress and the maximum temperature at the point of interest and occurring during the time interval k. For inelastic analysis the following equivalent stress quantity should be used

$$\sigma_e = \alpha_1 \sigma_I + \alpha_2 J_1 + \alpha_3 \bar{\sigma} \text{ ………………..RCC-MR} \qquad (2.2)$$

Where

$$\sigma_I = \max(\sigma_1, \sigma_2, \sigma_3)$$

$$J_1 = \sigma_1 + \sigma_2 + \sigma_3$$

$$\bar{\sigma} = \frac{1}{\sqrt{2}}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2\right]^{1/2}$$

and σ_{i} are the principal stresses. The constants α_1, α_2, and α_3 in equation 2.2 are material dependent (equal 1.0, 0.0 and 0.0, respectively, for EUROFER 97). The allowable time duration is determined by entering the stress-time to rupture curves at that stress value determined by dividing the maximum equivalent stress (at the point of interest during the time interval k) by the factor K' which is in general material dependent. However K' is specified as constant for EUROFER 97 equal 0.9.

$(\Delta t)_k$ = duration of the time interval k. The sum of the q time intervals must equal or exceed the total specified elevated temperature service life.

For the evaluation of the fatigue damage portion of any cycle type j, first term in equation 2.1, the equivalent mechanical strain range and the material specific design fatigue curves are required. The equivalent mechanical strain range shall be determined as described in section 2.2. In addition, to determine the creep damage fraction the material specific stress-to-rupture curves are necessary. Finally for the examination of 2.1 the material specific values of the allowable total creep-fatigue damage D' should be known.

2.2 Equivalent mechanical strain range

The equivalent mechanical strain range $\Delta\varepsilon$ is defined equal $\Delta\varepsilon_{\max}$ which is computed as follows:

Step 1. Calculate all mechanical strain components for each point i in time (ε_{11i}, ε_{22i}, ε_{33i}, ε_{12i}, ε_{23i}, ε_{31i}) for the complete cycle.

Step 2. Select a point when conditions are at an extreme for the cycle, either maximum or minimum. Refer to this time point by a subscript o.

Step 3. Calculate the history of the change in strain components by subtracting the values at the time o from the corresponding components at each point in time i during the cycle.

$$\Delta\varepsilon_{11i} = \varepsilon_{11i} - \varepsilon_{11o}$$
$$\Delta\varepsilon_{22i} = \varepsilon_{22i} - \varepsilon_{22o}$$
$$etc;$$

Step 4. Calculate the equivalent strain range for each point in time as:

$$\Delta\varepsilon_{eq.i} = \frac{\sqrt{2}}{2(1+\upsilon^*)}\Big[\left(\Delta\varepsilon_{11i} - \Delta\varepsilon_{22i}\right)^2 + \left(\Delta\varepsilon_{22i} - \Delta\varepsilon_{33i}\right)^2 + \left(\Delta\varepsilon_{33i} - \Delta\varepsilon_{11i}\right)^2 + 6\left(\Delta\varepsilon_{12i}^2 + \Delta\varepsilon_{23i}^2 + \Delta\varepsilon_{31i}^2\right)\Big]^{1/2} \qquad (2.3)$$

where

$\upsilon^* = 0.5$ when using the rules in inelastic analysis

$\upsilon^* = 0.3$ when using the rules in elastic analysis

Step 5. Define $\Delta\varepsilon_{\max}$ as the maximum value of the above calculated equivalent strain ranges $\Delta\varepsilon_{eq.i}$

2.3 Design fatigue curves

The design fatigue curves (mechanical strain range $\Delta\varepsilon$ vs. number of allowable cycles N_d) for EUROFER 97 are given by the following formula

$$\Delta\varepsilon = \min\left\{0.5\left(b_1 + b_2\left(c_{w,f}N_d\right)^{b_3}\right), b_1 + b_2\left(20 * c_{w,f}N_d\right)^{b_3}\right\} \tag{2.4}$$

with $c_{w,f}$ equal 1 for the base metal and 2 for the welds. The values of the temperature dependent parameters b_1, b_2 and b_3 are listed in Table 2-1. In Figure 2-1 and Figure 2-2 the design fatigue curves obtained accordingly for EUROFER 97 base metal and EUROFER 97 welds are plotted, respectively.

Table 2-1: Parameters of equation 2.4 determined for EUROFER 97

Temperature in °C	b_1	b_2	b_3
20	3.84×10^{-3}	0.555	-0.600
450	3.84×10^{-3}	0.363	-0.597
550	3.2×10^{-3}	0.307	-0.566

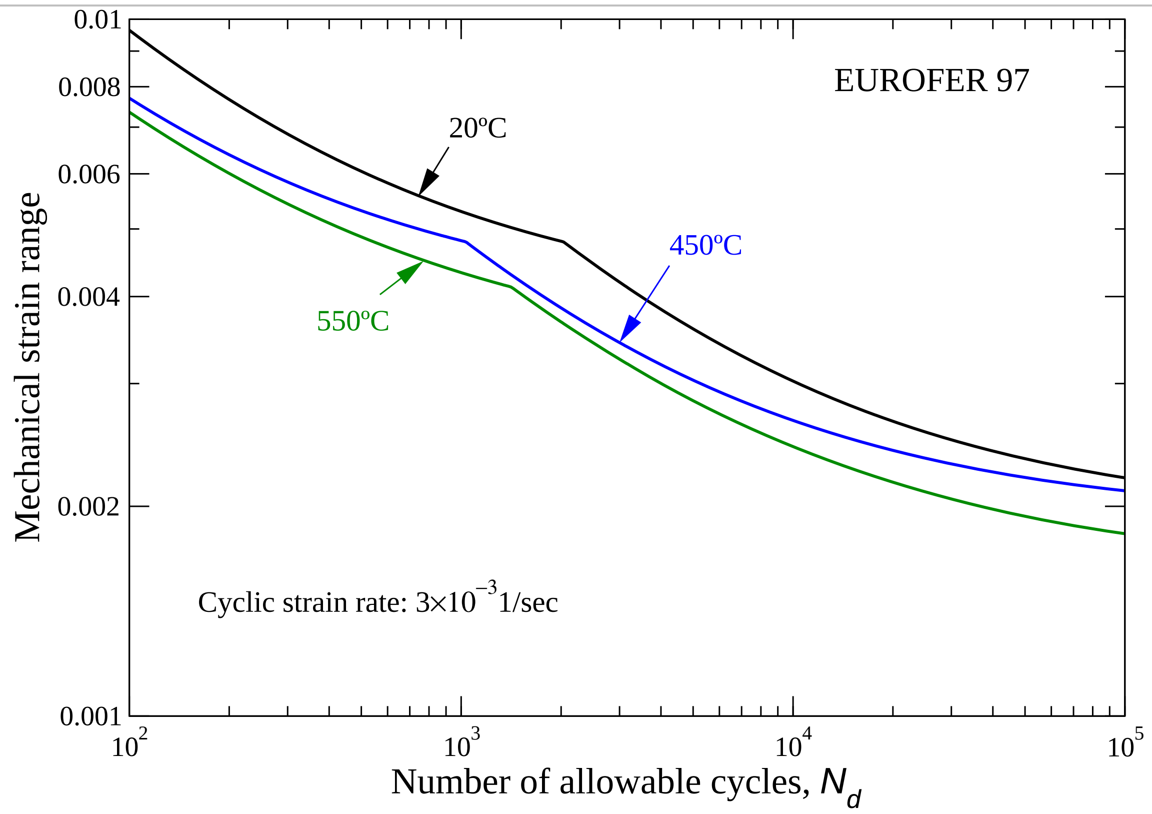

Figure 2-1 Design fatigue curves for EUROFER 97 base metal

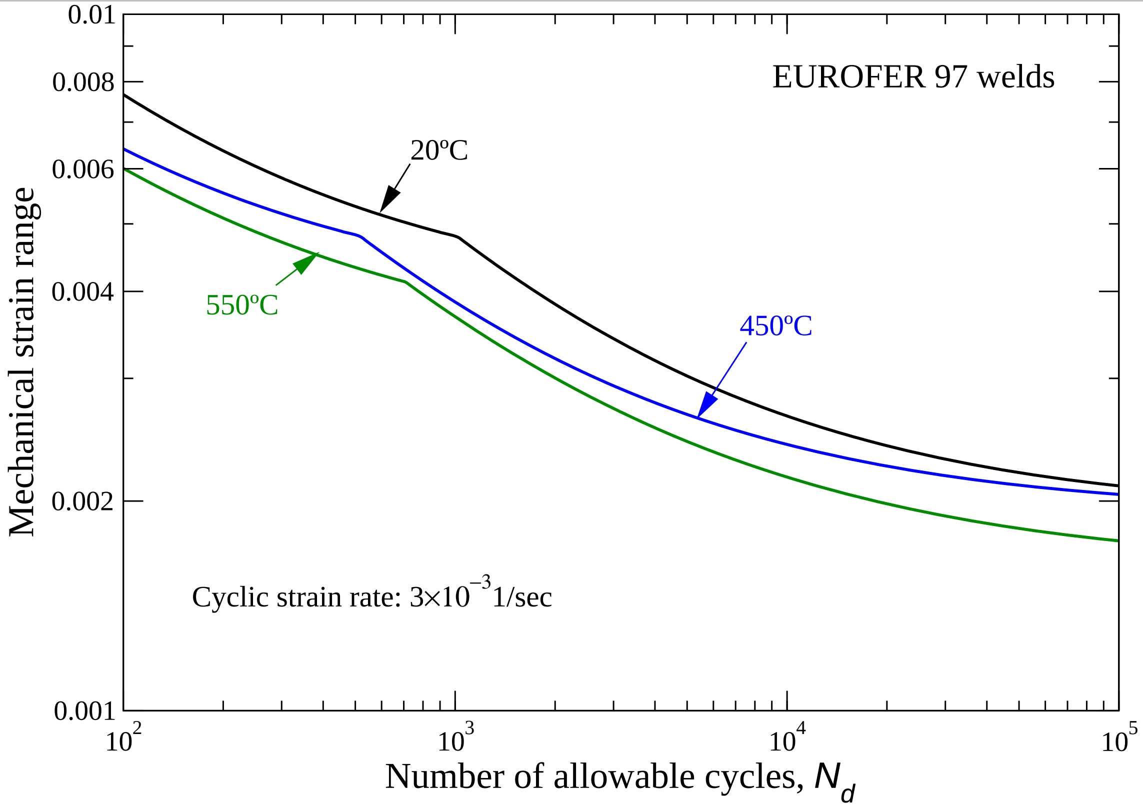

Figure 2-2 Design fatigue curves for EUROFER 97 welds

2.4 Stress-to-rupture curves

The stress-to-rupture curves are given by the following relation between the minimum stress value S_r and the Larson-Miller-Parameter P (S_r in MPa)

$$S_r = c_{w,c}\left(1936 - 88.452P + 0.888324P^2\right) \tag{2.5}$$

with $c_{w,c}$ equal 1 for the base metal and 0.8 for the welds. The Larson-Miller-Parameter P is determined as

$$P = \left(30 + \log(T_d)\right) * (\theta + 273)/1000$$

with T_d and θ denoting the allowable time in h (hours) and the temperature in °C, respectively. Figure 2-3 and Figure 2-4 shows the stress-to-rupture curves of EUROFER 97 base metal and EUROFER 97 welds, respectively, determined using equation 2.5 for different temperatures.

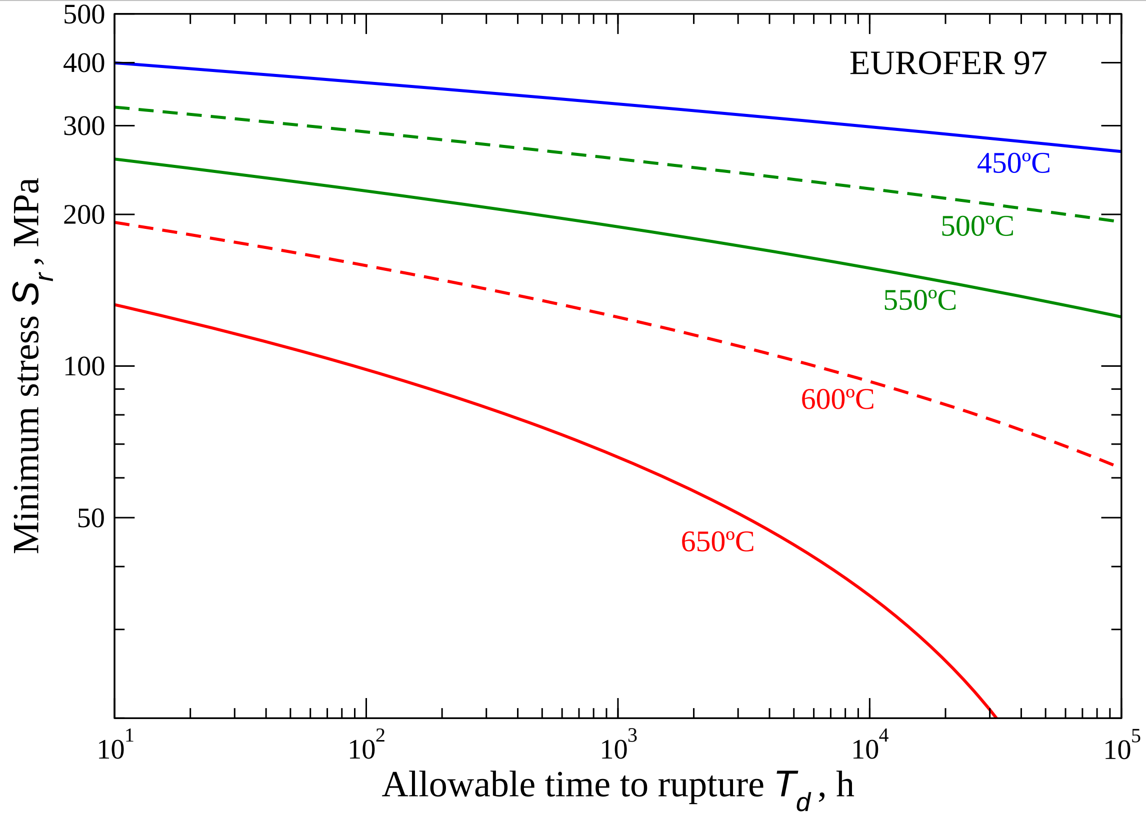

Figure 2-3 Stress-to-rupture curves for EUROFER 97

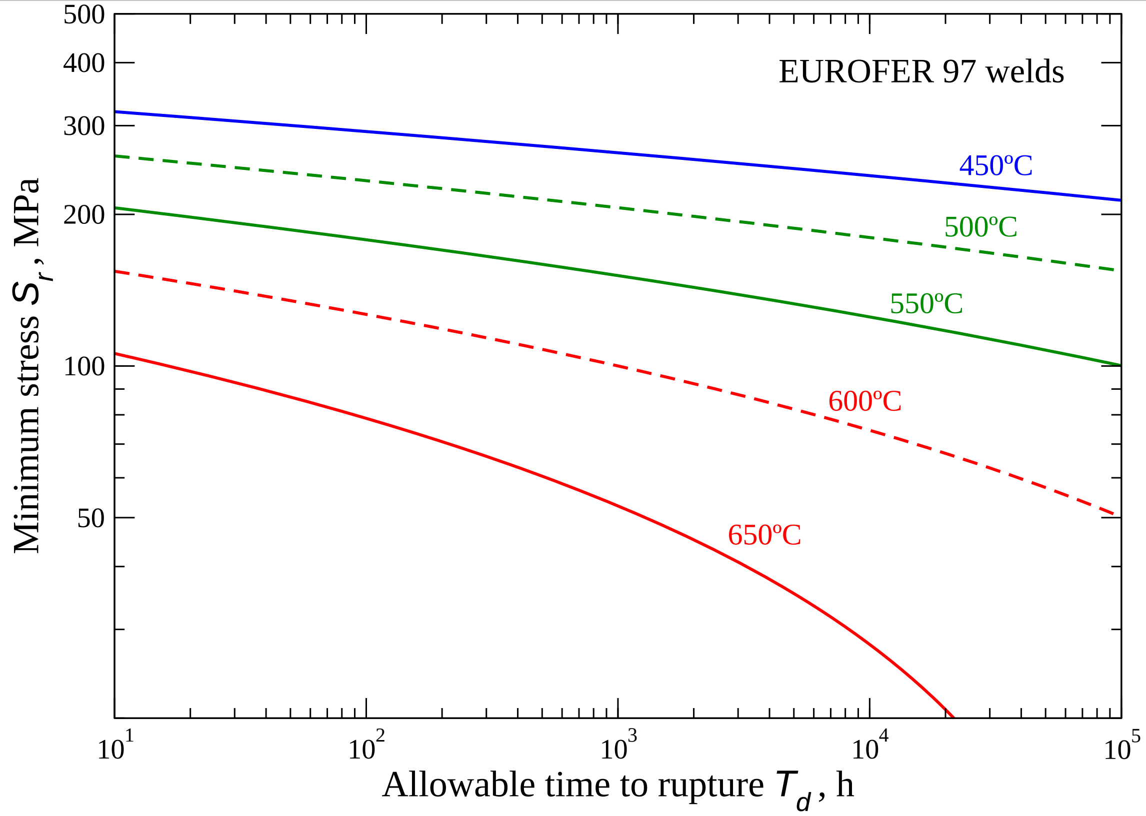

Figure 2-4 Stress-to-rupture curves for EUROFER 97 welds

2.5 Allowable total creep-fatigue damage

Taking into account nonlinear damage accumulation effects the allowable total creep-fatigue damage is not specified as constant equal to 1 but as a variable dependent on the creep and fatigue damage fractions, respectively. The dependence is given graphically in the form of a creep-fatigue interaction envelope, which shall not be exceeded by the sum of creep and fatigue damage fractions (left side in equation 2.1). This envelope is material specific and has to be derived on the base of experiments with variable creep and fatigue damage fractions. It assigns the minimums obtained for linear sums of creep and fatigue damage fractions calculated as specified on the left side of equation 2.1. Figure 2-5 gives the creep-fatigue interaction envelope for EUROFER 97 and its welds.

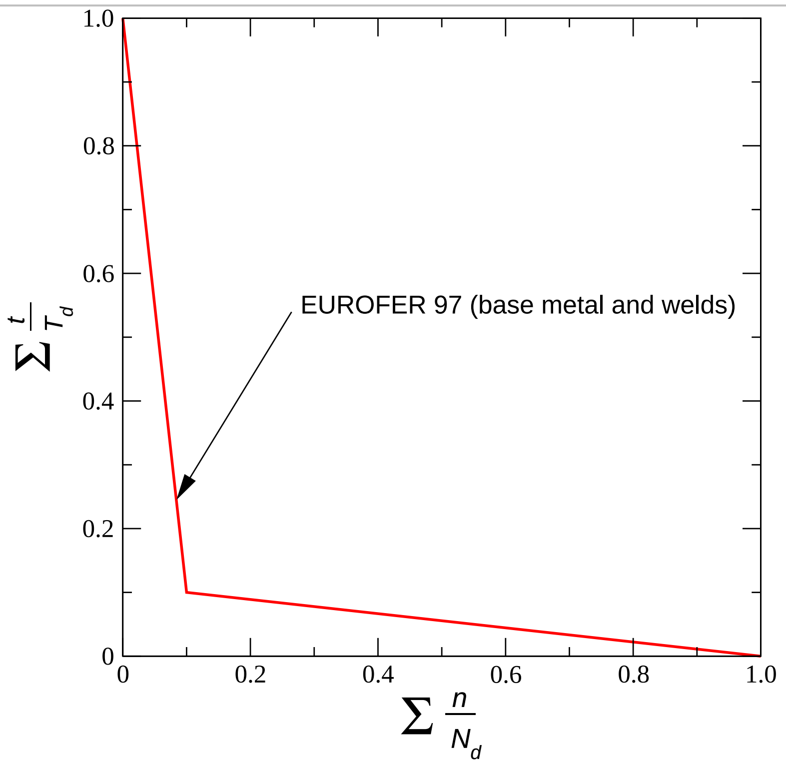

Figure 2-5 Creep-fatigue damage envelope for EUROFER 97 and its welds

3 Outlook

The creep-fatigue evaluation rules formulated above can be used now to assess components built from EUROFER 97 as well as EUROFER 97 welding joints. However, the qualification of the rules for this task needs in addition to the verifications done so far (see in [3]) further verifications for which numerous verification experiments have to be conducted. The following verification experiments are recommended:

- On EUROFER 97 base metal
    - Isothermal multiaxial fatigue tests with high loading amplitudes

  - ➢ Isothermal LCF tests with long dwell periods (up to hours) to verify the allowable creep fatigue summations
  - ➢ Thermo-mechanical fatigue tests on different specimen geometries to investigate deformation localisation effects
  - ➢ A benchmark experiment on a mockup built from EUROFER 97 and tested under thermo-mechanical multiaxial creep fatigue conditions
  - ➢ Round robin testing between different partners

- On EUROFER 97 welds
  - ➢ Isothermal LCF tests without and with dwell periods (up to hours)
  - ➢ Thermo-mechanical fatigue tests
  - ➢ Isothermal multiaxial fatigue tests
  - ➢ Round robin testing between different partners

  to verify the design fatigue curves for welds and the allowable creep fatigue summations.

4 Acknowledgment

This work, supported by the European Communities under the contract of Association between EURATOM and Forschungszentrum Karlsruhe, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

5 IP reporting

All the works provided under the present task were according to the current state-of-the art. No foreground IPR has been produced under this task. All information from involved external companies and sub-contractors is open and available, and no confidentiality or license agreement was signed. No invention or software development has to be declared.

6 References

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[2] ITER Structural Design Criteria for In-Vessel Components (SDC-IC), G 74 MA 8 01-05-28 W 0.2.

[3] J. Aktaa, M. Weick & M. Walter, "High temperature creep-fatigue structural design criteria for fusion components built from EUROFER 97," *Wissenschaftliche Berichte des Forschungszentrums Karlsruhe*, FZKA-7309, August 2007.