EUROFUSION WPMAT-PR(16) 14580

M. Mahler et al.

ANSYS creep-fatigue assessment tool for EUROFER97 components

Preprint of Paper to be submitted for publication in
Nuclear Materials and Energy

ANSYS creep-fatigue assessment tool for EUROFER97 components

M. Mahler*, F. Özkan and J. Aktaa
Karlsruhe Institute of Technology (KIT), Institute for Applied Materials, 76344 Eggenstein-Leopoldshafen, Germany

Abstract

The damage caused by creep-fatigue is an important factor for materials at high temperatures. For in-vessel components of fusion reactors the material EUROFER97 is a candidate for structural application where it is subjected to irradiation and cyclic thermo-mechanical loads. To be able to evaluate fusion reactor components reliably, creep-fatigue damage has to be taken into account. In the frame of Engineering Data & Design Integration (EDDI) in EUROfusion Technology Work Programme rapid and easy design evaluation is very important to predict the critical regions under typical fusion reactor loading conditions. The presented Creep-Fatigue Assessment (CFA) tool is based on the creep-fatigue rules in ASME Boiler Pressure Vessel Code (BPVC) Section III Division 1 Subsection NH which was adapted to the material EUROFER97 and developed for ANSYS. The CFA tool uses the local stress, maximum elastic strain range and temperature from the elastic analysis of the component performed with ANSYS. For the assessment design fatigue and stress to rupture curves of EUROFER97 as well as isochronous stress vs. strain curves determined by a constitutive model considering irradiation influence are used to deal with creep-fatigue damage. As a result allowable number of cycles based on creep-fatigue damage interaction under given hold times and irradiation rates is obtained. This tool can be coupled with ANSYS MAPDL and ANSYS Workbench utilizing MAPDL script files.

**E-mail: Michael.Mahler@kit.edu, Phone:0049 721 608 28388*

Highlights

- Creep-Fatigue Assessment (CFA) tool to identify EUROFER97 damage of complex 3D geometry
- CFA tool based on creep-fatigue rules of ASME BPVC
- Integrated in ANSYS MAPDL and Workbench as a post-processing tool
- Identification of the most critical region in the component

Keywords

- Creep damage
- Fatigue damage
- ASME BPVC
- EUROFER97

Nomenclature

n	number of applied repetitions	[-]
N_d	number of design allowable cycles	[-]
t	duration	[s]
T_d	allowable time duration	[s]

D	total damage	[-]
$\Delta\varepsilon_t$	total strain range to determine number of design allowable cycles	[-]
K_v	Multiaxial plasticity and poisson ratio adjustment factor (see ASME BPVC)	[-]
$\Delta\varepsilon_{mod}$	modified maximum equivalent strain range	[-]
K	local geometric concentration factor	[-]
$\Delta\varepsilon_c$	creep strain increment	[-]
$\Delta\varepsilon_{max}$	maximum local equivalent strain range from elastic analysis	[-]
S^*	stress indicator determined at $\Delta\varepsilon_{max}$ (see ASME BPVC)	[MPa]
S_m	allowable stress	[MPa]
$\Delta\sigma_{mod}$	modified stress range at $\Delta\varepsilon_{max}$ (see ASME BPVC)	[MPa]

Abbreviations

BPVC	**B**oiler **P**ressure & **V**essel **C**ode
CFA	**C**reep-**F**atigue **A**ssessment
EDDI	**E**ngineering **D**ata & **D**esign **I**ntegration
MAPDL	**M**echanical **A**NSYS **P**arametric **D**esign **L**anguage
TBM	**T**est **B**lanket **M**odule

Introduction

The creep-fatigue evaluation based on the rules in ASME Boiler Pressure Vessel Code (BPVC) [1] is often used to identify creep and fatigue damage. The procedure mentioned in ASME BPVC was adapted to the material EUROFER97 and implemented in a program written in FORTRAN named Creep-Fatigue Assessment (CFA) tool [2]. This tool uses the following failure criterion of ASME BPVC:

$$\sum\left[\frac{n}{N_d}\right]+\sum\left[\frac{t}{t_d}\right]\leq D \tag{1}$$

The first part on the left side of equation (1) represents the fatigue damage with the number of applied repetitions n and the number of design allowable cycles N_d for the specific cycle type. The second part on the left side shows the creep damage with the duration t and the allowable time duration t_d for a specific time interval. On the right hand side of the equation the variable D is the allowable total damage in case of creep-fatigue interaction which is not constant. The damage D is given by a creep-fatigue damage envelope as bi-linear curve [1]. The CFA tool is able to identify the design allowable numbers of cycles, the creep and the fatigue damage fraction on a defined path which is picked by two nodes in ANSYS MAPDL. Özkan & Aktaa [3] used this tool on complex test blanket module (TBM) of future fusion reactor components [4] to evaluate the creep and fatigue damage on specific paths using ANSYS MAPDL post-processing of thermo-mechanical elastic analysis. In addition they extended the CFA tool to consider irradiation effects into account [5]. Now the present paper shows how the most critical path can be identified in ANSYS MAPDL as well as in ANSYS Workbench using an extension of this CFA tool.

Approach of CFA tool

The approach which is shown in Figure 1 is based on Özkan & Aktaa [2]. Now this approach is extended to be able to automatically identify the most critical path. Therefore a region of interest has to be defined in ANSYS MAPL or Workbench, respectively. One region must be on the inner and one on the outer surface of the component. Based on this selection the attached nodes are extracted to create paths for stress linearization and to identify the elastic strain range based on the thermal and the two structural analysis (primary loads and primary + secondary loads). With this data the requirements for ratcheting rules according to ASME BPVC are checked. To identify the allowable numbers of cycles and the fatigue damage the total strain range must be calculated [1] for each path:

$$\Delta\varepsilon_t = K_v\Delta\varepsilon_{mod} + K\Delta\varepsilon_c \text{ with } \Delta\varepsilon_{mod} = \frac{K^2\Delta\varepsilon_{max}S^*}{\Delta\sigma_{mod}} \tag{2}$$

For this total strain range $\Delta\varepsilon_t$ the values for $\Delta\varepsilon_{mod}$, $\Delta\varepsilon_c$ and $\Delta\sigma_{mod}$ are calculated using among others the constitutive model under cyclic loading of EUROFER97 at high temperatures [6] including irradiation effects [7]. Considering only the elastic strain range $\Delta\varepsilon_{max}$ from finite element analysis instead of the total strain range $\Delta\varepsilon_t$ is underestimating the creep-fatigue damage. In addition the design fatigue curves [8] and the isochronous stress vs. strain curves [2] are necessary to identify the total strain range. Based on this total strain range the allowable number of cycles based on fatigue damage can be calculated.

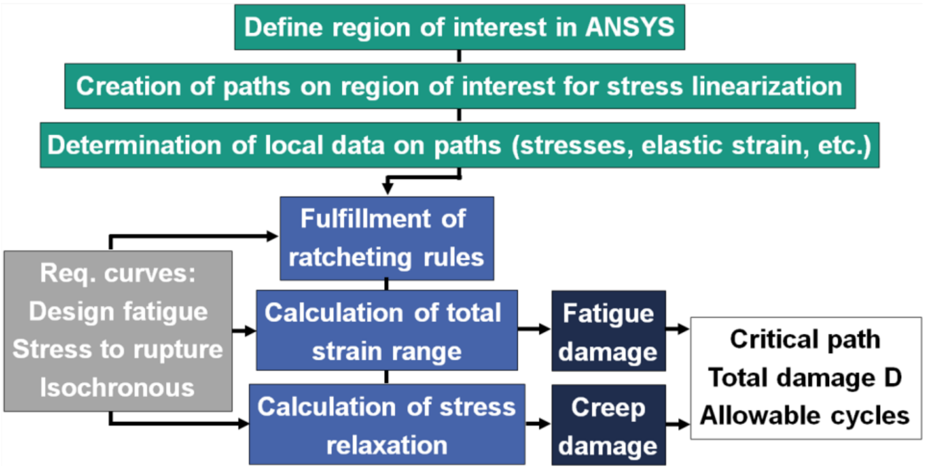


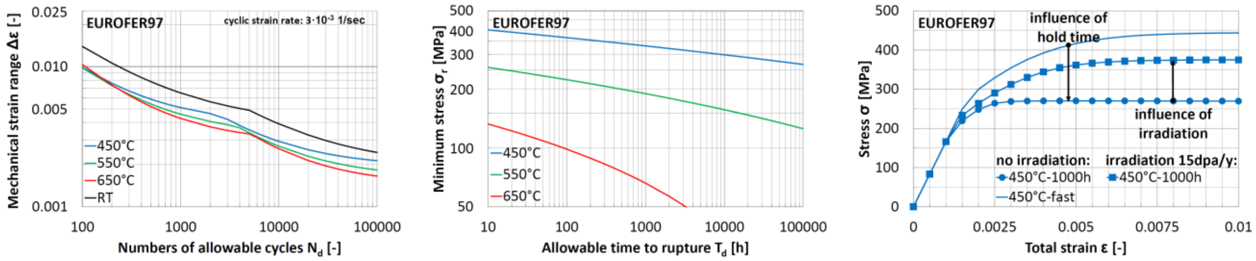
Figure 1Approach of CFA-Tool for critical path identification

To figure out the creep damage the creep stress vs. time to rupture curves are necessary. The required creep stress is calculated using isochronous stress vs. strain curves and by help of determined total strain range. After calculation of fatigue und creep damage for each path the critical path can be identified automatically. As a result the total damage and the allowable number of cycles can be carried out.

The main advantage of this approach shown in this paper is the automated determination of the most critical path based on the results obtained on all paths during creep-fatigue post-processing.

Required CFA data for EUROFER97 using a constitutive model

The CFA tool can be used for the material EUROFER97 in a temperature range between room temperature and 650°C. For EUROFER97 the design fatigue curves at different temperatures in Figure 2 a) by Aktaa et al. [8] are mandatory to get information about fatigue behavior. For a given total strain range the design allowable number of cycles N_d can be identified. The total strain range in equation (2) is determined according to ASME BPVC using the constitutive model for RAFM steels by Aktaa & Schmitt [6] considering irradiation effects [7] to calculate required stress and strain values. To consider creep behavior the stress to rupture curves at different temperatures in Figure 2 b) by Tavassoli [9] on EUROFER97 are used to get the allowable time to rupture T_d for a given creep stress which is determined by the constitutive model for RAFM steels by Aktaa & Schmitt [6], [7].



a) b) c)

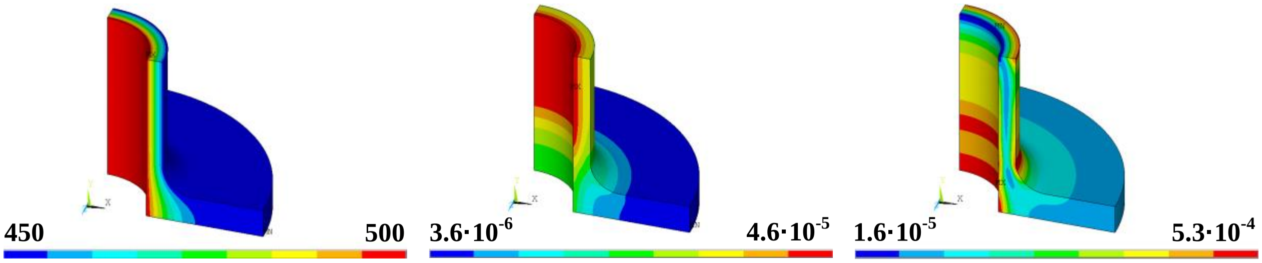
Figure 2 Design fatigue curves [8] a), stress to rupture curves [9] b) and isochronous stress vs. strain curves [2] including hold time and irradiation effects c)

Figure 2 c) shows isochronous stress vs. strain curves on EUROFER97 at 450 °C. These curves can be predicted using the constitutive model in [6], [7]. This figure shows the influence of irradiation and hold time on EUROFER97. For the non-irradiated state two curves are shown. One without hold time and one with a hold time of 1000 hours which results in a reduction of stresses in the stress vs. strain curve. For this hold time another curve with an irradiation rate of 15 dpa per year is shown. Compared to the non-irradiated curve this curve is shifted to higher stresses due to irradiation hardening.

All shown data is used to identify the required values for the creep-fatigue rules according to ASME BPVC.

Benchmark on a complex 3D geometry in ANSYS MAPDL

To show how the CFA tool is able to identify the most critical path in a selected region of interest a complex 3D benchmark example is used. Therefore a muff of EUROFER97 material with an inner pressure of 20 bar and temperature of 500 °C on the inner and 450 °C on the outer surface of the muff using symmetry boundary conditions have been performed with ANSYS MAPDL. Figure 3 a) shows the result of the steady state thermal analysis with the temperature distribution between the inner and the outer surface of the muff. This temperature distribution is used for the first elastic structural analysis considering the primary loads (inner pressure). The distribution of the equivalent total elastic thermal and mechanical strain is shown in Figure 3 b) with its maximum value of $4.6 \cdot 10^{-5}$ on the inner surface of the muff. The second elastic structural simulation considering the primary + secondary loads (inner pressure and thermal expansion) yields a maximum equivalent total elastic thermal and mechanical strain of $5.3 \cdot 10^{-4}$, see Figure 3 c).



a) thermal loads b) primary loads c) primary+secondary loads

Figure 3 Thermo mechanical elastic finite element analysis in ANSYS MAPDL

Based on these three elastic analyses the CFA tool is able to identify the most critical path by post-processing. Therefore an inner and outer region must be defined. Figure 4 shows the selected regions of the muff. In this example the green surface in Figure 4 is picked for the inner (GEOM-INNER) and the purple surface for the outer (GEOM-OUTER) region, respectively. Based on these two surfaces the nodes adjacent to them are selected to result in a set of inner (N_L1) and outer nodes (N_L2). Next an algorithm searches for the minimum distance between inner and outer region and selects all elements which are on that minimum distance paths. Using only the minimum distances between inner and outer region is an acceptable assumption, because other possible distance combinations are in practice in rare cases and however the tool provides realistic results for the chosen distances. The CFA tool linearizes the stresses along all that paths and calculates the allowable number of cycles, the creep and the fatigue damage.

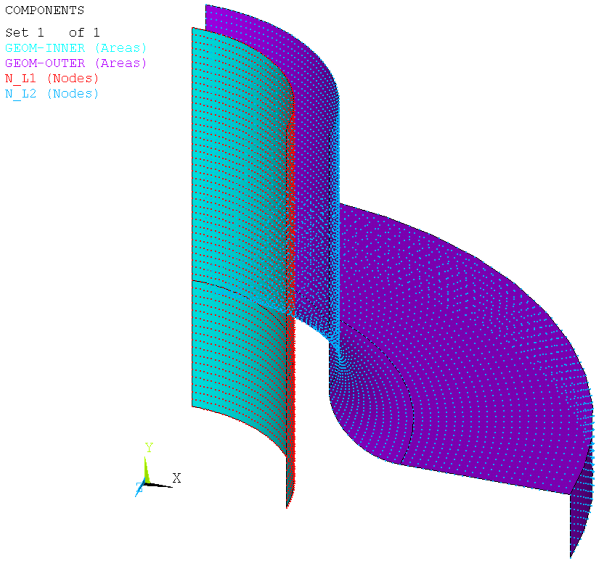
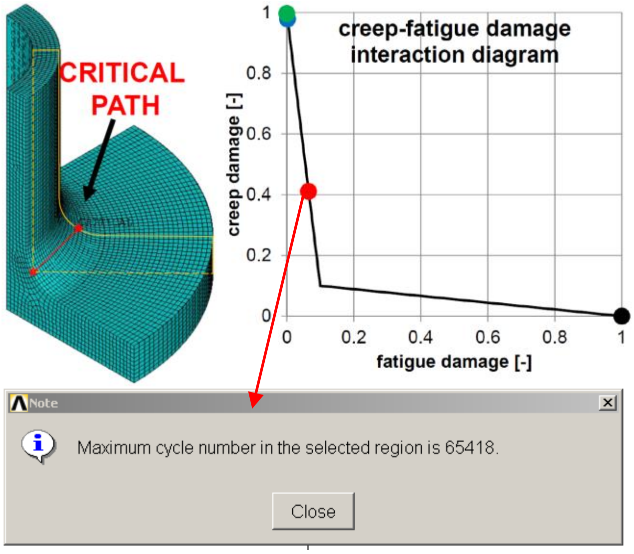


Figure 4 Selection of inner and outer region of interest



Maximum cycle number in the selected region is 65418.

Figure 5 CFA results for 15 dpa/year

After that calculation the minimum allowable number of cycles is identified to figure out the most critical path and its position. Figure 5 shows the result of CFA for an irradiation dose of 15 dpa per year. ANSYS MAPDL shows on screen the position of the critical path within the finite element mesh highlighted in red (Figure 5 left) and also the creep and fatigue damage visualized in the creep-fatigue damage interaction diagram (Figure 5 right). A prompt on screen shows in addition the maximum allowable number of cycles for this critical path which is equal to 65418 cycles under one hour hold time. The results of other hold times at same irradiation rate are listed in Table 1.

Table 1 CFA results for different hold times and irradiation rate of 15 dpa per year

Hold time [hour]	**Allowable cycles [-]**	**Fatigue damage [-]**	**Creep damage [-]**
0	>100000	1	0
1	65418	0.065	0.411
100	2370	0.002	0.979
1000	323	0.000	0.997

It is clearly visible that an increase in hold time reduces the fatigue and increases the creep damage. As a result the allowable numbers of cycles decrease with increasing hold time on the most critical path.

Conclusion

Based on the results the following conclusions can be deducted:

- A powerful creep-fatigue assessment tool for EUROFER97 was developed as post-processing for ANSYS MAPDL and also available for ANSYS Workbench.
- Preliminary thermo-mechanical elastic analysis for stress linearization is based on three finite element analysis:
  → thermal, primary and primary + secondary loads
- CFA tool can be used for any complex 3D structures.
- Automated identification of the most critical path in the component by selecting areas of interest is realized.
- CFA results for different hold times have been presented for an irradiation rate of 15 dpa per year.
- Application to real structures and further developments of resulting needs for optimization are ongoing.

Acknowledgement

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Literature

[1] ASME, *Boiler Presssure & Vesselt Code, Section III, Division 1, Subsection NH, Appendix T,* 2004.

[2] F. Özkan and J. Aktaa, "Creep fatigue assessment for EUROFER components," *Fusion Engineering and Design,* 2015.

[3] F. Özkan and J. Aktaa, "Creep-fatigue design rules for EUROFER97," in *ICFRM-16 Poster ID 16-170*, Beijing, China, 2013.

[4] F. Cismondi, S. Kecskes and G. Aiello, "HCPB TBM thermo mechanical design: Assessment with respect codes and standards and DEMO relevancy," *Fusion Engineering and Design,* pp. 2228-2232, 2011.

[5] F. Özkan and J. Aktaa, "Creep fatigue assessment macro in MAPDL for EUROFER," in *SOFT-2014 Poster ID P2.124,* San Sebastian, Spain, 2014.

[6] J. Aktaa and R. Schmitt, "High temperature deformation and damage behavior of RAFM steels under low cycle fatigue loading: Experiments and modeling," *Fusion Engineering and Design 81,* pp. 2221-2231, 2006.

[7] J. Aktaa and C. Petersen, "Modeling the constitutive behavior of RAFM steels under irradiation conditions," *Journal of Nuclear Materials 417,* pp. 1123-1126, 2011.

[8] J. Aktaa, M. Weick and M. Walter, "High Temperature Creep-Fatigue Structural Design Criteria for Fusion Components Built from EUROFER 97, FZKA 7309," Forschungszentrum Karlsruhe, 2007.

[9] F. Tavassoli, "Fusion Demo Interim Structural Design Criteria (DISDC), Technical Report TW4-TTMS-005-D01," CEA, 2004.