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ANSYS Creep-Fatigue Assessment tool for EUROFER97 components

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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 and 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 3 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.

1. 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. In contrast to ASME BPVC similar rules are available in RCCMRx code [2] where EUROFER97 is proposed to be included to this code [3]. The procedure mentioned in ASME BPVC was adapted to the ferritic-martensitic steel EUROFER97 [4] and implemented in a program written in FORTRAN named Creep-Fatigue Assessment (CFA) tool [5]. This tool uses the following failure criterion of ASME BPVC:

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

The first part on the left side of Eq. (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 and Aktaa [6] used this tool on complex test blanket module (TBM) of future fusion reactor components [7] 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 [8]. 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.

2. Approach of CFA tool and required data for Eurofer97

The approach which is shown in Fig. 1 is based on Özkan and Aktaa [5] where the creep and fatigue damage is calculated according to the creep-fatigue rules in ASME BPVC based on elastic analysis for a path which must be defined by the user in finite element program ANSYS during post-processing by hand. This selected path is then used for stress linearization to identify primary, secondary and peak stresses. The most important steps of this approach are

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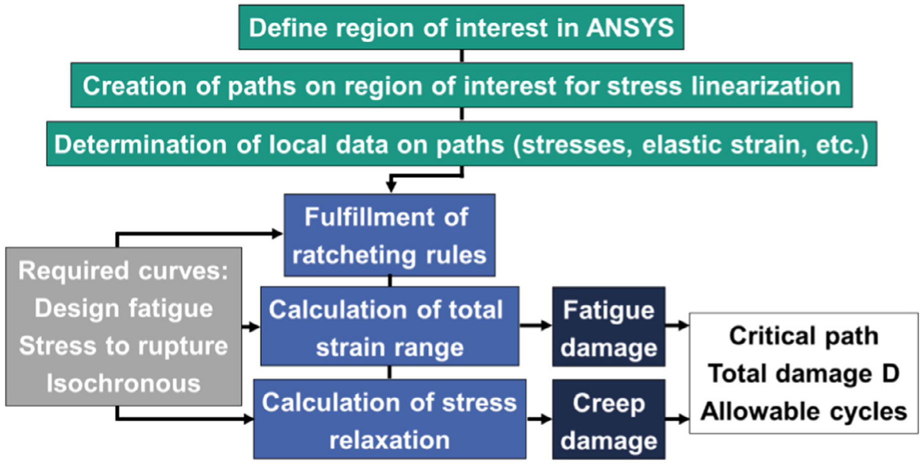

Fig. 1. Approach of CFA-Tool for critical path identification. (For interpretation of the references to osc

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	Boiler Pressure and Vessel Code
CFA	Creep-Fatigue Assessment
EDDI	Engineering Data and Design Integration
MAPDL	Mechanical ANSYS Parametric Design Language
TBM	Test Blanket Module

the ratcheting rules mentioned in ASME code like $3S_m$ rule including primary and secondary stress parameters (X, Y), the calculation of total strain range and calculation of the relaxation stress. These main steps are highlighted in Fig. 1 as blue boxes.

To check the ratcheting rules and calculate total strain range and stress relaxation for EUROFER97 in a temperature range between room temperature and 650 °C different material specific curves are mandatory like design fatigue, stress to rupture and isochronous stress vs. strain curve, see gray box in Fig. 1.

For EUROFER97 the design fatigue curves at different temperatures in Fig. 2(a) by Aktaa et al. [9] are used to get information about fatigue behavior. For a given total strain range [1]

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

the design allowable number of cycles N_d can be identified. The total strain range in Eq. (2) is determined according to ASME BPVC using the values $\Delta\varepsilon_{mod}$, $\Delta\varepsilon_c$ and $\Delta\sigma_{mod}$ which are calculated using the Creep-Fatigue Assessment tool. 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. Due to the lack of available isochronous stress vs. strain curves for EUROFER97 in ASME code a constitutive model for RAFM steels by Aktaa and Schmitt [10] considering irradiation effects [11] is used to calculate required stress and strain values for consideration of hold time effects. For the creep behavior stress to rupture curves at different temperatures in Fig. 2 (b) by Tavassoli [12] on EUROFER97 are used to get the minimum time to rupture T_d of a given creep stress which is based on the total strain range identified before and the use of the constitutive model for RAFM steels by Aktaa and Schmitt [10, 11] in terms of isochronous stress vs. strain curves.

Fig. 2 (c) shows examples of isochronous stress vs. strain curves on EUROFER97 at 450 °C. These curves are predicted using the constitutive model [10, 11] and show the influence of irradiation and hold time on EUROFER97. For the non-irradiated state two curves are visible. One without hold time and one with a hold time of 1000 h 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 is given. Compared to the non-irradiated curve this curve is shifted to higher stresses due to irradiation hardening.

All details and requirements on calculation of creep and fatigue damage are explained in ASME BPVC Section 3 Division 1 Subsection NH including a lot of steps to be taken into account. Due to the huge number of steps to be followed in ASME code and in some cases due to lack of available material data for EUROFER97 the Creep-Fatigue Assessment tool was initially developed [5]. At this development stage the main disadvantage of this tool was that the path for Creep-Fatigue Assessment must be selected by hand in ANSYS post-processing.

Now in the present paper the approach is extended to be able to automatically identify the most critical path. With this extension the disadvantage of selecting a specific path within a component by the user itself can be avoided. Therefore a region of interest has to be defined in ANSYS MAPL or Workbench post-processing, respectively. The general idea is shown with the green boxes in Fig. 1. 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 analyses for primary and primary + secondary loads.

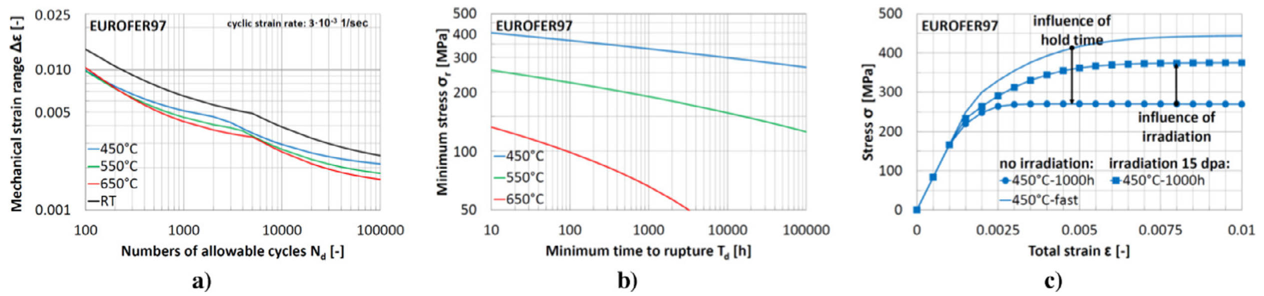

Fig. 2. Design fatigue curves [9] (a), stress to rupture curves [12] (b) and isochronous stress vs. strain curves [5] including hold time and irradiation effects (c).

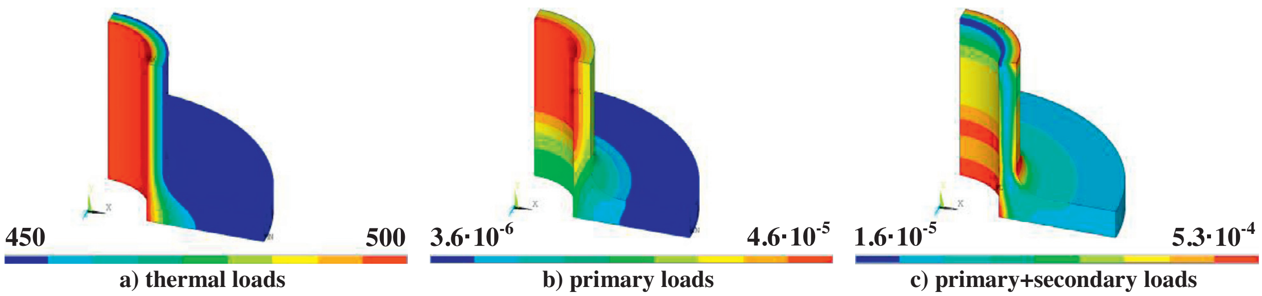

Fig. 3. Thermo mechanical elastic finite element analysis in ANSYS MAPDL.

After determination of allowable number of cycles and minimum time to rupture of each path in the selected region the CFA tool identifies the most critical one to finally calculate the fatigue and creep damage for this path based on Eq. (1). 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.

3. 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. Fig. 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 Fig. 3 (b) with its maximum value of 4.6×10^{-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 5.3×10^{-4}, see Fig. 3(c)).

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. Fig. 4 shows the selected regions of the muff. In this example the green surface in Fig. 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). In case of the green surface 3135 nodes are lying on this surface. Next an algorithm searches for the minimum distance between inner and outer region and selects all elements which are on that minimum distance paths

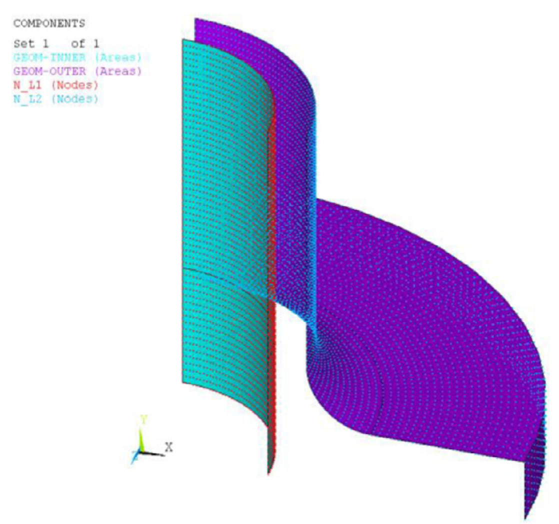

Fig. 4. Selection of inner and outer regions of interest. (For interpretation of the references to osc

which results in 3135 paths based on the number of nodes attached to the surface. 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. The computation time is about 8 min for post-processing like stress linearization and extraction of additional information and 1 min for CFA tool executable itself.

After that calculation the minimum allowable number of cycles is identified to figure out the most critical path and its position. Fig. 5 shows the result of CFA for an irradiation dose of 15 dpa. ANSYS MAPDL shows on screen the position of the critical path within the finite element mesh highlighted in red (Fig. 5, left) and also the creep and fatigue damage visualized in the creep-fatigue

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

Hold time (h)	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

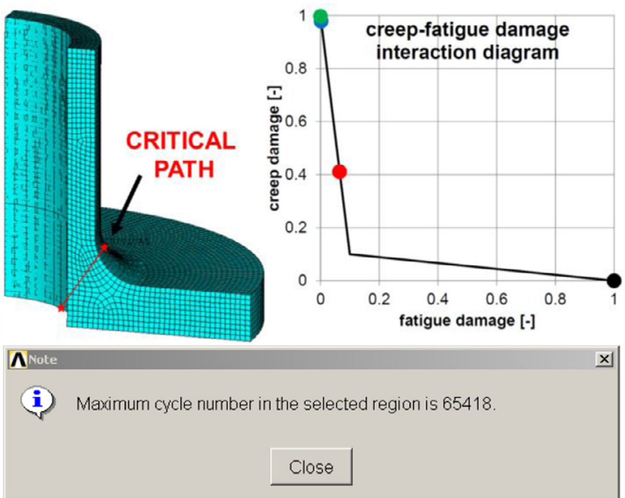

Fig. 5. CFA results for 15 dpa. (For interpretation of the references to osc

damage interaction diagram (Fig. 5, right). A prompt on screen shows in addition the maximum allowable number of cycles for this critical path which is equal to 65,418 cycles under 1 h hold time. The results of other hold times at same irradiation rate are listed in Table 1.

Due to the used shape of interaction diagram for calculation of creep and fatigue damage 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. The main advantage of this tool extension is that the user does not have to select the critical region by hand. As it is well known due to creep not the region of maximum stress must be the critical one. In some cases the region of maximum temperature is critical.

4. 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.
- Application to real structures and further developments of resulting needs for optimization are ongoing.

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