Abstract—The aim of the work presented is, firstly, an evaluation of existing design rules considered for austenitic steels exhibiting hardening cycle by cycle contrary to the reduced activation ferritic-martensitic steels (RAFM), which soften under cyclic loading. Secondly, it is a definition of the range of operation temperatures and loads for the current design of the test blanket module (TBM). Results of cycling tests of the EUROFER 97 performed by J. Aktaa & R. Schmitt [1] have been thereby used to adjust material parameters needed for an ABAQUS-own combined non-linear isotropic-kinematic hardening model. Furthermore, the visco-plastic material model considering material damage [1] implemented recently as an ABAQUS user material (UMAT) has been applied for simulations and the results have been compared with those obtained using the material model mentioned above.

Keywords-test blanket module, reduced activation ferritic-martensitic steel, EUROFER 97, structural design code, cyclic softening, stress categorization, ratcheting, high-temperature design rules

I. INTRODUCTION

This work is a part of the development activity of the ITER test blanket module (TBM). A determination of high-temperature design rules considering the creep/fatigue is the aim of the work. According to the present-day vision, the TBM should be manufactured from a reduced-activation ferritic-martensitic (RAFM) steel EUROFER 97, which exhibits severe softening during cyclic loading contrary to usual austenitic steels. This abnormal behavior leads definitively to a necessity to revise a traditional formulation of some important design rules such as the well-known $3S_m$ rule.

Such a revision requests, firstly, a wide experimental data base and, secondly, an advanced material model being able to describe a realistic behavior of a material. The fulfillment of both these requirements as well as at the room temperature (RT) provided by M. Weick [2] have been used to adjust material parameters required for an ABAQUS-own non-linear isotropic-kinematic hardening model [3]. This model is able to account e.g. for the Bauschinger effect, a cyclic hardening with plastic shakedown as well as for a ratcheting. A description of the material model is given in [3] and lies outside the paper. The determined values for the parameters $C$, $\gamma$, $Q$ and $b$ specified also in [3] are collected in tabs. I and II.

TABLE I. KINEMATIC HARDENING: THE FITTED PARAMETER $C$ FOR DIFFERENT TEMPERATURES; THE 2nd PARAMETER $\gamma = 1150$

<table>
<thead>
<tr>
<th>T, K</th>
<th>293</th>
<th>723</th>
<th>823</th>
<th>923</th>
</tr>
</thead>
<tbody>
<tr>
<td>C, MPa</td>
<td>147200</td>
<td>153922</td>
<td>180590</td>
<td>194900</td>
</tr>
</tbody>
</table>

TABLE II. ISOTROPIC HARDENING: THE FITTED PARAMETERS $Q$ AND $b$ FOR DIFFERENT TEMPERATURES.

<table>
<thead>
<tr>
<th>T, K</th>
<th>293</th>
<th>723</th>
<th>823</th>
<th>923</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q, MPa</td>
<td>-104.00</td>
<td>-133.00</td>
<td>-145.00</td>
<td>-108.77</td>
</tr>
<tr>
<td>b</td>
<td>0.89</td>
<td>1.05</td>
<td>1.80</td>
<td>3.70</td>
</tr>
</tbody>
</table>

III. DETERMINATION OF THE ELASTIC LIMIT

A. Finite Element Model

To verify the material model described above, a 2D model of a quarter of the TBM has been created according to the current design and meshed using PATRAN. The model is shown in fig. 1 together with mechanical constraints. The only external mechanical load in the non-accident operating mode is the hydrostatic pressure of 80 bar = 8 MPa in the cooling channels.

For those simulations where thermal stresses occur, ABAQUS promotes a so called generalized plane strain element formulation, which accounts for an elongation in the out-of-plane direction and thus avoids enormously high non-physical out-of-plane stresses. The 8-noded generalized plane strain elements CPEG8 have been used here.

B. Thermal Simulation

During the operating mode, it should be accounted for a heat flux of 250 up to 500 kW/m² (peak) on the plasma-facing side as well as a heat flux of 60 kW/m² and of...
35 kW/m² on the vertical and horizontal interior, respectively, due to breeder units, see fig. 2. For the reason of simplicity, boundary conditions depicted in fig. 2 have been considered in the simulations.

In order to determine admissible loads, the behavior of the TBM should be simulated under consideration of different temperature distributions. To obtain such distributions, thermal simulations have been performed for four values of the plasma heating: 250 kW/m² (the usual operating mode), 500 kW/m², 750 kW/m² and 1000 kW/m² as well as for three different temperatures in the cooling channels (T°C): 673K, 773K and 873K. The heating due to the breeder unit remains thereby constant. As an example of the typical temperature distribution, results of a thermal computation for the peak operating mode and T°C = 773K are shown also in fig. 2.

C. Mechanical Simulations using various Plasma Heating and Pressure in Cooling Channels (no cycling)

By variation of both the temperature in cooling channels and the plasma heating, a critical pressure has been determined. The critical pressure is defined as the minimum pressure causing an inelastic deformation after the 1st heating i.e. after the ½ of the 1st cycle.

The critical pressure is shown in fig. 3 in dependence on the plasma heating and the temperature in the cooling channels T°C.

Evidently, the critical pressure is strongly dependent on the temperature in the cooling channels and relatively slightly on the plasma heating up to 450 - 500 kW/m² approximately. Increasing plasma heating takes however a leading influence on the critical pressure whereas the temperature in the cooling channels plays a decreasing role and, finally, plastic deformation occurs for all T°C without pressure due to the temperature gradient alone if the plasma heating reaches 1000 kW/m². For this heating, the plastic deformation is localized in a narrow band along the plasma-facing side, see fig. 4 (on the left). A high pressure causes an additional plastic deformation located in a left bottom or left top corners of the 1st or 2nd cooling channels if the pressure in the channels reaches a critical value discussed above, see fig. 4 (on the right). The magnitude of the deformation is higher than the magnitude of the thermal plastic strain.

IV. Simulations of the Cyclic Behavior of TBM

The cyclic behavior of the TBM model has been studied using both the ABAQUS-own material model described above and the visco-plastic material model considering damage [1] implemented recently by J. Aktaa. Thereby, the following load case has been used: T°C = 600°C (873K); the plasma heating 750 kW/m² and the coolant pressure P = 50 MPa (500 bar). It was assumed on the basis of the study reported in the previous section that such abnormal high loads should cause an essential plastic deformation.

Figure 1. A 2D model of the TBM with mechanical constraints and loads.

Figure 3. The critical pressure as a function of the plasma heating and the temperature in cooling channels.

Figure 2. Temperature distribution due to the depicted thermal constraints and loads.

Figure 4. Distribution of the equivalent plastic strain in the most loaded region of the TBM for the plasma heating of 1000 kW/m² at T°C = 773K in the absence of pressure (on the left) and at the pressure of 50 MPa.
Each cycle consists of four steps: (1) a heating and application of the pressure, 30 sec; (2) a holding at the high temperature (HT) 400 sec; (3) a cooling to the RT, 100 sec and, finally (4) a holding at the RT 1400 sec. Note that the steps (2) and (4) are not relevant for the ABAQUS-own time-independent material model.

It was possible to simulate 300 cycles with the ABAQUS-own model and only 100 cycles with the UMAT because of the high cpu time needed. The results have been generated in a table format along the paths AB, CD, GF and KL depicted in fig. 1. A follow-up examination has shown that the highest plastic strain in the model occurs near the point L of the path KL as in fig. 4 (on the right). A change of the maximum equivalent plastic strain near the point L within the first 100 cycles is depicted in fig. 5 for both material models used. A detailed investigation shows an almost linear increase of the equivalent plastic strain in the case of the ABAQUS-own material model. However, the increase lies between 1.355E-3 and 1.366E-3 for the first 300 cycle.

The application of the UMAT leads evidently to considerably higher plastic strains due to the creep and damage of the material. Note that the values of the variable PEMAG (the magnitude of the plastic strain) after the 1st heating are of the material. Note that the values of the variable PEMAG considerably higher plastic strains due to the creep and damage and 1.366E-3 for the first 300 cycle.

The aim is now to compare the results discussed above with a prediction of some design rules based on linear-elastic simulations. To apply the design rules, $S_{mt}$, the minimum of $S_m$ and $S_t$ should be evaluated. Thereby, $S_{m}$ is the lowest stress intensity at a given temperature among the time-independent strength quantities and $S_t$ is a temperature and time-dependent stress intensity limit, see e.g. ASME code design rules [3].

A. Calculation of $S_m^*$

The available $S_m$ and $S_{mt}$ values do not consider a change of the tensile strength and yield stress cycle by cycle. This change can be however taken into account if $S_m$ is calculated on the basis of the experimental data reported by J. Aktaa and R. Schnitt in [1]. Thereby, the maximum achieved tensile stress must be used here for calculations instead of the ultimate tensile strength. To obtain the needed tensile strengths, tensile tests should be performed after e.g. 10, 20 etc. cycles.

The new-calculated in such manner value is represented in fig. 7 together with the $S_{mt}$ values from the DEMO SDC. It was assumed that each cycle is 1930 sec = 0.54 h long. To avoid a misunderstanding, the value has been labelled as $S_{m}^*$. Note that any stress leads to a plastic collapse already after 200 cycles at 650°C (923K). As follows from the diagrams in fig. 7, the DEMO SDC provides too high values of $S_{mt}/S_{m}$. For instance, values proposed for 650°C (923K) are valid for...
550°C (823K). On the other hand, the calculated values of S*_m can also be enhanced if the ultimate strength will be determined correctly.

B. Stress Categorization

To separate primary and secondary stresses, linear-elastic simulations have been performed for three load cases: thermal and mechanical loads acting together and separated. A comparison of the results obtained allows to recognize that the coolant pressure partially compensates the influence of the plasma heating.

Results of these simulations have been then linearized automatically along the four paths discussed above using the corresponding option of the ABAQUS VIEWER. Note that the ABAQUS VIEWER rotates axes during the automatic linearization procedure. For instance, the x axis is directed along the path chosen.

C. Application of Design Rules

Now, the following design rules (elastic route) can be checked:

- rules for prevention of an immediate plastic collapse and a plastic instability (M-type damage)
  \[ P_m \leq S_m \]
  \[ P_m + P_b \leq K S_m \] (1)
- the rule for prevention of a progressive deformation or a ratcheting (C-type damage)
  \[ P_m + P_b + Q \leq 3 S_m \] (2)

Thereby, K is the bending shape factor, which ranges in general between 1.0 and 2.0. Here, K = 1.5. The more conservative rule accounting for a possible embrittlement caused by irradiation is not considered here since the material tested is unirradiated. Besides this factor, the following conventional notations are used here: P_m and P_b denote the primary membrane and bending stresses respectively, Q is the secondary (thermal) stress.

The maximum values required for an evaluation of (1) and (2) are collected in tab. III. An easy comparison allows to see that none of the three criteria is fulfilled even for the S*_m value stemming from DEMO SDC at T^m = 600°C (873K). If the S_m value at the average temperature along the path (approx. 625°C or 899K) is considered, the difference becomes more essential. The S*_m value for this temperature is however out of any competition.

Thus, the chosen design rules predict (a) the plastic collapse and plastic instability as well as (b) the accumulation of the plastic deformation. The simulation results under application of the visco-plastic material model considering damage seems to show rather a shakedown. However, as mentioned above, to obtain a more definite result, more cycles should be simulated and, furthermore, additional load cases should be investigated.

<table>
<thead>
<tr>
<th>P_m^max</th>
<th>S_m^109K</th>
<th>S^* m^109K</th>
<th>S_m^873K</th>
<th>S^* m^873K</th>
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<tbody>
<tr>
<td>100.1</td>
<td>82.0</td>
<td>23.7</td>
<td>98.0</td>
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<tr>
<td>191.5</td>
<td>123.0</td>
<td>35.5</td>
<td>147.0</td>
<td>59.5</td>
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<tr>
<td>301.0</td>
<td>246.0</td>
<td>71.0</td>
<td>294.0</td>
<td>119.0</td>
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<table>
<thead>
<tr>
<th>(P_m+P_b)^max</th>
<th>K*S_m^109K</th>
<th>K<em>S^</em> m^109K</th>
<th>K*S_m^873K</th>
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VI. Conclusion and Outlooks

In the present work, material parameters required for the non-linear kinematic-isotropic hardening ABAQUS-own material model have been newly determined. These parameters have been then used to find out the coolant pressure causing a plastic deformation as a function of the temperature in the cooling channels and the plasma heating.

Furthermore, the cyclic behavior of the TBM has been simulated using both the ABAQUS-own material model and a visco-plastic material model considering material damage.

On the other hand, some important design rules have been applied and their predictions have been compared with the results of the cyclic simulations. It turned thereby out that the criterions are not fulfilled even if the conventional value of S_m is used. The newly calculated value S*_m introduced similar to S_m and accounting for the softening of the EUROFER 97 cycle by cycle leads to a larger gap between the target and actual results.

The results of the cyclic simulations exhibit neither the plastic collapse nor the ratcheting after the first 100 cycles. This discrepancy could mean that the criterions are possibly too conservative for EUROFER 97 and new design rules should be considered. The suggestion requires however a further in-depth study including a verification of all (elastic and elastic-plastic) design rules preventing both the M-type and C-type damage, a consideration of the irradiation, the hydrogen effect and corrosion effect by the coolant as well as the possible change of the actual TBM geometry.

Acknowledgment

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References

[4] ASME Boiler and Pressure vessel code: Section III, Division 1 – Subsection NH