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Non-linear assessment of critical failure modes in the first wall of the European TBM

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ABSTRACT

The assessment of the different components of the Helium Cooled Pebble Bed (HCPB) and Helium Cooled Lithium Lead (HCLL) Test Blanket Modules (TBMs) based on elastic FE analyses has been performed considering main failure modes and respective structural design criteria. This study has been carried out for the operation at full power and for the so-called Approach 2 cooling that is set up at reduced heat extraction capability for compliance with temperature targets to be relevant to DEMOnstration power plant blanket system. Consequently this situation is the worst condition in terms of cooling performance as a result it reveals that many locations in the First Wall (FW) become critical in the sense that certain criteria are not fulfilled, particularly those for immediate plastic flow localization, progressive deformation (ratcheting) and creep-fatigue interaction. Of course one can better reach code compliance by improving the cooling performance (so called Approach 1) but it will degrade the DEMO relevancy.

The critical failure modes are re-assessed performing non-linear analysis using an elasto-viscoplatic model, particularly developed for RAFM steels such as the structural material EUROFER97 by Aktaa & Schmitt, and considering the appropriate design criteria of the inelastic route of RCC-MRx and SDC-IC. Despite the conservatism in these criteria, the results show all-clear signal with respect to immediate plastic flow localization and at least much smaller breaches of the limits with respect to the other failure modes. Reporting details and results of the non-linear failure assessments demonstrates their potential and capability in supporting specific and efficient improvements to the design of highly loaded components. The conservatism in the considered design criteria and ways for its reduction are discussed in addition.

1. Introduction

The assessment of the different components of the HCPB and HCLL TBMs based on elastic FE analyses considering main failure modes and respective structural design criteria reveals that for the operation at full power (Cat. I load case 1a [1]) and for the so-called Approach 2 cooling (reduced heat extraction capability for compliance with temperature targets of DEMO [1,2]), many locations in the FW become critical in the sense that certain criteria are not fulfilled, particularly those for immediate plastic flow localization, progressive deformation (ratcheting) and creep-fatigue interaction. Some of these locations lay in the middle of the FW within the cutting plane number 5 (see Fig. 1a) whereas the most critical one in this plane is the position marked by the supporting line FW-5.12. It is identified based on the negative margins obtained for immediate plastic flow localization (see Table 1), progressive deformation (ratcheting) and creep-fatigue interaction (see Table 2) whose absolute values are in comparison the largest for this position.

Within the work reported here, the design assessment for the FW is extended considering the rules of the inelastic route provided by RCC-MRx and SDC-IC exploiting all options given by them. Therefore non-linear finite element simulations are performed using the coupled elasto-viscoplastic deformation damage model developed by Aktaa & Schmitt for EUROFER97 [3] and its implementation as a user material subroutine in the finite element code ABAQUS [4] (UMAT_RAFM). The review of the FE models for the HCPB-TBM, in particular the ABAQUS input files for the linear elastic thermo-mechanical analysis including meshes, loadings and boundary conditions, reveals in addition that for the middle part of the FW smaller FE sub-models can be extracted from the global FE models at a maintainable effort with no need of re-meshing. Such FE sub-models are however required for the time-consuming non-linear FE simulations using the elasto-viscoplastic model.

In the following the extraction of the FW sub-model and its validation are introduced. Thereafter the assessment results of the critical failure mentioned above are presented and discussed providing

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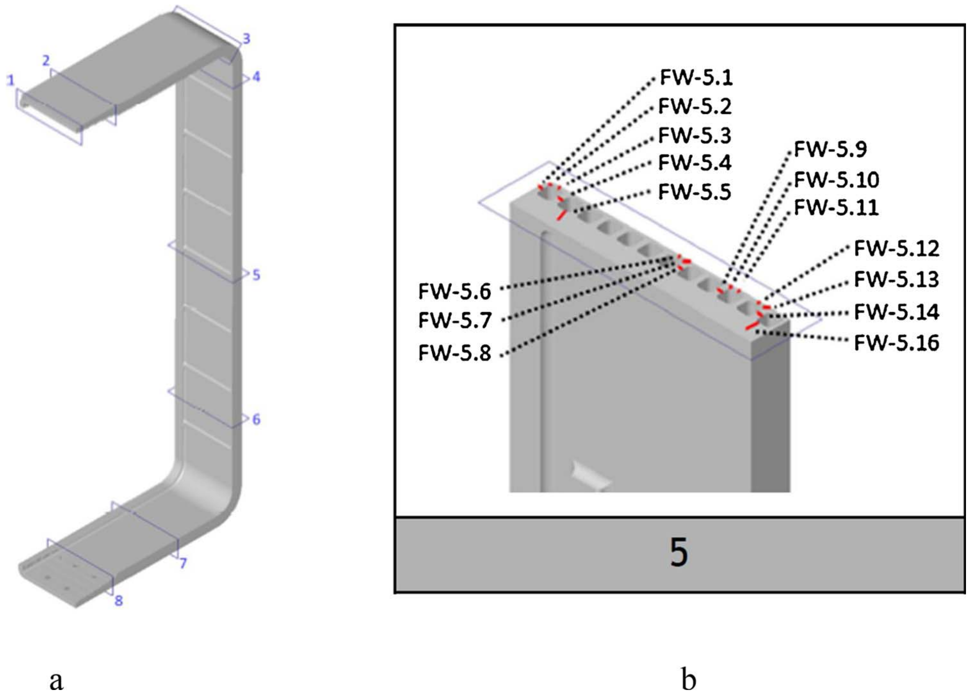

Fig. 1. (a) Planes of the supporting lines considered in the structural analysis of the FW; (b) Considered supporting lines at the middle of FW [1].

Table 1
Calculated margins for the criteria of P-type damage modes at selected positions located in the middle of the FW (see Fig. 1) [1].

		$\overline{P_m} \le S_m(T_m)$ (Operational)		$\overline{P_l + P_b} \le 1.5S_m(T_m)$ (Operational)		$\overline{P_L + Q_L} \le S_e(T_m)$ (Operational)
		LT	HT	LT	HT	
FW-5.11	HT	81%	99%	83%	99%	−12%
FW-5.12	HT	81%	99%	83%	99%	−14%
FW-5.13	HT	92%	99%	88%	99%	. −9%

Table 2
Calculated margins for the criteria of S-type damage modes at selected positions located in the middle of the FW (see Fig. 1) [1].

		Progressive Deformation			Fatigue	
		LT	HT		LT	HT
		$3S_m$ rule (RB 3261.116)	Test A-1 (IC 3231.1.1)	Test A-2 (IC 3231.1.2)	Margin (V_A^{-1})	Margin (V_A^{-1}, W_A^{-1})
FW-5.11	HT	−33%	−180%	−32%	0.92	−477%
FW-5.12	HT	−34%	−183%	−33%	0.84	−493%
FW-5.13	HT	−37%	−168%	−40%	0.71	−163%

additional details particularly about the approach pursued for simulating large number of operational cycles.

2. First wall sub-model

The ABAQUS input file for the linear elastic structural analysis on the HCPB-TBM is used to create a sub-model for the FW by importing the global model of the whole HCPB-TBM in ABAQUS CAE (the pre/post processing tool of ABAQUS) and deleting the meshes of the other parts and all dispensable surfaces, element and node sets as well as irrelevant contact and boundary conditions. In addition new node sets marking the contacts of the FW sub-model to the other parts are defined for which submodel boundary conditions are then created as additional loads in the different loading steps. Running the analysis the submodel boundary conditions are usually replaced by ABAQUS with the displacements extracted from the result file of the global model for the respective node and loading step (node-based submodeling).

Performing the linear elastic analysis on the FW sub-model, the same results are obtained compared to those obtained from the analysis on the global model.

3. Assessment of immediate plastic flow localization

For performing the non-linear inelastic analysis on the FW sub-model the type of elements selected for the elastic analysis, C3D8R – eight-node brick linear element with reduced integration (1 integration point) – is replaced by C3D8 – eight-node brick linear element with eight integration points – improving the discretization of the field problem and thus the accuracy and local resolution of the solution. Since the elasto-viscoplastic material behavior to be considered is time-dependent, the times of the loading steps are replaced by the real times and the TIMESCALE parameter is added to the submodel boundary conditions. In addition, the material and its elastic properties are substituted by the material, whose elasto-viscoplastic behavior is described by the elasto-viscoplastic model developed for RAFM steels by Aktaa & Schmitt [3] and implemented in the User Material Subroutine UMAT_RAFM including the temperature-dependent model parameters determined for EUROFER97.

For the assessment of immediate plastic flow localization, the procedure and criteria of the inelastic route of the ITER-SDC-IC are followed (IC 3121.2) [5]. Accordingly, the non-linear elasto-viscoplastic simulation shall be performed with amplified loads (IPFL loads):

- Mechanical loadings by the load factor 2.5
- Thermal and other deformation-controlled loadings by the strain factor 1.5

Both of the above loadings shall be concurrently applied to the structure in the elasto-viscoplastic analysis. The risk of immediate plastic flow localization at the considered cross section can then be excluded when the greatest positive principle strain of the mean plastic strain, $\varepsilon_{m,I}^{pl}$ (the significant mean strain) at all times satisfies the

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