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Numerical assessment of the thermomechanical behaviour of the DEMO Water-Cooled Lithium Lead inboard blanket equatorial module

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Within the framework of EUROfusion R&D activity, a research campaign has been carried out at the University of Palermo, in close cooperation with ENEA labs, in order to assess the thermo-mechanical performances of the DEMO Water-Cooled Lithium Lead (WCLL) inboard blanket equatorial module, whether properly integrated within its whole inboard segment. In particular, a detailed 3D model of this segment, including all the other modules, the back-supporting structure and the attachment system, has been considered in order to realistically simulate the boundary conditions affecting the equatorial module behaviour.

The study has been focused on the investigation of the module thermo-mechanical performances under the Over Pressurization (Level D) loading scenario envisaged for the DEMO WCLL breeding blanket as a consequence of a small in-box Loss Of Coolant Accident (LOCA) accident.

A theoretical-numerical approach, based on the Finite Element Method (FEM), has been followed and the qualified ABAQUS v. 6.14 commercial FEM code has been adopted.

The obtained thermo-mechanical results have been assessed in order to verify their compliance with the design criteria foreseen for the structural material. To this purpose, a stress linearization procedure has been performed along the most critical paths located within the inboard equatorial module structure, in order to check the fulfilment of Level D rules prescribed by the SDC-IC structural design code. The obtained results are herewith presented and critically discussed.

Keywords: DEMO; WCLL Blanket; Thermo-mechanics, FEM analysis.

1. Introduction

Within the framework of the activities foreseen by the Work Package Breeding Blanket (WPBB) of the EUROfusion action on the Water Cooled Lithium Lead (WCLL) blanket concept [1-5], a research campaign has been carried out at the University of Palermo, in close cooperation with ENEA, to assess the steady state thermo-mechanical performances of the WCLL inboard blanket equatorial module (IEM), whether integrated within its inboard segment, under the most significant loading scenarios to be considered in view of its design.

Attention has been focussed on the IEM thermo-mechanical performances under the Over Pressurization (OP) steady state loading scenario, conservatively envisaged to occur in a DEMO WCLL breeding blanket module as a consequence of a postulated small in-box Loss Of Coolant Accident (LOCA) accident. To this purpose, the IEM pre-conceptual design developed during 2016 has been assumed as reference [6].

The research campaign has been carried out following a theoretical-computational approach based on the finite element method (FEM) and adopting the qualified FEM code ABAQUS v. 6.14, already widely adopted for the numerical assessment of the WCLL outboard equatorial module thermo-mechanical behaviour [7-10]. Analysis models and assumptions are herein reported and critically discussed, together with the main results obtained.

2. Outline of WCLL inboard equatorial module

The WCLL inboard equatorial module consists of a Segment Box (SB) and a Breeder Zone (BZ) (Fig.1).

The SB is a EUROFER steel box composed of a tungsten-armoured First Wall (FW), directly exposed to the plasma, two Side Walls (SWs), a Top Cap (TC) and a Bottom Cap (BC), bounding the SB in its upper and lower part, and a Back Plate (BP), that delimits the SB in the radial direction. It is reinforced against internal loads by a set of vertical and horizontal Stiffening Plates (SPs), these latter dividing the BZ in 18 toroidal-radial cells along the poloidal direction. FW, SWs and caps are actively-cooled by pressurized water flowing through square channels with inlet temperature and pressure of 295°C and 15.5 MPa, respectively.

The BZ is devoted to house the Pb-Li liquid metal eutectic alloy, acting as neutron multiplier and tritium breeder. It slowly flows along a radial-poloidal-radial path through each cell, being guided by a toroidal-radial baffle plate that divides each cell into two poloidal halves. The BZ is cooled by a bundle of Double-Walled Tubes (DWTs) for each cell, where pressurized water coolant flows with inlet temperature and pressure of 295°C and 15.5 MPa.

The WCLL IEM BP is welded to a Back Supporting Structure (BSS), directly connected to the Vacuum Vessel (VV) according to the attachment system design

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guidelines agreed within the WPBB team [11]. The attachment system consists in a group of shear keys, aimed at contrasting moments and limiting radial displacements, and a poloidal spring, devoted to prevent excessive poloidal displacements (Fig. 2).

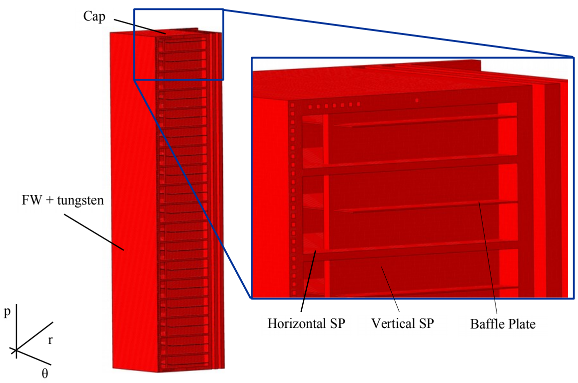

Fig. 1. WCLL inboard equatorial module 2016 design.

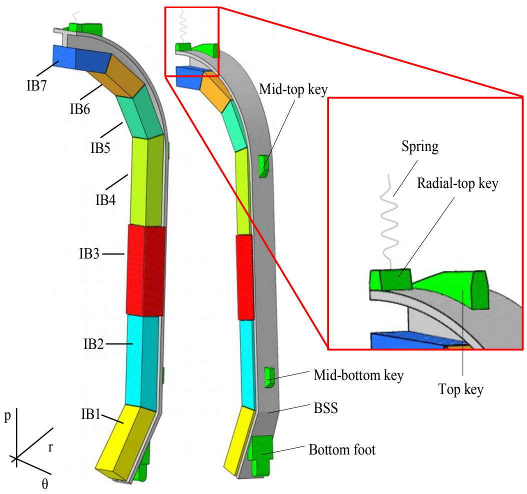

Fig. 2. WCLL blanket inboard segment and attachment system.

3. WCLL IEM thermo-mechanical analysis

The research campaign has been focussed on the theoretical assessment of the WCLL IEM thermo-mechanical behaviour under the OP steady state loading scenario by running a steady state thermo-mechanical FEM analysis.

3.1. FEM Model

To this purpose, a 3D FEM model of the entire WCLL blanket inboard segment has been set-up, consisting of ~$2.24 \cdot 10^6$ nodes connected in ~$1.67 \cdot 10^6$ linear hexahedral elements. It includes the WCLL IEM realistic model, deprived of breeder, DWTs and coolant to save computational time, those of BSS and attachment system keys, as well as the simplified models of other modules. In fact, in order to speed-up calculations, they have been modelled as "dummy" modules, consisting of solid blocks without any internal structure, directly tied to the BSS and characterized by effective thermo-mechanical properties (Young's modulus and density).

Actual EUROFER thermo-mechanical properties have been adopted for the WCLL IEM, the BSS and the attachment system keys. Concerning dummy modules, effective thermo-mechanical properties have been implemented. In particular, an effective density of 9032.5 kg/m^3 has been adopted in order to save the actual weight of modules, including both steel and breeder masses. This value has been calculated under the assumption that the percentages of steel and breeder inside each module are equal to that calculated for IEM. Moreover, an effective Young's modulus equal to one tenth of that of EUROFER has been assumed to properly tune the dummy modules stiffness according to the results reported in [7].

3.2. Models, loads and boundary conditions

Loading conditions relevant to the OP steady state scenario, classified as Level D in the SDC-IC structural design code, have been imposed. In particular the following loads and boundary conditions have been assumed:

- non-uniform thermal deformation field;
- internal pressure distribution;
- gravity load;
- mechanical restraints.

As to the non-uniform thermal deformation field a realistic radial temperature profile has been imposed to the modules and the BSS, directly inferred from the results of the WCLL outboard equatorial module (OB4) thermal analysis, previously carried out under the maximum nominal heat flux of 0.5 MW/m^2 and widely discussed in [7-10]. This temperature profile has been scaled considering the different radial depth of OB4 and IB3 and it is reported in Fig. 3.

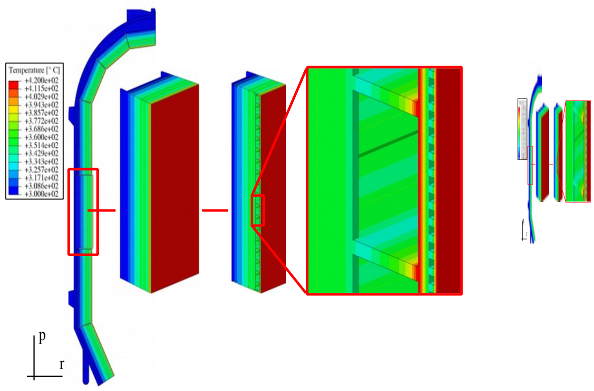

Fig 3. WCLL blanket inboard segment temperature profile.

Concerning the internal pressure exerted on cooling channels and breeder-wetted surfaces due to the exothermic PbLi-water interaction following an in-box LOCA accident, a uniform pressure distribution of 18.6

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MPa has been imposed, assuming conservatively that under the aforementioned LOCA accidental conditions a pressure peak 1.2 times higher than the coolant nominal pressure (15.5 MPa) might occur.

As to the gravity load, it has been simulated implementing into the FEM model, but the IEM one, the gravity acceleration. Conversely, in case of IEM FEM model, an effective gravity acceleration equal to 34.7 m/s^2 has been implemented in order to properly simulate the weight of the breeder, not included in the model.

Finally, the simulation of the attachment system action, devoted to connect the BSS to the VV, has been performed adopting a proper set of mechanical restraints shown in Figs. 4 and 5. Furthermore, it has to be underlined that modules have been considered as tied to the BSS, as well as the keys and the bottom foot.

Since the upper port shield has not been modelled, a spring allowing its interaction with the VV has been directly connected to the upper surface of the radial-top key, as shown in Fig. 5. Moreover, the spring characteristic curve has been properly assessed according to the procedure proposed in [11].

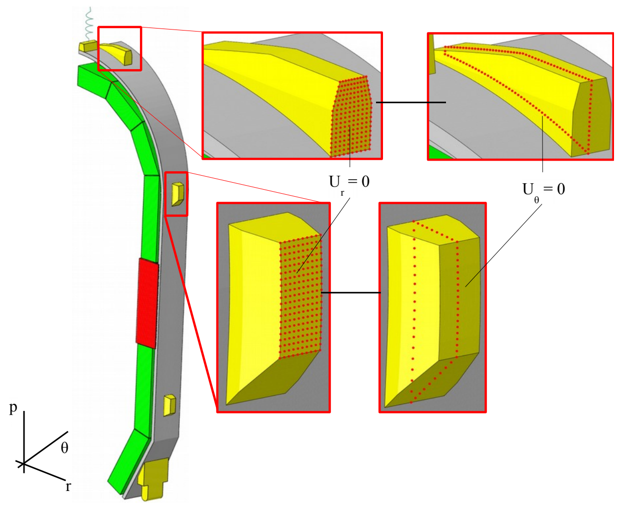

Fig. 4. Mid-top and top key restraints.

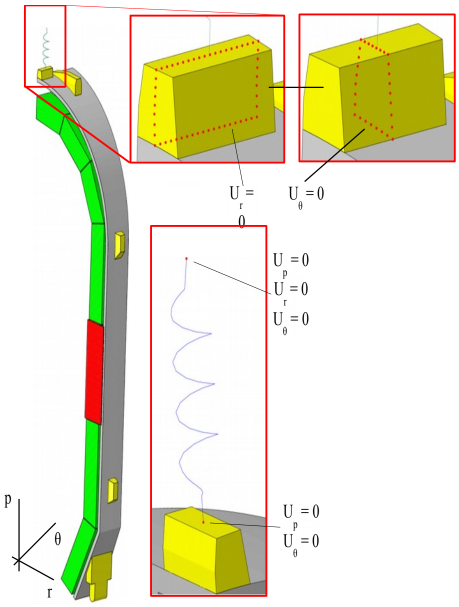

Fig. 5. Radial-top key and spring restraints.

3.3. Results

The thermo-mechanical performances of IEM, whether integrated within its inboard segment, have been numerically assessed under the OP loading scenario and its aptitude to withstand the primary and secondary loads it undergoes has been checked according to Level D criteria of the SDC-IC structural design code.

The Von Mises equivalent stress spatial distribution within IEM (Fig. 6) allows deducing that high stress values have been predicted in correspondence of sharp edges and within the caps, therefore suggesting the need for a partial review of the IEM design. Moreover, the same distribution has allowed to select several highly-loaded paths, located within FW, SPs and BP (Figs. 7-9), where the stress linearization procedure has been performed in order to check the verification of Level D criteria design rules prescribed by the SDC-IC code.

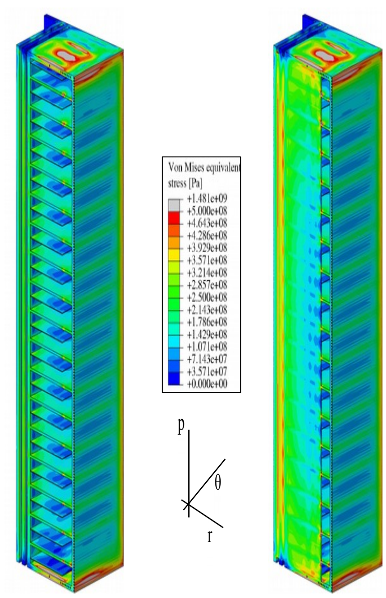

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Fig. 6. IEM Von Mises equivalent stress field.

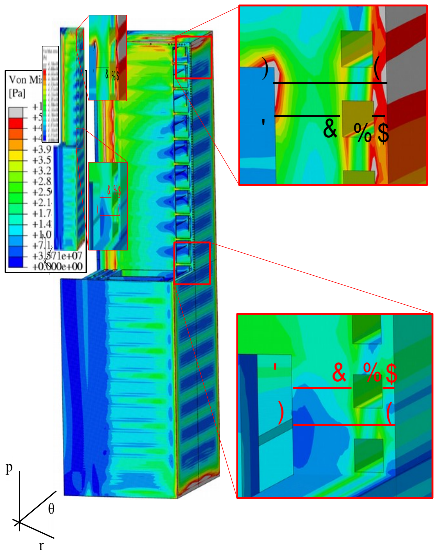

Fig. 7. Stress linearization paths - FW mid-toroidal region.

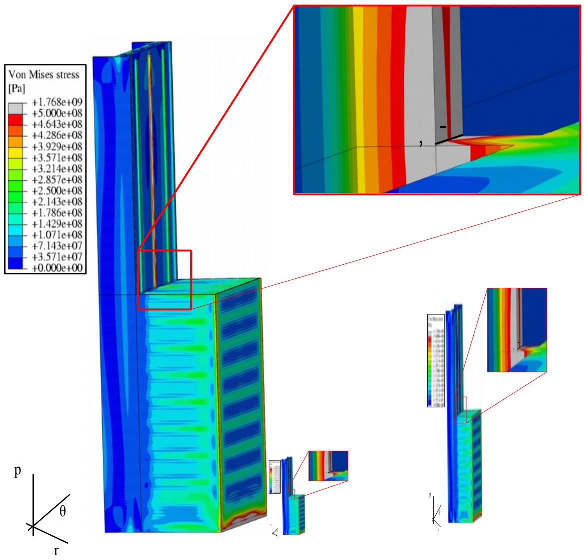

Fig. 8. Stress linearization paths - vertical SPs region.

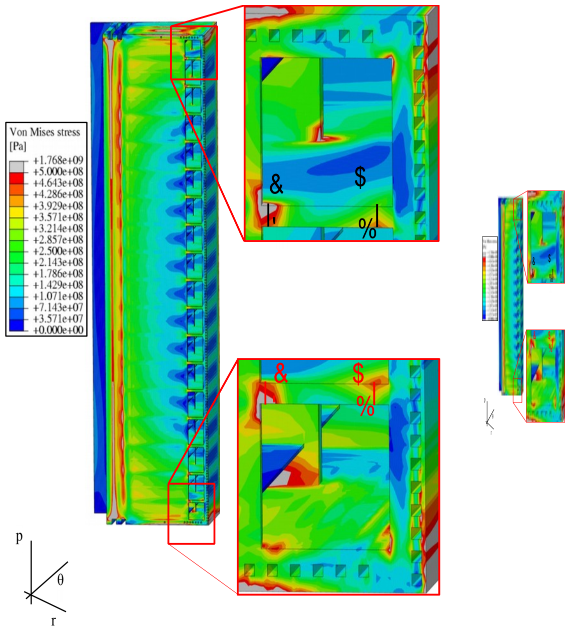

Fig. 9. Stress linearization paths - horizontal SPs region.

The verification procedure has been performed considering all Level D failure criteria, avoiding to check the criterion against the thermal-activated phenomena in case of paths whose maximum temperature would result lower than 450 °C [12-13].

SDC-IC Level D criteria have resulted to be generally fulfilled, nevertheless, some significant exceptions have been found (Tabs. 1-2). In fact, results indicate that structural criteria involving primary stresses, as well as that considering also secondary stresses and preventing from immediate plastic flow localization, are not fully met within some paths. In particular, they have resulted not met within the FW path located between the tungsten layer and the cooling channels, and within the SPs paths.

Tab. 1. Paths located within FW mid-toroidal region.

	Stress linearization path					
	AB	**CD**	**EF**	**AB**	**CD**	**EF**
$T_{Max\text{-}Path}$ [°C]	410.6	415.2	415.2	410.6	415.2	415.2
P_m/σ_{lim}	0.332	0.485	0.252	0.199	0.403	0.318
$(P_m+P_b)/K_{eff}\sigma_{lim}$	0.325	0.888	0.533	0.170	0.518	0.336
$(P_m+Q_m)/2S_e$	1.08	0.457	0.428	0.303	0.257	0.223

Tab. 2. Paths located within SPs region.

	AB	**AB**	**AB**	**IJ**
	θ-left	**θ-middle**	**θ-right**	**-**
$T_{Max\text{-}Path}$ [°C]	357.4	357.4	357.5	314.7
P_m/σ_{lim}	0.731	0.372	0.300	1.297
$(P_m+P_b)/K_{eff}\sigma_{lim}$	1.181	0.568	0.762	0.865
$(P_m+Q_m)/2S_e$	0.607	0.323	0.251	1.209

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Finally, attention has been paid also to the poloidal displacement field and to the comparison between deformed and un-deformed poloidal-radial profiles (Fig. 10) in order to check whether overlapping might occur between IEM and the neighbouring modules.

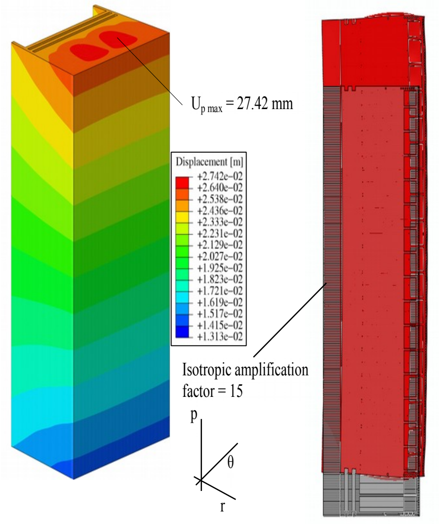

Fig. 10. IEM U_p field and deformed vs. un-deformed views.

From the analysis of the results obtained it can be argued that in the top region of the module a poloidal displacement higher than 27 mm is predicted. Since a maximum initial gap of 20 mm is foreseen between neighbouring blanket modules [14] and the upper module undergoes a poloidal displacement of 23 mm, it results, hence, that no mechanical contact between neighbouring modules may be predicted.

5. Conclusions

A research campaign has been carried out at the University of Palermo in order to investigate the thermo-mechanical performances of the DEMO WCLL inboard blanket equatorial module, whether connected through the BSS to its pertinent inboard segment, under the OP steady state loading scenario.

The research campaign has been carried out following a theoretical-computational approach based on the finite element method (FEM) and adopting a qualified commercial code.

Thermo-mechanical results obtained have shown that a revision of the SPs has to be performed in order to limit both their primary and secondary stresses, possibly by changing their thickness, as well as to enforce the FW top and bottom corner regions avoiding their failure due to immediate plastic flow localisation. Moreover, a revision of the module preliminary design in the direction of stiffening its SB is strongly suggested in order to reduce its poloidal displacement field and avoid any potential contact occurrence with neighbouring modules.

A further development of the present work aims to realistically assess the thermal field of the module, considering its actual distribution of nuclear-deposited thermal load and the DWTs lay-out, in order to check its potential influence on the modules structural performances under both over-pressurization and normal operation loading scenarios. Moreover, a more realistic simulation of the attachment system action will be pursued in order to obtain more reliable displacement values especially along the poloidal direction.

Acknowledgments

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