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On the effect of stiffening plates configuration on the DEMO Water Cooled Lithium Lead Breeding Blanket module thermo-mechanical behaviour

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Within the framework of the pre-conceptual design of the EU-DEMO Breeding Blanket (BB) supported by EUROfusion action, results of the research activities carried out in the last years have highlighted that changes in the proposed WCLL BB design have to be considered, especially as to the liquid breeder circulation path within the BB module. Therefore, in view of the definition of a final WCLL BB module layout, a parametric campaign of numerical analyses has been carried out at the University of Palermo in order to assess the impact of different SPs configurations on the module thermo-mechanical performances.

To this purpose, attention has been focussed on the WCLL BB Outboard Central Segment and two different concepts have been considered, both based on the use of mixed horizontal (toroidal-radial) and vertical (poloidal-radial) SPs and mainly differing as to the allowed breeder flow path. For each concept, three toroidal-radial cells of the outboard module equatorial region have been considered and the effects of the thickness, pitch and radial length of their SPs on the module thermo-mechanical performances have been investigated under the Over-Pressurization (OP) accidental scenario, following the event of an in-box Loss Of Coolant Accident.

The study has been carried out following a theoretical-numerical approach based on the Finite Element Method (FEM) and adopting the quoted Abaqus FEM code. The results obtained are herewith reported and critically discussed.

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

1. Introduction

Within the framework of the pre-conceptual design of the EU-DEMO Breeding Blanket (BB), supported by EUROfusion action [1-4], the DEMO baseline revision occurred in 2017 [5] together with the evidence of recent studies [6-13] have posed the need for a deep revision of the WCLL BB lay-out, inspired to the single module concept and composed of an actively-cooled Segment Box (SB), articulated in a First Wall (FW) and two Side Walls (SWs) connected to a Back-Plate (BP) and internally reinforced by Stiffening Plates (SPs), and a Breeder Zone (BZ), housing the Pb-Li breeder.

In particular, the potential suppression of breeder manifolds in the Back Supporting Structure together with the need to reduce the impact of magneto-hydrodynamic pressure drop [14] on Pb-Li flow have mainly pushed the WCLL BB design team to find an alternative solution to the SPs configuration that might optimize the liquid breeder circulation path, ensuring the module to safely withstand the thermo-mechanical and electro-magnetic loads it undergoes under nominal and accidental loading scenarios, while minimizing its impact on the module tritium breeding performances.

Therefore, within the framework of the R&D activities intended to revise and finalize the EU-DEMO WCLL BB pre-conceptual design, a research campaign has been performed at the University of Palermo to optimize the thermo-mechanical performances of its Stiffening Plates (SPs) as a follow-up of similar activities already carried out as to both the FW and the BZ Double Walled Tubes (DWTs) [15,16].

Attention has been focussed on the WCLL BB Outboard Central Segment and two different concepts have been considered, both based on the use of mixed horizontal (toroidal-radial) and vertical (poloidal-radial) SPs and mainly differing as to the allowed breeder flow path (single-U turn or snake-like poloidal flow).

For each of them, a parametric analysis has been launched to assess the potential influence of the SPs grid main parameters (thickness, pitch and radial length) on the module thermo-mechanical performances under the Over-Pressurization (OP) incidental scenario following an in-Box Loss Of Coolant Accident. Furthermore, a stress linearization procedure has been applied along the SB most severely stressed paths so to select the SPs grids allowing the fulfilment of all the pertinent RCC-MRx design criteria [17] and, thus, ensuring the module to safely undergo the OP loading scenario.

A theoretical-numerical approach based on the Finite Element Method (FEM) has been followed and the Abaqus v.6.14-2 commercial FEM code has been adopted together with a set of Python script files, able to automatically set-up FEM models, run calculations and stress linearizations and check design criteria fulfilment.

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2. SP Configurations

SPs are intended to reinforce SB so to safely withstand the thermo-mechanical and electro-magnetic loads it undergoes under both nominal and accidental conditions. Furthermore, they contribute to define the breeder flow path, strongly impacting MHD pressure losses, and to absorb slowing-down neutrons, deeply affecting the blanket tritium breeding performances.

Among the SPs configurations taken into account, attention has been focussed on those relying on the use of mixed horizontal (toroidal-radial, SP_h) and vertical (poloidal-radial, SP_v) SPs, for their expected positive impact on the module structural, thermal-hydraulic and nuclear performances. In fact, the adoption of these SPs allows a more distributed and effective SB reinforcement against pressure-induced toroidal-radial expansion, due to the presence of tens of thin horizontal plates instead of few thick vertical (poloidal-radial and poloidal-toroidal) ones. Moreover, their implementation encourages the use of toroidal-radial instead of poloidal DWTs, reducing coolant pressure drops and easing the integration with poloidal manifolds [13]. Finally, their aptitude to safely operate even leaving radial openings nearby the FW, in the highly-peaked neutron flux region, contributes to reduce their neutron absorptions and, hence, their negative impact on tritium breeding performances.

In particular, two mixed SPs configurations (Fig. 1), mainly differing as to the breeder flow path (single-U turn or snake-like poloidal flow) have been investigated.

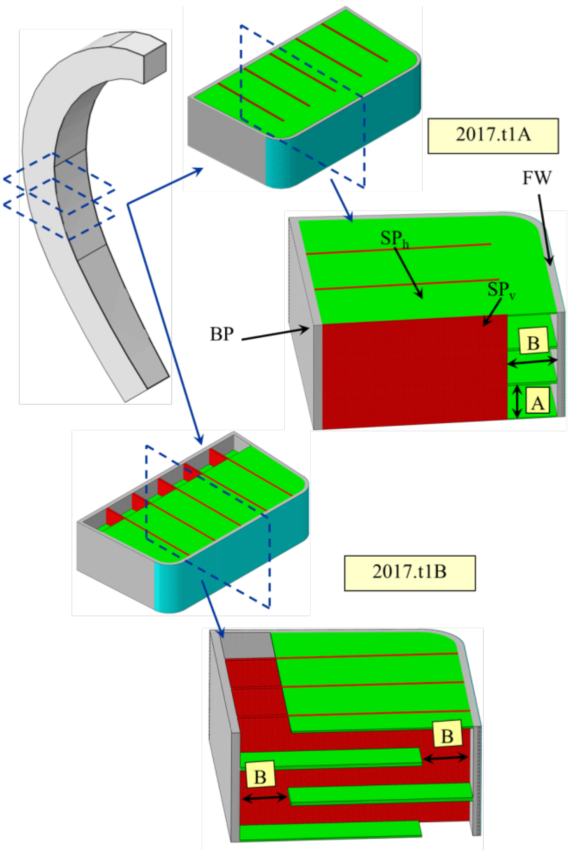

Fig. 1. SPs configurations investigated.

The first configuration, named WCLL2017.t1A, foresees a grid based on horizontal SPs, extending for the whole radial length of the BZ, together with vertical SPs, detached from the FW so to leave an opening in the radial direction (Fig. 1). The second configuration, named WCLL2017.t1B, is characterized by vertical SPs, extending for the whole radial length of the BZ, and horizontal SPs, leaving alternatively a radial opening in the frontal and rear part of the BZ so to induce a snake-like circulation of the breeder (Fig. 1).

Both the two SPs configurations give rise to a blanket module concept that relies on a poloidal stack of elementary toroidal-radial cells delimited by the SB and their horizontal SPs.

3. Parametric Analysis

The thicknesses of both horizontal and vertical SPs (t_h, t_v), the poloidal pitch between two horizontal SPs (A) and the opening radial width (B) have been selected as the main geometrical parameters of both SPs configurations investigated and their influence on the module thermo-mechanical performances under the OP incidental scenario has been numerically assessed by means of a dedicated parametric analysis.

The values of each geometrical parameter considered for the parametric analysis may be deduced from Table 1 from which it may be argued that 96 and 392 different SPs grids have been selected to be numerically investigated with reference to the configurations WCLL2017.t1A and WCLL2017.t1B, respectively.

Tab. 1. Geometrical parameters values.

	WCLL2017.t1A		WCLL2017.t1B	
Parameter	**Range**	**Step**	**Range**	**Step**
t_h [mm]	10÷13	1	10÷16	1
t_v [mm]	12÷17	1	14÷20	1
A [mm]	135÷162	27	135÷216	27
B [mm]	100÷170	70	87.5÷175	87.5

As a proper compromise between results' accuracy and computational effort, a simplified 3D FE model has been set-up by a Python script for each SPs grid studied, realistically reproducing a poloidal stack of three equatorial elementary cells of the WCLL BB module of a DEMO Outboard Central Segment (Fig.s 2, 3). In particular, breeder, DWTs and coolant have not been modelled to speed-up calculations and their thermo-mechanical effects have been simulated adopting a proper set of loads and boundary conditions [15].

FE models are composed of ~850÷900·10^3 nodes connected in ~700÷730·10^3 linear hexaedral elements. EUROFER steel has been assumed as the structural material, except for the 2 mm-thick FW armour (shown in cyan in Fig.s 2 and 3) supposed as made of tungsten. Materials have been considered uniform, isotropic and linearly elastic and their thermo-mechanical properties have been assumed to depend only on temperature [17].

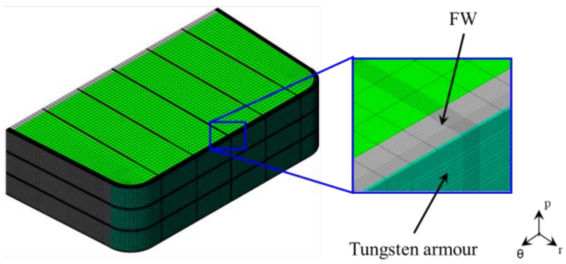

Fig. 2. FE model of configuration WCLL2017.t1A.

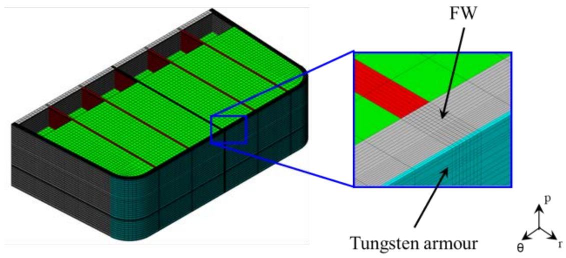

Fig. 3. FE model of configuration WCLL2017.t1b.

The OP scenario loading conditions have been simulated imposing a pressure of 18.6 MPa onto internal surfaces. Moreover, a proper non-uniform thermal strain field has been implemented adopting the nominal temperature profile calculated for the OB4 module [7]. Finally, in order to take into account the module poloidal continuity as well as to simulate the attachment system action, symmetry and plane strain conditions have been imposed to the model poloidal boundary surfaces and the set of restraints indicated in Fig. 4 has been applied to selected BP nodes.

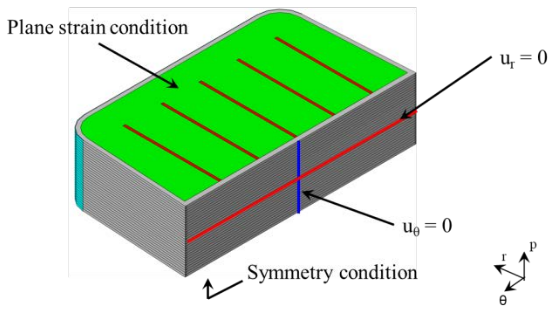

Fig. 4. Mechanical restraints.

A FEM steady state thermo-mechanical analysis has been run for each SPs grid, assessing the spatial distribution of primary, secondary and total stress tensor fields. Results have been automatically processed performing stress linearizations in ~100 critical paths, located within FW, SWs and SPs, to verify whether the calculated thermo-mechanical stress state would comply with the Level D criteria prescribed by the RCC-MRx code [17]. To this purpose, the utilization factor (F) has been calculated for each design rule considered, as the ratio between the calculated stress invariant invoked by the rule itself and the corresponding stress limit.

3.1. Configuration WCLL2017.t1A Results

Results obtained have indicated that a maximum SP_h pitch (A) of 135 mm (10 FW channels) may be tolerated in order to let the SPs configurations safely withstand the OP scenario thermo-mechanical loads (Table 2). Moreover, they indicate that the most stressed path lies within the SWs (Fig. 5), where the membrane component of the primary stress is particularly intense since vertical SPs, being not connected to the FW, do not directly contribute to its radial equilibrium, leaving the counterbalancing of SB pressurization to SWs and Caps radial stresses. Consequently, the impact of SP_v thickness on the F factor for primary and total membrane stress criteria results quite modest (Fig. 6).

Finally, since no significant differences have been found among the 48 eligible SPs grids, the optimized one (highlighted in green in Table 2) has been selected so to minimize the BZ steel amount, reducing it down to the 88.7% of its reference amount, with a maximum F of 0.875.

Tab. 2. Number N of allowable configurations.

A [mm]	N	t_h [mm]	N	t_v [mm]	N	B [mm]	N
135	48	10	12	12	8	100	24
162	0	11	12	13	8	170	24
		12	12	14	8		
		13	12	15	8		
				16	8		
				17	8		

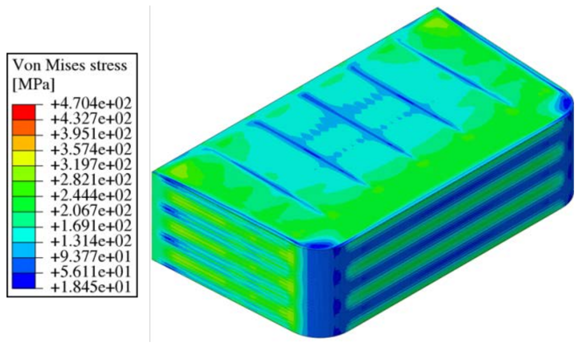

Fig. 5. Von Mises stress field in the optimized configuration.

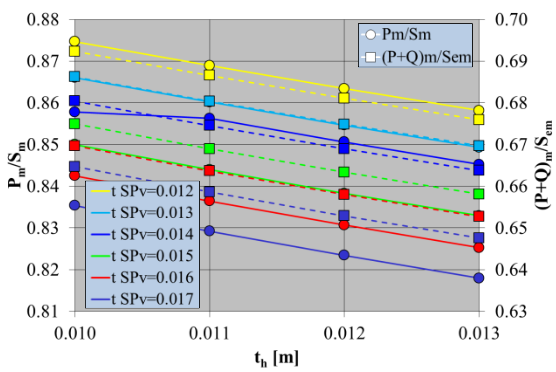

Fig. 6. F vs t_h and t_v - SW path 60 - A = 135 mm; B = 170 mm.

3.2. Configuration WCLL2017.t1B Results

Results obtained have shown that, among the 392 configurations investigated, only 64 comply with the RCC-MRx design criteria, being characterized by horizontal SPs with a maximum pitch of 135 mm and a minimum thickness of 11 mm (Table 3). They indicate also that the most stressed paths lie within the horizontal SPs and the FW (Fig. 7), where significant membrane primary stresses arise to guarantee the SB toroidal equilibrium, counterbalancing the pressurization effect. This is mainly due to the reduction of the poloidal-radial SP_h resistant section offered to SB toroidal equilibrium. Moreover, it has to be highlighted that vertical SPs, connecting BP to FW, effectively contribute to both the SB radial equilibrium, reducing the SWs membrane primary stress, and the FW constraining, limiting its bending primary stress. Therefore, the impact of SP_v thickness on the F factor for membrane and bending stress criteria on the FW becomes significant (Fig. 8).

Tab. 3. Number N of allowable configurations.

A [mm]	N	t_h [mm]	N	t_v [mm]	N	B [mm]	N
135	64	10	0	14	5	87.5	31
162	0	11	4	15	7	175	33
189	0	12	8	16	8		
216	0	13	11	17	10		
		14	14	18	10		
		15	14	19	12		
		16	13	20	12		

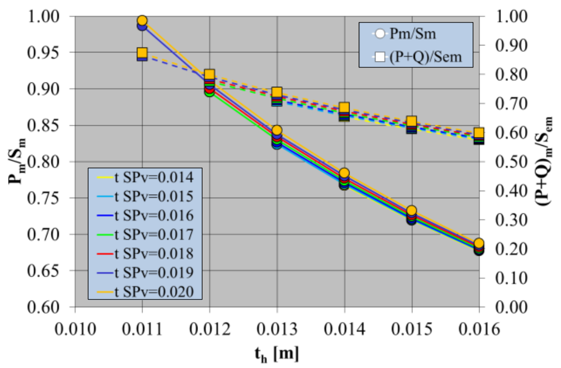

Fig. 7. F vs t_h and t_v - SP_h path 83 - A = 135 mm; B = 175 mm.

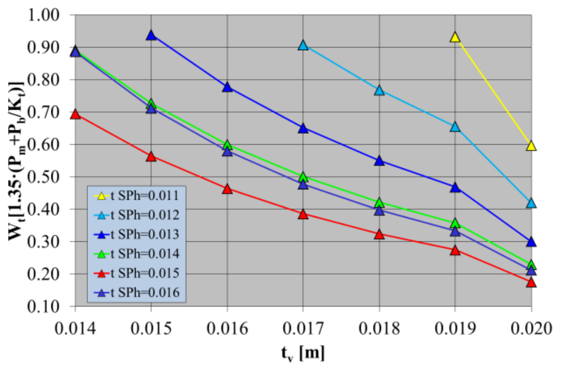

Fig. 8. F vs t_v and t_h - FW path 26 - A = 135 mm; B = 175 mm.

Finally, among the allowable configurations, it has been selected that highlighted in green in Table 3, that slightly reduces the BZ steel amount down to the 97.1% of its reference amount, with a maximum F of 0.94.

4. Conclusions

Within the framework of the EU-DEMO WCLL BB pre-conceptual design activities, a theoretical-numerical research campaign has been carried out at the University of Palermo to optimize the thermo-mechanical performances of its Stiffening Plates (SPs).

Attention has been put onto two configurations (WCLL2017.t1A and WCLL2017.t1B), commonly based on the use of mixed toroidal-radial and poloidal-radial SPs, and a numerical parametric analysis has been performed to assess the impact of the SPs thickness, pitch and radial length on the BB module thermo-mechanical performances under the OP scenario, with the final aim to select those optimised SPs grids allowing to reduce the BZ steel amount while complying with the RCC-MRx design criteria.

Results have allowed to find 48 and 64 viable SPs grids for the WCLL2017.t1A and WCLL2017.t1B configurations, respectively. Among them, the following "optimized" grids have been selected so to reduce the total amount of steel within the BZ (Table 4).

Tab. 4. Selected SPs grids.

Parameter	WCLL2017.t1A	WCLL2017.t1B
t_h [mm]	10	13
t_v [mm]	12	15
A [mm]	135	135
B [mm]	170	175

Finally, it has to be underlined that, due to the modelling assumptions, the results obtained have to be intended as strictly relevant to the BB module equatorial region and they cannot be extrapolated to its poloidal peripheral regions, that deserve a dedicated investigation by means of more detailed numerical models.

Acknowledgments

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