Structural assessment of the EU-DEMO WCLL Central Outboard Blanket Segment under normal and off-normal operating conditions

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Within the framework of the EUROfusion design activities concerning the EU-DEMO Breeding Blanket (BB) system, a research campaign has been carried out at the University of Palermo with the aim of investigating the structural behaviour of the DEMO Water-Cooled Lithium Lead (WCLL) Central Outboard Blanket (COB) segment. The assessment has been performed considering three different loading scenarios: the Normal Operation (NO), the Over-Pressurization (OP) and the Vertical Displacement Event up (VDE-up). In particular, NO scenario represents the loading case referring to the nominal operating conditions, whereas the OP scenario refers to the loading conditions due to an in-box LOCA accident, listed as one of the BB design basis accidental events. Lastly, the VDE-up scenario is an off-normal event reproducing the plasma disruption caused by an uncontrolled vertical motion of the plasma volume. This event brings the plasma in contact with the upper walls, generating a sudden energy discharge accompanied by relevant Electro Magnetic (EM) forces on the structure. The study has been conducted following a theoretical-numerical approach based on the Finite Element Method (FEM) and adopting the quoted ABAQUS v. 6.14 commercial FEM code. In particular, a detailed 3D FEM model of the whole COB segment, including the back-supporting structure and its attachment system to the vacuum vessel, has been set up. Several simulations have been carried out to assess the thermo-mechanical performances of the segment under the afore-mentioned loading scenarios, taking into account also the impact of the W-armour on the overall structural response. EM loads have been considered in all the assessed scenarios. In the first two, only magnetization forces have been taken into account, while in the VDE-up scenario also Lorentz's forces have been taken into account. The structural response has been evaluated in view of the RCC-MRx structural design rules. The obtained results are herewith presented and critically discussed.

Keywords: DEMO, WCLL, breeding blanket, VDE, FEM analysis.

1. Introduction

Within the framework of the European studies on the DEMO Breeding Blanket (BB) [1][2][3][4], promoted by the EUROfusion consortium, the Department of Engineering (DI) of the University of Palermo, in close cooperation with ENEA-Brasimone, is in charge of pursuing the conceptual design of the Water-Cooled Lithium Lead (WCLL) BB. In the present work, carried out in cooperation with Karlsruhe Institute of Technology (KIT) as well, the assessment of the thermo-mechanical performances of the WCLL BB Central Outboard Blanket (COB) segment in different levels of service is reported.

To this end, three different steady-state loading scenarios have been taken into account: the Normal Operation (NO), the Vertical Displacement Event up (VDE-up) and the Over-Pressurization (OP). The NO scenario considers the thermo-mechanical loads arising under the nominal operating condition and therefore it is considered as Level A scenario in RCC-MRx structural design code [5][6]. Instead, the VDE-up scenario refers to an off-normal event due to a plasma disruption, being classified as Level C. Lastly, the OP loading scenario refers to a severe accidental condition, relevant to a coolant leak within the segment, which ultimately entails the loss of the component. It is hence classified under Level D in RCC-MRx structural design code

Differently from the structural analyses conducted so fare for the WCLL BB [7], Electro Magnetic (EM) loads have been taken into account in all the postulated scenarios. In particular, static ferromagnetic loads have been considered for NO and OP scenarios, while, for what concerns the transient event, the most critical time steps have been selected and steady-state analyses have been performed assuming the corresponding EM loads spatial distributions. Moreover, in order to investigate the impact of the tungsten armour on the thermo-mechanical response of the COB segment, two different geometric layouts (with and without tungsten armour) have been set-up and assessed under the three considered loading scenarios.

Once calculated the stress field in all the assumed loading scenarios and for the two geometric configurations considered, a stress linearization procedure has been performed along paths located within the most stressed regions of the COB segment. The results have allowed verifying the fulfilment of Level A, Level C and Level D rules prescribed by the RCC-MRx structural design code.

To this purpose, a theoretical-numerical approach based on the Finite Element Method (FEM) has been followed and the quoted commercial FEM code Abaqus v. 6.14 [8] has been adopted. The obtained results are

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herewith presented and critically discussed, focussing on the follow-up of the performed research activity.

2. WCLL BB COB segment

According to the currently adopted DEMO baseline 2017 [9], 16 identical toroidal sectors are envisaged within the machine. As to BB, each sector is divided into 2 inboard and 3 outboard segments (Fig.1). In particular, according to the Single Module Segmentation (SMS) concept [7], a segment of the WCLL BB foresees the repetition of a single elementary cell along the poloidal direction. In this study the attention has been paid to the central outboard segment (COB) of a WCLL BB sector.

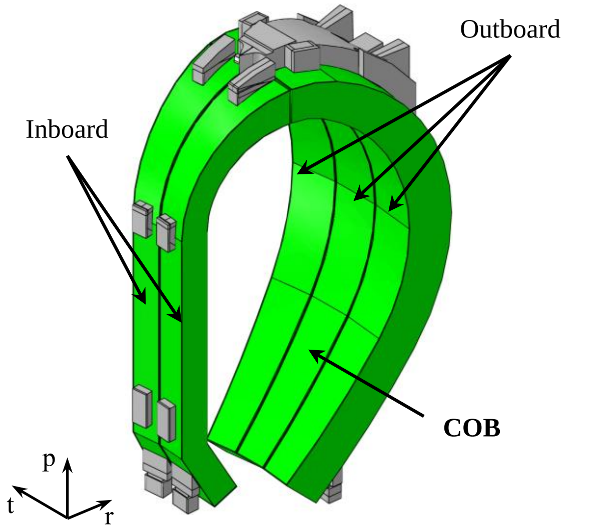

Fig.1 WCLL Breeding Blanket Sector

In particular, the COB segment (Fig.2) is mainly constituted by an external steel structure named Segment Box (SB). It is composed, in its turn, by First Wall (FW) and Side Walls (SWs), and it is closed vertically by upper and lower Caps [10]. The SB is internally reinforced by a system of Stiffening Plates (SPs). The SPs laying on the poloidal-radial plane are called vertical SPs whereas those laying on the toroidal-radial plane are the horizontal SPs [11].

Moreover, a 2 mm-thick Tungsten armour coats the FW and an attachment system is devoted to mechanically connect the SB to the Vacuum Vessel (VV). The SB encloses the Breeder Zone (BZ) in which the Lithium-Lead (PbLi), a liquid metal eutectic alloy acting as breeder and neutron multiplier, flows along the poloidal direction throughout the SPs, following the path highlighted in yellow in Fig.3. The SB internals, i.e. the BZ, are cooled by means of bundles of Doubled Walled Tubes (DWTs) [12][13] whereas FW, SWs and Caps are endowed with square section cooling channels. Inside both DWTs and channels, subcooled water at the pressure of 15.5 MPa flows. Here, in order to save computational resources and speed-up calculations, the model developed for the purposes of this study has been simplified removing DWTs and square channels (Fig.3), but their effect on the thermal field have been purposely considered.

Two Finite Element models, one with W-armour and one without, composed of ~2.3M nodes connected in ~4.6M tetrahedral and hexahedral linear elements have been set-up. Water and breeder have not been modelled but their effects on the thermo-mechanical behaviour have been reproduced considering proper loads and boundary conditions.

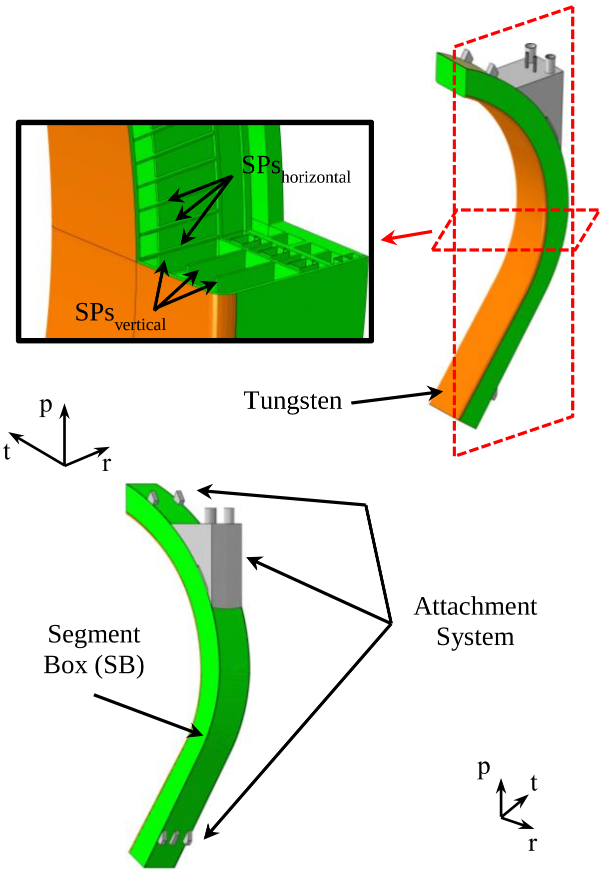

Fig.2 Central Outboard Segment architecture

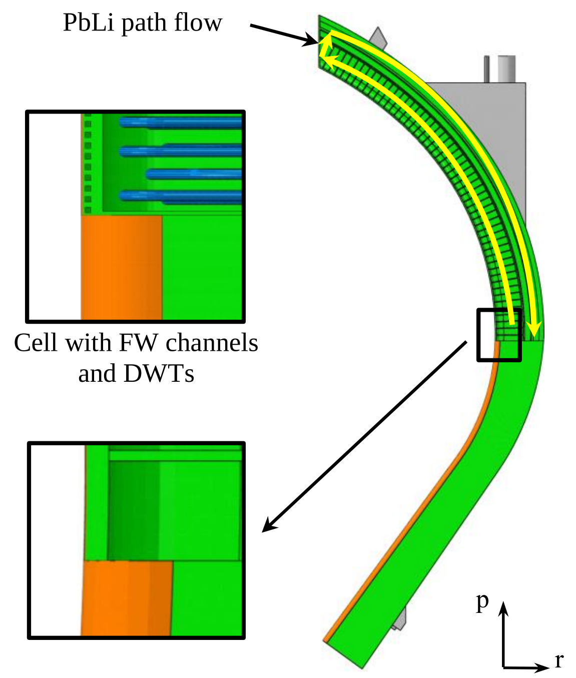

Fig.3 Central Outboard Segment architecture detail

3. Loads and Boundary conditions

In order to correctly reproduce the NO, OP and VDE-up loading scenarios, a set of loads and boundary condition has been implemented [14][15]. In particular, the following loads and boundary conditions have been taken into account:

- Non uniform thermal deformation field;
- Pressure;
- Gravity load;
- Electro-Magnetic loads;
- Mechanical restraints.

A non-uniform temperature spatial distribution, drawn from reference WCLL COB Equatorial region analysis [12], has been imposed to the COB structure in order to obtain the corresponding non-uniform thermal deformation field. In particular, the applied thermal field has been found out by a detailed interpolation procedure of the thermal analysis results obtained in [12]. To this purpose, different regions have been considered for the original thermal field interpolation: SW-FW-SW, 6 regions for the toroidal-radial SPs, delimited by poloidal-radial SPs, 5 regions for the vertical SPs and manifold region (Fig. 4). In particular, a polynomial function of one or two variables has been adopted for each region in order to best reproduce the original thermal field:

- SW-FW-SW region: 14^{th} degree polynomial function of two variables (radial and toroidal direction);
- Manifolds region: 9^{th} degree polynomial function of one variable (radial direction);
- SPh regions: six different $8/10^{th}$ degree polynomial functions of two variables (radial and toroidal direction), one per region;
- SPv regions: five different 12^{th} degree polynomial functions of one variable (radial direction), one per region.

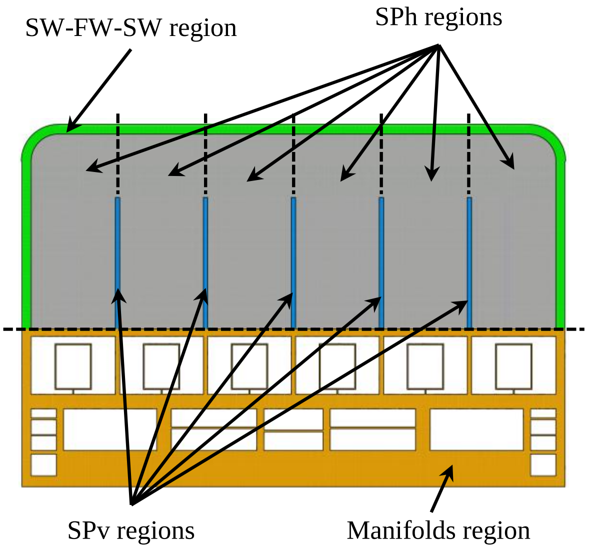

Fig. 4 Regions for the thermal field interpolation

Then, the so obtained interpolating polynomials have been applied to the whole COB segment as shown in Fig.5.

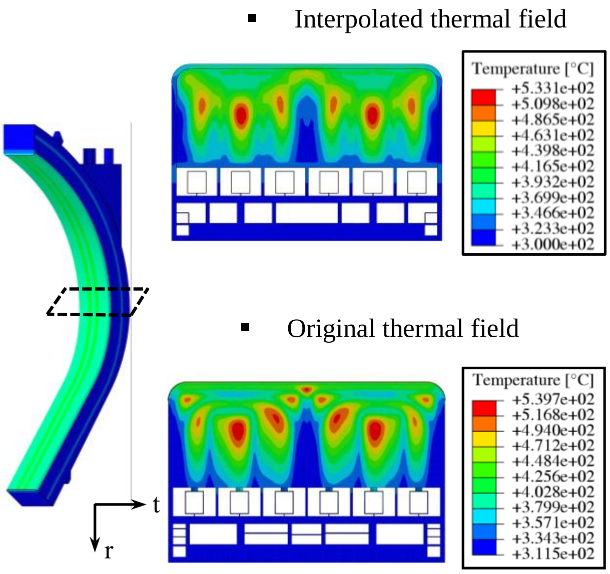

Fig.5 Comparison between original and imposed thermal field

As prescribed in [14][15], the design pressures, calculated as the nominal pressure multiplied by a safety factor of 1.15, have been adopted for this study. Therefore, a coolant design pressure ($P_{des,coolant}$) of 17.825 MPa and a breeder design pressure ($P_{des,breeder}$) of 0.575 MPa have been set. Concerning NO and VDE-up scenarios, $P_{des,coolant}$ has been imposed onto all the coolant manifolds surfaces while $P_{des,breeder}$ has been assumed acting on the breeder-wetted surfaces. Instead, for OP loading scenario, $P_{des,coolant}$ has been considered for both manifolds and breeder-wetted surfaces as this scenario represents the over-pressurization conditions due to an in-box LOCA event.

The reduced activation Ferritic/Martensitic (RAFM) Eurofer steel has been considered as SB structural material, covered by a thin Tungsten layer. Water and breeder have not been modelled, so, in order to simulate their presence in terms of weight force, an Eurofer equivalent density have been calculated (assumption already adopted in previous analyses [7]). In particular, this value has been calculated considering the percentage of steel, breeder and water inside an equatorial cell. Temperature-dependent properties of Eurofer [16][17] and Tungsten [18] have been adopted and considered in the analysis, properly modifying the EUROFER density, as afore mentioned. So, the acceleration of gravity value has been imposed on the whole structure.

During both normal and off-normal operations, EM loads arise and act within the structure. In the case of a steady state analysis, the EM loads related to a single instant of time (time step) are considered and implemented. In particular, during the NO loading scenario, according with the assumption that the Lorentz's forces due to the variation of the poloidal field coils during the flat-top is negligible [19], only the contribution given by the ferromagnetic loads has been considered. According to [14][15], the same EM loads have been used for the OP loading scenario. On the contrary, during the considered plasma vertical displacement event (VDE-up) loading scenario, the impact of Lorentz's forces is not negligible and must be taken into account. Since EM loads related to a plasma disruption undergo great variations [20][21], a selection of the most demanding time steps has been made and respective equivalent static analyses (neglecting dynamic effects) have been launched. In particular, looking at the time behaviour of the force and moment components acting on the COB segment (Fig.6), the time steps corresponding to the maximum of the radial force (t = 11.52 s) and moment (t = 11.585 s) have been considered for the structural analyses.

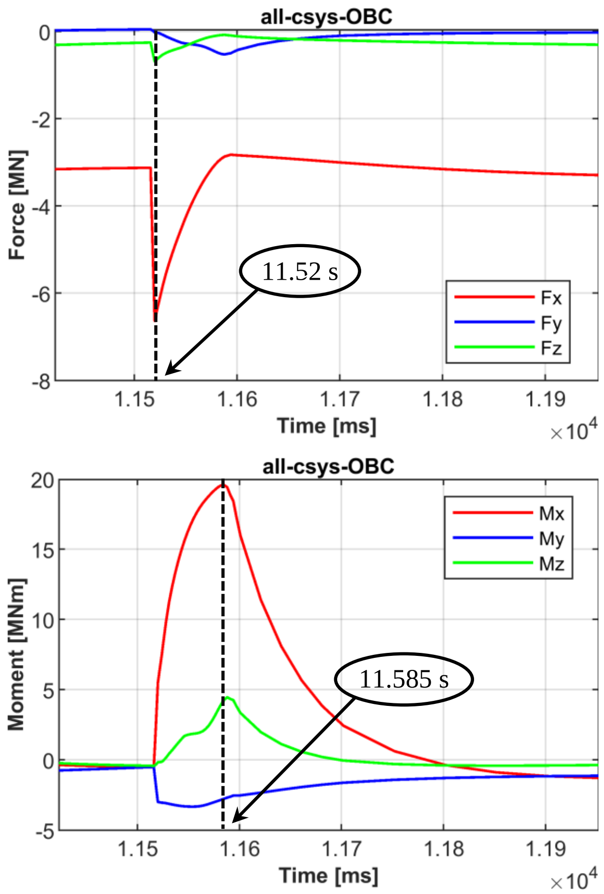

Fig.6 Force and moment time behaviour during a VDE-up [19] and maximum component (i.e. radial) time steps

Thus, in total, four operative steady state scenarios have been considered and, for each of them, the thermo-mechanical performances of the WCLL BB COB segment with and without tungsten armour have been investigated.

Lastly, in order to reproduce the mechanical action of the COB attachment system to the VV, a set of mechanical restraints has been imposed. In particular, a set of springs has been located in correspondence of each blanket support structure, as reported in [22].

4. COB thermo-mechanical assessment

Steady state analyses have been launched in order to assess the thermo-mechanical behaviour of COB in both configurations with and without the W-armour.

Von Mises equivalent stress field (primary + secondary stress) obtained for the different assessed scenarios, in both cases with and without tungsten, are shown in Fig.7, Fig.8, Fig.9 and Fig.10. For all four loading operative scenarios, it is possible to observe that the most of the investigated domain experiences stress values lower than 500 MPa. Moreover, in all the four operative loading scenarios investigated, in the configuration without tungsten an average stress level greater than the case where the armour is considered is predicted.

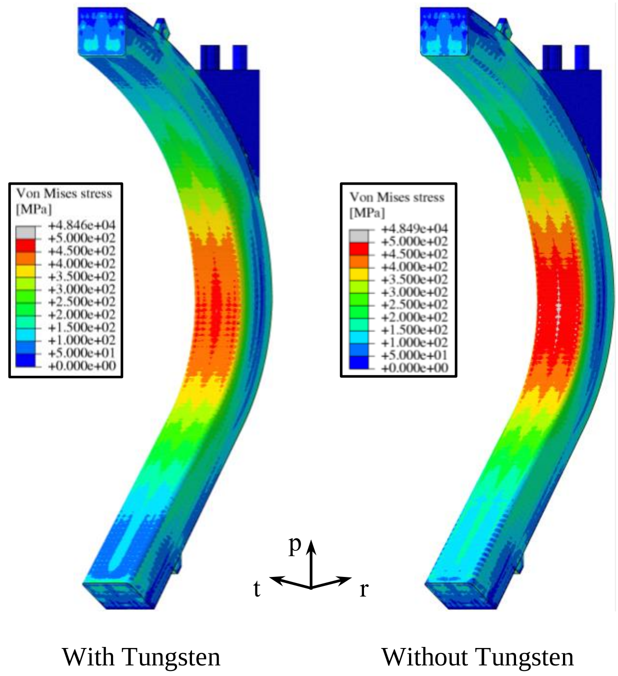

Fig.7 NO Von Mises stress field

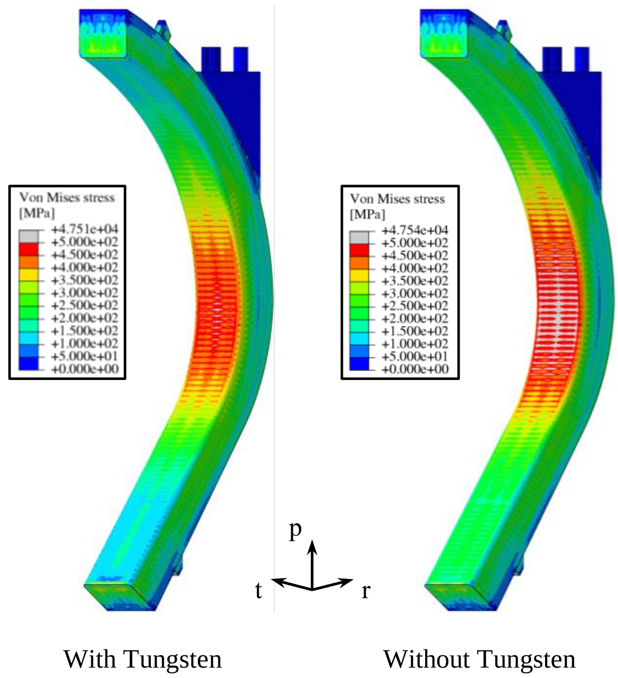

Fig.8 OP Von Mises stress field

Moreover, the deformed (with an isotropic deformation amplification factor equal to 30) vs. undeformed shapes are reported in Fig.11, Fig.12, Fig.13 and Fig.14, also showing the total displacement fields. The maximum displacement values obtained along the three directions (radial, toroidal and poloidal) have been reported in Tab.1. In particular, the deformation field is almost the same in all the assessed scenarios with a maximum displacement along the radial direction, value obtained in the NO loading scenario, with W-armour, equal to 46.63 mm. On the other hand, only small displacements occur in toroidal direction, quite symmetrically.

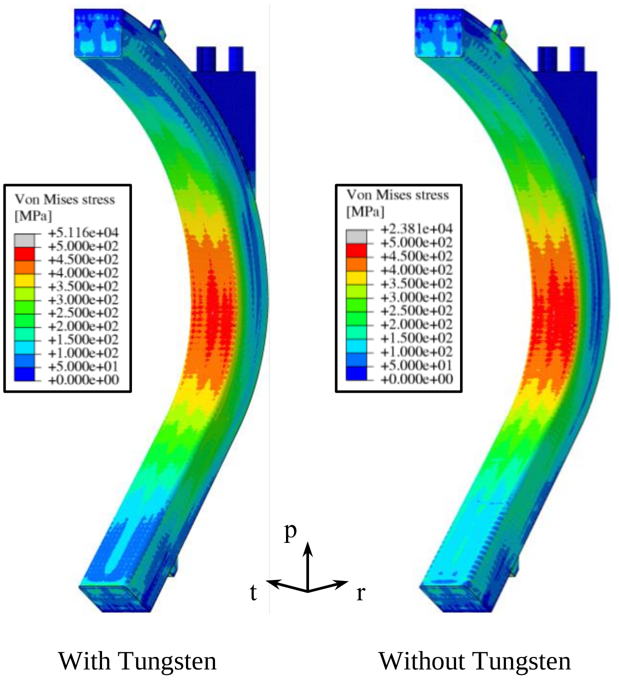

Fig.9 VDE-up Von Mises stress field - T= 11.585 s

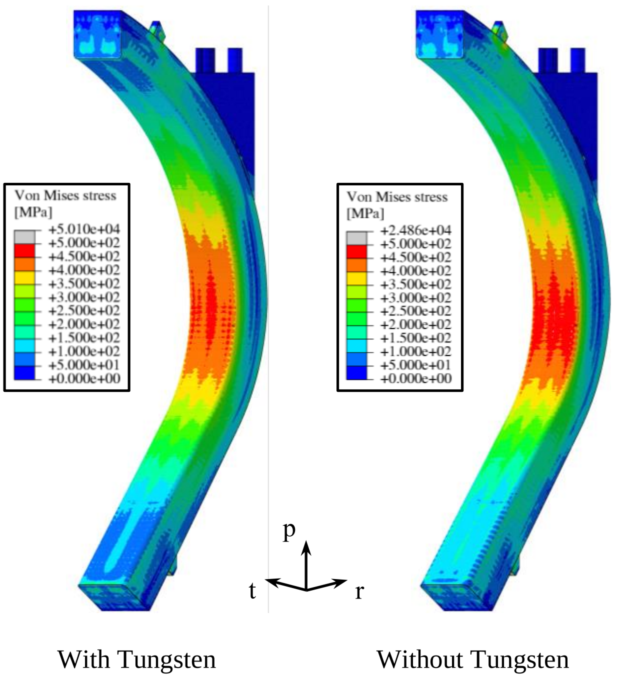

Fig.10 VDE-up Von Mises stress field - T= 11.52 s

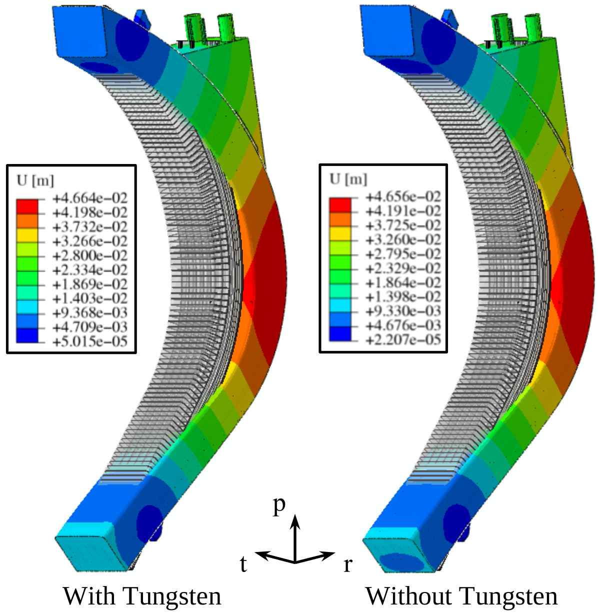

Fig.11 NO Def. vs. Undef. Shapes

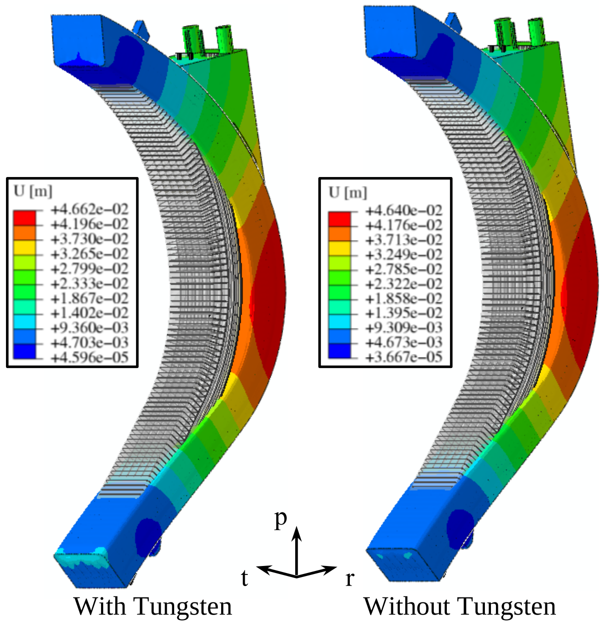

Fig.12 OP Def. vs. Undef. Shapes

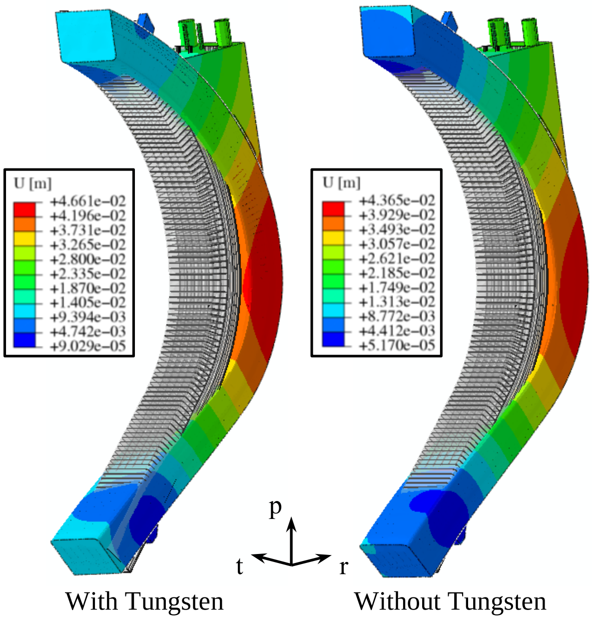

Fig.13 VDE-up Def. vs. Undef. shapes - T= 11.585 s

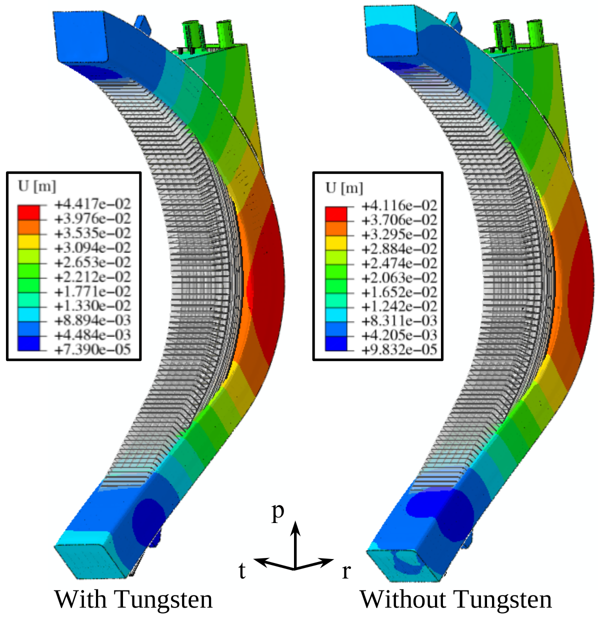

Fig.14 VDE-up Def. vs. Undef. shapes - T= 11.52 s

Maximum displacements				
	NO W	**NO** NO W	**OP** W	**OP** NO W
u(r)	**46.63 mm**	46.50 mm	46.61 mm	46.40 mm
u(-r)	9.81 mm	9.24 mm	9.56 mm	9.23 mm
u(t)	3.84 mm	4.02 mm	4.18 mm	4.29 mm
u(-t)	4.41 mm	4.43 mm	4.44 mm	4.46 mm
u(p)	21.77 mm	21.76 mm	22.16 mm	22.14 mm
u(-p)	7.85 mm	7.76 mm	8.17 mm	8.07 mm
	VDE-up T=11.52 W	**VDE-up T=11.52** NO W	**VDE-up T=11.585** W	**VDE-up T=11.585** NO W
u(r)	44.13 mm	41.11 mm	46.58 mm	43.57 mm
u(-r)	10.01 mm	8.88 mm	10.92 mm	8.63 mm
u(t)	5.08 mm	5.21 mm	7.67 mm	6.06 mm
u(-t)	5.23 mm	5.09 mm	12.74 mm	7.33 mm
u(p)	22.15 mm	22.65 mm	22.06 mm	22.52 mm
u(-p)	7.14 mm	7.06 mm	8.06 mm	7.19 mm

Tab.1 Maximum displacement values in all the assessed scenario

In order to evaluate the thermo-mechanical behaviour of COB in the different scenarios taken into account, a stress linearization procedure has been carried out within the most critical regions individuated. In particular, the most stressed regions have been identified within the poloidal-radial and toroidal-radial SPs and proper paths have been built. No paths have been considered along the SW-FW-SW region due to the absence of the cooling channels. In particular, four paths have been considered for a single elementary cell, two throughout vertical SPs and two throughout horizontal SP, as depicted in Fig.15. Paths located in the same position as the central cell have also been identified in other two cells located in the upper part and in lower part of the COB, indicated in red in Fig.15.

After the stress linearization procedure was performed, the RCC-MRx structural design criteria have been checked in order to verify the structural integrity of the component. In particular, P-type failure, resulting from applying a constantly increasing load, have been considered. The rules taken into account are: Immediate Excessive Deformation (IED), Immediate Plastic Instability (IPI) and Immediate Plastic Flow Localization

(IPFL) criteria. In detail, the first two take into account the primary stresses (membrane and bending stresses, P_m and P_b, respectively) while the latter also considers secondary stresses, Q_m, that portion of the total stress which can be relaxed as a result of small scale permanent deformation, i.e. thermal stresses, swelling stresses and stresses due to imposed displacements or deformations. In Tab.2 the criteria are reported, where S_m is the maximum allowable primary membrane stress intensity of the material, S_{em} is the maximum allowable primary plus secondary membrane stress, function of temperature and irradiation and K_{eff} is a factor called "plastic collaboration coefficient", equal to 1.5 for rectangular sections. Values of S_m and S_{em} [23] have been differently calculated for Level A, C or D.

	Criteria
Immediate Excessive Deformation	$P_m/S_{m,A\text{-}C\text{-}D}<1$
Immediate Plastic Instability	$P_m+P_b/K_{eff}\cdot S_{m,A\text{-}C\text{-}D}<1$
Immediate Plastic Flow Localization	$(P_m+Q_m)/S_{em,A\text{-}C\text{-}D}<1$

Tab.2 RCC-MRx safety criteria

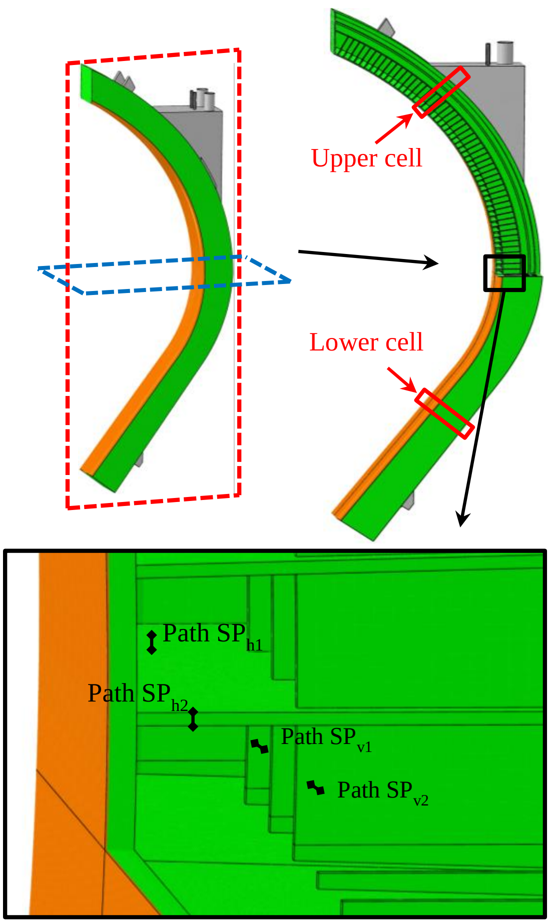

Fig.15 Stress linearization paths in the central cell

Stress linearization results have shown that during the NO and OP loading scenarios W-armour does not influence the paths response to the criteria. In NO loading scenario (Fig.16, Fig.17 and Fig.18) IED and IPI criteria are fulfilled along all paths, while the IPFL criterion is not. In this case, the paths located within the vertical SPs are the most critical. Instead, in OP loading scenario (Fig.19, Fig.20 and Fig.21) not all criteria are fulfilled along all the paths taken into account and the path individuated along the external SP_v (named SP_{v1}) in the central elementary cell do not fulfil any criteria. Moreover, during both VDE-up loading scenarios assessed, IED (Fig.22 and Fig.25) and IPI (Fig.23 and Fig.26) criteria are widely fulfilled within all the paths taken into account. Instead, only the path located along the external SPv (called SP_{v1}), in all three cell position considered, does not fulfil the IPFL criterion (Fig.24 and Fig.27), in both configuration. No significant differences have been found between the two case with and without tungsten armour.

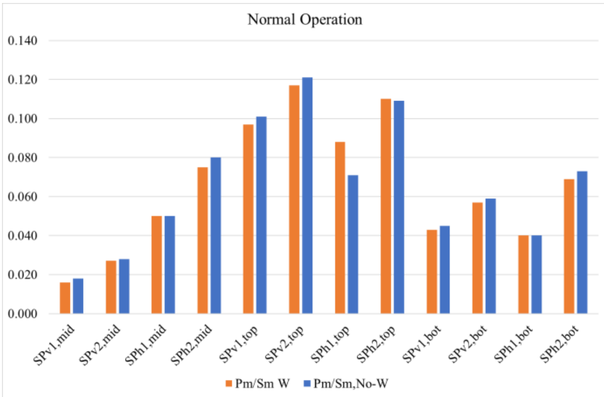

Fig.16 SL results under NO loading scenario - P_m/S_m Level A RCC-MRx safety criteria

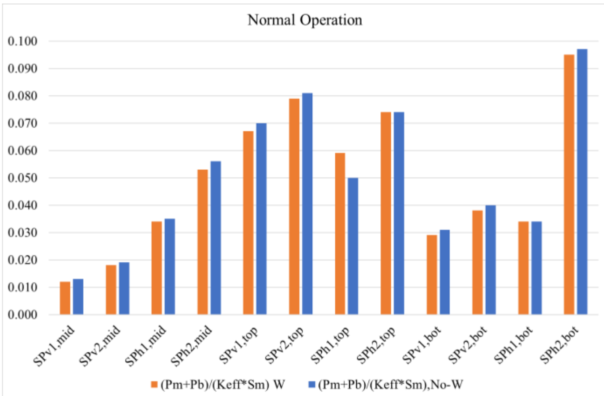

Fig.17 SL results under NO loading scenario - $(P_m+P_b)/K_{eff}\,S_m$ Level A RCC-MRx safety criteria

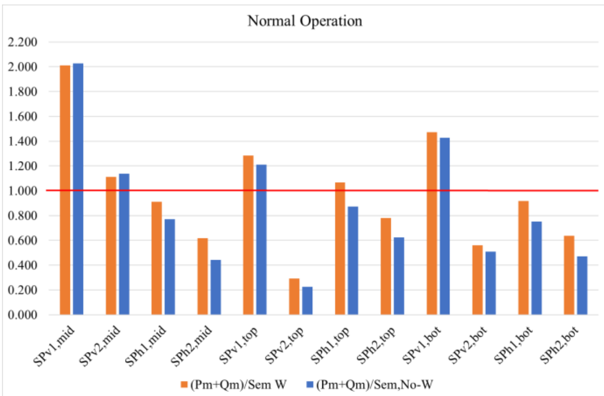

Fig.18 SL results under NO loading scenario - $(P_m+Q_m)/S_{em}$ Level A RCC-MRx safety criteria

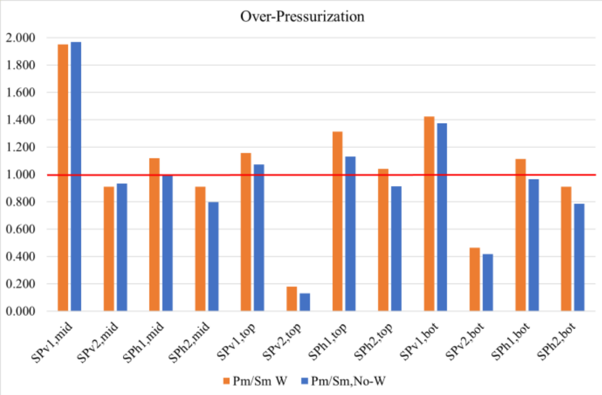

Fig.19 SL results under OP loading scenario - P_m/S_m Level D RCC-MRx safety criteria

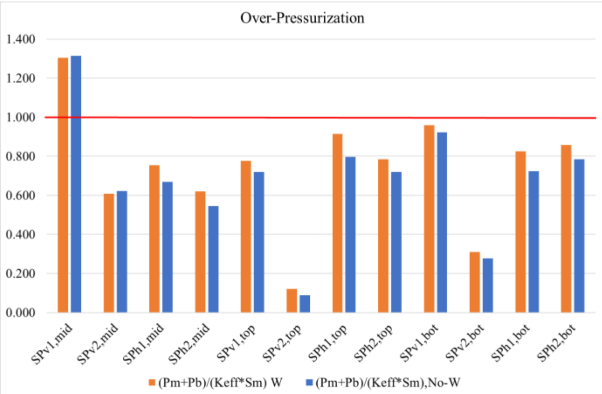

Fig.20 SL results under OP loading scenario - $(P_m+P_b)/K_{eff}S_m$ Level D RCC-MRx safety criteria

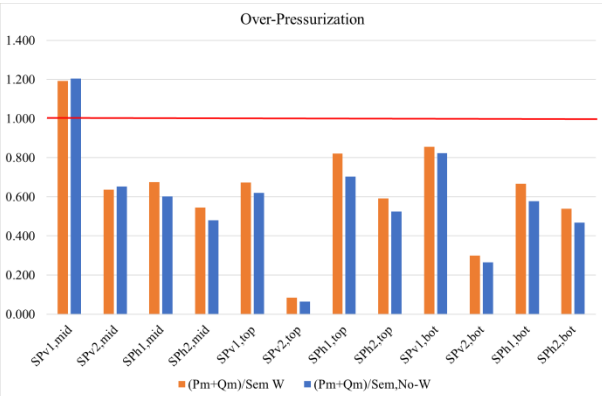

Fig.21 SL results under OP loading scenario - $(P_m+Q_m)/S_{em}$ Level D RCC-MRx safety criteria

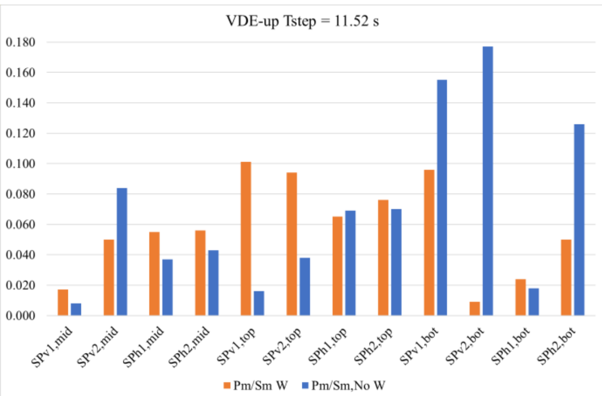

Fig.22 SL results under VDE-up loading scenario - P_m/S_m Level C RCC-MRx safety criteria

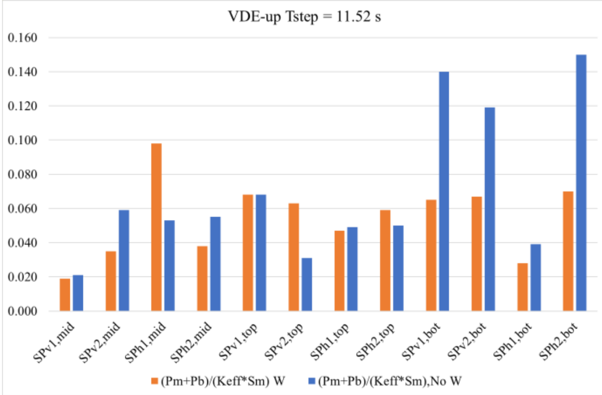

Fig.23 SL results under VDE-up loading scenario - $(P_m+P_b)/K_{eff}S_m$ Level C RCC-MRx safety criteria

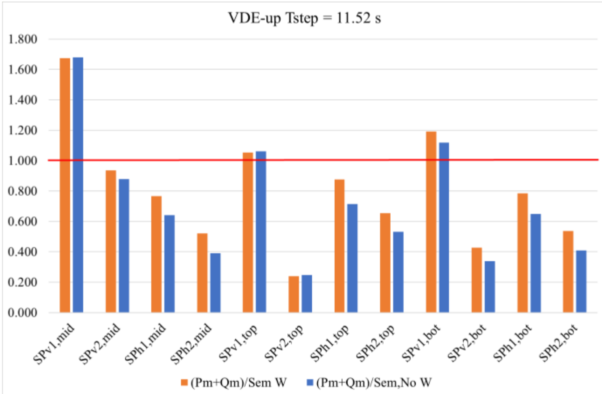

Fig.24 SL results under VDE-up loading scenario - $(P_m+Q_m)/S_{em}$ Level C RCC-MRx safety criteria

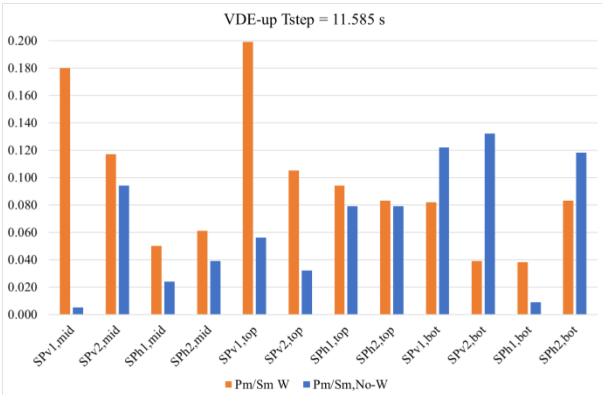

Fig.25 SL results under VDE-up loading scenario - P_m/S_m Level C RCC-MRx safety criteria

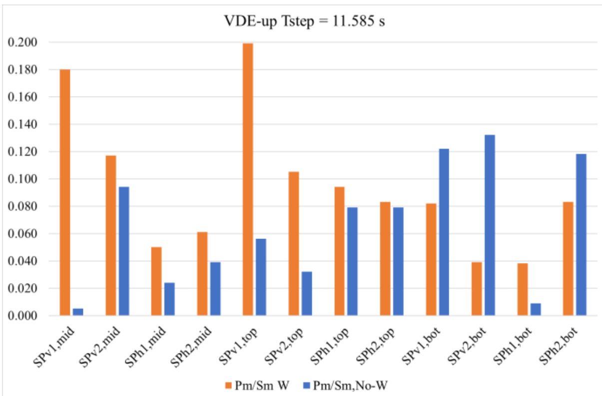

Fig.26 SL results under VDE-up loading scenario - $(P_m+P_b)/K_{eff}S_m$ Level C RCC-MRx safety criteria

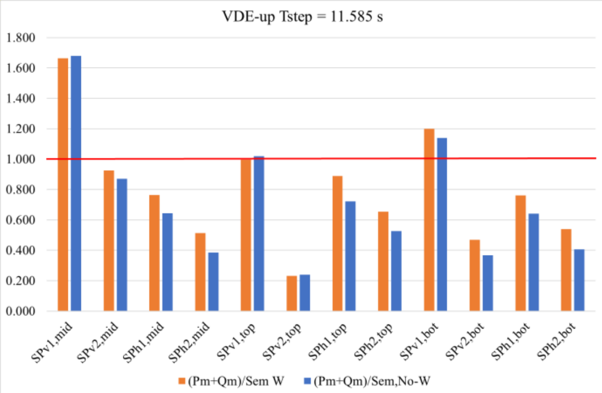

Fig.27 SL results under VDE-up loading scenario - $(P_m+Q_m)/S_{em}$ Level C RCC-MRx safety criteria

5. Conclusion

Within the framework of the European DEMO BB studies, a research campaign aimed at investigating the thermo-mechanical response of WCLL COB segment has been performed at University of Palermo. The assessment has been carried out considering different operative scenarios, NO, OP and VDE-up, with the aim of verifying the fulfilment of the RCC-MRx structural design criteria.

Results obtained highlight that, globally, not all criteria are fulfilled along the paths taken into account and, in particular, paths considered within the poloidal-radial SPs are the most stressed. Furthermore, none of the cases fully verified the criteria against the Immediate Plastic Flow Localization, which takes into account secondary stresses. Moreover, COB segment generally shows a most stressed Von Mises equivalent stress field in correspondence of the FW whenever the mechanical effect of the W-armour is not taken into account.

The displacement field is similar in all of the assessed loading scenarios. However, a remarkable displacement along the radial direction has been observed. This common trend probably can be due to the fact that the attachment system does not foresee any support, in the equatorial region, to prevent the radial displacement of the segment, thus showing a very large deformation.

Analysis results have shown that further studies need to be carried out. In particular, the COB supporting system needs to be reviewed in order to avoid too large displacements and improve its thermomechanical behaviour. Moreover, the mechanical impact that removing the FW channels, done in order to simplify the model, has on the whole structure, needs to be investigated.

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References

[1] T. Donnè, European Research Roadmap to the Realisation of Fusion Energy, November 2018, ISBN: 9783000611520.
[2] G. Federici et al., An overview of the EU breeding blanket design strategy as an integral part of the DEMO design effort, Fusion Engineering and Design, 141 (2019) 30-42, doi: 10.1016/j.fusengdes.2019.01.141.
[3] A. Del Nevo et al., Recent progress in developing a feasible and integrated conceptual design of the WCLL BB in EUROfusion project, Fusion Engineering and Design, 146 (2019) 1805-1809, doi: 10.1016/j.fusengdes.2019.03.040.
[4] F. Cismondi et. al, Progress in EU breeding blanket design and integration, Fusion Engineering and Design, 109-111 (2018), 1464-1474, https://doi.org/10.1016/j.fusengdes.2018.04.009
[5] C. Bachmann et al., Initial definition of structural load conditions in DEMO, Fusion Engineering and Design, 124 (2017), 633-637, https://doi.org/10.1016/j.fusengdes.2017.02.061
[6] RCC-MRx, Design and Construction Rules for Mechanical Components of Nuclear Installations, AFCEN, 2013.
[7] G. Bongiovì et al., Multi-Module vs. Single-Module concept: Comparison of thermomechanical performances for the DEMO Water-Cooled Lithium Lead breeding blanket, Fusion Engineering and Design, 136 (2018) 1472-1478, doi: 10.1016/j.fusengdes.2018.05.037.
[8] Abaqus Analysis User's Guide: Online Documentation. Version 6.14-2, Providence, RI, Simulia, Dassault System.
[9] DEMO1 Reference Design - 2017 March ("EU DEMO1 2017") - PROCESS Two Page Output (2NE9JA v1.0) (current)
[10] R. Forte et al., Preliminary design of the top cap of DEMO Water-Cooled Lithium Lead breeding blanket segments, Fusion Engineering and Design, 161 (2020), 111884, doi: 10.1016/j.fusengdes.2020.111884
[11] P.A. Di Maio et al., On the effect of stiffening plates configuration on the DEMO Water Cooled Lithium Lead Breeding Blanket module thermo-mechanical behaviour, Fusion Engineering and Design, 146 (2019), 2247-2250,doi: 10.1016/j.fusengdes.2019.03.163
[12] A. Del Nevo et al., Internal Deliverable BB-3.2.1-T006-D001: WCLL BB design and Integration studies 2019 activities, Final Report (2020), EFDA IDM Ref. EFDA_D_2P5NE5.
[13] I. Catanzaro et al., Parametric study of the influence of double-walled tubes layout on the DEMO WCLL breeding blanket thermal performances, Fusion Engineering and Design, 161 (2020), 111893, doi: 10.1016/j.fusengdes.2020.111893
[14] G. Bongiovì et al., BB.WCLL-DEF-2-CD1-BB WCLL Load Specifications Document, Final Report on Deliverable (2020), EFDA IDM Ref. EFDA_D_2P6MJG.
[15] G. A. Spagnuolo et al., Development of load specifications for the design of the breeding blanket system, Fusion Engineering and Design, 157, 111657, 2020
[16] B. Van der Schaaf et al., The development of EUROFER reduced activation steel, Fusion Engineering and Design, 69 (1-4) (2003) 197-203, doi: 10.1016/S0920-3796(03)00337-5.
[17] F. Gillemot et al., Material Property Handbook pilot project on EUROFER97 (MTA EK, KIT), (2016), EFDA IDM Ref.: EFDA_D_2MRP77.
[18] Goodfellow, Metals, Alloys, Compounds, Ceramics, Polymers, Composites. Catalogue 1993/94.
[19] I. A. Maione et al., Assessment of EM results – 2018, Final

Report on Deliverable (2019), EFDA IDM Ref. EFDA_D_2NUFTN.

[20] I.A. Maione et al., Analysis of EM loads on DEMO WCLL Breeding Blanket during VDE-up, Fusion Engineering and Design, 136 (2018), 1523-1528.

[21] I.A. Maione et al. A complete EM analysis of DEMO WCLL Breeding Blanket segments during VDE-up, Fusion Engineering and Design, 146 (2019), 198-202.

[22] C. Bachmann et al., IDD - Blanket Mechanical Supports, (2019), EFDA IDM Ref. EFDA_D_2NHC86.

[23] G. Zhou et al., Preliminary structural analysis of the new HCPB blanket for EU DEMO reactor. International Journal of Hydrogen Energy 41 (2016) 7053-7058.