Preliminary thermal optimization and investigation of the overall structural behaviour of the EU-DEMO Water-Cooled Lead Lithium Left Outboard Blanket segment

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The conceptual design phase of the EU-DEMO reactor has been recently launched, with the aim of evolving the DEMO pre-conceptual layout towards a more robust and articulated geometric configuration able to cope with most of the design requirements and to show further margins for the passing of the current potential show-stoppers. Hence, the achievement of the conceptual design of the Water-Cooled Lead Lithium Breeding Blanket (WCLL BB) is one of the milestones the EUROfusion consortium aims to achieve in the close future. To this purpose, within the framework of the research activities promoted by EUROfusion, a research campaign has been launched at the University of Palermo, in close cooperation with ENEA-Brasimone, in order to investigate, from the thermal and thermomechanical standpoints, the WCLL BB Left Outboard Blanket (LOB) segment performances. The scope of the analysis carried out has been the advancement of the WCLL LOB segment design in view of the prescribed thermal and structural design requirements. To this end, the nominal WCLL BB operating conditions as well as accidental steady-state scenarios derived from the in-box loss of coolant accident and the upper vertical plasma disruption event have been considered. In the first part of the study, the internal Double-Walled Tubes (DWTs) layout of the WCLL LOB equatorial region have been preliminarily optimized so to find a geometric configuration able to cool the segment structure maintaining the maximum temperature below the suggested limit of 550 °C. Then, a purposely set-up analytical procedure has allowed obtaining a set of interpolating functions able to accurately reproduce the calculated thermal field and to extrapolate it to the whole WCLL LOB segment. Afterwards, the thermo-mechanical analysis of the entire segment has been performed under the selected loading scenarios. The structural behaviour of the segment has been assessed in compliance with the RCC-MRx code, adopting the set of criteria on the basis of the nature of the considered loading scenario. The obtained results, herewith presented and critically discussed, have allowed introducing significant design improvements with respect to the WCLL LOB segment reference geometric layout, coming from the pre-conceptual design phase, paving the way for future, and more detailed, structural investigations.

Keywords: WCLL, breeding blanket, lateral outboard, DWTs optimization, thermomechanics, FEM analysis.

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1. Introduction

Within the framework of the research activities, promoted by the EUROfusion consortium [1], aimed at achieving a conceptual design of the DEMO Breeding Blanket (BB) [2][3], the University of Palermo is long-time involved, in close cooperation with ENEA, in the design of the Water Cooled Lithium Lead BB. Until now, different studies have been carried out regarding the design and the thermal and mechanical optimization of the DEMO WCLL BB [4][5], focussing first on a single portion and then on an entire Blanket segment. In particular, a huge research activity has been conducted on the Central Outboard Blanket (COB) segment [6], in order to investigate its overall behaviour under normal and off-normal conditions, giving a remarkable contribution to the development of this blanket concept. Instead, no detailed studies have ever been carried out on the other Outboard segment of a Blanket sector. Therefore, as the DEMO reactor is currently moving from the pre-conceptual to the conceptual design phase, in this work the focus has been paid on the design of the Left Outboard Blanket (LOB) segment.

Starting from the reference geometric layout of the segment, conceived at the end of the pre-conceptual design phase [7], a preliminary thermal optimization study of the equatorial region has been performed and reported in the Section 2 of this paper, with the aim of determining a First Wall (FW) cooling channels layout and a Double-Walled Tubes (DWTs) spatial arrangement capable of ensuring the fulfilment of the suggested thermal requirements (i.e. maximum temperature within the Eurofer RAFM steel lower than 550 °C). Afterwards, a purposely developed interpolation procedure has been adopted to obtain a 3D thermal field for the whole segment, as reported in the Section 3, and then, as depicted in Section 4, the WCLL LOB segment thermo-mechanical performances have been investigated. In particular, the normal operation (NO) loading scenario has been considered to assess the segment structural performances under the typical WCLL BB steady state operational conditions. Then, the over-pressurization (OP) scenario has been defined to consider a particularly severe steady state loading scenario, deriving from an in-box loss of coolant accident, foreseeing the pressurization of the whole SB at the coolant's pressure because of the accident. Lastly, a steady state loading scenario representing the most critical time step of a plasma Upper Vertical Displacement Event (UVDE) has been assumed, assuming the corresponding spatial distribution of the electro-magnetic loads originated by such a kind of plasma disruption. In all these scenarios, a thermo-mechanical analysis has been carried out and the obtained results have been evaluated to verify the fulfilment of the RCC-MRx design criteria, selecting the set of rules pertinent to the level of the considered loading scenario. In fact, the NO scenario is classified as Level A since it represents the operational loading conditions, whereas the UVDE off-normal scenario belongs to Level C and OP scenario to Level D, since the latter represents the BB design-driving accident. To this purpose, a stress linearization procedure has been carried out along significant paths located within the most critical regions of the segment and the obtained results are compared and critically discussed, highlighting the drawbacks of the current geometric configuration. In the end, in Section 5, the conclusions are given and the follow-up of the WCLL LOB design activity is outlined.

The study has been performed adopting a theoretical-numerical approach based on the Finite Element Method (FEM) and the qualified commercial FEM code ABAQUS has been used.

2. Preliminary thermal optimization of the WCLL LOB segment

The determination of the thermal field arising within the WCLL LOB segment is pivotal to perform its thermo-mechanical analysis aimed at investigating its overall structural behaviour. To this purpose, following a "Design-by-Analysis" approach, the thermal performances of the equatorial region of the WCLL LOB segment have been investigated, with the aim of finding a cooling system layout allowing to obtain a temperature spatial distribution characterised by a maximum value predicted within the structural components lower than 550 °C. Afterwards, a proper interpolation procedure has been developed and applied to allow the extrapolation of the thermal field to the whole segment. To achieve these goals, a preliminary thermal optimization of the WCLL LOB equatorial region has been necessary. In particular, starting from the WCLL LOB architecture conceived at the end of the pre-conceptual design phase [7], the number of the FW cooling channels and the DWTs spatial layout have been determined in view of the suggested limitation on the structural material maximum temperature.

2.1. The geometric model of the WCLL LOB equatorial region

The WCLL LOB segment consists in a single toroidal-radial elementary cell, repeated approximately 100 times for the entire poloidal length of the segment, which is closed at the end by means of the so-called Top and Bottom Caps, as reported in Figure 1. The external structure, the Segment Box (SB), is composed of a First Wall, covered by 2 mm of Tungsten, (in orange in Figure 1), two asymmetric Side Walls (SWs), closing the SB laterally, and a Back Plate (BP), closing the SB in the back. The FW-SWs complex is cooled by means of square cooling channels. In particular, 4 cooling channels per elementary cell are foreseen for the entire poloidal length of the segment with the exception of the lower region, where 6 channels per cell are expected. The SB structure is internally reinforced by means of Stiffening Plates (SPs) located on poloidal-radial (or vertical, namely SPv) and toroidal-radial (or horizontal, namely SPh) planes, with a thickness of 12 and 10 mm respectively. The SB encloses the Breeder Zone (BZ) where the breeder flows throughout the SPs complex, guided by the baffle plates interposed in between two consecutive SPsh, and it is cooled down by the DWTs. The Back Supporting Structure (BSS), located at the rear of the structure, closes the manifolds region and supports the attachment system, which connects the segment to the Vacuum Vessel (Figure 1).

In order to perform the preliminary thermal optimization of the WCLL LOB equatorial region under the steady state nominal operational conditions, three adjacent cells located in proximity of the radial-toroidal equatorial plane have been extracted cutting the LOB segment geometric model, as shown in Figure 2. Each cell has been endowed with 4 SB cooling channels, as foreseen for the reference layout conceived at the end of the pre-conceptual design phase. It has to be highlighted that this represents a first guess for the WCLL LOB segment, since no detailed thermal studies have been yet carried out for a lateral blanket segment. Concerning the DWTs spatial arrangement, on the basis of the outcomes found in the thermal optimization study performed for the WCLL Central Outboard Blanket (COB) segment [8], the alternative cross-24 and cross-26 DWTs layouts (foreseeing, respectively, 24 and 26 tubes per elementary cell, Figure 3) have been adopted for the WCLL LOB equatorial region. Since, unlike the COB segment, the LOB segment layout presents asymmetrical SWs and its equatorial region is larger than the COB one (Figure 4), the original cross-24 and cross-26 DWTs layout conceived for the COB segment have been properly modified, by moving, re-shaping and slightly re-sizing the DWTs in order to adapt them to the peculiarities of the LOB segment geometry.

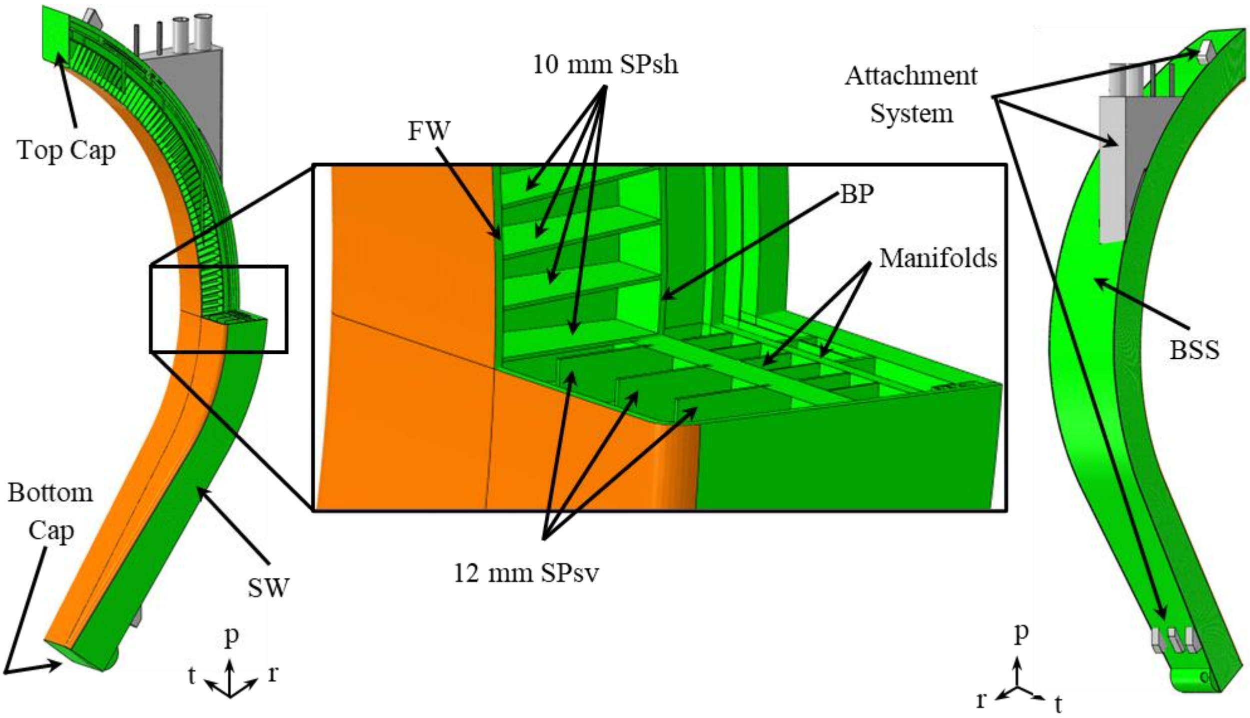


Figure 1. WCLL LOB segment architecture.

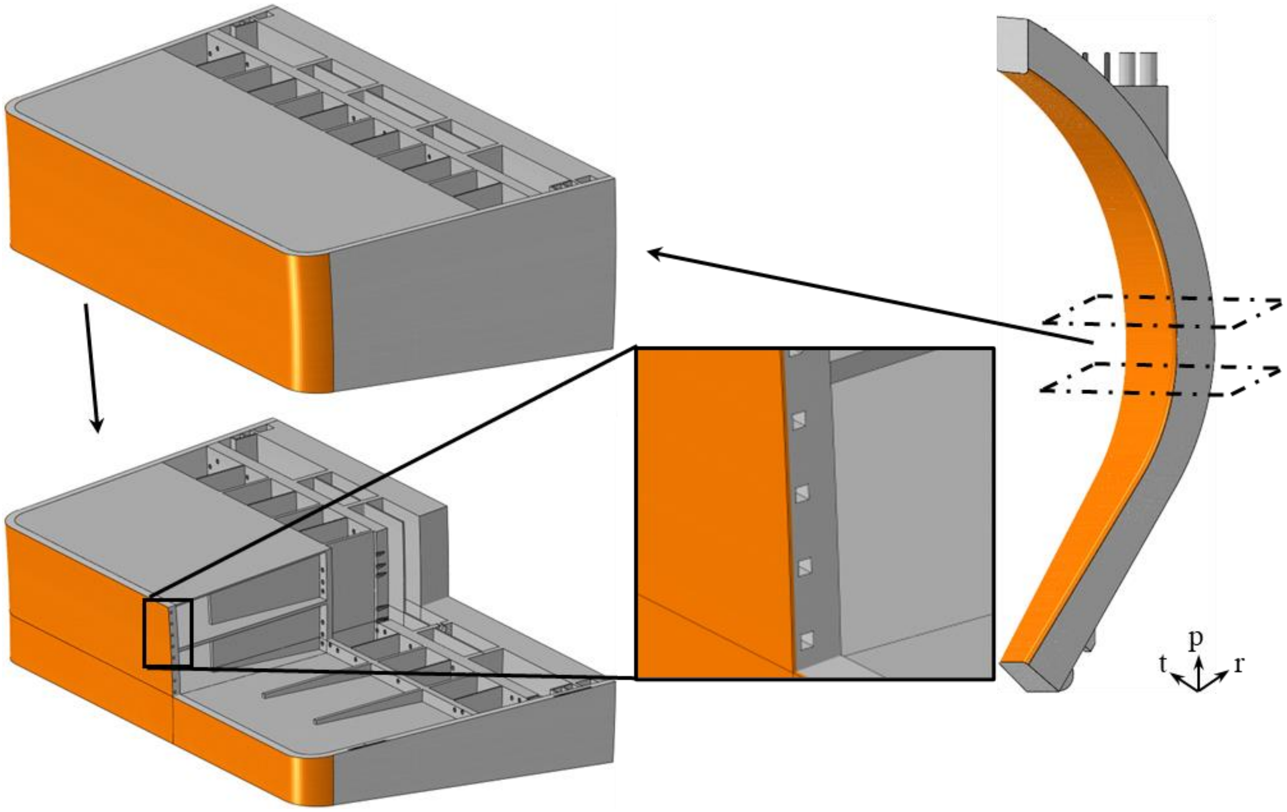


Figure 2. The equatorial region of the WCLL LOB segment.

Hence, a first attempt DWTs arrangement, called LOB_1, has been set up, as reported in Figure 5, based on the cross-24 DWTs layout. Then, several alternative DWTs layouts have been conceived (sometimes slightly moving or modifying one, or a couple, of tubes along radial, toroidal and/or poloidal directions to locally reduce the hotspots) and assessed in order to obtain a thermal field showing a maximum temperature within structural components lower than 550 °C. Hence, starting from the LOB_1 configuration, a parametric campaign of thermal analysis has allowed modifying the initial DWTs configuration, finally obtaining the LOB_2 DWTs layout (Figure 5) characterised by the adoption of the cross-26 DWTs layout, properly modified and slightly re-shaped to allow better cooling performances. Afterwards, after other iterations, the final LOB_3 configuration (Figure 5) has been conceived. It is characterised by the same number of tubes as the LOB_2 configuration, further re-shaped and moved to improve their thermal performances. For the sake of brevity, in the following, only results concerning these three major configurations will be presented to describe the main outcomes of the preliminary thermal optimization of the equatorial region of the WCLL LOB segment.

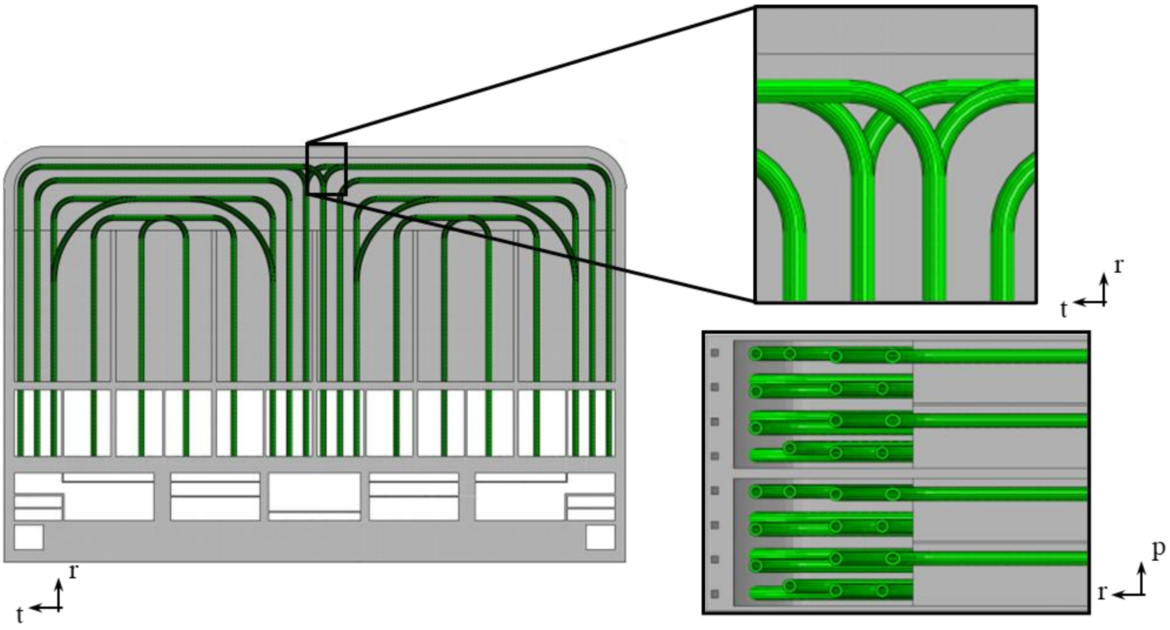


Figure 3. The cross-26 DWTs layout set-up for the WCLL COB segment.

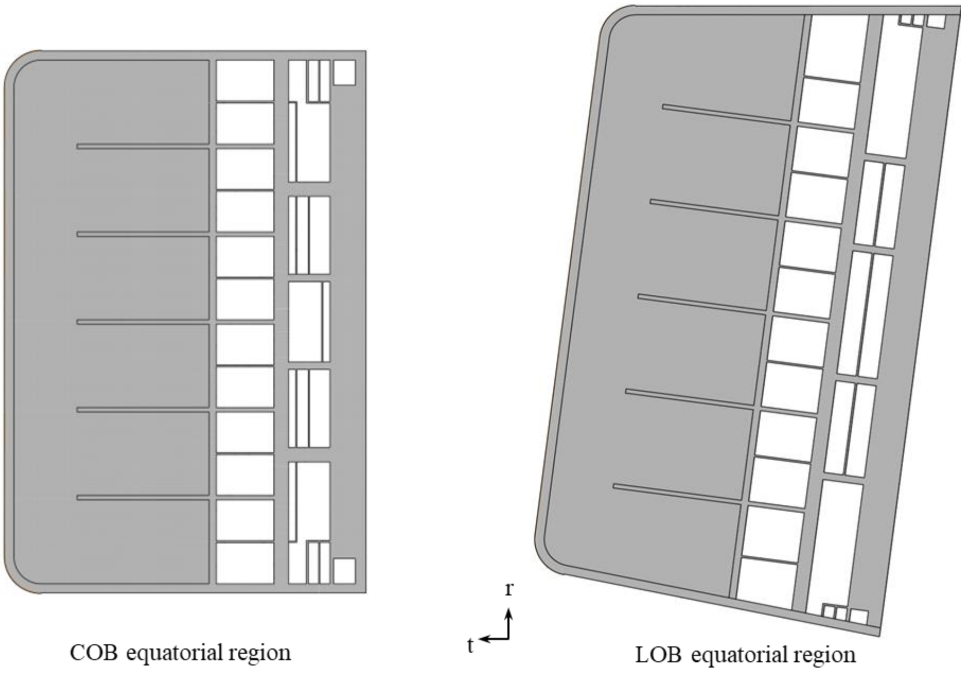
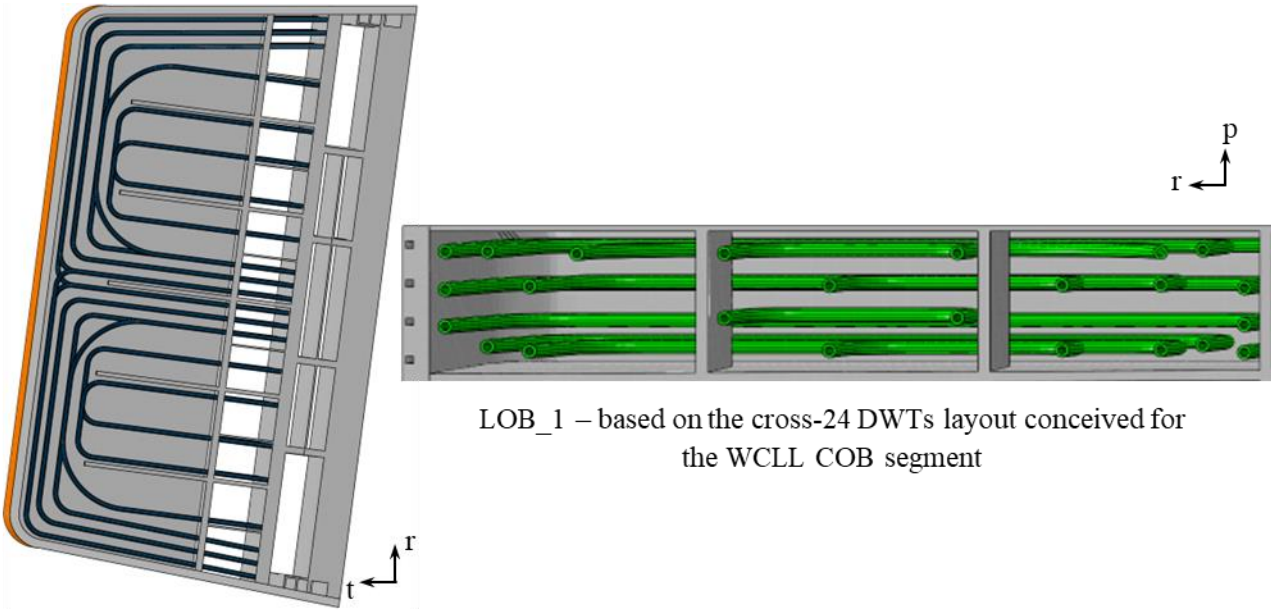
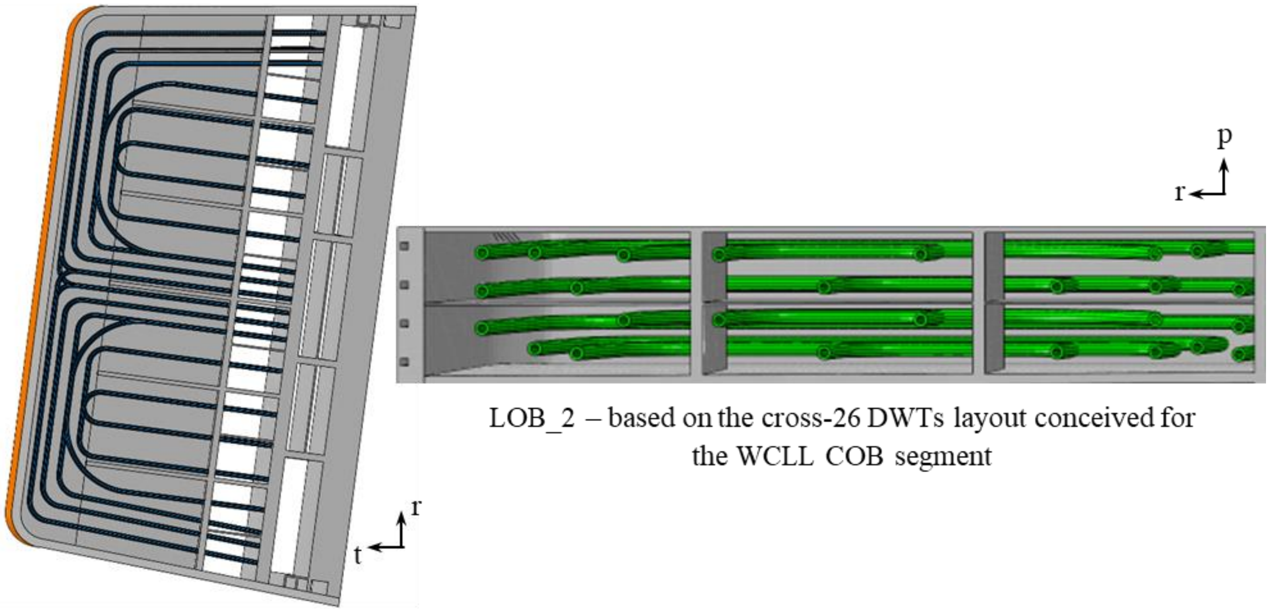


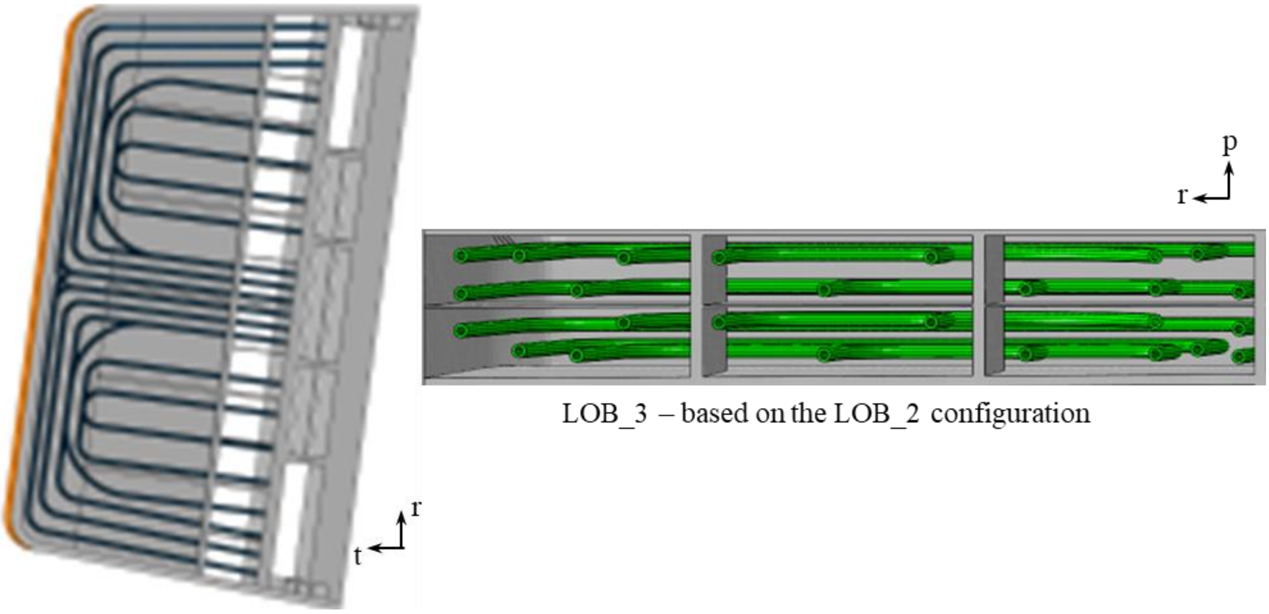
Figure 4. WCLL COB and LOB segments equatorial regions.



LOB_1 – based on the cross-24 DWTs layout conceived for the WCLL COB segment



LOB_2 – based on the cross-26 DWTs layout conceived for the WCLL COB segment



LOB_3 – based on the LOB_2 configuration

Figure 5. The cross-26 DWTs layout adapted for the WCLL LOB segment equatorial region.

2.2. The FEM models

In order to perform the preliminary thermal optimization of the WCLL LOB equatorial region under the steady state nominal loading conditions, a 3D FEM model has been developed for each triplet of cells equipped with the investigated DWTs layouts. Since the FEM models reproducing the equatorial region of the WCLL LOB segment differ each other only for the DWTs geometric layout considered, they share almost all their features. In general, each 3D FEM model is composed of about 3 million of nodes connected in hexahedral and tetrahedral elements, opportunely used to discretize the different components. Details of the mesh features have been reported in Table 1.

Table 1. Mesh features.

	LOB_1	**LOB_2**	**LOB_3**
Node number	~3.05M	~3.46M	~3.04M
Element number	~7.24M	~7.06M	~6.57M

The FEM models include the SB covered by the 2mm thick tungsten armour facing the plasma, the internal SPs and DWTs, the manifold region and the BSS plus the breeder domain, purposely modelled to take into account the thermal power here deposited by neutrons and gammas and removed by the coolant flowing within the DWTs, as well as its thermal interactions with the SB walls. Instead, the water domain has not been modelled in order to speed up the analyses, but its thermal effect has been properly simulated by means of a convective boundary condition fully characterised by means of a proper iterative procedure. Moreover, in order to realistically perform the thermal analysis, temperature-dependent material properties for Eurofer, breeder and tungsten have been considered [9][10][11].

As far as the nominal scenario definition is concerned, the following set of loads and boundary conditions has been defined and assumed:

- a heat flux equal to 0.27 MW/m^2 [12] onto the straight surface of the FW plasma facing surface (i. e. onto the tungsten armour), decreasing to 0 on the SWs following a cosine-dependent law onto the bend FW surfaces;
- a not-uniform 3D spatial distribution of heat power volumetric density [13], given by the heat power deposited by neutrons and gamma photons, to the whole model taking also into account the contribution given by the decay heat power density, due to the heat power deposited by the decay of the activated nuclei, drawn from [14];
- the thermal contact between the PbLi, considered as stagnant due to its very low flow velocity, and the internal steel surfaces, simulated assuming a conservative thermal conductance value equal to 100 kW/m^2·°C;
- thermal coupling between the radial-toroidal top and bottom surfaces of the geometric model, to simulate the poloidal continuity of the segment;
- the forced convective heat transfer between water and Eurofer, within SB channels and DWTs. Such a condition has been simulated adopting a simplified method, considering a unique bulk temperature value equal to 311.5 °C (i.e., the average value between the inlet and outlet temperatures of 295°C and 328°C, respectively) and using an iterative procedure for the calculation of the Heat Transfer Coefficients (HTCs). In particular, in the first analysis of the iterative procedure the HTC values

calculated by Dittus&Boelter correlation have been used. Then, the new HTCs values have been calculated on the basis of the power extracted on the surfaces wetted by the coolant flowing inside the DWTs and SB cooling channels, and the new mass flow rates values evaluated in the previous analysis, considering a coolant thermal rise of 33 °C;

- a uniform temperature equal to 311.5 °C onto the water manifolds surfaces.

2.2. Thermal analysis and results

Once defined the steady state nominal loading scenario, a campaign of thermal analysis has been launched. For the sake of brevity, only results concerning the three major layouts assessed (LOB_1, LOB_2 and LOB_3) are herein reported. To this end, the obtained 3D spatial temperature distributions are reported in Figure 6. Here, the radial-toroidal views reported on the left of the picture are obtained at the poloidal mid-plane, so to show the thermal field at the half of the considered model, namely far enough from the boundaries. For the sake of completeness, also radial-poloidal views are reported on the right of the picture, obtained making a toroidal mid-plane section.

As depicted in Figure 6, adopting, initially, the LOB_1 DWTs layout, large areas of the WCLL LOB equatorial region experience temperatures higher than the suggest limit of 550 °C (namely areas in grey in Figure 6, where only the Eurofer domain is depicted). Then, moving to LOB_2 configuration, characterized by a higher number of tubes, the critical areas have been reduced even if their extension is still significant. In the end, adopting the DWTs LOB_3 layout, temperatures overtaking the critical value are predicted mainly within tiny areas located within the baffle plates and at the upper and lower poloidal borders of the model, whereas the rest of the Eurofer domain in the SB shows lower temperatures. However, since the baffle plates do not play any primary structural role and the temperature on the top and bottom radial-toroidal faces strongly depends on the coupling boundary condition imposed, such a configuration has been assumed as the reference one and the resulting thermal field has been kept for the follow up of the study. Furthermore, it has to be noted that, differently from the previous cases, the maximum temperature (~ 560.8 °C) is only 10.8 °C (namely less than the 2%) greater than the limit, so it can be accepted in this phase since it may be due also to numerical uncertainties and singularities, as well as to the application of a coupling poloidal boundary conditions to a geometric model not perfectly symmetric along that direction since the top and bottom faces are not parallel.

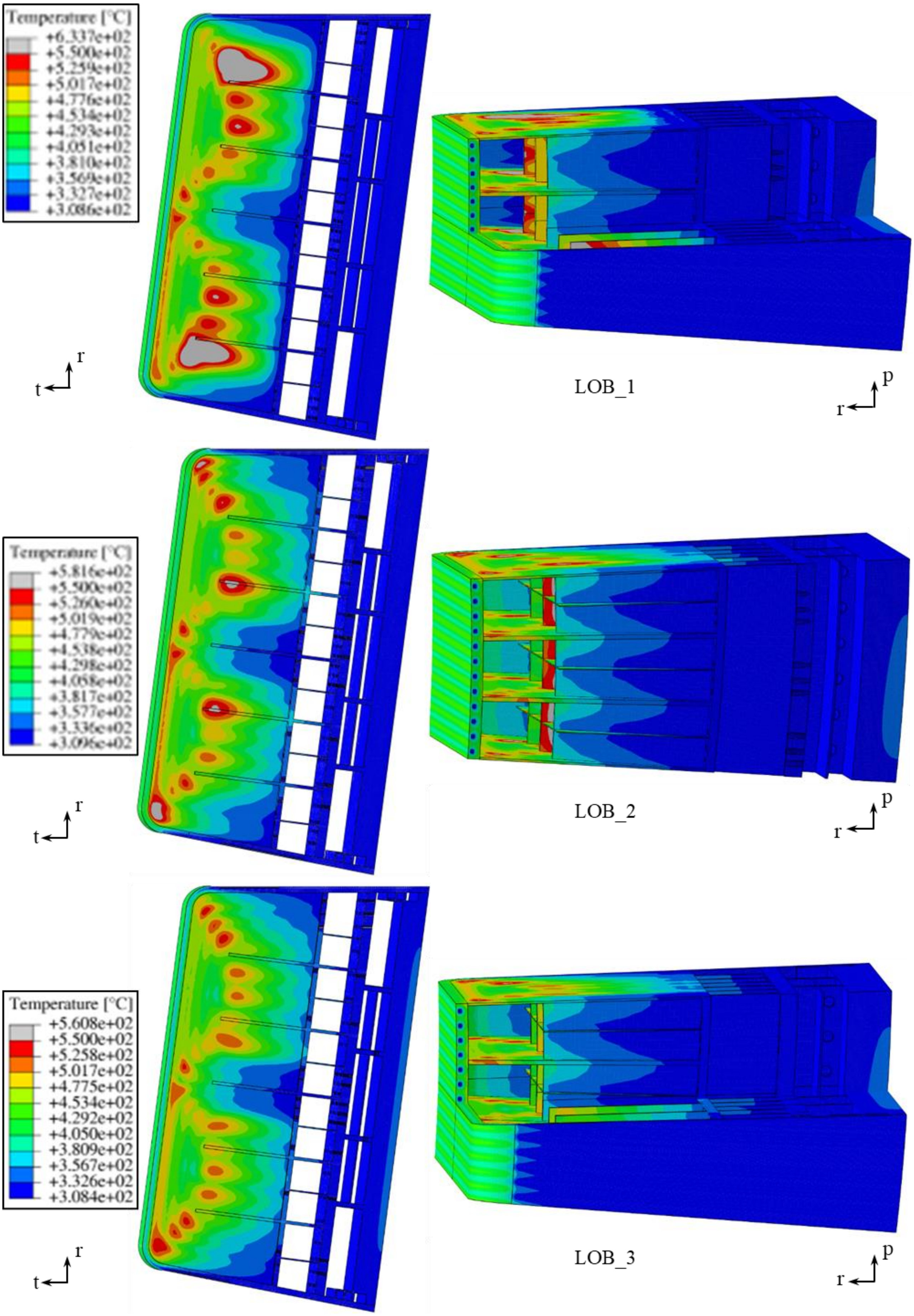


Figure 6. Thermal field within the WCLL LOB segment equatorial region – Eurofer domain.

3. Determination of the thermal field for the whole WCLL LOB segment

The campaign of thermal analysis previously described has allowed predicting a thermal field within the equatorial region of the WCLL LOB segment compliant with the suggested thermal requirements. Afterwards, an interpolation procedure has been purposely set-up in order to find a set of polynomial functions capable of representing the thermal field arising within the equatorial region with a remarkable level of confidence [8] [15]. Then, the found functions have been used to obtain a 3D thermal field for the whole WCLL LOB segment.

In particular, the set-up interpolation procedure foresees the subdivision of the geometric domain in several sub-regions. Thus, a polynomial function of the radial and toroidal variables is searched for each of them, drawing the temperature spatial distribution. As depicted in Figure 7, the equatorial region of the WCLL LOB segment has been subdivided into 15 regions and a polynomial function has been found each of them:

- FW region: 13th degree polynomial function of the radial variable;
- SW regions: two different 14th degree polynomial function of the radial variable;
- SPv regions: five different 12th degree polynomial function of the radial variable;
- SPh regions: six different 8th-10th degree polynomial functions of the radial and toroidal variables;
- Manifolds region: 9th degree polynomial function of the radial variable.

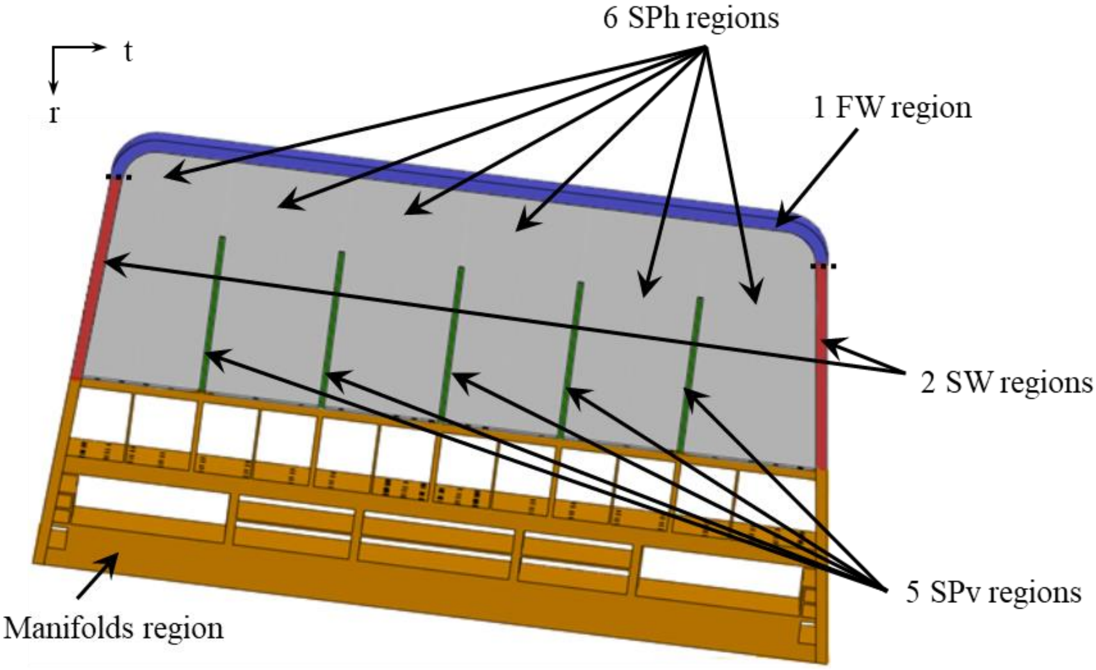


Figure 7. Regions for the thermal field interpolation.

Thanks to this approach, the thermal fields calculated within each region by the different polynomial functions have been stitched together and an overall 3D thermal field has been extrapolated to the whole WCLL LOB segment, as depicted in Figure 8, thanks to a proper user routine coded within the Abaqus environment in order to introduce the dependence on the poloidal variable. Moreover, a unique temperature value equal to 300°C has been imposed for the attachment system support, which are connected to the VV.

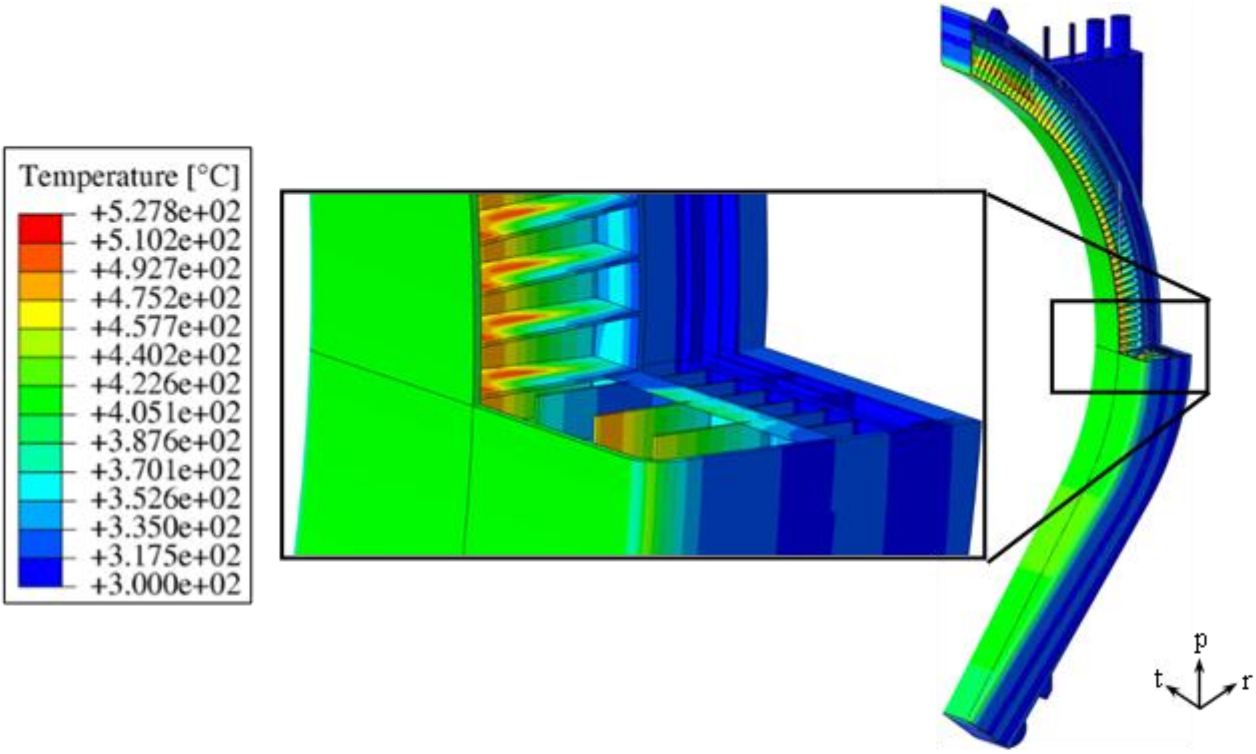


Figure 8. The 3D thermal field for the WCLL LOB segment.

4. Investigation of the overall structural behaviour of the WCLL LOB segment

In order to evaluate the structural performances of the WCLL LOB segment under the selected steady state loading scenarios, thermo-mechanical analyses have been carried out assuming the thermal field obtained by means of the interpolation procedure previously described. In particular, the NO, OP and UVDE loading scenarios have been considered and proper FEM models have been set-up.

4.1. The FEM models

In order to investigate the overall structural behaviour of the WCLL LOB segment, its reference geometric configuration has been considered. Due to its lack of maturity, no SB cooling channels are designed in the global model. In addition, baffle plates and DWTs has not been included in the developed FEM models, as their structural role is negligible. Lastly, in order to significantly reduce the modelling effort and the computational burden, the breeder domain has not been included in the model, but its mechanical effect has been considered assuming a proper pressure load on its wetted surfaces.

A mesh composed of ~2.9M nodes connected in ~7.1M tetrahedral and hexahedral elements has been set-up and the proper loads and boundary conditions have been imposed in accordance with the selected loading scenario [16]. In particular, the following loads and boundary conditions have been applied:

- a 3D thermal deformation field, arising within the structure as effect of the imposed thermal field (i.e. the thermal field coming from the interpolation procedure) and the volumetric expansion coefficient;
- a pressure load onto the breeder wetted surfaces, depending on the considered loading scenario. In particular, in NO and UVDE scenario the breeder design pressure of 0.575 MPa is considered whereas, in OP scenario, the coolant design pressure of 17.825 MPa is imposed considering that such a scenario conservatively assumes that the whole segment is pressurized at the maximum

pressure because of an in-box loss of coolant accident;

- the gravity load, imposing to the structure a temperature-dependent equivalent density to take into account the weight of the breeder and the water;
- the 3D spatial distribution of the ferromagnetic loads [17][18], acting on the structure in all the assessed scenario since they depend on the Eurofer ferromagnetic nature;
- the 3D spatial distribution of the Lorentz’s electro-magnetic forces arising in case of an UVDE. In particular, since EM loads undergoes great variations, the most severe time steps, related to the maximum radial forces and moment, are normally considered in order to apply the relevant loads spatial distributions. With regards to LOB segment, unlike the COB one, these two time steps coincide and are equal to 11.594 s. Hence, the Lorentz’s EM loads 3D field arising at t=11.594 s, calculated in a separate electro-magnetic analysis [17][18], have been applied to the LOB FEM model by a dedicated computational procedure;
- a set of mechanical restraints aimed at reproducing the mechanical effect of the attachment system devoted to connecting the WCLL LOB segment to the VV (Figure 9). In particular, the action of the attachments has been modelled thanks to a set of spring elements, located nearby the supports, with axis oriented along their specific working direction (indicated in Figure 9), each one with a different elastic constant value calculated to simulate this connection [19].

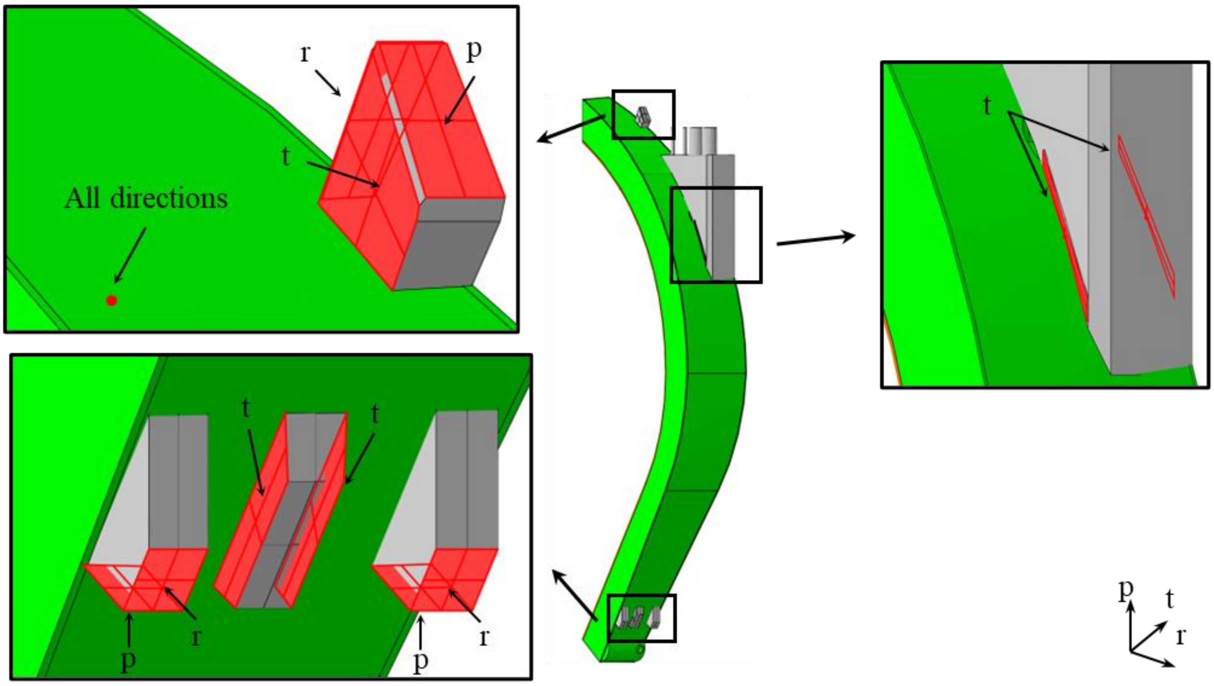
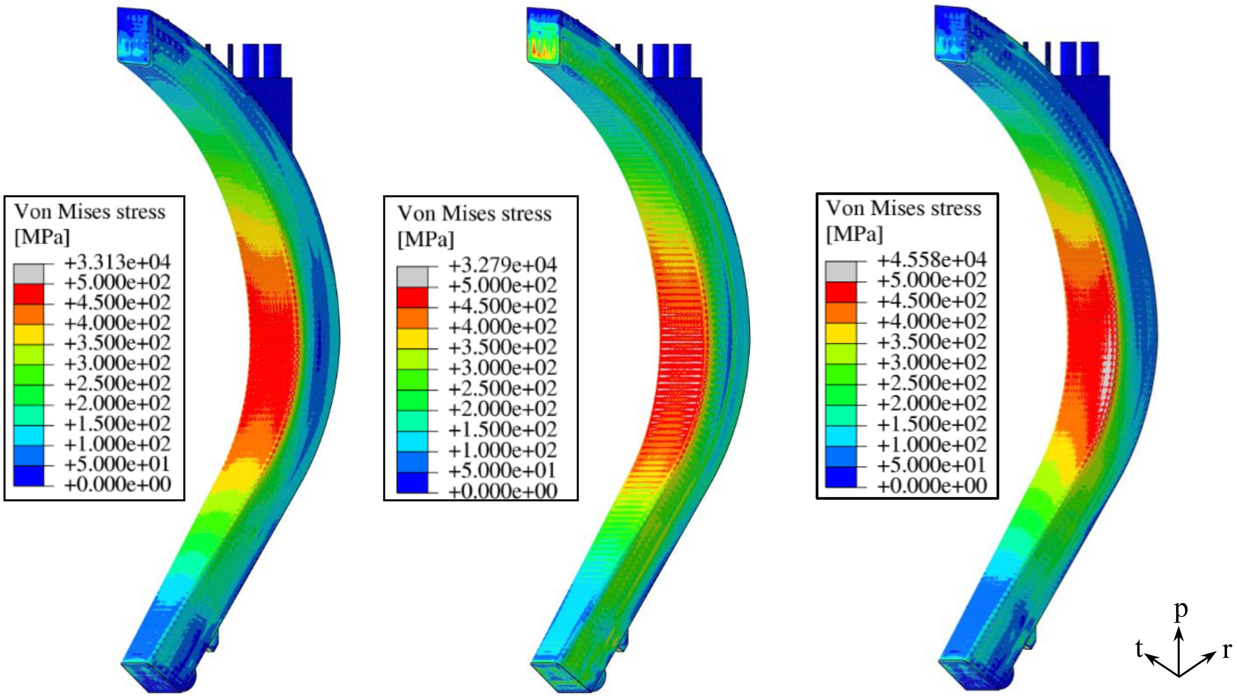


Figure 9. The attachment system for the WCLL LOB segment.

4.2. Thermo-mechanical analysis and results

Once set-up the FEM model and imposing loads and boundary conditions, steady state thermo-mechanical analyses have been launched to evaluate the overall structural response of the WCLL LOB segment under the different loading scenarios considered. Then, the results have been evaluated verifying the structural design criteria prescribed by the RCC-MRx design code. As regards the three scenarios, NO, UVDE and OP are classified as Level A, Level C and Level D, respectively, in the selected structural design code and, therefore, the pertinent sets of criteria and stress limits have been considered.

Looking at the equivalent Von Mises stress field arising within the Eurofer domain, reported in Figure 10, the equatorial region shows to be the most stressed one regardless of the considered loading scenario. Furthermore, the Von Mises stress spatial distribution reflects the asymmetrical nature of the segment geometry both in terms of SB shape and attachments' location. It has to be noted that, in NO and OP scenarios, almost all the SB geometric domain experiences Von Mises stress values lower than 500 MPa. The highest values are predicted in correspondence of the points of application of the spring elements devoted to simulating the attachments' actions. Hence, they are originated by the numerical assumptions and are not physically meaningful. Lastly, in the UVDE scenario, within a small region of the FW Von Mises stress values slightly greater than 550 MPa are predicted (small area in grey in Figure 10), because of the effect of the EM loads.



NO scenario

OP scenario

UVDE scenario

Figure 10. Von Mises stress field under NO, OP e UVDE loading scenarios within Eurofer.

Moreover, the deformed vs. undeformed view for all the three assessed loading scenarios is reported in Figure 11 with an isotropic amplification factor equal to 20, and the maximum and minimum displacement values along the radial, toroidal and poloidal (r, t and p) directions have been reported in Table 2. In all the three assessed scenarios, a large displacement in the radial direction at the equatorial region of the segment occurs, where no attachment system supports are present. The Table 2 shows, in fact, that the maximum value of displacements occurs in the radial direction, reaching up to about 43 mm in the OP loading scenario. It can be also seen that in the UVDE scenario the displacements in the toroidal direction are greater that in the other two simulated scenarios, probably due to the imposed EM loads relative to the considered time step (corresponding to maximum radial force and moment).

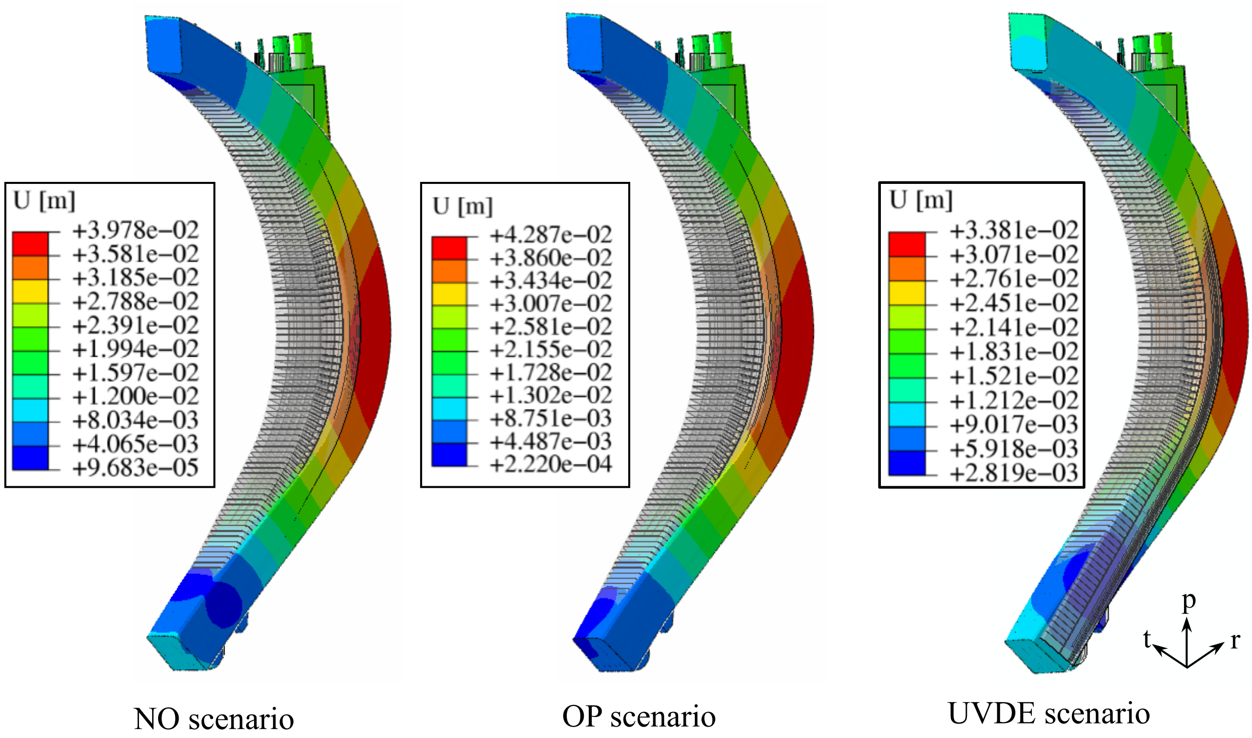


Figure 11. Deformed vs. Undeformed shapes under NO, OP and UVDE scenarios within Eurofer.

Table 2. Maximum and minimum displacements values obtained.

	NO	**OP**	**UVDE**
Ur, max [m]	0.0395	0.0427	0.0337
Ur, min [m]	-0.0085	-0.0075	-0.0113
Ut, max [m]	0.0058	0.0073	0.0088
Ut, min [m]	-0.0066	-0.0071	-0.0105
Up, max [m]	0.0207	0.0221	0.021
Up, min [m]	-0.0077	-0.0073	-0.0077

Finally, the overall structural performances of the WCLL LOB segment have been assessed under the NO, OP and UVDE scenarios by means of the verification of the design criteria reported in the RCC-MRx standards. To this end, a stress linearization procedure has been carried out along some significant paths located in the most critical regions emerged from the analysis of the Von Mises stress and total displacement fields. Five paths have been individuated within the SPs grid, two in the horizontal and three in the vertical ones, as depicted in Figure 12, in the equatorial region. Moreover, in order to study more in detail the "transition regions" within the top and bottom regions of the segment, namely those regions where the vertical SPs number passes from 5 to 3 (circled in red in Figure 12), the paths depicted in Figure 12 have been identified. For each path, four criteria have been checked for the structural evaluation: Immediate Excessive Deformation ($P_m < S_m$), Immediate Plastic Instability ($(P_m+P_b) < (K_{eff} \cdot S_m)$), Immediate Plastic Flow Localization ($(P_m+Q_m) < S_{em}$) and Immediate Fracture due to exhaustion of ductility ($(P_m+P_b+Q+F) < S_{et}$). While the first two criteria only consider the primary stresses, the others also take into account secondary stresses occurring along the analysed path. Then, the proper value of the stress limit has been calculated taking into account the path average temperature and the safety values corresponding to the service level the considered scenario belongs to.

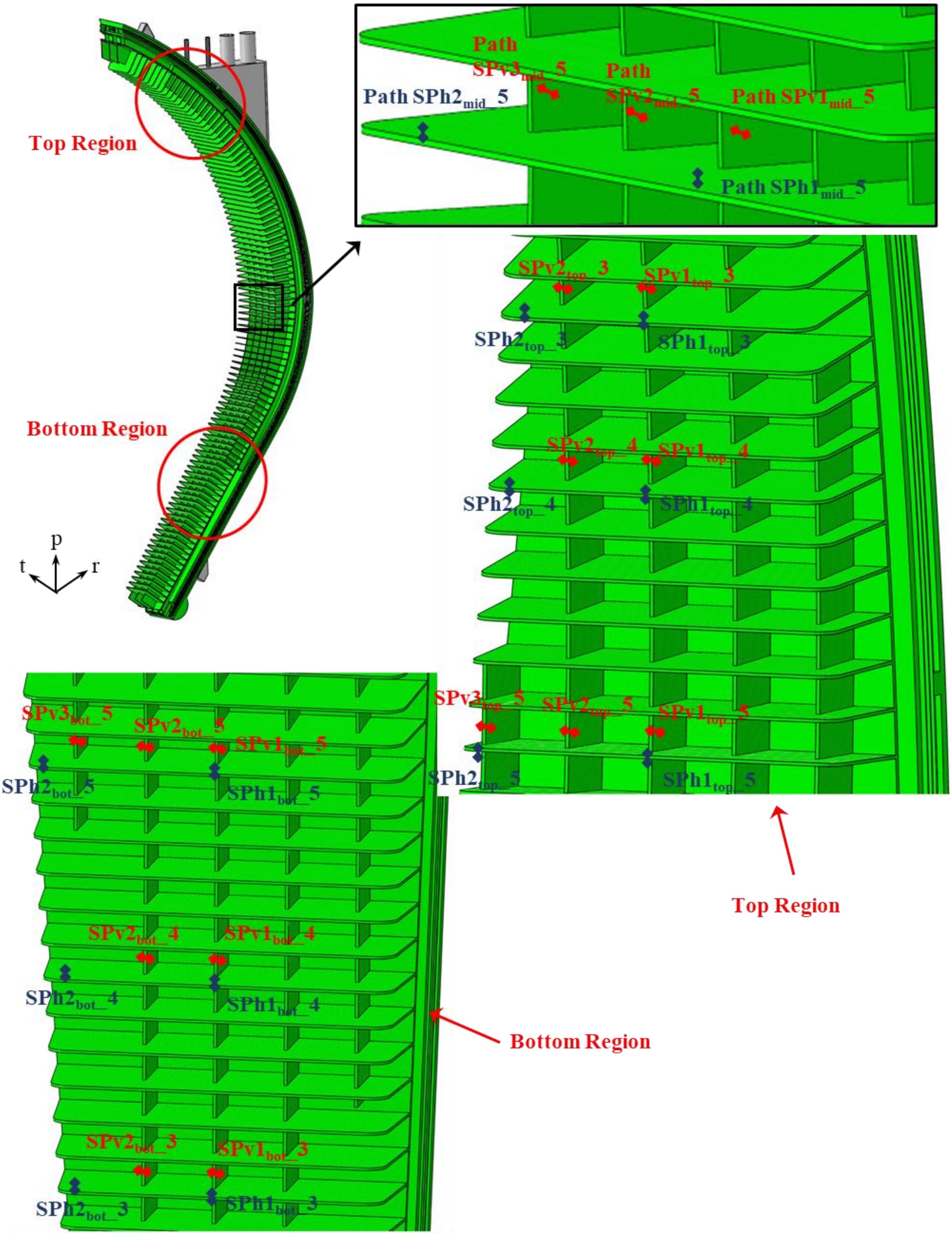


Figure 12. Paths within SPs region at the Top, Bottom and Equatorial poloidal regions.

A summary of all the criteria verifications carried out is reported in Figure 13, Figure 14 and Figure 15, under NO, OP and UVDE loading scenario, for the equatorial, top and bottom region respectively. The figures display, for each path and for each considered criterion, the ratio between the equivalent stress value calculated along the path and the stress limits value, indicating with a red line when the ratio reaches the limit value of 1.

Results show that all the considered paths fulfil the criteria involving only the primary stress and the criterion against the Immediate Fracture due to exhaustion of ductility. Instead, the criteria against the Immediate Plastic Flow Localization (i.e. $(P_m+Q_m) < S_{em}$), taking into account the membrane secondary stresses, is not verified along some paths located within the vertical SPs. In particular, the path named SPv2 is the most stressed in all the assessed scenarios and at every poloidal height considered. Globally, the SPv2 path shows a high average temperature, due to the thermal field arising because of the selected cooling scheme and, for this reason, it is particularly stressed compared to the paths on the other vertical SPs. Moreover, both SPv1 and SPv3 paths in the equatorial region also do not fulfil completely the Immediate Plastic Flow localization criteria. In particular, the ratio reaches in some cases a high value (>0.9), indicating, together with the large radial deformation, a critical condition in the equatorial region of the segment.

It has to be noted that no path has been considered within the SB, since in the reference geometric layout it is not designed with the cooling channels. Hence, a stress linearization would not reflect the real structural behaviour of the box.

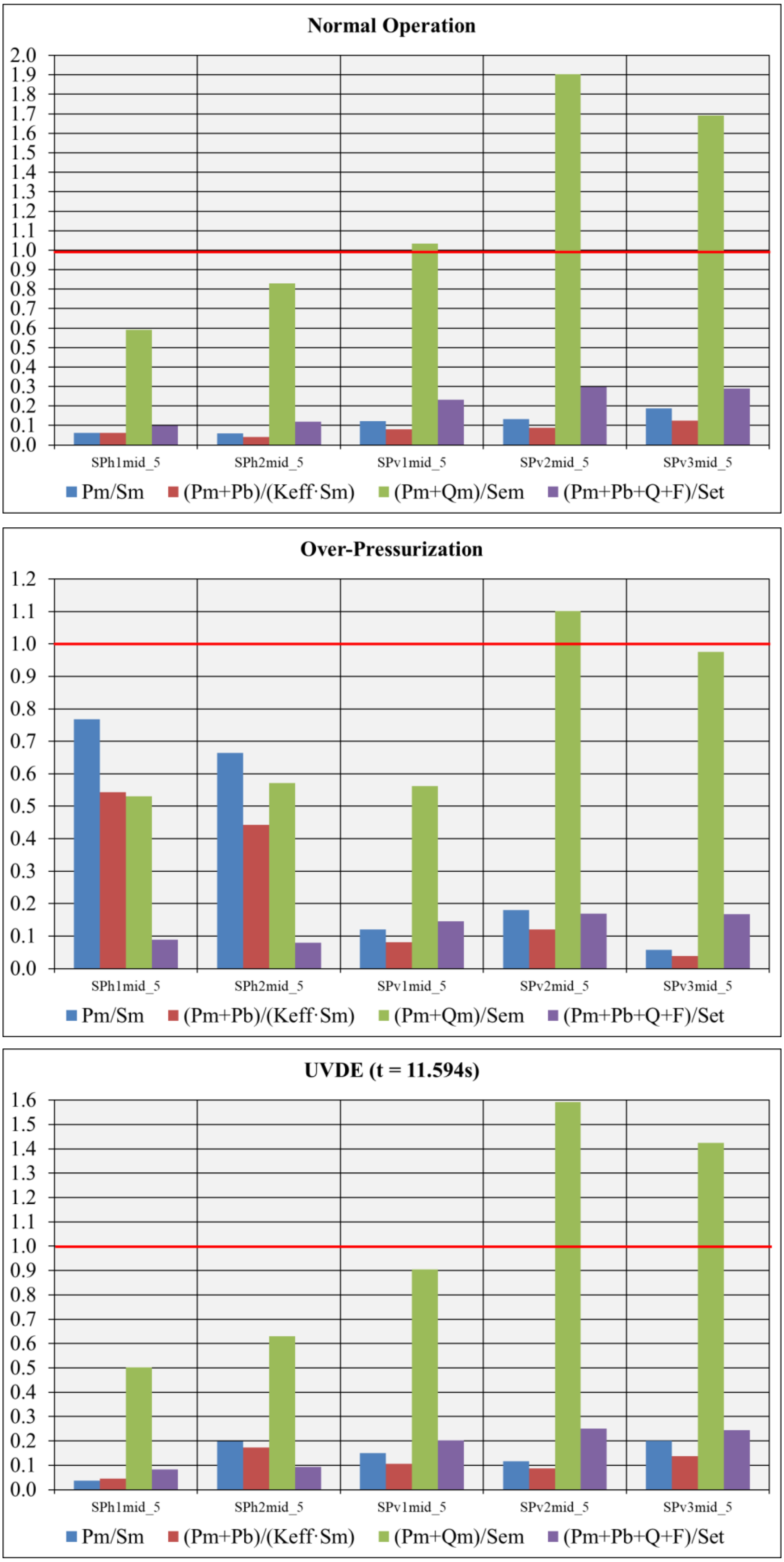


Figure 13. RCC-MRx criteria verification within the equatorial region.

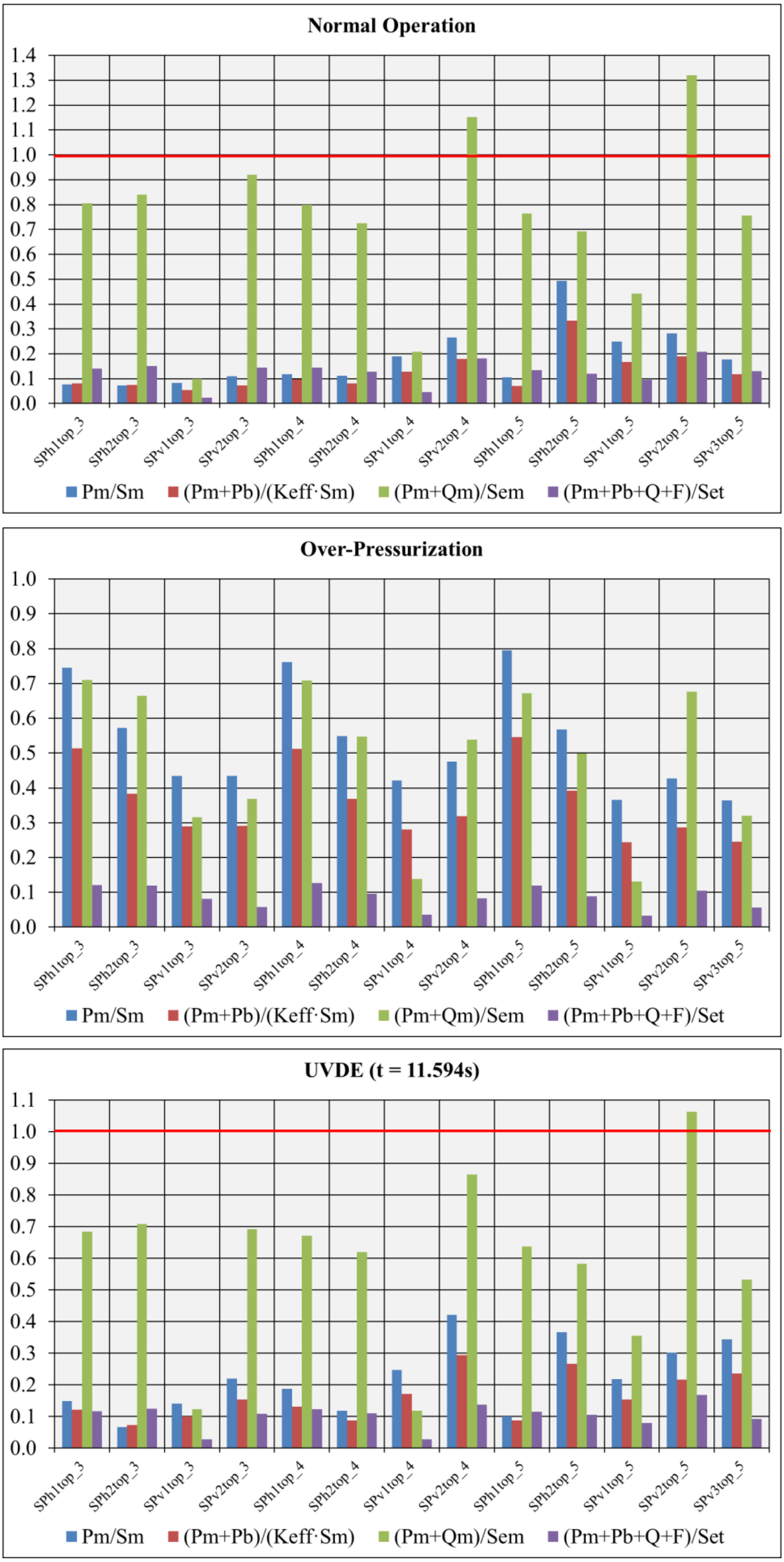


Figure 14. RCC-MRx criteria verification within the Top region.

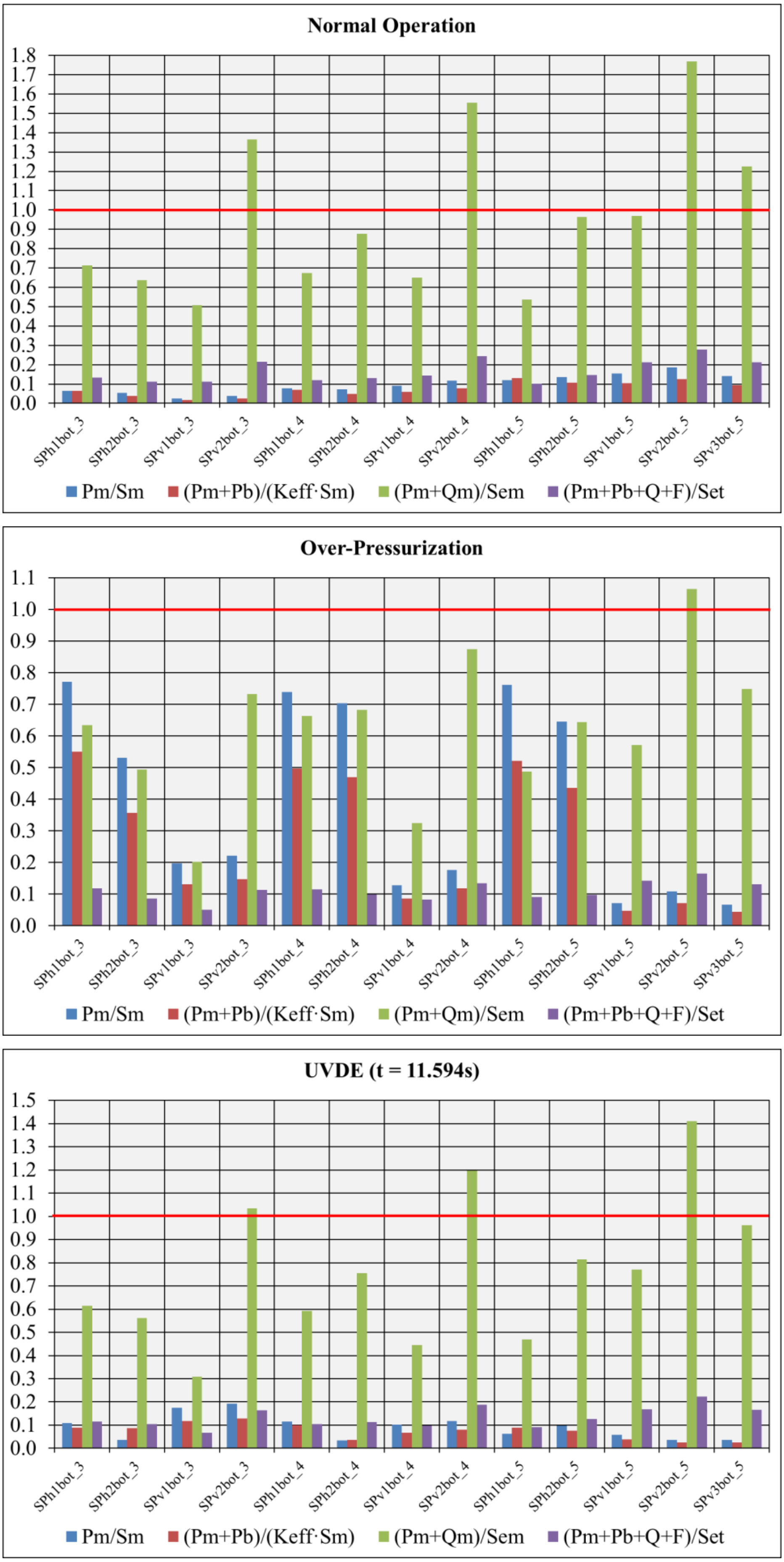


Figure 15. RCC-MRx criteria verification within the Bottom region.

5. Conclusion and follow-up

In this work, the preliminary thermal optimization of the equatorial region of the WCLL LOB segment and the investigation of the overall segment's structural behaviour is reported. The obtained results have allowed globally assessing the segment, to gather results for future and more detailed investigations aimed at evolving the current reference geometric configuration in view of the prescribed design requirements.

In the first part of the work, a geometric spatial arrangement of the DWTs has been found so to allow the fulfilment of the suggested thermal requirement on the maximum Eurofer temperature, which should not overcome the 550 °C in the structural components. Due to the asymmetric shape of the LOB segment, a dedicated assessment is necessary to obtain an acceptable DWTs layout for the whole segment and, as a consequence, being able to purposely design the water manifolds. In any case, the "crossing" of the DWTs within each elementary cells seems to be necessary to avoid the hotspots insurgences on the SPsh. Moreover, the DWTs distance from the SPsv should be kept sufficiently low to ensure their cooling. As a consequence, strong variations in the DWTs layout are expected in the transition regions, where the SPsv number passes from 5 to 3.

In the second part of the study, thanks to the extrapolation to the whole segment of the thermal field obtained from the thermal analysis of the equatorial region, the overall thermomechanical behaviour of the segment has been assessed under normal and off-normal steady state loading scenarios. The obtained results have allowed highlighting the necessity to revise the attachment system in order to reduce the deformation in the equatorial region. This is the main responsible of the failure in the RCC-MRx criteria verification, particularly problematic within the SPsv because of the secondary stress.

In the end, the main follow up of the reported activity is represented by local analysis of some regions of the WCLL LOB segment in order to consider the effect on the structural performances of the SB cooling channels, here not designed because of the lack of maturity of the reference geometric design of the WCLL LOB segment. In particular, adopting the sub-modelling technique, it shall be possible to locally assess particularly meaningful regions (e. g. the equatorial region and/or the transition regions) taking into account a portion of the SB endowed with the proper cooling channels and assuming as boundary condition, at the border of the assessed region, the displacement field predicted in the overall analysis of the whole segment. In this way, it will be possible improving the reliability of the results, looking in depth at the SB thermo-mechanical response and simulating more realistically the SPs surrounding components considering, at the same time, the mechanical influence of the rest of the segment.

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