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Structural Assessment of the European DEMO Water-Cooled Lithium Lead Breeding Blanket Central Outboard Segment Under Remote Maintenance Loading Conditions

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Abstract: Within the framework of the European research activities devoted to design the DEMO breeding blanket (BB), the Water-Cooled Lithium-Lead (WCLL) BB concept is one of the candidates currently assessed in EU. One of the main issues connected to its design is represented by the remote maintenance (RM) operations. In particular, previous thermo-mechanical analysis highlighted a Ductile to Brittle Transition Temperature (DBTT) shift above the room temperature within the WCLL central outboard (COB) segment during normal operation. This may pose problems during the RM operations foreseen in the BB replacement phase. Indeed, within those WCLL COB segment's regions where the DBTT shifted above the room temperature, the stress level arising during RM operations may be able to promote crack growth and migration resulting in a fragile fracture event. Then, in this work, the structural assessment of the DEMO WCLL COB segment under RM scenarios is performed, in order to provide the fracture mechanics analysis with the necessary input in terms of stress spatial distribution and to understand if the deformation occurring during RM can be accommodated by the available space reservation. Several potential RM scenarios have been considered, taking into account also the potential occurrence of a seismic event or the necessity to remove the WCLL COB segment with the liquid breeder not drained. The study has been performed adopting a numerical approach based on the Finite Element Method and adopting the quoted Abaqus code. The obtained results are quite encouraging and will allow, in the follow up, the refinement of the RM plan foreseen for the WCLL BB.

Keywords: WCLL BB, Thermo-mechanics, COB Segment, Remote Maintenance, Seismic

1. Introduction

Within the framework of the research activities on the nuclear fusion technology carried out in EU [1], the accomplishment of a sound conceptual design for the DEMO reactor represents a big milestone. To this goal, the EUROfusion consortium has been created. After the completion of the pre-conceptual design phase, the EU DEMO project is now beginning its conceptual design phase aimed at significantly improving and refining the design of the machine in accordance with the foreseen plant states, taking into account the integration among the different systems and components.

In this context, the definition of the remote maintenance (RM) plan for the DEMO in-vessel components plays a pivotal role [2]. In particular, the in-vessel components should be robust enough to safely withstand the loads they undergo during RM procedures, both in case of nominal and accidental conditions. Hence the DEMO Breeding Banket (BB) [3, 4], which is the main DEMO in-vessel component to be remotely handled, must be designed to ensure the RM tool operating properly according to the foreseen RM plan. In this regard, a big issue is represented by the Ductile to Brittle Transition Temperature (DBTT) shift above the room temperature occurring during nominal operations [5]. Consequently, the stress level arising within a BB segment during RM operations may be able to promote crack growth and migration resulting in a fragile fracture event.

In this work, the structural assessment of the Central Outboard Blanket (COB) segment under properly selected RM loading scenarios is reported. In particular, the attention has been paid to the Water-Cooled Lithium Lead (WCLL) BB COB segment [5]. The RM plan for the BB foresees to hook the BB segments in the RM tool, connected to the segments' chimneys, lifting them from their nominal positions and to moving them once they hang from the tool.

Three steady state loading scenarios, each related to a different RM potential condition, have been postulated and the corresponding structural analyses have been performed. First the nominal RM conditions, in which the WCLL COB segment is hooked in the RM tool and lifted from its nominal position, have been considered. Such a scenario envisages the BB segment totally drained from its functional fluids (cooling water and breeder). Second, an off-normal loading scenario foreseeing the WCLL COB segment without water but with the total amount of PbLi (i. e. the breeder) still inside has been assumed. Then, lastly, an earthquake occurring during the nominal RM conditions have been assessed considering the peak ground accelerations along vertical and horizontal directions. In all the assessed scenarios the attention has been paid to the stress and displacement spatial distributions, in order to check the onset of potential critical regions characterised by excessive stress and/or deformation.

The scope of this work is to provide reliable stress and displacement spatial distributions within the WCLL COB segment under different possible RM scenarios to be used for further assessments aimed at ensuring the RM operations can be safely performed. In particular, the stress spatial distribution shall be used to perform fracture mechanics analysis in those regions experiencing a DBTT shift above the room temperature, whereas the displacement field can be used to check if the BB space reservation and the envisaged RM sequence allow the segment replacement without hitting adjacent segments and/or the vacuum vessel.

The study has been performed adopting a theoretical-numerical approach based on the Finite Element Method (FEM) and using the quoted commercial FEM code Abaqus v6.14.

After this introduction, in Section 2 the geometric configuration of the WCLL COB segment is described, whereas in Section 3 the assumed loading scenarios and the FEM models set-up are depicted. Lastly, in Section 4 the obtained results are shown and critically discussed, focussing on the potential follow-up of this work. Conclusion is finally given in section 5, focussing on the potential follow up of this activity.

2. The WCLL BB COB Segment Geometric Layout

The design of the DEMO BB strictly reflects the reactor lay-out. The current EU DEMO configuration [6, 7] foresees 16 toroidal field coils dividing the machine in 16 sectors of 22.5° each. Hence, a proper Remote Maintenance system has been developed accordingly [8-10]. As a consequence, the BB can be split in 16 sectors too. A generic sector can be further split, basing on the current baseline, in five BB segments, two in the inboard region [11], namely Left and Right Inboard Blanket segments (LIB and RIB) and three in the outboard region, namely Left, Central and Right Outboard Blanket segments (LOB, COB, and ROB). Within a generic WCLL BB segment, five main regions can be identified: I) the First Wall-Side Wall (FW-SW), a U-shaped and actively cooled plate, covered by a tungsten armour, mainly devoted to face the plasma, II) the Breeding Zone (BZ), the area where breeding reactions take place and the Stiffening Plates (SPs) are located, III) the Manifolds, a region where the functional fluids are distributed and re-collected, IV) the Back Supporting Structure (BSS), a backbone structure having the main duty of withstand mechanical loads and assuring the BB connection with the Vacuum Vessel (VV) and V) the caps, two actively cooled plates that close the segment along the poloidal direction.

The complex of regions I, III, IV and V forms the Segment Box (SB), namely the structure devoted containing the breeder and internally reinforced by the SPs. An "exploded" view of the WCLL COB segment is reported in Figure 1.

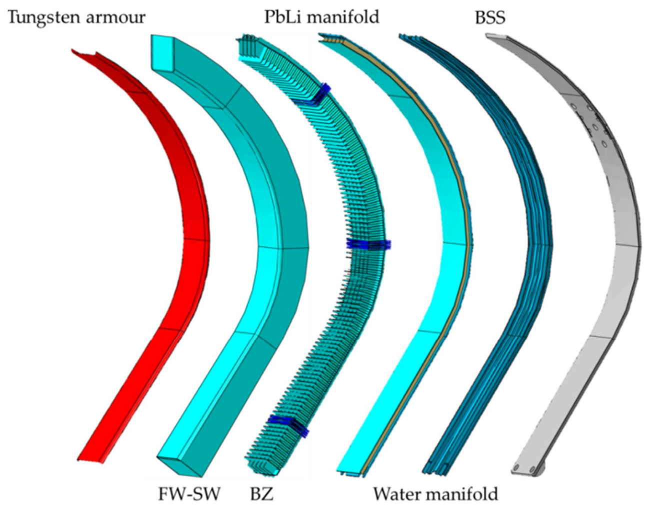

Figure 1. *Exploded view of the COB segment [5].*

The WCLL BB FW-SW complex is, as above said, a 25 mm thick U-shaped plate cooled by water at PWR conditions flowing in square channels with a 7×7 mm^2 cross section. Cooling channels run through a radial-toroidal-radial path. They are fed in counter-current by means of proper manifold system. In the current design, they are placed at a radial distance of 3 mm from the tungsten layer.

The BZ is that area of the segment enveloped by the FW-SW complex and delimited in the back part by a 20 mm back-plate. It contains the liquid lead-lithium eutectic alloy deputed to the tritium production and neutron multiplication. Moreover, it houses bundles of double-walled tubes devoted to remove the heat power deposited by neutrons and γ rays interacting with both the breeder and the steel. Indeed, most of the heat power arising from nuclear fusion reactions is deposited in this region of the blanket. The BZ is equipped with a grid of radial-toroidal (i.e., horizontal) and radial-poloidal (i.e., vertical) SPs, devoted to reinforcing the segment's structure.

The manifolds are that region of the BB segment devoted to distributing and re-collect water coolant and lead-lithium alloy to the BZ and FW-SW areas.

The BSS is that component of the BB segment that sustains the whole structure and contributes to the load withstanding. It mainly consists of a solid steel plate with a thickness of 100 mm, with the only exception of the lateral regions, where part of the FW manifolds is hosted. The BSS hosts the BB attachment system with the VV, mainly consisting in some shear keys to be placed on the lower and upper part of its VV facing surface.

Finally, there are the top and bottom caps. The detailed design of this component is still under development. A radial-toroidal section of the COB segment in correspondence of the equatorial plane is reported in Figure 2, where the details of the WCLL BB internals are depicted. More details on the WCLL COB segment reference design configuration can be found in [5].

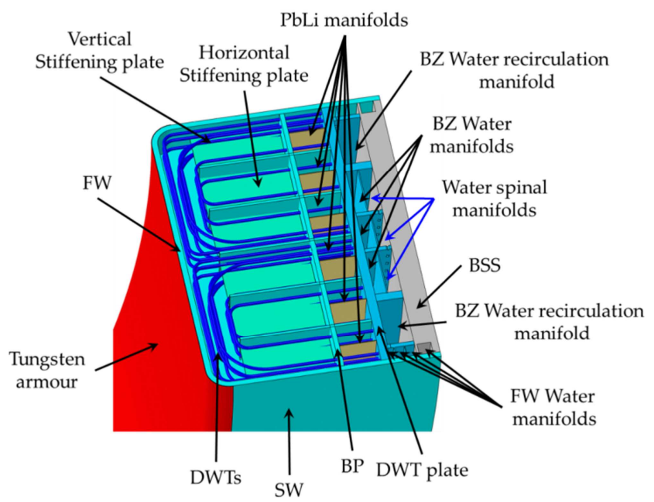

Figure 2. *Radial-toroidal section of the WCLL COB segment [5].*

3. The WCLL BB COB Segment FEM Models

In order to investigate the steady-state structural performances of the WCLL BB COB segment under RM loading scenarios, a proper FEM model has been set-up for each of the considered load combinations.

First, a spatial discretization grid (i. e. a mesh) composed by ~2.35M nodes connected in ~4.95M linear tetrahedral and hexahedral elements has been set-up (Figure 3) in order to reproduce the geometric layout of the WCLL BB COB segment plus the tungsten layer and the attachment system devoted to connecting it to the VV during the nominal conditions and ensuring the interface with the RM tool for the planned RM operations. In particular, the tungsten domain is depicted in yellow in Figure 3, whereas the SB is shown in green and the attachments in grey. Both the segment and the attachments are made of Eurofer steel.

Then, three different RM conditions have been postulated and the three corresponding loading scenarios have been defined. In all the three scenarios postulated, the WCLL COB segment is considered hanging from the RM tool, connected through the segment's chimneys (Figure 3). The envisaged RM scenarios are:

nominal RM scenario: a loading scenario representing the nominal RM conditions, foreseeing the WCLL COB segment hooked in the RM tool and lifted from its nominal position totally drained from its functional fluids (cooling water and breeder);

accidental RM scenario: a loading scenario representing a deviation from the nominal RM conditions, foreseeing the WCLL COB segment hooked in the RM tool totally drained from water and full of breeder;

seismic RM scenario: a loading scenario aimed at assessing the WCLL COB segment hooked in the RM tool and lifted in nominal conditions (i. e. totally drained from its functional fluids) undergoing an SL-1-type seismic event.

These scenarios could represent and update to the DEMO BB load specifications [12], as they must be part of the plant operating phases.

In all the scenarios investigated, the WCLL COB segment has been supposed to be at the room temperature, set equal to 20°C. Moreover, an acceleration of gravity equal to -9.81 m/s^2 along the Z direction (Figure 3) has been imposed to the whole domain in order to take into account the weight of the structure. In addition, the RM tool-BB connection has been simulated preventing the displacement along all the directions to the nodes highlighted in red in Figure 3. As it can be observed, an encastre condition has been imposed to a node set of the COB segment's chimneys to simulate the connection to the RM tool.

Hence, as far as the nominal RM scenario is concerned, it represents the WCLL COB segment hanging from the BB-RM gripping interface only subjected to its weight, given by the sum of the Eurofer steel and tungsten weights.

As far as the accidental RM scenario is concerned, the breeder domain has not directly modelled. Hence, the weight of the breeder (LiPb) has been simulated by assigning to the Eurofer volume (V_{Eur}) composed by the SB and the internal SPs (green region in Figure 3), an equivalent density ρ_{eq} calculated by the formula:

$$\rho_{eq} = \frac{\rho_{Eur} \cdot V_{Eur} + \rho_{LiPb} \cdot V_{LiPb}}{V_{Eur}}$$

Considering, at the room temperature of 20°C, $\rho_{Eur} = 7744$ kg/m^3 and $\rho_{LiPb} = 10172$ kg/m^3, an equivalent density of 25943 kg/m^3 has been calculated and applied to the SB and SPs in this scenario. In this way, the total weight imposed to the structure considers also the contribution of the breeder, in addition to the Eurofer steel and the tungsten.

Moreover, regarding the seismic RM scenario, the occurrence of a SL-1 earthquake during nominal RM has been considered. Preliminary seismic analyses [13] report, for an SL-1 event, the maximum equivalent accelerations of the BB in horizontal and vertical directions. In particular, in this work, an acceleration of -2.7 m/s^2 has been added to the acceleration of gravity as far as the seismic acceleration is concerned.

Concerning the seismic acceleration along horizontal direction, it has been considered as a parameter. Indeed, its total value of 0.8 m/s^2 has been imposed alternatively along X direction, Y direction and on the XY plane considering an acceleration vector forming an angle of 45° with respect to both the axes. Hence, three sub-scenarios, called seismic RM scenario-X, seismic RM scenario-Y and seismic RM scenario-XY45 have been investigated.

Lastly, the complete set of loading scenarios investigated is reported in Table 1.

Table 1. *Summary of the loading scenarios investigated.*

Scenario	T [°C]	PbLi [%]	g [m/s^2]	Seismic accelerations [m/s^2]		
			Z dir	X dir	Y dir	Z dir
Nominal RM	20	0	-9.81	0	0	0
Accidental RM	20	100	-9.81	0	0	0
Seismic RM-X	20	0	-9.81	0.8	0	-2.7
Seismic RM-Y	20	0	-9.81	0	0.8	-2.7
Seismic RM-XY45	20	0	-9.81	0.8·cos 45°	0.8·sin 45°	-2.7

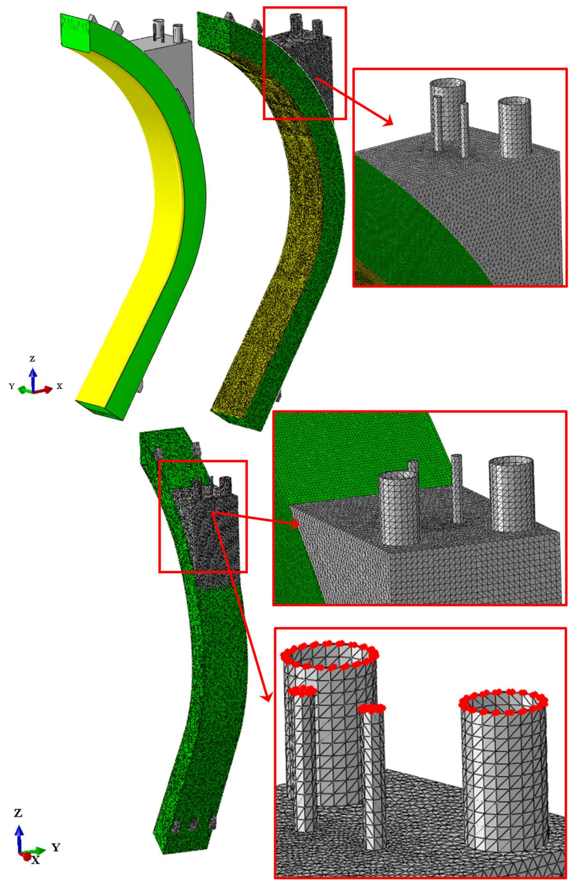

Figure 3. *The mesh set-up for the WCLL COB segment and the detail of the nodes constrained to simulate the BB-RM gripping interface.*

4. Analyses and Results

The results obtained from the steady state structural analysis performed using the FEM models described in the previous section are reported in the following. In particular, the spatial distributions of the Von Mises equivalent stress arising within the WCLL COB segment structure under the assumed loading scenarios are shown in Figure 4. As it can be observed, the maximum stress predicted within the segment's structure is lower than 75 MPa in all the five loading scenarios investigated. Von Mises stress values greater than 75 MPa are calculated only within the chimneys, namely in correspondence of the boundary conditions aimed at simulating the RM gripping sections. Hence, they are not physically meaningful as they are originated from the imposed mechanical restraints.

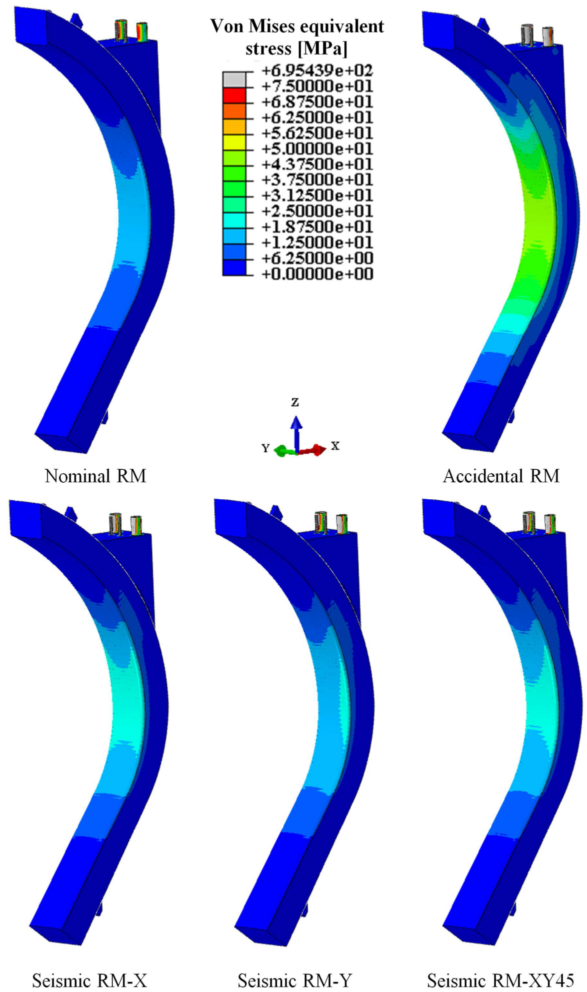

Figure 4. *The Von Mises equivalent stress spatial distributions.*

In the same way, the predicted total displacement fields under the loading scenarios investigated are depicted in Figure 5. As expected, due to the RM-BB interface location in the segment's upper chimney, the highest displacement is predicted in the segment's lower region.

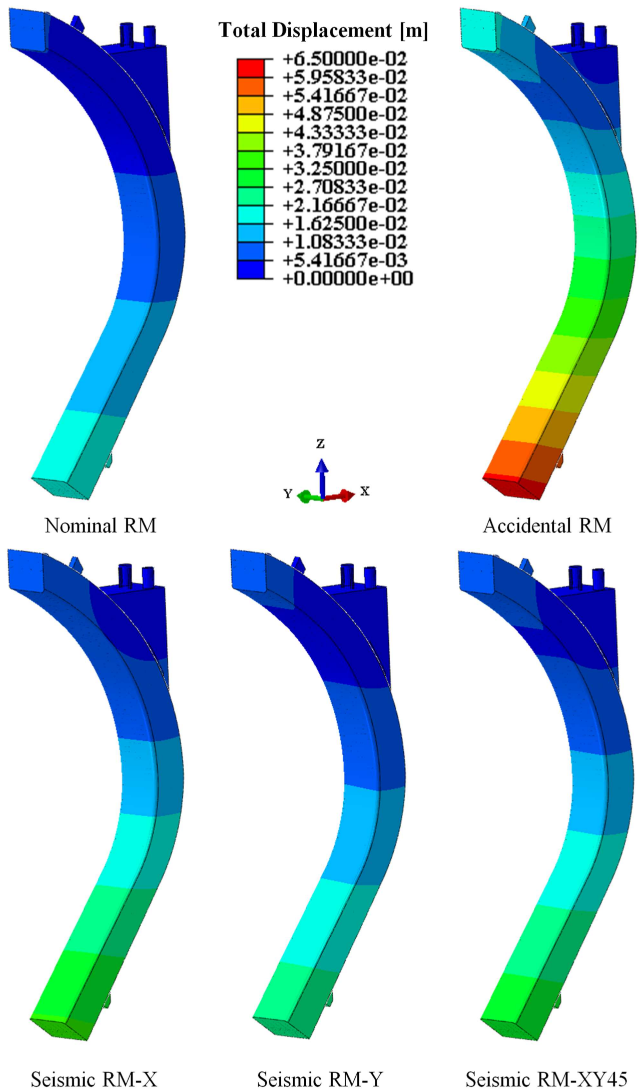

Figure 5. *The total displacement spatial distributions.*

In the following Figure 6 the undeformed geometric configuration, shown in wireframe view, is superimposed to the displacement fields already depicted in Figure 5. In the latter, the deformation is here amplified by an isotropic factor equal to 15 in order to highlight it.

From the stress and displacement fields reported above, as well as from the deformed vs. undeformed superimposed views, it is possible concluding that the most critical scenario is the Accidental RM one, namely that loading condition in which the WCLL COB segment is remotely lifted with the LiPb still inside. Moreover, among the three seismic loading scenarios, the most critical seems to be that in which the horizontal acceleration is directed along the X direction. This is due to the reduced resistant section that the segment offers along the X direction in comparison with that exhibited along the Y direction.

Lastly, in Table 2, the maximum and minimum displacement (indicated with U) along the three directions is summarized. From the reported values, it seems that the maximum displacement along X direction under the Accidental RM scenario may be problematic during the WCLL COB segment maintenance.

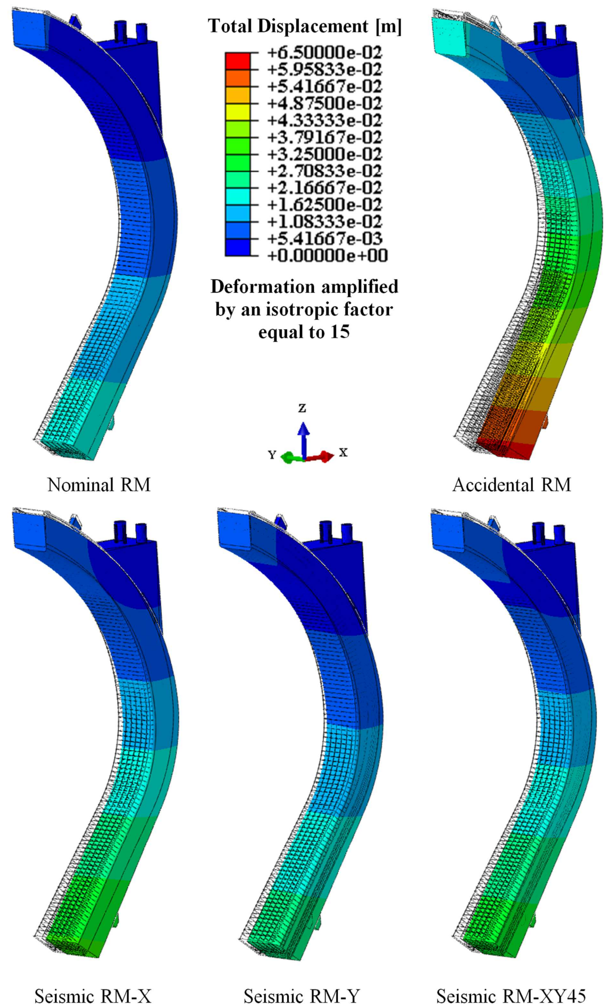

Figure 6. *The deformed vs undeformed configurations.*

Table 2. *Maximum and minimum displacement along the three directions.*

Scenario	Ux [m]		Uy [m]		Uz [m]	
	Max	Min	Max	Min	Max	Min
Nominal RM	1.97·E-02	-1.68·E-03	7.01·E-05	-3.02·E-05	1.19·E-03	-6.63·E-03
Accidental RM	6.01·E-02	-5.06·E-03	1.72·E-04	-8.76·E-05	3.67·E-03	-2.02·E-02
Seismic RM-X	3.28·E-02	-2.76·E-03	7.94·E-05	-6.38·E-05	2.03·E-03	-1.08·E-02
Seismic RM-Y	2.52·E-02	-2.20·E-03	2.07·E-03	-1.14·E-05	1.60·E-03	-8.52·E-03
Seismic RM-XY45	3.06·E-02	-2.61·E-03	1.47·E-03	-1.52·E-05	1.94·E-03	-1.02·E-02

5. Conclusion

In this work, the structural analysis of the WCLL COB segment under different RM potential conditions have been performed. The considered loading scenarios have regarded both nominal and accidental conditions, taking into account also the potential occurrence of seismic events.

The obtained results in terms of stress and displacement shall be used in further analysis to determine if the foreseen RM plan can be performed fulfilling all the safety requirements. In particular, an issue currently under investigation is represented by the potential crack propagation during the RM operations. To this end, fracture mechanics studies are ongoing to determine if the stress field arising during RM scenarios is able of promoting the crack growth and migration, until to generate a fragile fracture condition. Therefore, the results obtained in this work are crucial to perform the proper fracture mechanics assessments in the Eurofer domain [14].

Moreover, the predicted displacement may be used to understand the space reservation necessary to allow segments RM without hitting the adjacent segments and/or the vacuum vessel [15].

More in general, accurate studies on the structural response of a breeding blanket segment during remote maintenance scenarios should be performed in the follow-up of the DEMO project, since the condition to remotely handle segments which exhibit a fragile behaviour may represent a showstopper. In particular, the assessments here reported have been performed at room temperature, so to have only primary stress arising within the structure, but analysis at different temperatures and/or considering proper temperature spatial distributions could be performed in the future, to consider also the arising of secondary stress in case the remote maintenance had to take place in conditions different from the room temperature.

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