WPBB-CPR(17) 17438

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Preprint of Paper to be submitted for publication in Proceeding of 13th International Symposium on Fusion Nuclear Technology (ISFNT)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Transient thermal analysis and structural assessment of an ex-vessel LOCA event on the EU DEMO HCPB breeding blanket and the attachment system

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In the framework of the EUROfusion Consortium a blanket attachment system is under development, which allows the integration of the breeding blanket (BB) into the EU DEMO tokamak. The blanket attachment system is thereby responsible for the mechanical connection of the BB to the DEMO vacuum vessel (VV). It transfers the mechanical loads between BB and VV. The high mechanical and thermal loads on the blanket segments during normal and off-normal conditions especially pose strong requirements to the blanket attachment system. This article focuses on the off-normal event of an ex-vessel Loss Of Coolant Accident (LOCA) in the Helium Cooled Pebble Bed (HCPB) BB. The performance of its blanket attachment system is assessed as this event will induce a large temperature increase and thus an additional thermal expansion in the blanket, posing big challenges for the blanket attachment system and the blanket supporting structure itself. A 3D transient thermal analysis under an ex-vessel LOCA of the HCPB BB is presented. The structural assessment of HCPB blanket segments and the current blanket attachment system with respect to RCC-MRx rules is also reported, giving also an estimation of the resulting reaction loads to the VV during such an accidental event.

Keywords: EU DEMO, Breeding Blanket, Thermal Analysis, Structural Assessment, Ex-vessel LOCA

1. Introduction

In the framework of the EUROfusion Breeding Blanket (BB) Project, the Karlsruhe Institute of Technology (KIT) is developing the Helium Cooled Pebble Bed (HCPB) BB concept for European DEMO [1], in collaboration with BME and Wigner-RCP (Hungary) and CIEMAT (Spain).

Together with the HCPB BB, a BB attachment system is also being developed [2]. This system establishes the mechanical connection between the BB segments and the vacuum vessel (VV). The high mechanical and thermal loads on the blanket segments during normal and off-normal conditions pose strong requirements to the blanket attachment system. As the development of the attachment system requires the consideration of relevant off-normal conditions, this article focuses on the conditions during an ex-vessel LOCA event. This event represents a very demanding load case for the blanket attachment system due to strong temperature increase of the blanket segments and the related high thermal expansion. Therefore, a 3D transient thermal analysis during an ex-vessel LOCA in the HCPB BB is performed by using the Finite Element Method (FEM) code ANSYS. The outcome of this analysis together with mechanical, gravity and electro-magnetic loads are used as inputs to assess the structural integrity of HCPB BB segments and the current proposed design of the blanket attachment system with respect to the available structural design code RCC-MRx. The analysis also gives an estimation of the resulting reaction loads onto the VV during such an accidental event.

2. HCPB design description

The HCPB BB uses 8 MPa helium gas as coolant, with an inlet temperatures of 300 °C and an outlet temperature of 500 °C, respectively. The breeding zone (BZ) of the current reference HCPB BB design is comprised of a “sandwich” architectures of flat cooling plates (CPs). The volumes between the CPs are filled alternately with pebble beds of lithium orthosilicate (Li_4SiO_4) and beryllium (Be). Li_4SiO_4 thereby acts as tritium breeder and Be as neutron multiplier, respectively (Fig. 1e). The CPs are enclosed in modules delimited by: (1) the so-called First Wall (FW), which is a U-shaped and actively cooled plate, protected by a 2 mm layer of W-armor on the plasma-facing surface, (2) actively cooled caps on top and at the bottom of each module and (3) back plates at the back. Each module is connected to the so-called back supporting structure (BSS).

Each group of modules supported by a BSS, forms a segment. The European DEMO segmentation is arranged in 7 outboard (OB) and 7 inboard (IB) blanket modules in each OB/IB blanket segment (see Fig. 1). The BSS provides the coolant for the FW and BZ of each blanket module by BSS manifold pipes. The current EU DEMO tokamak baseline (EU DEMO baseline 2015) is divided into 18 sectors, the sectors thereby base on the 18 toroidal field coils. A blanket sector comprises 3 OB and 2 IB segments. A total number of 9 independent cooling loops are used to feed the BB system, consisting of 6 OB and 3 IB loops [3]. The blanket segments are connected to the tokamak VV via the blanket attachment system (see Fig. 5 and Fig. 12), which should be able to support the weight of the blanket segments, allow the thermal

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expansion of the blanket segments, accommodate the seismic and electro-magnetic loads during normal and off-normal conditions. Detailed description of the current design of the blanket attachment system is presented in [2] and [4].

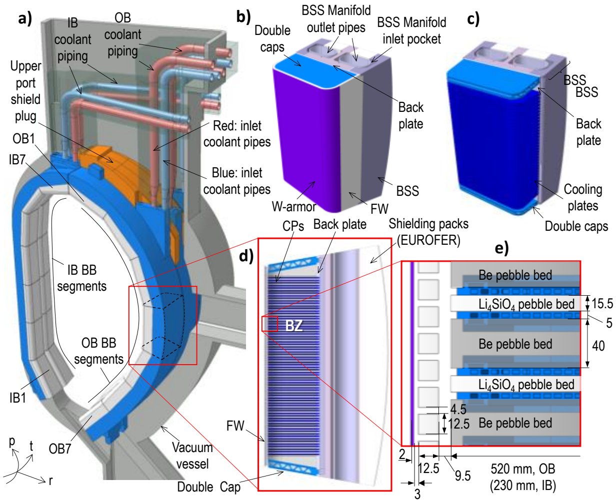

Fig. 1. Current HCPB Design: (a) Blanket sector; (b)&(c) 3D views of the OB4 module; (d) section cut of the OB4 module; e) detail of the BZ [5].

The FW cooling channels have a cross-section of 12.5 mm × 12.5 mm. The FW front part (plasma side) thickness is 3 mm, resulting in a total FW thickness of 25 mm, which is thin enough to contribute to a good tritium breeding performance (TBR ~ 1.15) while still satisfying structural requirement. The CP cooling channels have a rectangular cross-section of 3 mm × 5 mm. The Li_4SiO_4 pebble bed have a thickness of 15.5 mm, the CP of 5.0 mm and the Be pebble bed of 40.0 mm. Detailed dimensions of the BZ and the BB modules are shown in Fig. 1.

3. FEM models

An ex-vessel LOCA event is a design basis accident [6], which may cause large thermal gradients in the blanket module, thus inducing large thermal stresses in the BB attachment system. Under such an accident, it is of vital importance to conduct the structural assessment of the blanket attachment system. Taking profit of the periodicity of the alternating layers of Li_4SiO_4 pebble bed, CP and Be pebble bed of the BZs and considering the vast computational resources that a whole blanket sector would demand, a typical unit slice model from OB4 blanket module is then used to assess the transient thermal behavior of blanket (see Fig. 2). This unit slice consists of half thickness of Li_4SiO_4 bed, a complete CP and half thickness of Be bed and corresponding FW, back plates and BSS.

The critical time instant (t = 3.1 s, see section 4) is chosen when the BSS reaches the maximum temperature gradient (thus inducing the highest thermal expansion). The temperature profile at the critical time instant is then reconstructed (copied) from the unit slice model to the whole poloidal dimension of the OB blanket segments.

3.1 Boundary conditions and loads

It is conservatively assumed that before the accident happens, the reactor is operating in the flat-top burning phase (i.e. the blanket temperature reaches the asymptotic regime of the flat-top). The ex-vessel LOCA is assumed here to be triggered by a large rupture of the pipes outside the VV in the OB segments cooling loop (see Fig. 3). Therefore, only the OB blanket segments are affected, as the cooling loops for IB blanket segments and OB blanket segments are independent, as described in section 2 (also see Fig. 3). The asymptotic radial temperature profile of the FW of the unit slice model at the flat-top is taken from [5] and it is used for the FW in the IB blanket segments in the whole blanket sector.

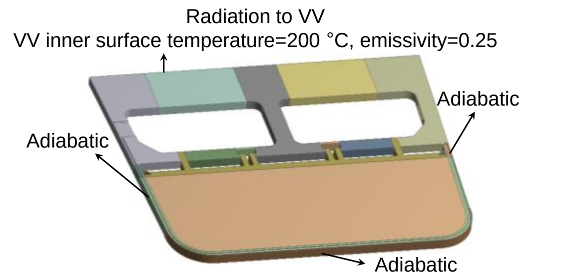

Fig. 2. Boundary conditions under ex-vessel LOCA.

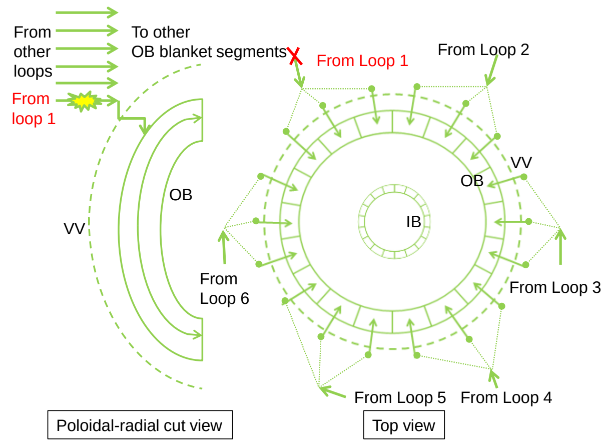

Fig. 3. Schematic of ex-vessel LOCA in OB blanket segments.

It is considered that the high pressure helium gas coolant is lost immediately in the 3 affected OB blanket segments. That means the thermal radiation from the blanket to the inner shell of VV is the only heat sink after accident (see Fig. 2). It is also considered that there is no heat transfer at the side walls between two adjacent blanket modules, since the two blanket modules have the same boundary conditions and loads. The thermal radiation between the OB FW and the intact IB FW has not been considered. Symmetric boundary conditions are applied on top and at the bottom surfaces of the unit slice model. After discussions with safety experts [7], it has been suggested that under ex-vessel LOCA soft plasma shutdown (without plasma disruption) within 100 ~ 150 s is to be used in EU DEMO: in this paper 120 s is used. The nuclear heating power density is taken from [8] and a typical normal operation heat flux of 0.5 MW/m^2 is applied on FW plasma-facing surface. After the initiation of the ex-vessel LOCA, it takes 3 s to trigger the plasma shutdown system [9]. Thereafter, the heat flux and nuclear heating power density ramp down linearly from the normal operation values to the decay heat power. After complete shutdown, the decay heat from [10] is the only heat source (Fig. 4).

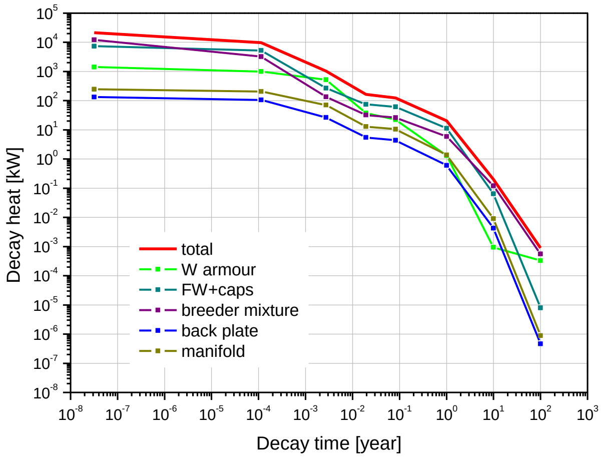

Fig. 4. Decay heat in EU HCPB-DEMO reactor [10].

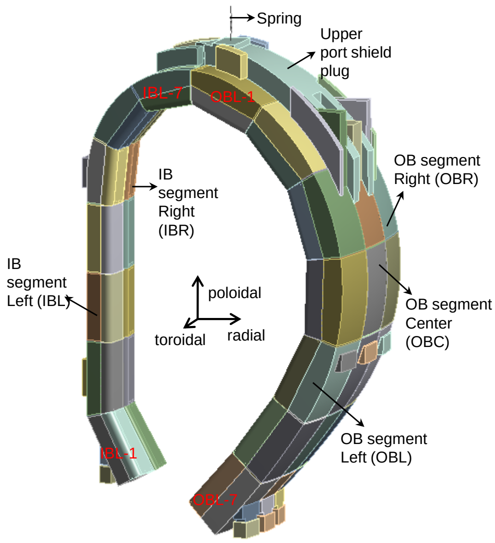

Fig. 5. Global model for structural analysis.

The global model consists of 3 OB blanket segments with their attachments, 2 IB blanket segments with their attachments, the upper port shield plug and the corresponding VV counterparts, as shown in Fig. 5. Since the BB attachment system and the connected BSS are of most interest for the structural assessment in this article, the internal details of the BZ are not presented in the global model in order to reduce the computation time. Proper material properties of the structural material are used [4]. The temperature profiles obtained from the unit slice model at the pulse flat-top [5] are reconstructed to the global model by using an averaged radial temperature profile for the IB blanket FW. On the other side, due to the larger nuclear heating expected in the IB BSS in comparison to the OB BSS, the temperature field on the IB blanket BSS has been obtained using 3D thermal analysis on the global model by implementing nuclear heating and applying convective heat transfer by the Gnielinski-correlation [11] in the BSS manifolds. Additionally, the thermal radiation between the BSS and the VV inner shell is considered with an emissivity of 0.25 and with a background temperature of 200 °C (VV operating at 200 °C [12]).

8 MPa pressure is applied on the surfaces in contact with the helium coolant (i.e. cooling channels and manifolds) in IB blanket segments and no pressure is applied on the cooling channels of OB blanket segments since it is considered that there is no helium coolant left at 3.1 seconds after ex-vessel LOCA in OB blanket segments due to the fast expansion of high pressure helium.

The loads induced by electro-magnetic effect for the blanket segments under the current ex-vessel LOCA condition are comprised of Maxwell forces and Lorentz forces (during plasma shrinking), which are applied to the volume geometrical center of each blanket module and the corresponding BBS behind. The electro-magnetic loads are taken from [13].

Gravity is applied on all bodies in the global model. The environment temperature for the analysis is 200 °C, as the VV is assumed to be operating at 200 °C as shown in [12]. All the structures of the VV are therefore set to 200 °C. The mechanical constraints are reported in [4].

3.2 Mesh

The major parts of the mesh for the structural analysis are hexahedron-dominant, with mid-side node kept. Since the global model is large, for the first step a coarse mesh (see Fig. 6 left) is used to identify the most critical regions (that is: OB segment Left and IB segment Left), where larger stresses are expected. After obtaining a first result a refined mesh (see Fig. 6 right) is used in the most critical regions while keeping a coarse mesh in the rest of the model. There are totally 281942 elements (906015 nodes) in the coarse mesh and 652015 elements (2228518 nodes) in the refined mesh.

Fig. 6. Coarse and refined mesh of global model.

4. Results and analysis

4.1 Transient thermal analysis of ex-vessel LOCA

Based on the unit slice model from the equatorial OB4 module described in section 3, the transient thermal analysis has been conducted. The ex-vessel LOCA starts at t=0 s. The plasma shutdown system triggers the shutdown 3 s after the accident happens [9]. As defined in section 3.1, the plasma is considered to be shut down softly within 120 s. The transient simulation ends at 10 hours after the accident initiation. The maximum temperature evolution as function of time of different sub-components after the ex-vessel LOCA initiation is shown in Fig. 7. It is found that the temperatures of the Li_4SiO_4 and Be pebble bed are decreasing quickly after the triggering of the plasma shutdown system. While the FW temperature in the first stage (from 0 s to 27.1 s) is increasing even after triggering the plasma shutdown, the FW temperature is decreasing gradually after 27.1 s. In the long term and despite the remaining decay heat, the temperatures of all sub-components are decreasing due to the thermal radiation from the BB to the VV. It is found that at t=3.1 s the thermal gradient of BSS is the largest. Therefore, the temperature profile at this time instant has been used as thermal load to calculate the thermal stress and the expansion on BSS.

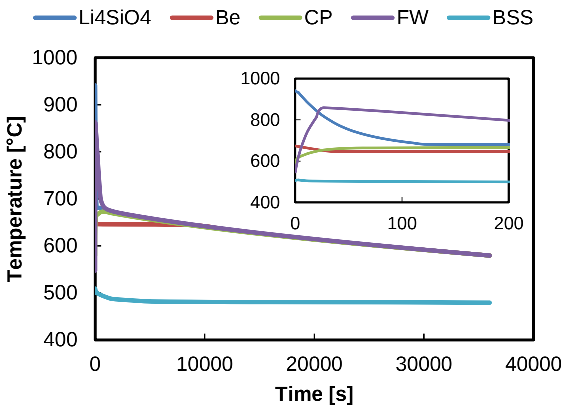

Fig. 7. Maximum temperature evolution of different sub-components after ex-vessel LOCA initiation.

The temperature contours at the ex-vessel LOCA initiation (t=0 s) and 10 hours after accident initiation are shown in Fig. 8.

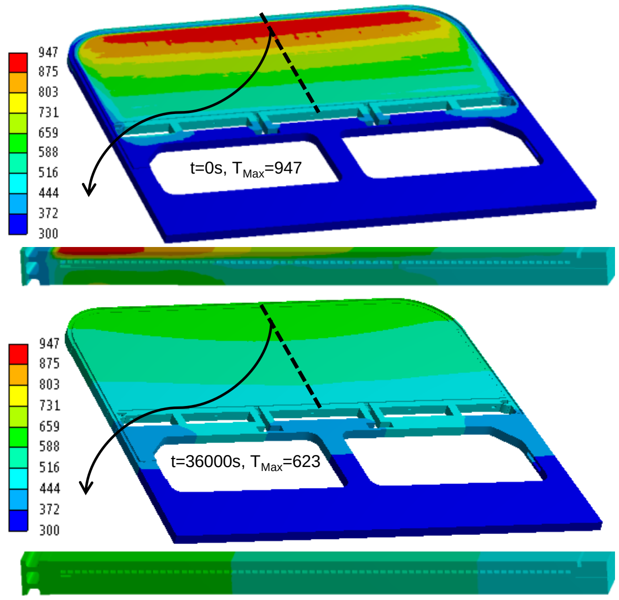

Fig. 8. Temperature contours at t=0 s and t=10 h [°C].

4.2 Structural assessment under ex-vessel LOCA

The temperature field on the 3 OB and 2 IB blanket segments is obtained based on the methodology mentioned in section 3. The temperature contour on the 3 OB and 2 IB blanket segments is shown in Fig. 9.

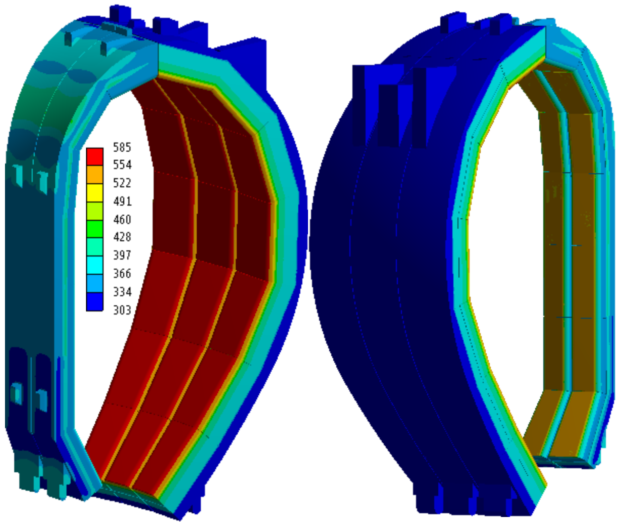

Fig. 9. Temperature contours on blanket segments [°C].

The von Mises stress field of the whole global model is shown in Fig. 10. Due to similar behavior of 3 different OB segments and 2 different IB segments, the structural assessment has been then focused on one OB (e.g. OBL) and one IB segment (e.g. IBL), shown in Fig. 11.

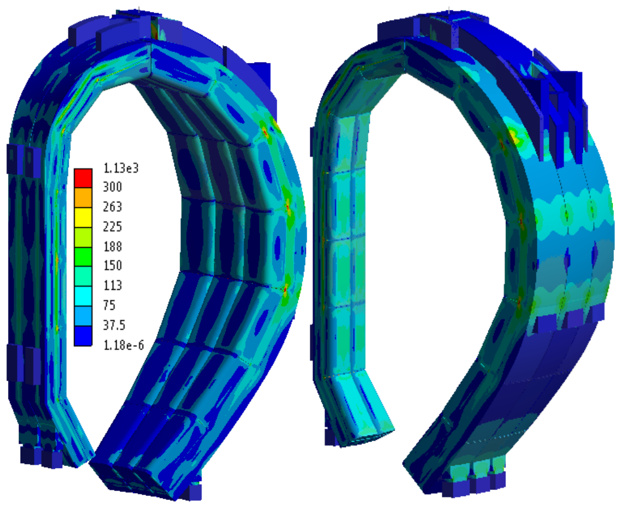

Fig. 10. Von Mises stress field on blanket segments under ex-vessel LOCA [MPa].

The maximum stresses are located at the regions where two blanket modules interact with each other. The stresses are then assessed with respect to the nuclear code RCC-MRx. The procedure to assess the stresses in that code is based on the linearization of the stress tensor on a path defined along the thickness of a region where von Mises stress is the highest [14]. The damage modes of immediate plastic collapse (IPC), immediate plastic instability (IPI) and immediate plastic flow localization (IPFL) are assessed with the corresponding allowable stress values at Level D criteria of RCC-MRx. The linearized stresses at most critical regions and the comparison with corresponding allowable stresses are presented in Table 1. It has been found that under the selected ex-vessel LOCA the HCPB BB and the attachment system shows good structural performance, satisfying the selected damage modes under the Level D criteria.

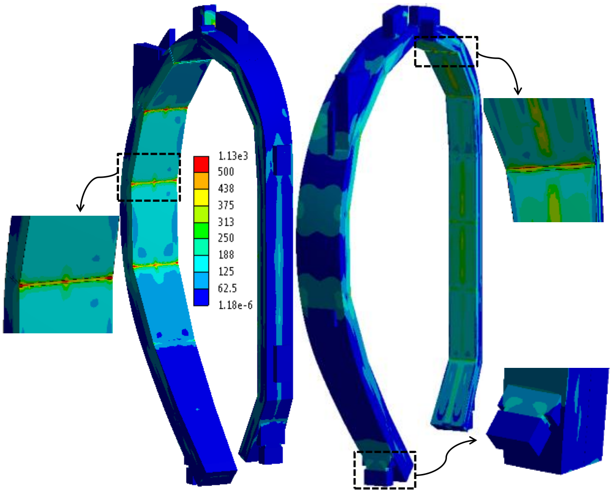

Fig. 11. Von Mises stress field on OBL and IBL under ex-vessel LOCA [MPa].

Table 1. Stresses assessment with respect to RCC-MRx Level D criteria on the most critical path on OBL, IBL and attachments [MPa]

	IPC		IPI		IPFL	
	$\overline{P_m}$	Limit	$\overline{P_L+P_b}$	Limit	$\overline{P_m+Q_m}$	Limit
OBL	16	332	27	498	364	506
IBL	24	340	142	509	169	506
Attach.	98	361	220	541	102	506

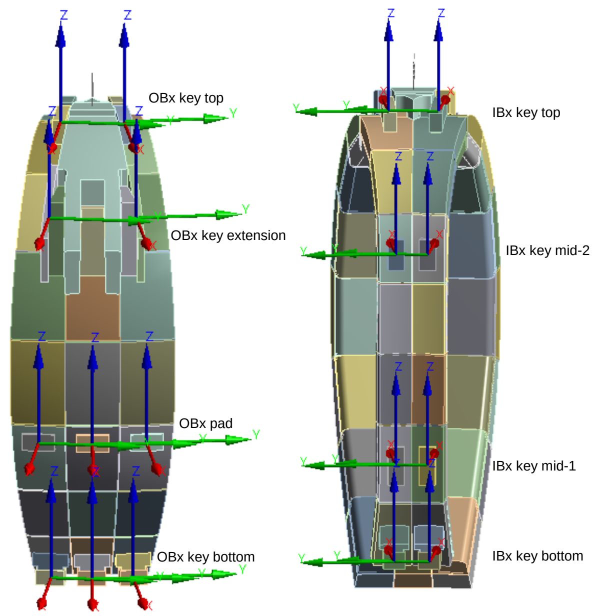

Fig. 12. Local coordinates for reaction forces and moments at attachments

The reaction forces and moments on the VV under the ex-vessel LOCA are reported in Table 2. Fig. 12 shows the local coordinates for reaction forces and moments acting on the VV.

Table 2. Reaction forces and moments at attachments acting upon VV (F-force, M-moment)

	Fx	Fy	Fz	Mx	My	Mz
Units	MN	MN	MN	MN·m	MN·m	MN·m
OBR key bottom	3	-7e-2	6	-6e-2	1e-1	-8e-3
OBR pad	4e-4	-3e-8	5e-3	-6e-8	6e-6	-5e-8
OBC key bottom	3	-3e-2	6	2e-1	1e-1	3e-2
OBC pad	0	0	5e-3	-2e-8	-3e-6	2e-11
OBL key bottom	3	5e-2	6	-9e-2	1e-1	-4e-2
OBL pad	5e-4	-2e-8	5e-3	-5e-8	1e-5	1e-7
OBR key extens.	6e-1	-9	-3e-2	8e-1	5e-2	6e-1
OBR key top	3	-2e-1	-4	3e-1	-1	2e-1
OBL key extens.	6e-1	1e+1	-3e-2	-1	8e-2	-1
OBL key top	3	2e-2	-4	-3e-1	-9e-1	-2e-1
IBR key bottom	9e-1	3e-2	4	-1e-2	7e-3	2e-2
IBR key mid-1	2	2e-2	3e-2	-3e-3	-2e-1	3e-3
IBR key mid-2	6	-2e-1	-2e-1	2e-2	6e-1	-8e-3
IBR key top	-3e-1	1e-1	-3	4e-2	-2e-1	6e-2
IBL key bottom	8e-1	5e-2	5	2e-2	4e-3	-2e-2
IBL key mid-1	2	-1e-1	4e-2	-3e-3	-2e-1	-1e-2
IBL key mid-2	6	3e-1	-3e-1	-6e-2	7e-1	2e-2
IBL key top	-3e-1	-2e-1	-4	-6e-2	-4e-1	-2e-1

5. Conclusions

Transient thermal analysis of the current reference HCPB BB design for EU DEMO baseline 2015 under an ex-vessel LOCA has been presented, showing a sufficient cooling down of decay heat by thermal radiation to VV after accident. The structural assessment of the HCPB BB segments under the selected accident conditions have been conducted, showing large margins against selected damage modes with respect to the RCC-MRx Level D criteria. The reaction forces and moments at attachments, acting on VV under selection accident conditions are obtained. As the final design optimization of BB involves many design iteration (thermal hydraulics, neutronics, thermos-mechanics etc.), these results will be useful for further improving the design of the HCPB BB and its attachment system.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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