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Structural assessment of the HCPB breeding blanket segments in the EU DEMO reactor under normal operation and a central plasma disruption

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The aim of the work reported in this paper is to evaluate the structural integrity of the Helium Cooled Pebble Bed (HCPB) breeding blanket segments in the EU DEMO reactor under the boundary conditions given by the current version of the attachment system, which connects the segments to the vacuum vessel. A 3D model of a DEMO sector has been developed using the FE software ANSYS and thermo-mechanical analyses are performed considering thermal and mechanical loads under normal operation as well as additional EM loads during a central plasma disruption. The results of the structural analysis are presented and the stresses on the back supporting structure of the breeding blanket segments are evaluated taking into account the RCC-MRx code. The design of back supporting structure fulfills the required criteria for the normal as well as the considered off-normal operation conditions. With respect to the iterative development process, these results represent an important input for the further optimization of the design of the attachment system.

Keywords: DEMO, HCPB breeding blanket, EM loads, structural analysis

1. Introduction

The breeding blanket (BB) is one of the key components of the EU DEMO reactor as it represents the core of the reactor. The main functions of the BB is to breed tritium, extract heat from the nuclear power generated in the plasma and to transfer it to the Primary Heat Transfer System (PHTS) as well as to shield the components behind the BB system from the neutron irradiation. The BB system is divided into sectors and each sector into inboard (IB) and outboard (OB) segments.

At present four different concepts for the BB systems are developed in the EU as possible candidates for the integration in the EU DEMO reactor. Each concept represents a different combination of functional materials and cooling media. A detailed overview of the status of the BB studies is given in [1]. This paper is focused on the structural assessment of the segments of the Helium Cooled Pebble Bed (HCPB) BB concept, which uses Li_4SiO_4 and Be in the form of pebble beds as breeder material and neutron multiplier respectively. Helium at high pressure serves as coolant and helium at low pressure purges the Li_4SiO_4 pebble beds [2].

As plasma-facing components, the BB segments are subjected to high thermal and mechanical loads during normal and off-normal operation. The thermal loads are given by the radiation and charged particle heat flux on the first wall and volumetric nuclear heating, while the mechanical loads originate mainly from the gravity and electro-magnetic (EM) loads, which are one of the most demanding loads on the segments. While static EM forces, the so-called Maxwell forces, act on the BB segments during normal operation, additional transient Lorentz forces during off-normal operation, e.g. plasma disruption events, are present.

The mechanical boundary conditions for the BB segments are posed by the so-called attachment system, which establishes the connection between the segments and the vacuum vessel (VV). Therefore, the attachment system has to support the segments in such a way that the high mechanical loads are transferred to the VV while assuring the structural integrity of the segments. On the other hand, it has to allow the thermal expansion of the BB segment relative to the VV in order to limit thermal stresses.

The optimization of the design of the BB system and the attachment system is an iterative process driven by the structural assessment of the blanket segments and the requirements imposed by remote maintenance (RM) operations. Hence, the aim of this work is to evaluate the structural integrity of the HCPB BB segments under the boundary conditions given by the current version of the attachment system, which is based on a proposal compliant with the RM requirements [3], as important part of the iterative design process.

The thermo-mechanical analyses are performed based on a 3D model of a DEMO sector developed in the FE software ANSYS. Two scenarios are considered in these analyses, which represent the conditions under normal operations and the additional EM loads during a central plasma disruption.

2. HCPB Breeding Blanket system

The present design of the HCPB BB system is based on the EU DEMO1 baseline BL2015, which subdivides the reactor in 18 sectors each consisting of 3 OB segments and 2 IB segments (Figure 1). Each of the IB and OB segments is formed by 7 BB modules connected to a back supporting structure (BSS).

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The current design of the attachment system represents an adaption of the attachment system presented in [3] from BL2014 (16 sectors) to BL2015 (18 sectors). It consists of several support elements, keys and pads as depicted in Figure 1. The port shield connects the IB and OB segments and is pushed by a spring pack onto the BSS. Gaps are defined in between the attachment elements on the side of the segments and the counterparts on the VV side in such a way that the gaps are closed after the thermal expansion of the segments under normal operation conditions.

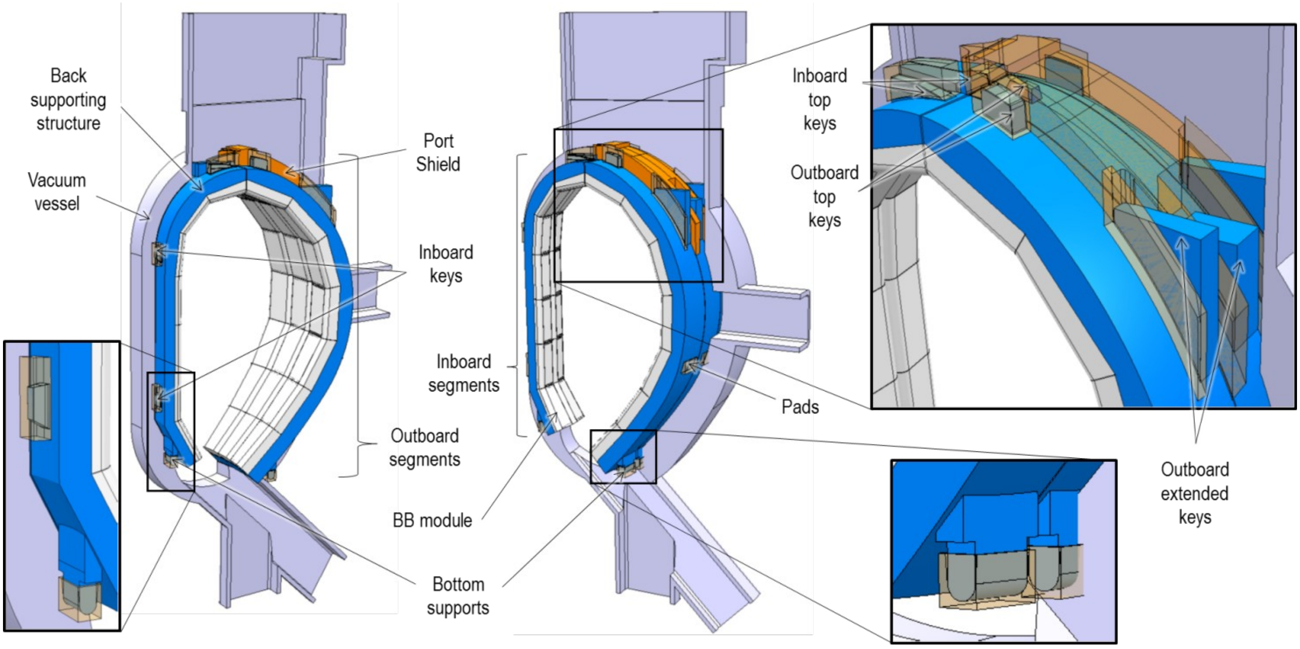

Fig. 1. Sector of the DEMO reactor with HCBP Breeding Blanket system and attachment system.

3. Structural assessment of the HCPB BB system

The structural integrity of the HCPB BB system is studied taking into account two scenarios: the conditions under normal operation and the conditions during a central plasma disruption. The temperature distribution on the segments for both scenarios is obtained by a simplified thermal analysis of the normal operation conditions, i.e. a change of the temperature distribution during a plasma disruption is neglected due to the short duration in relation to the thermal inertia of the BB system. Consequently, the two scenarios only differ by the applied EM force distribution. The boundary conditions are described in detail in section 3.2.

3.1 FE model

The FE model of the HCPB BB system includes all 5 segments in a sector as they are connected by the port shield and therefore interact with each other. Furthermore, the attachment elements on the side of the segments are modelled in detail in order to represent the kinematic constraints of the attachment system. The counterparts on the VV side only represent the portions of the VV that are in contact with the attachment system.

The BB modules consist of empty boxes as shown in Figure 2. In order to take into account the real weight of the modules, the density of the walls has been increased by a factor of 2.2. The Young’s modulus of the module walls has been scaled by a factor of 0.45 to represent the stiffness of a complete module. The BB modules, the BSS and the attachment elements on the side of the BB segments are made of EUROFER97. The material properties of stainless steel 316-L(N)-IG are applied to the port shield and the portions of the VV.

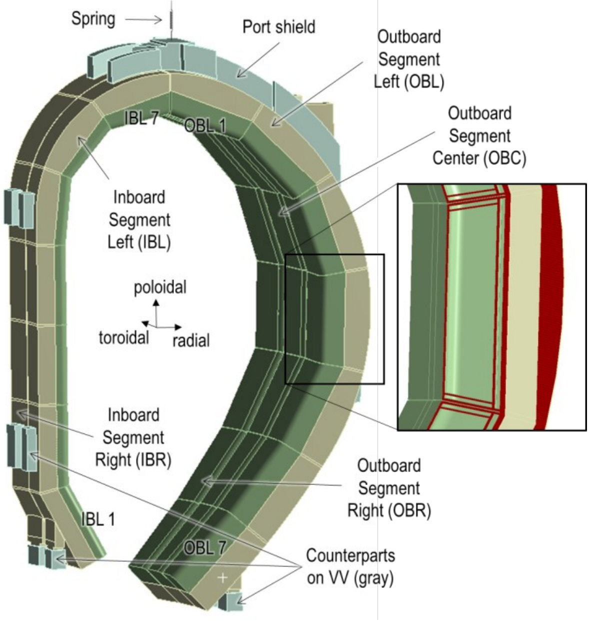

Fig. 2. FE model of the DEMO sector

Two FE models of the sector have been built with different FE meshes. By a FE model with coarse mesh the highest stresses have been identified on the inboard and

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author’s email: christian.zeile@kit.edu outboard segments left (IBL and OBL), which then have been refined in a second FE model. Due to the high number of non-linear contact conditions, the refined FE model also comprises the entire sector. However, in this model the elements sizes on the IBL and OBL segments are significantly reduced. This finally leads to a FE mesh with about 2×10^6 nodes and 5×10^5 elements. The results, which are presented in the following, are always based on the refined FE model.

3.2 Boundary conditions

The thermal boundary conditions for both scenarios represent the conditions under normal operation. In the plasma disruption scenario, the transient Lorentz forces are applied in addition to the Maxwell forces, which are present in both cases.

3.2.1 Thermal boundary conditions

The thermal boundary condition for the BB segments and the attachment elements on the side of the segments are obtained by two different approaches. The temperature distribution along the poloidal extension of the OB and IB blanket modules is assumed similar to the radial-toroidal temperature profile of a unit slice of the OB4 blanket module in the equatorial plane during normal operation [2]. For the sake of simplification, the average temperature in the First Wall (FW) steel in toroidal direction along the radial direction has been extracted from the unit slice, applied to the OB modules and rescaled for the IB modules to represent the smaller radial thickness of the IB modules.

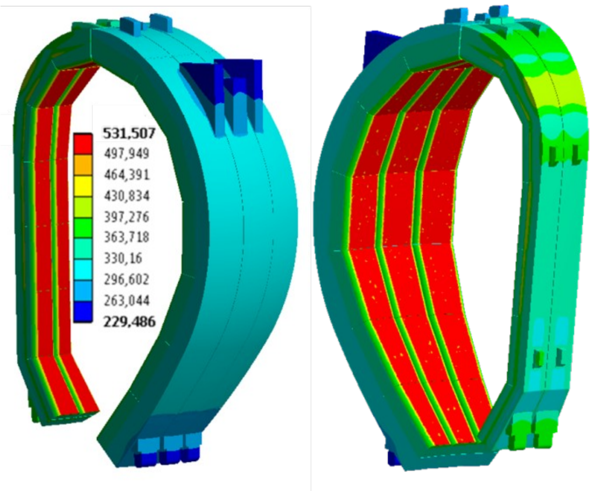

Fig. 3. Temperature distribution in °C on the BB segments during normal operation

A different approach is required for the BSS and the attachment elements, as the nuclear heating in the BSS of IB and OB differs by an order of magnitude and therefore the unit slice temperature cannot equally be assumed for the IB BSS. For this reason, a simplified thermal analysis has been performed for the BSS of the IB and OB BB segments. Nuclear power densities are specified on the BSS and attachment structures by scaling of the radial nuclear power density for OB4 and IB4 with the neutron wall load (NWL) along the poloidal direction. A heat transfer coefficient (HTC) is specified in the cooling channels of the BSS obtained by calculation of the Nusselt number with the Gnielinski correlation at a helium temperature of 300 °C. Conductive heat transfer between the attachment elements and the VV is neglected, which is a conservative approach under the assumption of electrically and thermally insulated contacts. Radiation between the backside of the BSS and the VV has been considered, assuming a constant VV temperature of 200 °C and an emissivity of 0.25. The resulting temperature distribution under normal operation is shown in Figure 3. The highest temperature on the attachment elements occur on the IB segments with about 390 °C at the bottom supports.

3.2.2 Mechanical boundary conditions

The mechanical boundary conditions are given by the EM force distribution, the helium pressure inside of the BSS cooling channels of 8 MPa and gravity.

The EM forces are applied to the BB modules and corresponding volumes of the BBS behind each module in terms of force and moment components obtained for the geometrical center for each volume by EM analyses. The Maxwell forces are specified in [4]. The Lorentz forces are taken at the time considered as worst case during a simplified central disruption as defined in [5].

The spring on top of the port shield is represented by a spring element that is defined as a two-stage spring. The first stage is used to accommodate the thermal expansion and to apply a preload of about 10 kN. The second stage works as a hard-stop. Furthermore, the counterparts on the side of the VV are fixed.

3.3 Structural assessment under normal operation and central plasma disruption

The structural integrity of the HCPB BB system is investigated under normal operation conditions and a central plasma disruption. The structural assessment of the BB system for both scenarios is based on static thermo-mechanical analyses, which can be also considered as conservative approach for the fast transient Lorentz forces during a plasma disruption.

As the VV is only represented by the counterparts of the attachment elements, the position and shape of the counterparts corresponds to the VV state at 200 °C. Hence, the reference temperature of 200 °C is specified for the analyses under the assumption that no thermal stresses are present at this temperature since the entire DEMO sector has a temperature of 200 °C. Therefore, the portion of the total deformation coming from the thermal expansion has to be considered with respect to this reference temperature.

The total deformation of the HCPB BB segments and the port shield under normal operation and a central plasma disruption can be seen in Figure 4. The deformation in both scenarios is very similar with a maximum deformation of about 43 mm at the port shield. However, during the plasma disruption a small twisting of the segments around the poloidal axis is visible. This also

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leads to a slight tilting of the port shield. In addition, the port shield extensions are losing the contact to the BSS in both scenarios, which means that the contact to the BSS is only maintained in the area below the spring pack. All other attachment elements are in contact with their respective counterparts on the VV with exception of the OB BSS and the pads.

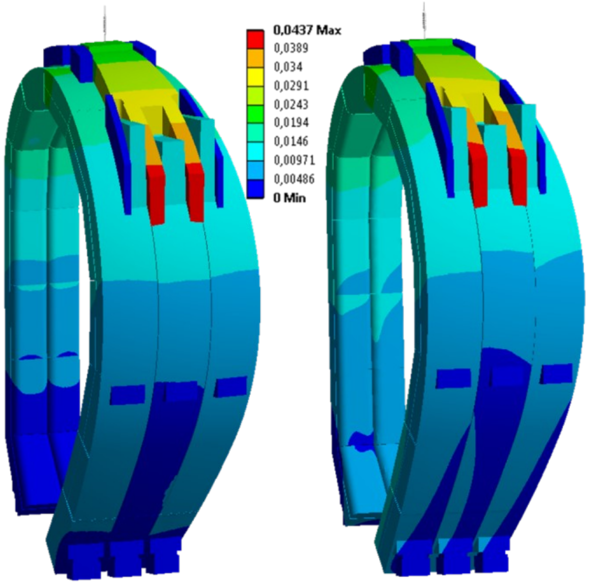

Fig. 4. Total displacement in m of the DEMO sector under normal operation (left) and a central plasma disruption (right)

The assessment of the structural integrity is focused on the BSS and the attachment elements on the segments, as they have to resist and transfer the mechanical loads to the VV and therefore experience the strongest loads. The resulting von Mises stresses on the left IB and OB BSS are given for both scenarios in Figure 5 and Figure 6. The stress distribution is also very similar for both scenarios. However, the stress level on the OB BSS is slightly higher, especially on the back part. The maximum stresses occur on the BSS structure in the interspace between two modules, as the cross-section is smaller in this area.

Furthermore, the stresses on the BSS have been evaluated by the procedure specified in the design code RCC-MRx. In particular, the design has been checked according to the rules against immediate plastic collapse (IPC), immediate plastic instability (IPI), immediate plastic flow localization (IPFL) and progressive deformation (PD), which allow for a first meaningful assessment of the structural integrity. The required stress linearization for the most critical path on the IBL and OBL under normal operation (NO) condition and a central plasma disruption (PDis.) is given in Table 1. The design of the BSS satisfies the given criteria with the smallest margin of 9 % for the rule against IPI for the OBL segment during the plasma disruption scenario. However, the margin under normal operation for the IPI criterion is only slightly higher. By comparing the results of stress linearization according to the IPI and PD rule, it can be seen that the secondary stresses Q are more dominant on the IBL than on the OBL segment.

Table 1. Stress linearization according to RCC-MRx on the most critical paths on IBL and OBL

[MPa]	IPC P_m	IPI P_m+P_b	IPFL P_L+P_Q	PD (P_m+P_b) + ΔQ
Limits	**S_m**	**1.5 S_m**	**S_{em}**	**3 S_m**
(350 °C)	**165**	**247.5**	**313**	**495**
OBL (NO)	13.6	215.8	65.2	274.4
IBL (NO)	22.7	138.0	170.1	299.6
OBL (PDis.)	25.9	226.0	78.7	286.5
IBL (PDis.)	21.9	121.7	169.2	286.0

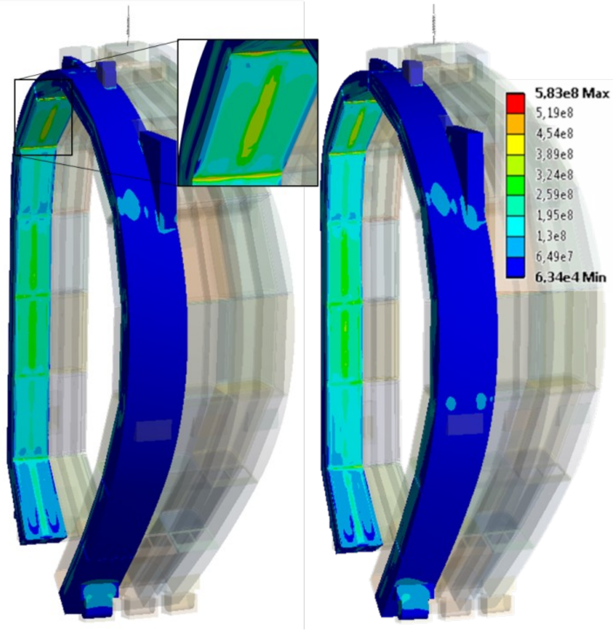

Fig. 5. Von Mises stresses in Pa on the left IB BSS under normal operation (left) and a central plasma disruption (right)

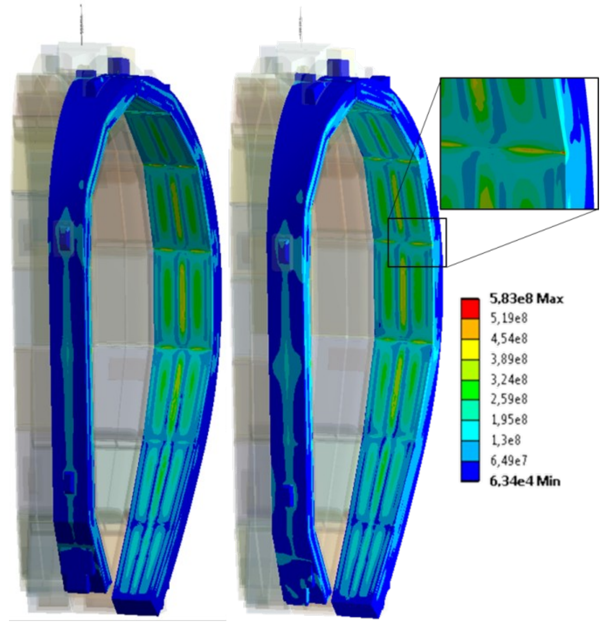

Fig. 6. Von Mises stresses in Pa on the left OB BSS under normal operation (left) and a central plasma disruption (right)

A simplified stress evaluation has been performed on the attachment elements by comparison of the maximum stress with yield stress and check of the rule against PD. The comparison of the yield stress for EUROFER97 of

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416 MPa at 400 °C and maximum stresses of 200 MPa at the attachment elements yields a sufficient margin.

Due to the high EM forces that have to be transferred to the VV, high reaction forces and moments occur at the contact points of the attachment system to the VV. The maximum reaction force and moment are calculated at the OB extended keys with about 2.8 MN and 11.4 MNm.

4. Conclusions

This work presents the assessment of the HCPB breeding blanket segments in the EU DEMO reactor under a normal operation and a simplified central plasma disruption scenario. The assessment is based on thermo-structural analyses with the FE software ANSYS using a FE model of one entire DEMO sector considering the EU DEMO1 baseline BL2015. The current version of the attachment system, which is part of an iterative design optimization process, has been adapted to the baseline BL2015.

The temperature distribution on the breeding blanket segments during the defined operation conditions is obtained by a simplified thermal analysis. The result shows an acceptable maximum temperature of about 390 °C at the attachment elements even without active cooling.

During the plasma disruption scenario, transient Lorentz forces occur in addition to static Maxwell forces, which are present in both scenarios. The deformation is very similar for both scenarios with a maximum of 43 mm at the port shield mainly due to the thermal expansion of the segments. However, the Lorentz forces lead to a slight twisting of the segments around the poloidal axis, which also leads to small tilting of the port shield. In both scenarios, the port shield is only in contact to the back supporting structure (BSS) below the spring pack. If this concept is further pursued, a more distributed application of the spring force should be considered to assure a contact all along the BSS. Furthermore, it could be observed that the pads are not in contact with the BSS on the OB segments during both scenarios. Nevertheless, they still serve as defined contact points during idle times or maintenance operations.

The maximum stresses occur on the BSS structure in the interspace between two modules, as the cross-section is smaller in this area. The evaluation of the stresses on the BSS according to the design code RCC-MRx and a simplified stress evaluation on the attachment elements show that the design of the HCPB breeding blanket system fulfills the required criteria. However, the rule against immediate plastic instability only yields a small margin of 13 % and 9 % on the outboard BSS for the normal operation and the considered plasma disruption scenario. Hence, this criterion represents the limiting factor for a design optimization of the BSS as well as if the EM loads will significantly change when considering different plasma scenario (e.g. VDEs), electrical boundary conditions (e.g. electrical contacts between VV and BB) or general improvement of the EM analysis [6]. These results also indicate that the current BSS manifold dimensions (radial dimension and ≈60 mm outer contour thickness) are adequate and there is virtually no margin left for its reduction in radial direction.

Furthermore, it could be observed that the secondary stresses are more dominant on the inboard BSS than on the outboard BSS. In general, the design of the attachment system follows the principle to allow the free thermal expansion of the segments in order to limit the secondary stresses. Consequently, the further development of the attachment system should be supported by detailed thermal analyses of the whole HCPB breeding blanket system.

The presented results are based on a FE model of a full sector of the EU DEMO reactor considering all attachment elements as realistic non-linear contacts. This allows studying the complex contact behavior of the attachment elements and the resulting mechanical constraints for the segments in detail. Hence, these results represent an important input for future attachment system design based on similar contact conditions.

Acknowledgments

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