EUROFUSION CP(15)06/09

I.A. Maione et al.

Evaluation of EM Loads Distribution on DEMO Blanket Segments and their Effect on Mechanical Integrity

12th International Symposium on Fusion Nuclear Technology (ISFNT)
Jeju Island, Korea
(14th September 2015 – 18th September 2015)

Evaluation of EM loads distribution on DEMO blanket segments and their effect on mechanical integrity

Ivan Alessio Maione[a], Christian Zeile[a], Lorenzo V. Boccaccini[a], Alessandro Vaccaro[b]

[a] Institute for Neutron Physics and Reactor Technology (INR),
[b] Institute for Applied Materials (IAM),
Karlsruhe Institute of Technology (KIT), Campus Nord, Hermann-von-Helmholtz-Platz 1,
76344 Eggenstein-Leopoldshafen, Germany

This work is aimed to analyze the EM internal forces distribution on the blanket system (blankets modules and segment back supporting structure) of the EU PPPT DEMO 2015 reactor configuration. In order to validate their impact on the segment structure, an EM analysis is conducted using a simplified plasma central disruption. The calculated forces distributions are then used as input for structural analyses focusing on the mechanical integrity of the segment back supporting structure. In particular, the electrical and structural assumptions used in this work are based on the HCPB blanket design developed at the Karlsruhe Institute of Technology.

Keywords: EM loads, structural analysis, internal forces, HCPB, DEMO, blanket, fusion.

1. Introduction

On the basis of the ongoing studies on possible design solutions for DEMO in-vessel components, this work is aimed to analyze the electromagnetic (EM) internal forces distribution on the blanket system (blankets modules and segment back supporting structure) of the EU PPPT DEMO reactor configuration. These forces have been only marginally addressed in previous works [1][2], mainly focused on the evaluation of EM loads on modules and segments attachments for which internal forces, due to their natures, are not relevant for the resultant force and moment. Nevertheless, preliminary considerations on the intensity and particular distribution of internal forces during off normal events have shown that they can have a strong impact on the segment structure. In order to validate this assumption and preparing the ground for future detailed investigations, an EM analysis is conducted using a simplified central plasma disruption, since calculated plasma inputs are still not available. The calculated forces distributions are then used as input for structural analyses. In particular, the electrical and structural assumptions used in this work are based on ongoing design solutions proposed for the HCPB blanket segment design, however the results can give usefull information also for the other blanket concepts in the EUROfusion Breeding Blanket Project that are following a similar design architecture [3].

The FEM models implemented for the EM and structural simulations have been developed on the basis of the EU PPPT DEMO 2015 reactor configuration [4], whose main characteristic are reported in Table 1.

In the following the two implemented FEM models and the obtained results are described.

Table 1. Main characteristic of the EU PPPT DEMO 2015 reactor configuration.

Description		Value	Unity
Major radius	R	9.07	m
Minor radius	a	2.93	m
Elongation	k	1.781	
Triangularity	t	0.5	
Plasma cross section area	S	44.8	m^2
Total plasma current	I_p	19.6	MA
Toroidal field @ R	B_{tor}	5.67	T
Number of Sectors	N	18	

2. Electromagnetic model

EM loads acting on fusion reactor components are strongly dependent on the specific event scenario as well as on the components dimension, composition and electrical connections. Since they constitute a severe issue for the mechanical structure integrity, a careful analysis of their distribution and intensity has to be performed in order to consolidate the present reactor knowledge and technology in view of a reference design.

In comparison with the previous studied DEMO designs [5], the new DEMO configuration shows a different aspect ratio, a lower toroidal field and, in particular, a higher number of sectors. These differences, resulting also in a different space reservation for each component, strongly modified the EM force distribution and intensity not allowing the use of previous results for a structural analysis and, thus, leading to the need to perform new EM simulations in order to evaluate the related loads.

2.1 FEM model for the EM analysis

A poloidal view of the implemented FEM model is shown in Fig. 1. It represents a 20-degree sector of the considered DEMO configuration on which only the vacuum vessel (VV), blankets, and poloid (PF), central (CS) and toroidal (TF) field coils are considered. Each

---

author's email: ivan.maione@kit.edu

sector is then divided into 5 segments, 2 inboard (IB) segments (10-degree) and 3 outboard (OB) segments (6.67-degree), with a separation of 2 cm between each other.

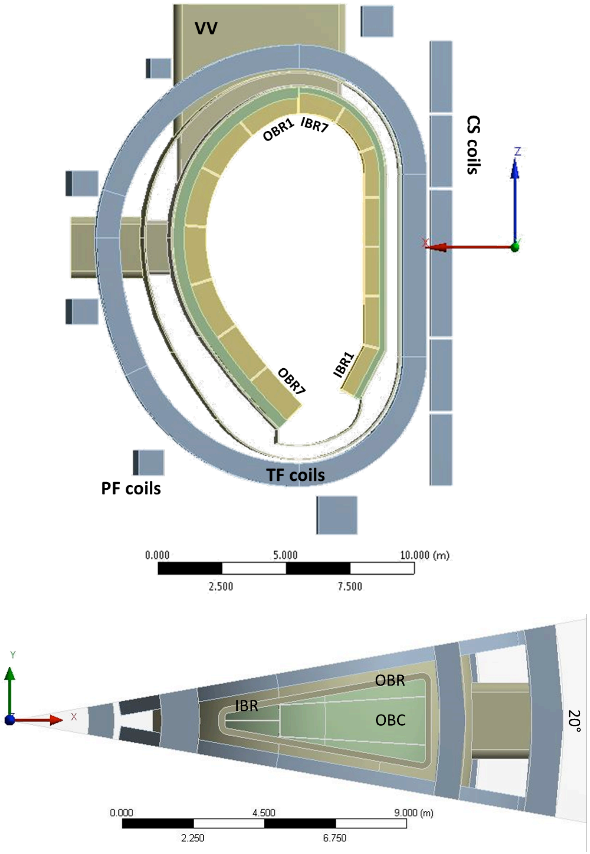

Fig. 1. Poloidal and toroidal view of the implemented FEM model.

The radial segmentation of the inboard (IB) and outboard (OB) blankets has been defined on the basis of the last HCPB design as developed at the Karlsruhe Institute of Technology (KIT) [4]. Considering a module average poloidal length of 2 m, each segment has been divided in 7 modules connected to a strong back supporting structure (BSS).

Due to the complex internal structure of each blanket sub-component, e.g. the first wall (FW) and breeding zone (BZ) that exhibit a high quantity cooling channels, the blanket has been schematized as in Fig. 2 in order to reduce the dimension of the FE model mesh and, consequently, the computational time.

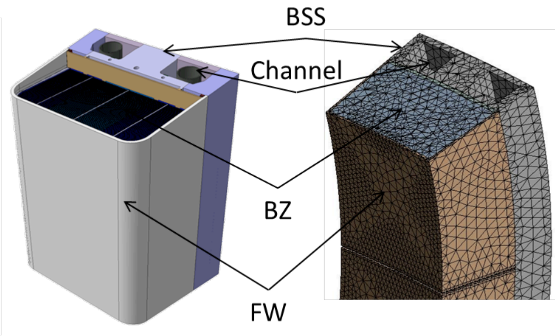

Fig. 2. Schematic view of the HCPB blanket developed at KIT and the relative implementation in the EM model.

The electrical properties of materials associated to the solids in the FE model have been defined as macroscopic parameters averaged on the considered spatial region according to the percentage of conductive material as made in [6]. Since these properties are temperature dependent, average temperatures have been estimated for each sub-component and used in the analyses. Taking into account the complexity and time consuming of the analyses considering ferromagnetic properties of the EUROFER steel [7], it has been decided to perform the reported analyses neglecting this effect and using instead the vacuum permeability. This effect has been evaluated in previous analyses leading to an increase of about10% of the forces if the non-linear properties of EUROFER are integrated in the defined material properties. This increase has been used to correct the input loads used in the structural analysis.

All coils' currents are defined constant during the plasma disruption. For PF and CS coils the current value is given in [4], while a total current of 17.5 MA is applied to the TF coils in order to obtain a toroidal magnetic field of 5.67 T @ 9 m.

Since, at present, no calculated plasma disruptions are available, a plasma central disruption with a linear quench has been implemented. The plasma current density has been defined with a quadratic distribution with elliptical cross-section, while a quench time of 77 ms has been used on the basis of the data reported in [8].

Thirty loads steps (time step of 2.57 ms) have been set up in the transient analysis to represent the plasma evolution. Additionally, other 7 load steps (with no plasma current and a time step of 5 ms) have been considered in order to evaluate the evolution of eddy currents, and thus EM loads, after the plasma shutdown.

2.2 Results of the EM analysis

Force distribution as well as the total force and moment acting on the whole blanket segments and each component (modules and BSS) have been calculated.

In this section (as in the follow) the labels OBC and OBR are used to identify the central and side outboard blankets respectively. This discrimination is necessary, as the ripple of the toroidal field results in different EM loads on the three OB blankets. Moreover, in the following, all the reported load values are referred to the global Cartesian coordinate systems as depicted in Fig. 1.

As already shown in previous work, force and moment exhibit similar behavior for each component: (1) a strong force compensation due to the particular eddy current loop that reduces the total force magnitude; (2) a predominant total radial moment (Mx) due to the high toroidal magnetic field (in comparison with the poloidal one). As example, the radial, toroidal and vertical forces/moments acting on the IB blanket are shown in Fig. 3. In addition, the norm of the total force and moment acting on blankets components is shown in Fig. 4.

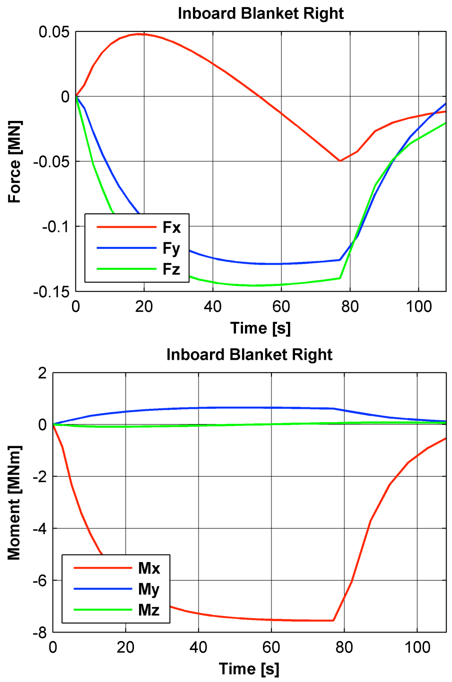

Fig. 3. Time evolution of the force and moment components for the inboard blanket.

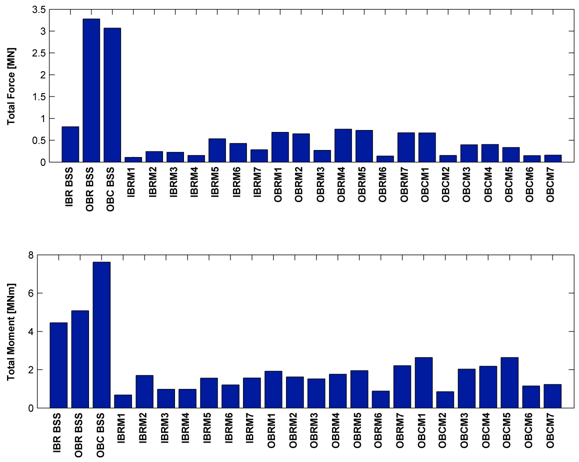

Fig. 4. Norm of the total force and moment acting on blankets components (BSS and modules).

3. Structural analyses

Structural analyses of the DEMO blanket segments have been carried in order to investigate the stress distribution on the blanket BSS region caused by electro-magnetic forces during a simplified central disruption. As this study is based on static structural analyses, a worst-case scenario for each segment has been defined considering the evolution of the force distribution over time.

In addition, the following assumptions have been made concerning the fixation of the segments inside the vacuum vessel. Firstly, each inboard and outboard blanket is individually attached to the vacuum vessel and therefore not in contact with the other surrounding segments. Secondly, as the focus of these analyses is on the stress distribution on the BSS region, the attachment system has not been considered in detail. It is only represented by the mechanical constraints, which it poses to the segment.

3.1 Models used in structural analyses

The two structural FEM models for the inboard and outboard blanket are based on the FEM models used in the electro-magnetic simulations. This means that, except for the breeding zone, the geometry of the two models is identical. The breeding zone of the HCPB concept consists of a high number of parallel cooling plates, which are separated by breeding material pebble beds. This zone is represented by a single solid in the electro-magnetic model. For the structural analyses, the cooling plates contribute to the stiffness of the blanket module. However, the modelling of the individual cooling plates would significantly increase the necessary number of elements. Therefore, as the focus of the analyses is on the stress distribution of the BSS region, the model constitutes of empty modules with an adjusted stiffness of the box walls in order to represent the overall stiffness of the module. A section view of the model of the outboard segment is shown in Fig. 5.

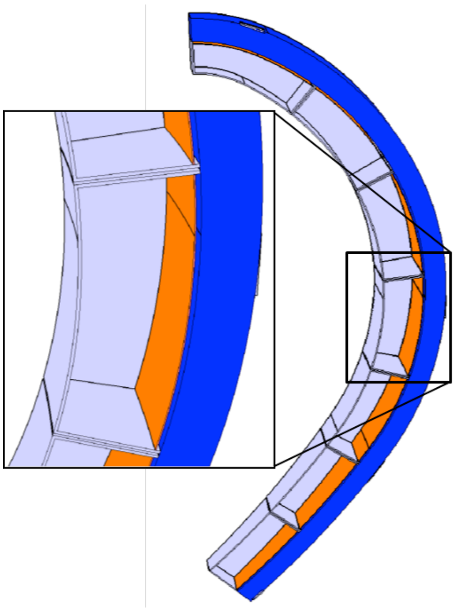

Fig. 5. Section view of outboard segment

3.2 Boundary conditions

As at the moment a detailed design of the attachment system is not available, the stress analysis suffers of some limitations. This mainly applies for the determination of the thermal stresses. In fact, depending on the general segment constraint used to perform this kind of analysis (statically determinate or indeterminate) this stresses can vary a lot. For this analysis the constraint system is assumed to be designed in such way to minimize the thermal stresses (“quasi” statically determinate) so that thermal stresses can be neglected focalizing only on the effect of the primary stresses due to the EM loading. Therefore, a uniform temperature of 300 °C is assumed on the entire segment corresponding to the temperature of the BSS, on which the structural analyses are focused, only to take into account the material properties of the structural material EUROFER at this temperature level. Nevertheless, the attachment system is represented by simplified mechanical constraints of a possible attachment concept.

The EM analyses have shown a very high radial and poloidal moment acting on the segments. For this reason, the constraints of the possible attachment system concepts have been defined in such a way to support these moments at different points on the BSS in order to relieve the structure. Hence, the following mechanical boundary conditions have been specified for the outboard and inboard blanket: a poloidal support at the bottom, two toroidal supports at top and bottom as well as a radial support at top and bottom. The inboard blanket has an additional toroidal shear key. The specified constraints at top and bottom also avoid a poloidal rotation. All constraints are illustrated in Fig. 6.

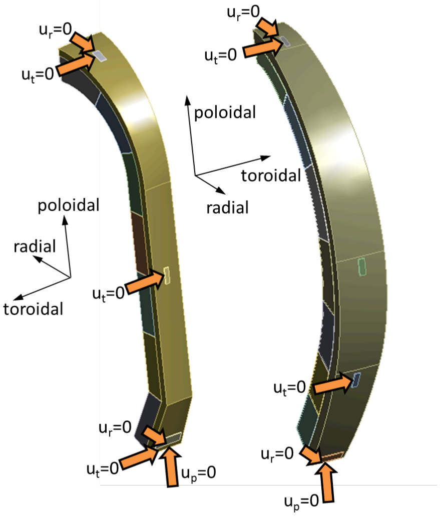

Fig. 6. Mechanical boundary conditions posed by the attachment system on inboard (left) and outboard (right) segment

A worst-case scenario during a simplified central disruption as defined in section 2.1 is considered as mechanical loading on the segments. For this purpose, the force distribution calculated by the electro-magnetic analyses is applied to each segment in two different ways. As the geometry of the model of the BSS is identical in the electro-magnetic and structural analyses, the force distribution can be directly mapped to the BSS of the structural model. In contrast, the blanket modules are represented by empty boxes in the structural model. Therefore, the force distribution of each module obtained by the electro-magnetic analysis has been summed up in a central point as resulting force and moment vector. This resulting force representation has been applied as external force to the walls of the corresponding module. By this procedure, it can be assured that the BSS region experiences the mechanical loading according to the real force distribution on each blanket module. Figure 7 shows the force distribution on the BSS region and the force vector applied to each module.

2.3 Results of the structural analysis

For each sector, only one inboard segment, the central outboard segment and one lateral outboard segment has to be investigated due to the periodicity of the tokamak geometry. As no thermal expansion of the segments is considered in these analyses, the calculated stresses only represent primary stresses produced by EM loading.

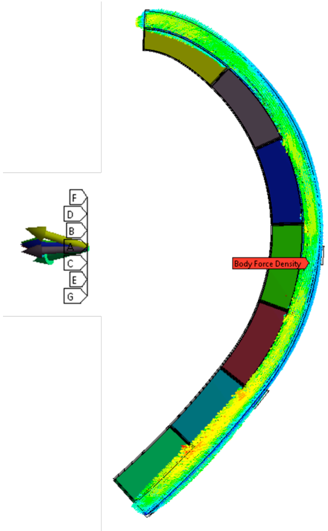

Fig. 7. Force distribution on outboard segment as applied in structural analysis (schematic): Forces and moments on the modules specified by external force and moment vector and force distribution directly mapped on the BSS

Figure 8 shows the von Mises stresses on the BSS region of the outboard segment right for the defined load case. The displayed stresses range is adjusted according to the maximum stresses on the BSS region not related to the simplified representation of the attachment system (peak stresses at the attachment points have been ignored). It can easily be noticed that the maximum stresses are located in the interspace between two adjacent modules as these locations represent the smallest cross-sections considering the entire segment as single structure. The similar observation can be made for the von Mises stresses on the BSS region of inboard blanket, which are given in Figure 9. The maximum values $\sigma_{vM\ max}$ for both outboard segments and the inboard segment are listed in Table 2.

In addition, an assessment of the stresses based on the rules defined for the evaluation of primary stresses according to the design code RCC-MRx has been conducted. This assessment has shown that the criteria to prevent immediate plastic collapse and instability are satisfied for each segment.

The maximum displacements in poloidal, toroidal and radial direction $u_{p\ max}$, $u_{t\ max}$ and $u_{r\ max}$ are given as well in Table 2. These deformations are strongly influenced by the constraints given by the attachment system. For example, the poloidal displacements occur at the top, where no poloidal support is defined. As well as the maximum radial displacements are located in the center of the segments where no radial support is specified.

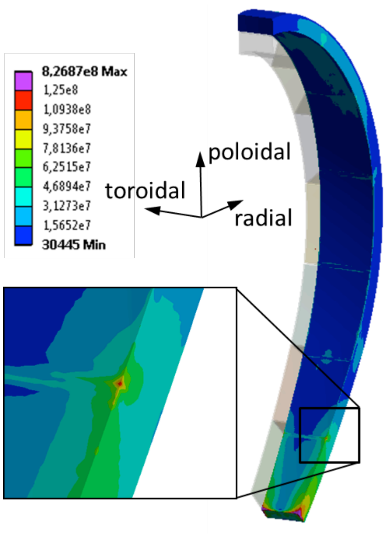

Fig. 8. Von Mises stresses in MPa on outboard segment right (OBR) during simplified central disruption

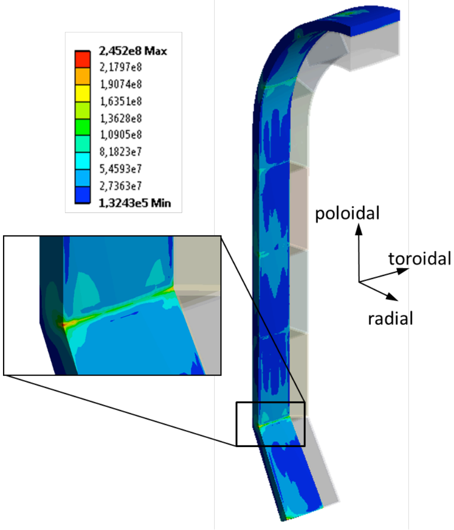

Fig. 9. Von Mises stresses in MPa on inboard segment (IBR) during simplified central disruption

Table 2. Maximum displacements and maximum von Mises stresses on segments during simplified central disruption

Blanket Segment	$u_{p\,max}$	$u_{t\,max}$	$u_{r\,max}$	$\sigma_{vM\,max}$
	mm	mm	mm	MPa
Inboard	-8.4	-2.0	-7.2	245
Outboard right	4.0	4.5	-2.9	124
Outboard center	4.6	3.8	-3.1	85

4. Conclusions

This work presents a study on the new DEMO 2015 reactor configuration focused on the evaluation of the EM force distribution and the effect on the structural integrity of segments. Also if the FEM models used for EM and structural analysis are different (incorporating different level of approximations in order to capture the peculiarities of the two different analyses) an effort has been done to keep the high level geometry (i.e. solid bodies) as much as possible identical. This allows a direct mapping of the EM force distribution on the BSS and the application of an equivalent force distribution on the single modules. EM analyses have been conducted using a simplified plasma central disruption, since no plant specific plasma simulations are available at the present. The results show a qualitative agreement with previous works.

On the other side, the results of the structural analyses show stress concentrations located at the interspace between two adjacent modules where the cross-section of the segment is smaller. A preliminary assessment of the primary stresses according the design code RCC-MRx confirms the ability of the segments to resist the EM forces, where the lowest margin is given by the immediate plastic instability criterion on the inboard segment with 14 %. In a next step, this preliminary conclusion has to be verified taking into account new plasma disruption data and a detailed model of an attachment system concept. In this way, also secondary stresses due to the thermal expansion can be considered in order to check the assumption of minimized thermal stresses.

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.

References

[1] I.A. Maione and A. Vaccaro, Analysis of electromagnetic loads on EU-DEMO inboard and outboard blanket vertical segments, Nuclear Engineering and Design Fusion 89 (2014) 7-8.

[2] I.A. Maione and A. Vaccaro, Parametric analysis of EM loads acting on DEMO vertical segments with respect to module's dimension, Fusion Engineering, 25th Symposium on. IEEE (SOFE) 2013.

[3] L.V. Boccaccini et al., Objectives and status of EUROfusion DEMO blanket studies, this conference.

[4] R. Wenninger, DEMO1 Reference Design - 2015 April ("EU DEMO1 2015") - PROCESS Full Output, EFDA_D_2MDKFH v1.0

[5] DEMO design summary, EFDA_D_2L2F7V (2012)

[6] I.A. Maione et al., Study on remanent magnetization of Fe-9Cr steel and its effect on in-vessel remote handling for future fusion reactors, IEEE Instrumentation and Measurement Technology Conference (2011)

[7] F. Tavassoli, "DEMO interim structural design criteria." Appendix A3.S19AS EUROFER steel (2010).

[8] G. Ramogida, Disruption_Physics_PPPT_Final-Report, EFDA_D_2LGWX6 v1.1