EUROfusion

WPBB-CPR(17) 17534

P Chiovaro et al.

Multi-Module vs. Single-Module concept: comparison of thermomechanical performances for the DEMO Water-Cooled Lithium Lead breeding blanket

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.

Multi-Module vs. Single-Module concept: comparison of thermomechanical performances for the DEMO Water-Cooled Lithium Lead breeding blanket

P. Chiovaro[a]*, P. Arena[a], G. Bongiovì[b], P. A. Di Maio[a], A. Del Nevo[c], R. Forte[a]

[a]*Dipartimento di Energia, Ingegneria dell'Informazione e Modelli Matematici, Università di Palermo, Viale delle Scienze, I-90128 Palermo, ITALY*
[b]*Institute for Neutron Physics and Reactor Technology (INR), Karlsruhe Institute of Technology (KIT), Eggenstein-Leopoldshafen, GERMANY*
[c]*ENEA C.R. Brasimone, I-40032 Camugnano (BO), ITALY*

Within the framework of EUROfusion R&D activity an intense research campaign has been performed at the University of Palermo, in close cooperation with ENEA labs and KIT, in order to compare the thermomechanical performances of the Multi-Module and Single-Module concepts of DEMO Water-Cooled Lithium Lead breeding blanket (WCLL). To this purpose, detailed 3D models of the DEMO WCLL right inboard and central outboard segments, structured according to the two concepts, have been set-up.

The study has been performed considering the Normal Operation and Central Major Disruption steady state loading scenarios. In particular, the former scenario implies the thermomechanical loads arising under reference nominal conditions whereas the latter scenario deals with the loading conditions induced by a plasma disruption, taking into account both Lorentz's and Maxwell's electromagnetic forces and moments.

A theoretical-numerical approach, based on the Finite Element Method (FEM), has been followed and the qualified Abaqus v. 6.14 commercial FEM code has been adopted.

The obtained thermo-mechanical results have been assessed in order to verify their compliance with the design criteria foreseen for the structural material. To this purpose, a stress linearization procedure has been performed along the most critical paths located within the structure, in order to check the fulfilment of the rules prescribed by the SDC-IC structural design code. The obtained results are herewith presented and critically discussed.

Keywords: DEMO, WCLL, breeding blanket, thermomechanics, FEM analysis

1. Introduction

Within the framework of the DEMO nuclear fusion reactor R&D activities supported by EUROfusion action, an intense research campaign has been launched at the University of Palermo, in close cooperation with ENEA labs and KIT, in order to compare the thermomechanical performances of the Multi-Module System (MMS) and Single-Module System (SMS) concepts of DEMO Water-Cooled Lithium Lead breeding blanket (WCLL).

The study has been framed within the European researches on liquid metal blanket concepts, in which University of Palermo has been, long time now, involved [1-8]. A numerical approach, based on the Finite Element Method (FEM), has been followed, adopting the qualified Abaqus v. 6.14 commercial FEM code. The assumptions, adopted methodology and obtained results are herewith reported and critically discussed.

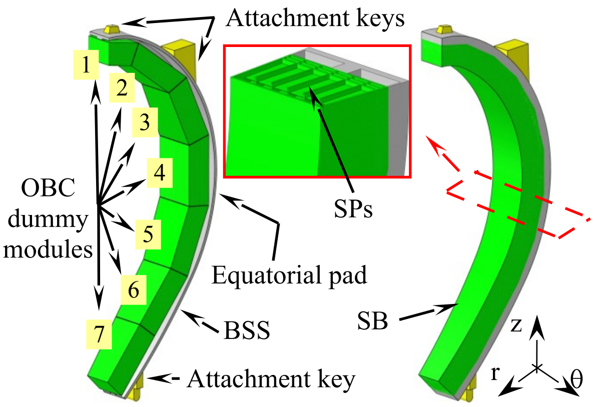
2. MMS and SMS concept of DEMO WCLL

In the framework of WCLL R&D activities, MMS and SMS concepts are currently being assessed in order to select a reference concept for the WCLL design phase prosecution. In this study, attention has been paid to right inboard blanket (IBR) and central outboard blanket (OBC) segments set-up according to the two concepts.

OBC segment

The OBC segment designed according to the MMS concept (Fig. 1) foresees 7 modules directly tied to the Back Supporting Structure (BSS). This latter is properly endowed with the attachment system [9] devoted to connect the segment to vacuum vessel. In this study, in order to save computational resources and time, modules have been represented as "dummy" components, namely as full bricks without internal details.

Eurofer steel has been assumed as structural material. As to dummy modules, a Young´s Modulus equal to one tenth of Eurofer one has been assumed in order to reproduce the actual modules stiffness, whereas an equivalent density of 10393.6 kg/m³ has been purposely calculated and assumed in order to take into account steel and breeder masses.



author's email: pierluigi.chiovaro@unipa.it

Fig. 1. The MMS (left) and SMS (right) OBC segment.

On the contrary, regarding OBC segment conceived according to the SMS concept (Fig. 1), the Stiffening Plates (SPs) have been properly modelled inside the Segment Box (SB), designed without cooling channels.

In order to investigate its thermomechanical performances under the selected loading scenarios, 3D FEM models of the WCLL OBC segment conceived according the two concepts have been set-up. As to MMS, a mesh composed of ~1.6M nodes connected in ~1.4M linear hexahedral elements has been set-up, whereas, regarding SMS, a spatial discretization consisting in ~4.6M nodes connected in ~3.6M linear hexahedral elements has been generated.

<u>IBR segment</u>

The IBR segment designed according to the MMS concept (Fig. 2) presents the same architecture of MMS OBC. The same assumptions made for OBC, regarding modules modelling and equivalent material properties have been adopted with the only difference of the calculated equivalent density value, amounting for IBR modules to 9032.5 kg/m^3.

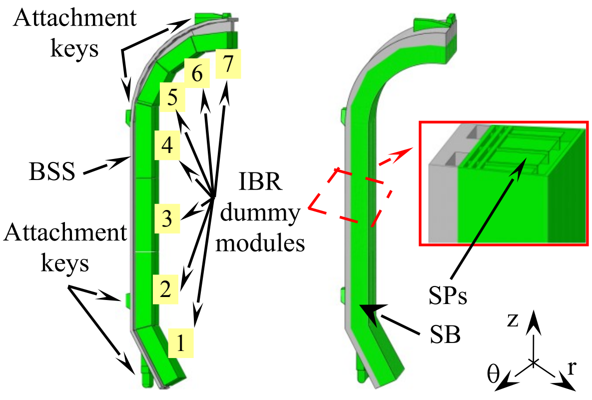


Fig. 2. The MMS (left) and SMS (right) IBR segment.

Also for SMS IBR (Fig. 2), the same approach followed for SMS OBC has been adopted. Regarding 3D FEM models, as to MMS IBR a spatial discretization characterized by ~2.5M nodes connected in ~2.4M linear hexahedral elements has been set-up whereas, as to SMS, a mesh made of ~6.2M nodes connected in ~5.4M tetrahedral and hexahedral elements has been considered.

3. Loads and boundary conditions

The loading conditions relevant to the steady state scenarios of Normal Operation (NO) and Central Major Disruption (CMD), both classified as Level A in SDC-IC code [10], have been investigated in order to compare the thermomechanical performances of MMS and SMS concepts for the WCLL OBC and IBR segments. In particular, as to NO scenario, non-uniform thermal deformation field, gravity load, a set of mechanical restraints devoted to simulate the attachments action and a set of mechanical interactions, have been imposed. Regarding CMD scenario, loads, boundary conditions and interactions already introduced in NO scenario have been maintained and, moreover, the purposely calculated Electro-Magnetic (EM) loads [11], pertaining to a plasma central major disruption event, have been imposed.

<u>OBC segment</u>

As to the non-uniform thermal deformation field, arising within the model as a consequence of the thermal field and its volumetric expansion tensor, a radial temperature profile inferred from module OBC4 thermal analysis [8] has been assumed for both concepts (Fig. 3).

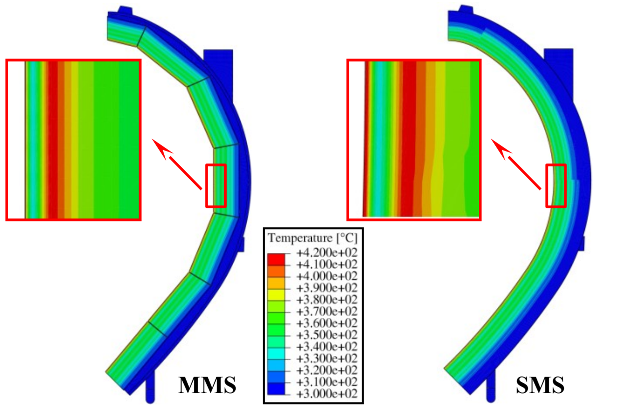


Fig. 3. The assumed radial temperature profile.

Concerning gravity load, the abovementioned equivalent density has been assumed for the "dummy" modules in MMS whereas, regarding SMS, an equivalent acceleration of gravity equal to ~42.2 m/s^2 has been purposely calculated and applied in order to simulate the weight of the steel, breeder and tungsten within SB. Moreover, regarding the BSS and attachments, the acceleration of gravity of 9.81 m/s^2 has been imposed for both the concepts.

As regards the EM loads, applied only in CMD scenario, Maxwell´s and Lorentz´s forces calculated in [11] on the SMS geometric model have been directly applied to this concept. Instead, as to MMS, equivalent concentrated forces and moments have been calculated in [11] and applied to the centres of mass of modules and corresponding BSS regions. In order to transmit these concentrated loads to the structure, the centres of mass have been purposely coupled, by a multi-point constraint, to the surrounding nodes (Fig. 4).

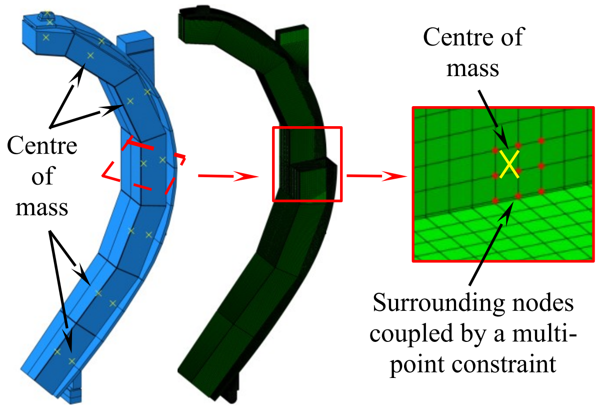


Fig. 4. EM loads application points.

author's email: pierluigi.chiovaro@unipa.it

A proper set of mechanical restraints have been assumed for both SMS and MMS in order to simulate the attachments action (Fig. 5). Regarding the spring, its non-linear characteristic curve has been set-up according to the procedure described in [9].

As far as mechanical interactions are concerned, as to MMS concept the modules have been considered as tied to the BSS central rib. Moreover, as to the interaction between equatorial pad and BSS, a proper contact model, characterized by a Coulombian friction factor (μ) of 0.25, has been implemented (Fig. 5). A similar approach has been followed in order to simulate the action of the upper attachments under EM loads, simulated imposing a contact model, characterized by μ = 0.25, between them and purposely designed rigid surfaces. These surfaces, which simulate the attachment housings, have been conceived under the assumption that, during NO scenario, they do not experience any contact with the attachments thanks to purposely calculated gaps (Fig. 6) devoted to accommodate attachments thermal expansion.

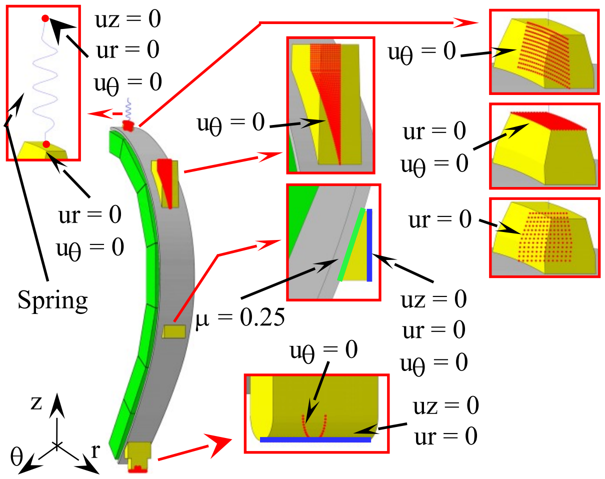


Fig. 5. The imposed mechanical restraints.

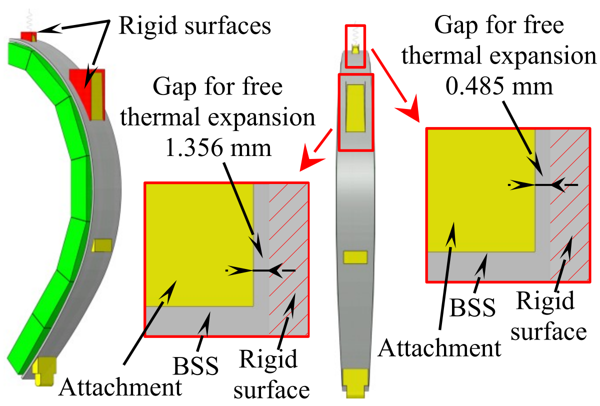


Fig. 6. The rigid surfaces.

IBR segment

As far as IBR is concerned, the same loads, interactions and boundary conditions already described for OBC have been assumed, with the pertinent differences due to the different segment and attachment system geometric layouts. In particular, as to the non-uniform thermal deformation field, the radial temperature distribution imposed to OBC has been properly scaled according to the ratio of IBR3 and OBC4 modules radial thicknesses whereas, as to gravity load, an equivalent acceleration of gravity equal to ~34.7 m/s^2 has been calculated and applied to SMS SB. Finally, regarding mechanical restraints, displacement has been prevented to nodes hig[illegible] in Fig. 7.

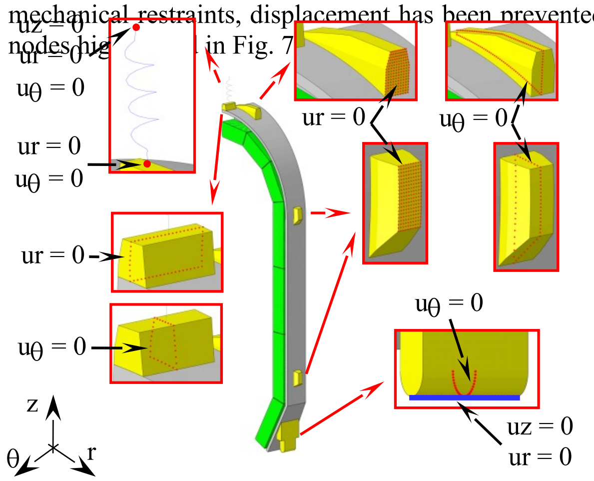


Fig. 7. The imposed mechanical restraints.

4. Analysis and results

In order to compare the thermomechanical performances of MMS and SMS concepts for DEMO WCLL OBC and IBR segments, un-coupled steady state thermomechanical analyses have been performed under the previously described NO and CMD loading scenarios. The main outcomes are reported in the following and critically discussed.

OBC segment

Concerning results obtained under NO scenario, the Von Mises stress field is shown in Fig. 8. It has to be observed that, since "dummy" modules have been considered in the MMS concept, only the Von Mises stress field arising within BSS has been reported for it. Results show that, for both the concepts, stress values well below 300 MPa are predicted for almost all the domains investigated.

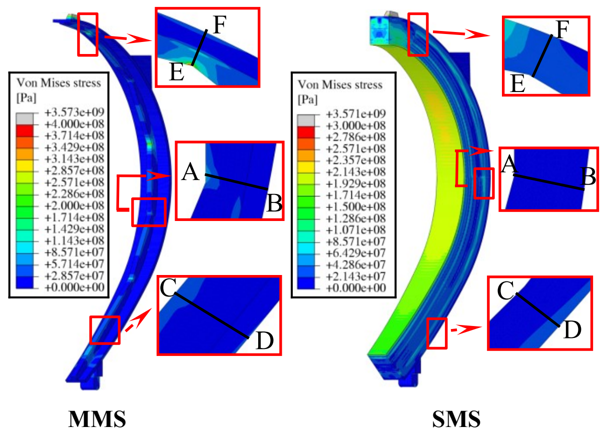


Fig. 8. NO Von Mises stress and stress linearization paths.

Moreover, a stress linearization procedure has been

author's email: pierluigi.chiovaro@unipa.it

performed in some critical paths located within BSS (Fig. 8), in order to verify the fulfilment of the SDC-IC criterion against the immediate plastic flow localisation $(P+Q)_m/S_e$ as it represents the most critical among those prescribed by the design code. Results, reported in Table 1, indicate a full verification of the aforementioned criterion with a remarkable margin.

Table 1. NO scenario - $(P+Q)_m/S_e$ criterion verification.

	AB	CD	EF
MMS	0.04	0.05	0.07
SMS	0.05	0.15	0.05

Finally, the deformed vs. un-deformed shapes for both MMS and SMS concepts are shown in Fig. 9. It has to be noted that deformation mainly along vertical direction has been predicted.

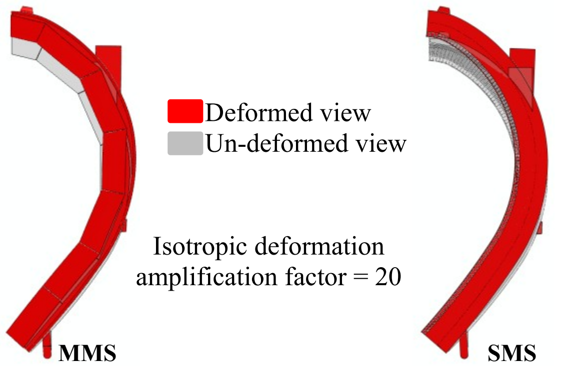


Fig. 9. NO deformed vs. un-deformed shapes.

Regarding results obtained under CMD scenario, the Von Mises stress field for both MMS and SMS concepts is reported in Fig.10.

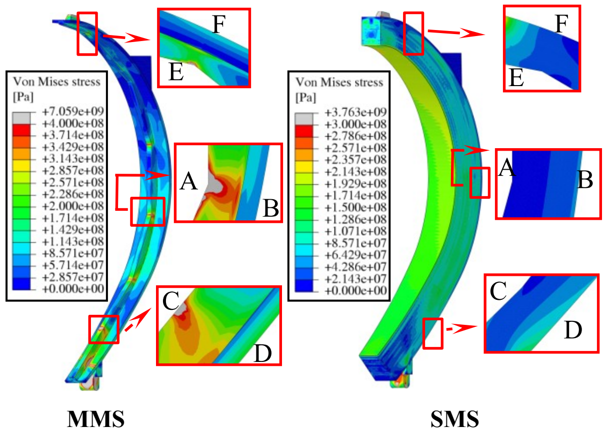


Fig. 10. CMD Von Mises stress and stress linearization results.

Results concerning the verification of $(P+Q)_m/S_e$ criterion, prescribed by SDC-IC code, within the BSS most critical paths (Fig. 10) are reported in Table 2.

Table 2. CMD scenario - $(P+Q)_m/S_e$ criterion verification.

	AB	CD	EF
MMS	0.30	0.25	0.57
SMS	0.21	0.13	0.10

Lastly, deformed vs. un-deformed shapes for both concepts are shown in Fig.11. It can be observed that the most important effect of the EM loads is the twisting of the segment. Observing the deformed shapes, the twisting is more accentuated in the MMS, due to the less modules stiffness in comparison with the SMS SB. Therefore, assessing results obtained under the two scenarios investigated, it can be observed that OBC segment conceived according to SMS concept seems to show a better aptitude, with respect to MMS, to withstand the foreseen thermomechanical loads, especially when EM loads are considered.

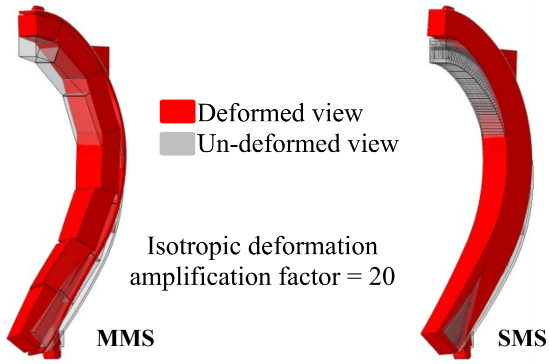


Fig. 11. CMD deformed vs. un-deformed shapes.

<u>IBR segment</u>

As to results pertaining to NO scenario, the Von Mises stress field is shown in Fig. 12 together with paths, located within BSS, set-up to perform a stress linearization procedure aimed at the verification of the $(P+Q)_m/S_e$ criterion. It can be observed that, for both concepts, stress values below 400 MPa are predicted almost everywhere. Results reported in Table 3, indicate a total verification of the prescribed SDC-IC criterion.

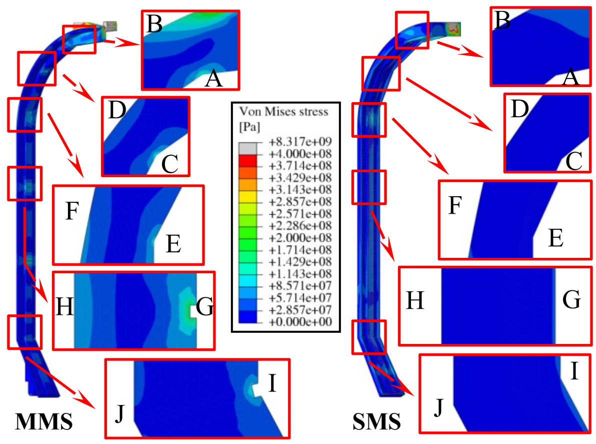


Fig. 12. NO Von Mises stress and stress linearization paths.

Table 3. NO scenario - $(P+Q)_m/S_e$ criterion verification.

	AB	CD	EF	GH	IJ
MMS	0.13	0.04	0.06	0.05	0.03
SMS	0.12	0.05	0.08	0.11	0.06

Finally, the deformed vs. un-deformed shapes are shown in Fig. 13 for both concepts. Also in this case the poloidal deformation is the most relevant.

author's email: pierluigi.chiovaro@unipa.it

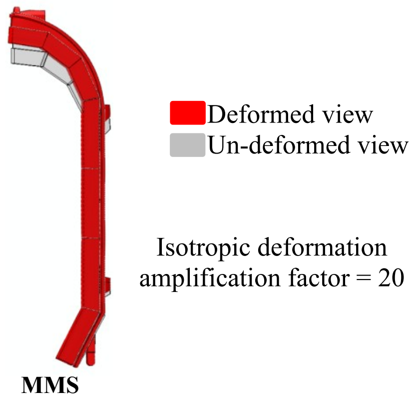


Fig. 13. NO deformed vs. un-deformed shapes.

As to CMD scenario, the Von Mises stress field and stress linearization paths are shown in Fig.14, whereas results of the verification of $(P+Q)_m/S_e$, criterion are reported in Table 4. Finally the deformed vs. un-deformed shapes, shown in Fig. 15, allow to highlight, even if with a lower extent than OBC, the twisting effect due to EM loads, which mainly affects MMS concept. Therefore, also for IBR, it is possible to conclude that segment conceived according to SMS concept seems to show a better aptitude, with respect to MMS, to withstand envisaged thermomechanical loads.

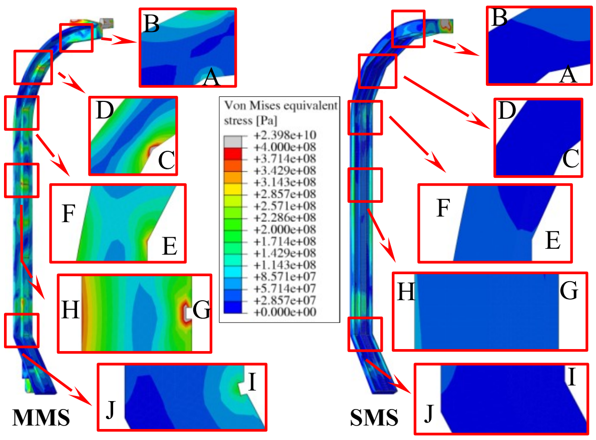


Fig. 14. CMD Von Mises stress and stress linearization paths.

Table 4. CMD scenario - $(P+Q)_m/S_e$ criterion verification.

	AB	CD	EF	GH	IJ
MMS	0.21	0.26	0.40	0.36	0.23
SMS	0.14	0.05	0.19	0.22	0.11

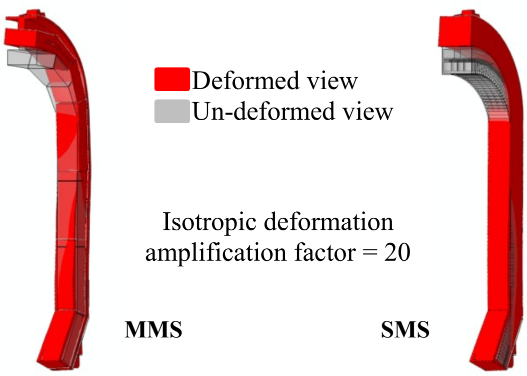


Fig. 15. CMD deformed vs. un-deformed shapes.

5. Conclusion

Within the framework of EUROfusion action, a research campaign has been performed in order to compare the thermomechanical performances of the MMS and SMS concepts of DEMO WCLL under NO and CMD steady state scenarios. In particular, attention has been paid to OBC and IBR WCLL segments. Results obtained have shown that both concept BSSs fulfil the SDC-IC design criterion against immediate plastic flow localization $(P+Q)_m/S_e$. In particular, SMS concept BSS is predicted to show a margin against the criterion stress limit ranging from 1.5 to 6 times that predicted for the MMS one. Furthermore, the comparison of SMS and MMS concept deformed vs. un-deformed shapes allows concluding that the former, accounting for a more stiffen structure, is able to withstand EM loads better than the latter and, therefore, could be selected as the reference for DEMO WCLL further design activities.

Acknowledgment

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] P. Chiovaro et al., Assessment of the thermo-mechanical performances of a DEMO water-cooled liquid metal blanket module, Journ. of Fus. En., vol. 34, (2), pp. 277-292, 2015.

[2] P. A. Di Maio et al., Analysis of the thermo-mechanical behaviour of the DEMO Water-Cooled Lithium Lead breeding blanket module under normal operation steady state conditions, Fus. Eng. Des., vol. 98-99, pp. 1737-1740, 2015.

[3] P. A. Di Maio et al., Optimization of the breeder zone cooling tubes of the DEMO Water-Cooled Lithium Lead breeding blanket, Fus. Eng. Des., vol. 109-111, Part A, pp. 227-231, 2016.

[4] P. A. Di Maio et al., On the optimization of the first wall of the DEMO water-cooled lithium lead outboard breeding blanket equatorial module, Fus. Eng. Des., vol. 109-111, Part A, pp. 335-341, 2016.

[5] P. A. Di Maio et al., On the thermo-mechanical behavior of DEMO water-cooled lithium lead equatorial outboard blanket module, Fus. Eng. Des., DOI: 10.1016/j.fusengdes.2017.05.051, 2017.

[6] P. A. Di Maio et al., Structural analysis of the back supporting structure of the DEMO WCLL outboard blanket, Fus. Eng. Des., DOI: 10.1016/j.fusengdes.2016.12.018, 2017.

[7] A. Del Nevo et al., WCLL breeding blanket design and integration for DEMO 2015: status and perspectives, Fus. Eng. Des., DOI: 10.1016/j.fusengdes.2017.03.020, 2017.

[8] E. Martelli et al., Advancements in DEMO WCLL breeding blanket design and integration, Int. Journ. of En. Res., DOI: 10.1002/er.3750, 2017.

[9] F. Hernandez et al., Development of a common attachment

author's email: pierluigi.chiovaro@unipa.it

system for a DEMO BB, IDM ref. 2N87GY_v1_1.
[10] ITER structural design criteria for in-vessel components.
[11] I. A. Maione, Results of EM simulations - Inputs for the structural analysis, IDM ref. 2N83EY_v2_1.

author's email: pierluigi.chiovaro@unipa.it