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Progress on DEMO Blanket Attachment Concept with Keys and Pins

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The blanket attachment has to cope with gravity, thermal and electromagnetic loads, also it has to be installed and serviced by remote handling. Pre-stressed components suffer from stress relaxation in irradiated environments such as DEMO. To circumvent this problem pre-stressed component should be either avoided or shielded, and where possible keys and pins should be used. This strategy has been proposed for the DEMO multi-module segments (MMS).

The blanket segments are held by two tapered keys each, designed to allow thermal expansions while providing contact with the vacuum vessel and to resist the poloidal and radial moments the latter being dominant at 9.1 MNm inboard and 15 MNm outboard. On the top of the blanket segment there is a pin which provides vertical support. At the bottom another vertical support has to lock them in position after installation and manage the pre-load on the segments. The pre-load is required to deal with the electromagnetic loads during disruption. This is provided by a set of springs, which require shielding as they are preloaded. These are sized to cope with the force (3MN inboard, 1.4 MN outboard) due to halo currents and the toroidal moment which can reverse.

Calculations show that the flexibility of the blanket segment itself plays a significant role in defining the required support system. The blanket segment acts as a preloaded spring and it has to be part of the attachment design as well.

Keywords: DEMO, blanket segment, keys, pins, springs

1. Introduction

Attaching the blanket segments to the vacuum vessel has to meet a number of requirements: it has to be able to support itself after installation (gravity load at room temperature), during operation it has to allow for thermal expansion, and it has to withstand the electromagnetic loads (due to eddy and halo currents) in disruptions. Moreover the blanket segments will be installed and maintained by remote handling and so the attachment system has to be compatible with that.

A previous study [1] showed that bolted connections face a challenge in the DEMO environment. The issue is mainly the loss of preload due to the different thermal expansion of the bolt and the bolted components as well as the neutron radiation induced stress relaxation of the bolt material. This issue drove the design away from bolted connections to alternative attachments. This paper focuses on a method where the blanket segments would be attached to the vacuum vessel by a set of keys and pins. The multi-module segments (MMS) would be held by two keys each designed to allow thermal expansions. Close to the keys on the top there are pins which help the remote handling installations and provide vertical support against upward movements (Fig. 1). The fact that the upper keys are close to the pins should eliminate thermal stress issues in this region. At the bottom of the segments another vertical support had to be developed to cope with downward movements. This support has to lock the blanket segments in position after installation and manage the preload on thethem. Preload is required to deal with the electromagnetic loads during disruption. The focus of the bottom support is on forces due to halo currents as the loads due to eddy currents result in moments which are taken by the keys. The force due to the halo currents can act either down- or upwards. The springs at the lower support of the blanket segment have to be preloaded at least to the magnitude of the halo current force; this way in the case of an upward force the springs will never become unloaded and thus the blanket segment will not become loose; in the case of a downward force the pin at the top of the blanket segment will not become disengaged (and therefore no impact load will have to be considered).

The springs are also preloaded components, however they are placed behind the blanket segments or the divertor, close to the vacuum vessel wall and thus shielded from the neutrons and therefore less affected by stress relaxation.

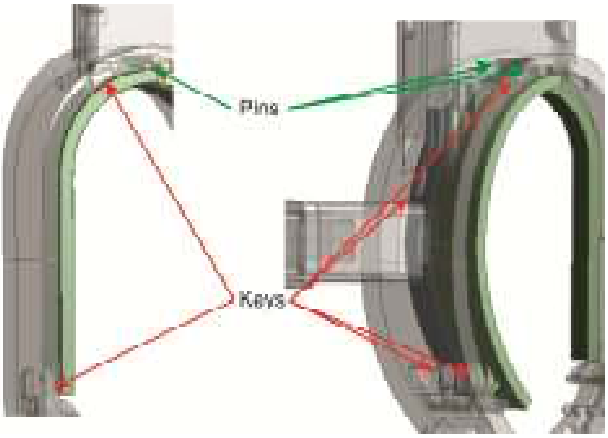

Fig. 1.: Keys and pins on the inboard and outboard segments.

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2. Analysis

2.1 Keys

The blanket segments will be supported by keys at two locations which shall withstand the forces and torques induced by the eddy currents. The keys are part of the MMS rather than the vessel wall. Although the MMS is made of Eurofer 97 which has lower ductility than the vessel wall (SS316L(N)), its ductility is still sufficient with total elongations around 20% at 300 °C [2]. The initial dimensions of the keys were defined based on analytical calculations.

2.2 Springs

The blanket segments will be supported with preloaded springs at their lower end. The calculations show that, due to the different thermal expansion of the vessel and the blanket segment, the relative displacement of the vessel and the segment at the bottom can be around 17 mm on the inboard and around 20 mm on the outboard.

We designed a spring set with a two-stage progressive characteristic (Fig. 2, 3). The first stage is a softer spring set to provide for the remote handling installation. This first stage is consumed by the weight of the blanket segment. The second stage allows for the thermal expansion which will preload the springs and the displacement in this stage is driven by that amount. It is necessary that the preload is not lost completely at any stage. As the halo force can be both up- and downwards, the thermal expansion has to create at least equal force to the maximum halo force, which is 3MN on the inboard and 1.4 MN on the outboard. The force due to the halo current can add on top of the load in the springs due to the thermal expansion or it can unload them. When the disruption load adds up to the preload large displacement is not required, in fact it should be avoided, therefore a 3rd stage is not required. The spring set combination in Table 1 was chosen based on the unrestricted expansion of the blanket segment back plates. At the same time at the nominal load the springs are not completely flattened this way allowing the back plates to expand more in the case of an unexpected temperature rise in the blanket (e.g. loss of coolant accident). Of course this will increase the load in the springs until the springs are completely flat.

Neutron irradiation induced creep and stress relaxation is a problem for all components in DEMO. Eurofer97 could suffer 55% of stress relaxation at 2.7 dpa [3]. Stainless steel (CW 316 tested at at 370 and 330 °C) shows stress relaxation levels of 18-36% at 0.64 dpa [4]. However the damage at the vessel wall – which is effectively where the springs are – is expected to be much lower. The inboard blanket thickness is about 650 mm, outboard is 1400 mm. At this depth the damage is very low indicated, by [5] and according to [6] it is less than 0.02 dpa/fpy. Previous calculation [1] shows values of 0.23-0.37 dpa (Eurofer-Inconel) for 5 fpy 60 cm in the blanket. Based on [5], extrapolating the Fe curve (Fig. 4 in [5]) the damage level is about 0.3 dpa/fpy on the inboard and less that 0.01 dpa/fpy on the outboard. Damage level of 0.3 dpa translates to less than 10% stress relaxation (for CW 316 SS [4]), although it has to be remembered that this is a result of a fission study.

We allowed extra 10% of preload for the spring set to cope with the stress relaxation due thermal expansion and irradiation.

The inboard spring set cannot be placed behind the blanket segment due to the lack of space and therefore it is only protected by the divertor. The expected irradiation level has to be investigated and if necessary additional protection needs to be provided to keep the damage at an allowable level.

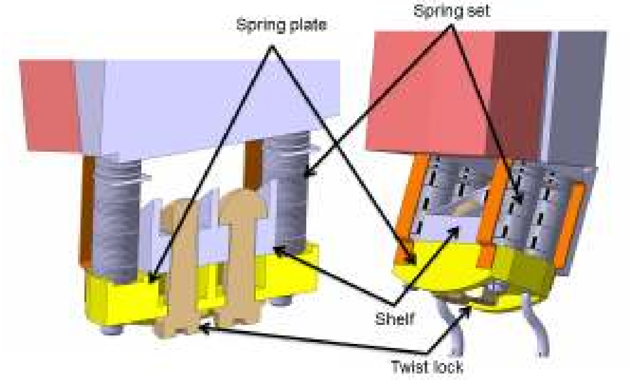

Fig. 2.: Spring set at the lower support of the inboard blanket segment.

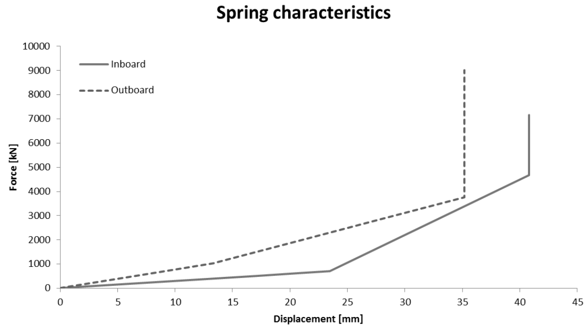

Fig. 3.: Spring characteristics at the in- and outboard segments.

Table 1. Schnorr spring stacks (material: X22 CrMoV 12-1, the numbers: column x stacks x times x type).

	Inboard	Outboard
Stage 1	4x2x4x219400	4x3x1x219400
Stage 2	4x6x6x004014	4x7x7x003095

This spring design is based so far on analytical calculations In order to check that it works as expected one sector out of the 16 has been modelled with one back plate installed at a time with keys, pin, twist lock, spring plate and springs (Fig. 2). The springs are modelled with a spring element; in the analysis it was assumed that the first stage is fully consumed by the installation preload and the stiffness of the second stage is given as stiffness parameter. The blanket segment back plates used in these models do not include any internal features, such as cooling channels.

The most important observations from the FE results are the following:

The radial eddy torque is supposed to be taken by the two keys. The results indicate that the pin also participates in this which is useful especially in the case of the middle outer blanket segment where the keys are closer to each other than in the outer blanket segments. There are localised highly stressed regions at the corner of the key slot.

In the analytical calculation we assumed that the poloidal torque will be taken once again by the two keys, and their dimension was chosen based on the radial distance between them. However, the FE calculations show that instead of this mechanism, the poloidal torque wants to twist the key out of its slot. On the plus side the pin again takes its share helping the situation at the key slots. Nevertheless, there are still localised highly stressed regions at the key slots. These localised high stress regions may be rectified by modifying the depth of the key slots so the reaction forces at the top and bottom of the slot have a larger distance between them and therefore the magnitude of this reaction force is reduced.

There seems to be a problem with preloading the springs to the required preload by the thermal expansion. This is mainly caused by the flexibility of the blanket segment back plate (despite it does not contain cooling channels).

In order to explore this lack of preload we carried out two exercises. In the first case the inboard blanket segment springs are preloaded to a total 4MN preload (by defining the initial spring preload parameter in ANSYS) and no thermal load is applied. We found that the preload in the springs has decreased to only 2.7 MN due to deformation of the back plate. The large force in the springs makes the back plate bow out towards the vessel. The deformed shape is such that the pin is lifted out of the pin hole. In the second case an outboard segment was investigated. We have implemented four cooling channels in this model. Instead of spring force we simply applied the 1.4 MN desired preload at the spring location. Also, in this case we applied the thermal load as well. Similarly to the inboard module the back plate is bowing out once again, the relative displacement to the vessel wall is 21 mm. More importantly, the gap between the spring plate and the blanket segment is increasing by 2-3 mm (Fig. 4). It means that in this case it would be actually impossible to preload the springs by the thermal expansion only because that would require the gap to reduce.

What this all means is that the stiffness of the blanket segment back plate has a major influence on the spring design, in fact, it itself is part of the spring and as such the preload mechanism. Therefore the blanket segment back plate is essential to finalise the spring design or any preload solution in conjunction with the blanket design.

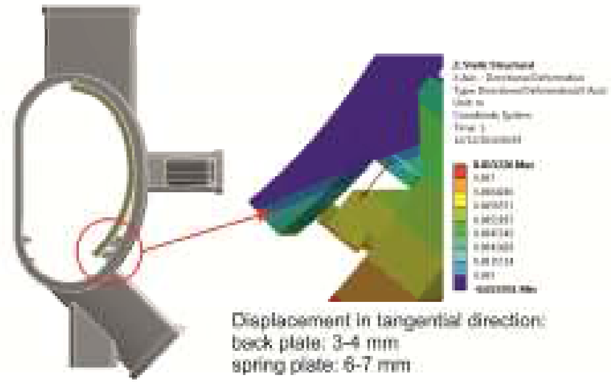

Fig. 4.: Blanket segment back plate bending towards the vessel wall due to applied preload.

2.3 Twist locks, spring plate and shelf

The support assembly at the lower end of the blanket segment (Fig. 2) will keep the spring stack in place after installation. The load is transmitted from the springs to the spring plate and via the twist locks to the shelf. This assembly will have to withstand the load from both the thermal expansion and the halo currents. Static analysis has been carried out to assess the stresses.

The material of the twist lock assumed to be A4-80 (typical bolt material) which has yield strength of 450 MPa at 300 °C. The load on the twist locks will result mainly in membrane stress in the shaft therefore the limit on it is Sm (300 MPa). The twist lock has a tapered shaft providing sufficient cross sectional area at both ends, but at the same time there is a larger landing area under the head. The equivalent stress distribution is acceptable in the shaft, however there are localised high peak stress regions at the neck of the twist lock (Fig. 5). Further optimising this region (e.g. modifying the radii) may be necessary relieving these stresses.

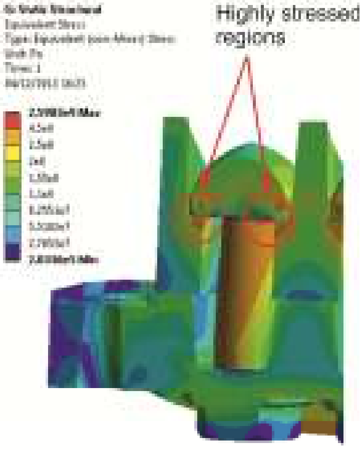

Fig. 5.: Equivalent Stress distribution in the twistlock and the shelf – section view from the vessel wall.

The shelf is part of the vacuum vessel. The loading is such that the shelf is a cantilevered beam, therefore high bending stresses are likely at the vessel side. The loads are large, especially on the inboard size (potentially 6

MN), that SS316L(N) material specification does not seem to be able to cope with it. We recommend another austenitic steel XM-19, which has a higher strength and the shelf and the joining vessel piece could be one machined product that is welded inside the vacuum vessel.

The spring plate has also overloaded regions; these are, however, small and with further modifications the cross sectional properties can be improved. Due to the magnitude of the stress we recommend Eurofer 97 material, because its yield strength around 450 MPa, although its ductility is limited at this temperature (100-300 °C).

3. Thermal analysis

A thermal analysis has been carried out to check the effect of the volumetric neutron heat load on the springs. Although, there is "cooling" provided to the springs: the centre rod by which the springs are aligned is capable of carrying the coolant. The coolant temperature in the tokamak in the case of helium cooling is between 300 and 500 °C, the maximum allowed operating temperature for the springs is 500 °C.

The volumetric heat load for the analysis was based on these equations [6]:

Inboard: (1): $r \leq 30cm,\ E(r)=16.8e^{-0.1r}$

(2): $r > 30cm,\ E(r)=16.8e^{-0.09r}$

Outboard: (3): $r \leq 40cm,\ E(r)=16.7e^{-0.09r}$

(4): $r > 40cm,\ E(r)=16.8e^{-0.085r}$

On the inboard 650 mm material thickness was assumed while it is 1400 mm on the outboard. This assumption may have to be changed depending on the actual material thickness in front of the inboard spring set. In any case the critical assembly is the inboard one. The actual temperature distribution will depend on the emissivity, in this calculation ε=0.25, 0.5 and 0.75 is assumed. The boundary conditions are minimalistic; there is conduction between the springs in parallel and through the bonded contact areas, but between the spring in serial there is only radiation assumed. The back of the shelf is at fixed 100 °C and the top surface of the top spring is at 300 °C. The spring plate and the plate close to the top can radiate to the 300 °C ambient but no other heat transfer is assumed. Active cooling is not assumed in the calculations.

Although the temperature will depend on the actual emissivity, the results and the fact that the helium coolant is diverted in the spring rods (not modelled), we should be able to keep the springs in their operating temperature range, under 500 °C.

4. Summary

The described blanket attachment concept is not finalised yet as the springs at the lower support of the blanket segments will have to be modified to match the blanket segment back plate stiffness. The flexibility of the back plate has a major impact on the preload on the springs and blanket segment, in fact, the back plate is part of the spring set, it needs to be sufficiently stiff in order to preload the springs. The preload is necessary to avoid the blanket segment becoming loose or the pin separate from its slot due to the disruption loads. The required preload is driven mainly by the vertical halo current.

The inboard lower support is most critical from all points of view: it has the largest electro-magnetic load, it is closer to the plasma, it is not behind the blanket segment due to the lack of space, but behind the divertor. Additional shielding may be required to protect both the springs and the vacuum vessel from excessive irradiation.

Acknowledgments

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References

[1] Zs. Vizvary, D. Wilson, S. Zheng, J. Thomas: *Feasibility Limits for DEMO In-Vessel Bolts* (WP12-DAS-IVC-T07) EFDA_D_2KVVWV (2012)

[2] G. Le Marois, R. Lindau, C. Fazio: *4.1.4 The Eurofer 97 - Structural Material for the EU Tests Blanket* (22EYUD v2.0) (G 74 MA 10 W 0.3).

[3] N.V. Luzginova, M. Jong, J.W. Rensman, J.B.J. Hegeman, J.G. van der Laan: *Irradiation-induced stress relaxation of Eurofer 97 steel*, Journal of Nuclear Materials 417 (2011) 104-107

[4] J. P. Foster, T.M. Karlsen: *Irradiation Creep and Irradiation Stress Relaxation of 316 and 304L Stainless Steel.* 14th International Conference on Environmental Degradation of Materials in Nuclear Power Systems-Water. Virginia, USA (24-28 August 2009).

[5] M.R. Gilbert, S.L. Dudarev, S. Zheng, L.W. Packer and J.-Ch. Sublet: *An integrated model for materials in a fusion power plant: transmutation, gas production, and helium embrittlement under neutron irradiation*. Nuclear Fusion (52) (2012).

[6] D. Stork: *EU Materials Assessment Group Conclusion of the Roadmap Assessment.* IAEA DEMO Programme Workshop UCLA (2012).

[7] [7] Zs. Vizvary, D. Wilson, S. Zheng, J. Thomas, *Feasibility Limits for DEMO In-vessel Bolts*, Report for TA WP12-DAS-IVC-T07, EFDA_D_2KVVWV, 2012