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MECHANICAL ANALYSIS OF THE ENEA TF COIL PROPOSAL FOR THE EU DEMO FUSION REACTOR

M.E. Biancolini, R. Bonifetto, A.Chiappa, F. Giorgetti, V. Corato, L. Muzzi, *Senior Member, IEEE*, S. Turtù, *Senior Member, IEEE*

***Abstract*—The design of the superconducting magnet system of the European DEMO fusion reactor is currently being pursued in the framework of the EUROfusion Magnets Work Package (WPMAG). Three alternative winding pack (WP) options for the Toroidal Field Coils (TFCs) are being proposed by different research units, each featuring a different conductor manufacturing technology (react-and-wind vs. wind-and-react) or winding layout (layer vs. pancake).**

One of the options (namely, WP#2), proposed by Italian ENEA, features a layer-wound WP design adopting a wind-and-react conductor with rectangular cross section with high aspect ratio, obtained squeezing an initially circular conductor.

In order to assess the capability of all the TFC components to withstand the electromagnetic loads due to the huge Lorentz forces without any structural failure during the magnet lifetime, the mechanical analysis of the 2016 version of the WP#2 design option is performed here applying a hierarchical approach herein defined as the Stress Recovery Tool (SRT): the Finite Element Analysis (FEA) of a whole magnet (including the casing) is performed at a low computational cost adopting a coarse WP model with smeared (homogenized) properties. The displacements computed on the smeared WP are then used as boundary conditions for a refined FEA of some WP slices, located in selected (critical) poloidal positions, where all the conductors detailed features (jacket, insulations) are properly accounted for.

***Index Terms*—DEMO TF Coil, nuclear fusion, stress recovery tool, structural analyses**

I. INTRODUCTION

Nuclear Fusion may represent an effective way to face the increasing energy demand in the future. In such a context is placed the ambitious European project to build a DEMO reactor, the fusion device designated to produce net electricity for the grid in the early 2040s, generate the needed amount of tritium for a close fuel cycle and demonstrate all the technologies required for a Fusion Power Plant (FPP) realization [1].

DEMO is the middle step between ITER ("The Way" in Latin), whose construction is well under way nowadays at Cadarache, France, and a commercial FPP in the so called "fast-track" approach of the EU roadmap [2]. In view of the future realization of DEMO the R&D pre-conceptual activities are ongoing, exploiting and updating the knowledge gained so far with ITER [3].

One of the crucial issues is represented by the design of the large scale TFC structures as well as the WP components [4]. In fact the very high current (70.8 kA) coupled with the magnetic field up to 12 T, induces huge electromagnetic (EM) Lorentz forces. In the TFC WP#2 design option, proposed by ENEA in 2016, these forces acting on each of the 202 conductor turns in a TFC are withstood locally by the steel jacket of the conductor, whose thickness increases with the radial distance from the plasma in order to balance the mechanical load increase, and globally by a thick stainless steel casing in which the WP is encapsulated.

A possible way to analyze the TFC structural behavior is to perform Finite Element Analysis (FEA) of the whole TFC, modeling all the details of the casing and WP geometry. This kind of model would require at least 10 million nodes and consequently a high computational cost, but allows to catch the local stresses in all components. Another possibility, aimed at reducing the computational burden, is to perform the FEA modeling of the WP as a homogenized orthotropic material. As a drawback, this strategy does not allow to assess the capability of the WP components (mainly jacket and insulation layers) to withstand the aforementioned forces.

A further approach, combining the positive aspects of the two previously-mentioned strategies, is represented by the use of the Stress Recovery Tool (SRT), developed in the past years at University of "Tor Vergata", Rome. The SRT, whose workflow is depicted in Fig. 1, allows to recover the stress state at micro geometry level (e.g. in the WP components) performing first a FEA of the full D-shaped TFC with a smeared WP and then a second FEA of selected slices of the detailed WP model applying to the latter as boundary conditions (BCs) the displacements computed with the first FEA. The run of two FEA dealing with models requiring a low computational cost allows a consistent time saving. This hierarchical approach, strongly based on Radial Basis Functions (RBFs) interpolation of the EM loads (both on the smeared and on the detailed WP models), and of the displacements is fully described in [5] where its successful

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M.E. Biancolini, A. Chiappa and F. Giorgetti are with University of Rome "Tor Vergata", Rome, Italy (e-mail: biancolini@ing.uniroma2.it, andrea.chiappa@uniroma2.it, francesco.giorgetti@uniroma2.it).

R. Bonifetto is with the NEMO Group, Dipartimento Energia, Politecnico di Torino, Torino, Italy (e-mail: roberto.bonifetto@polito.it).

V. Corato, L. Muzzi and S. Turtù are with ENEA, Frascati, Italy and also with Italian Consortium for Applied Superconductivity (ICAS), Frascati, Italy (e-mail: valentina.corato@enea.it, luigi.muzzi@enea.it, simonetta.turtu@enea.it).

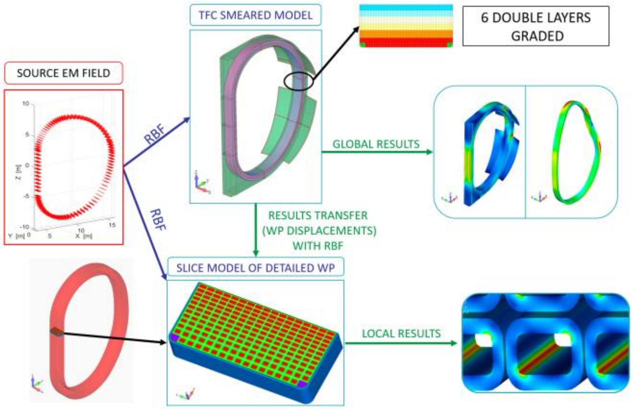

Fig. 1. Stress Recovery Tool workflow applied to the 2016 ENEA proposal for the DEMO TF WP.

validation, comparing the results of the proposed method with those of a fully detailed high-accuracy model of the leg, is provided. It's worth to notice that the development of SRT was necessary for this specific task as standard sub modelling tools available in FEA solvers are not able to properly manage this problem. The validated procedure, which consists in transferring only some components of the displacement during the mapping (in particular in-plane displacements of the cross sections of the WP slice are not constrained) and of re-introducing Lorentz loads at effective conductor locations of the local model, requires in fact a specific customization.

The present paper shows the outcome of the mechanical analyses conducted for the WP#2 design option, proposed by ENEA in 2016 for the DEMO TFC. After the description of the FE model and the setup of the analysis, the results are presented and commented.

II. FINITE ELEMENT MODELS

The hierarchical SRT calculation requires the use of two FE models. The first one is the TFC with a WP modelled as a homogenized orthotropic material; the second one is a slice of the WP, in which all geometrical details and corresponding real material properties are represented.

The ENEA layer-wound WP features 6 graded Double Layers (DL), with a jacket thickness decreasing together with the EM forces towards the plasma (from 11.7 mm of DL6 to 3.9 mm of DL1). In order to take into account such a grading in the FEA, the coarse WP model has been divided in 6 strips whose equivalent, smeared orthotropic properties (different from each other, in view of the different jacket thicknesses) were computed by the dedicated homogenization approach reported in [6]. All the analyses were performed with FEMAP (v. 11.0.1) as pre/post processor and NX Nastran (v. 8.5) as solver. The main FEM details are resumed in Table I.

TABLE I
MESH NODES AND ELEMENTS OF SRT MODELS

Model	Number of Nodes	Number of Elements
Smeared TFC	487k	318k
WP detailed Slice	260k	204k

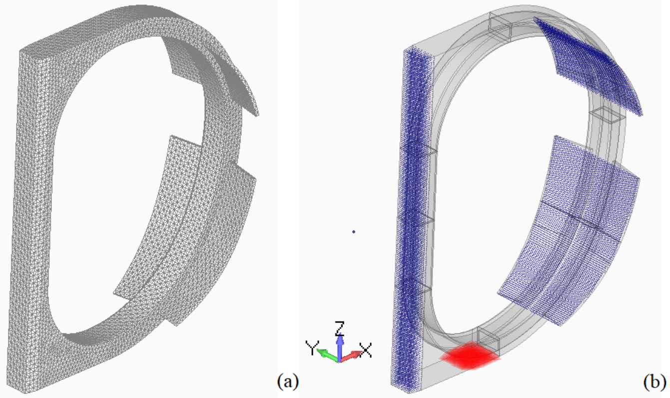

Fig. 2. View of the smeared TFC model (a) and (b) of the applied constraints, namely the equations in the inner leg wedges and OIS (blue dots) and gravity support (red dots).

III. ANALYSIS SETUP

Although the load scenario is the same for both models, the SRT approach requires to apply a different set of BCs and constraints, as described in this Section.

A. *Smeared TFC model*

The global model is meshed using tetrahedrons with mid-side nodes in order to gain the desired accuracy.

The BCs applied to this model, whose mesh is shown in Fig. 2a, allow to reproduce the cyclic symmetry of the whole TFC system. In particular, a series of constraint equations were used to connect the nodes displacements (radial, toroidal and vertical) on the wedge sides of the TFC inner leg and at the Outer Intercoil Structures (OIS), see Fig. 2b.

At the bottom a group of nodes serves to simulate the structural (gravitational) support, that allows only radial displacements, see again Fig. 2b.

Between the smeared WP and the casing a contact condition with a friction coefficient of 0.3 was imposed.

The applied loads include both the Cool Down (CD), i.e. thermal, loads induced by the different thermal contractions of the different materials and the static EM loads evaluated at the End-of-Flat top (EoF) instant of the pulsed plasma scenario, the latter considering the out of plane forces.

The EM Lorentz forces, whose distribution along the coil is depicted in Fig. 3a, were applied using the meshless RBF procedure. As explained in [7], it allows to interpolate a scalar quantity, known at a set of given points, everywhere in the space: starting from a source clouds of points (produced with the Tosca Software), the EM loads components were interpolated onto the mesh nodes of the smeared WP (Fig. 3b).

B. *Full detailed WP slice*

The local model is meshed using a mapped mesh of hexahedra, that are accurate even if using linear formulation.

The WP displacements computed in the simulation of the full D with the smeared WP were used as input to the detailed model of a WP slice (reported in Fig. 4) located at the equatorial plane of the inboard leg, see below, prescribing

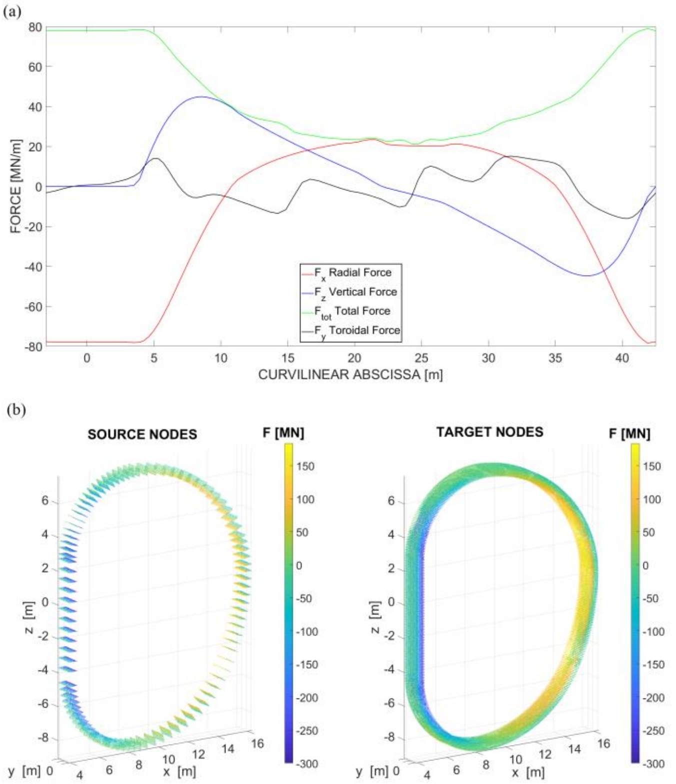

Fig. 3. (a) EM Lorentz forces distributions along coil. (b) EM radial force interpolation from source cloud of points to target smeared conductor nodes.

them at the boundaries of the slice model in order to simulate the contact interface between the WP and the casing and to reproduce the interaction with the adjacent slices as well. These operations required two different interpolations, because different displacement components were used for the different boundaries. In particular, all the displacement components were interpolated and applied to the boundaries in contact with the casing, while to simulate the interaction with the adjacent slices of the WP only the component normal to the contact surface itself was used.

TABLE II
MESH NODES AND ELEMENTS OF SRT MODELS

Stress component [MPa]	
Radial max	-90
Toroidal max	200
Vertical max	-150

A further RBF interpolation is needed for the volume loads, namely the EM Lorentz forces. In this case the force was applied to the actual cable nodes only, being the WP modelled with detailed geometry.

IV. RESULTS

In this section the results, in terms of stress and displacements are exposed. Global results are computed on the full model with equivalent WP and local results are computed on the slice placed at equatorial plane, where the EM field generates the higher Lorenz forces, thus the greater stresses.

A. Global results

On the casing (see Fig. 5) the stress hot spots (800 MPa in terms of Tresca stress) are located under the OIS junctions; even if the peak stress is not considered in static assessments, a careful design of the OISs is recommended, as they widely exceed the allowable value of 500 MPa. Moreover, the peak stress is relevant for direct comparison with other WP and casing designs. Also on the sharp edges of inner leg straight portion the Tresca stress reaches the value of about 750 MPa, higher than the allowable value (667 MPa).

From the TFC model featuring the smeared WP, it is possible to extract the stress state on the casing and to exploit the stresses on smeared WP in order to locate the critical position where further local analysis is required. The maximum value of stress components, useful only to localize the most critical section where the local analysis will be performed, are collected in Table II.

It is important to underline that the maximum of radial

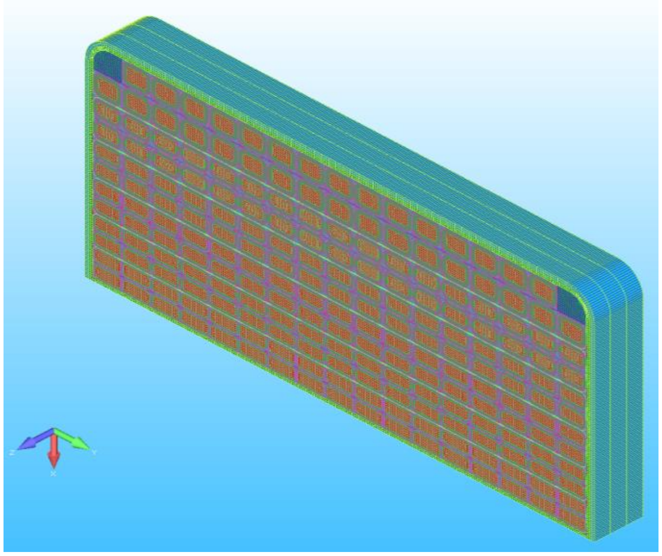

Fig. 4. View of the mesh of the detailed model of a WP slice.

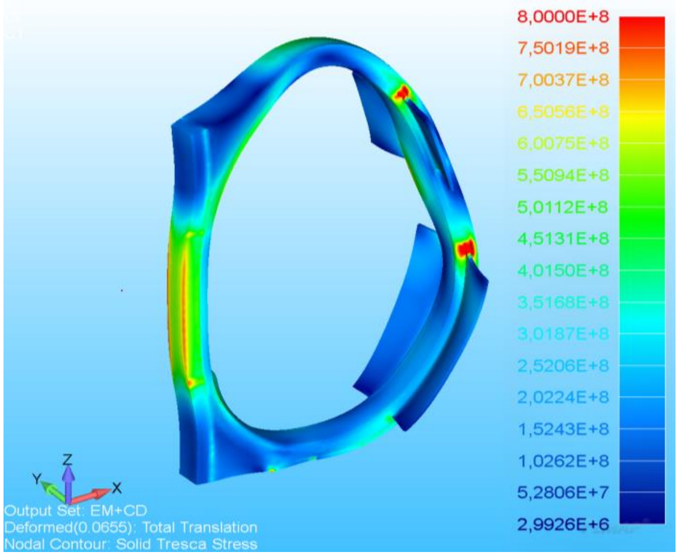

Fig. 5. Computed Tresca stress distribution in the TFC casing.

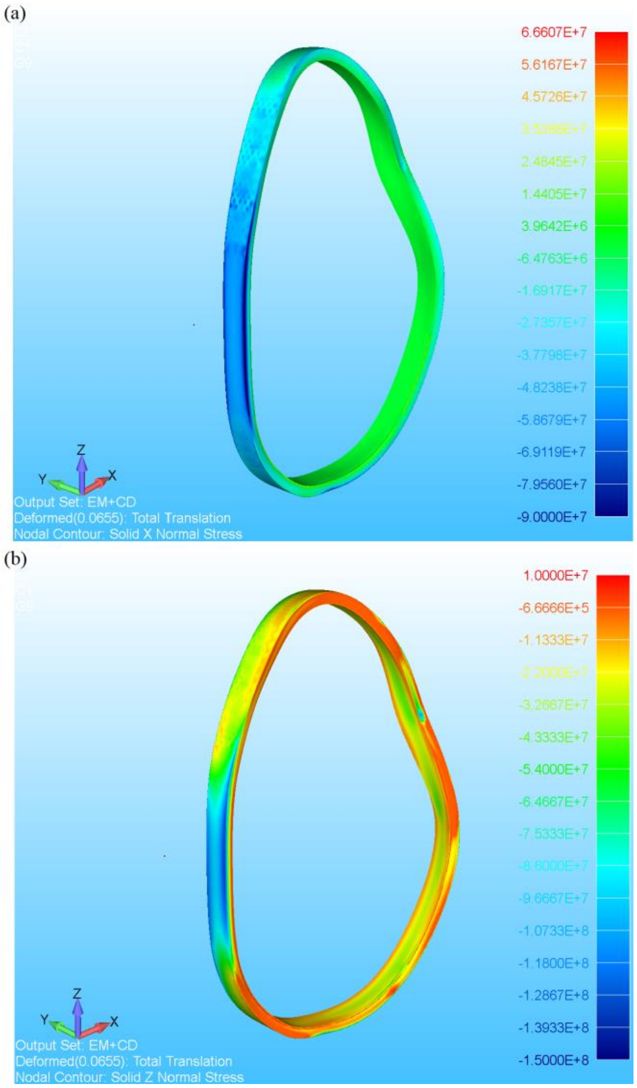

Fig. 6. Computed radial (a) and vertical (b) components of stress on smeared WP.

compression (Fig. 6a) and vertical (Fig. 6b) stress both occurs along the inner leg straight portion, where a detailed, local analysis is then required.

B. Local results

The maximum stress value is located at internal fillet of jacket (see Fig. 7a), situated in the DL5 as documented in Fig. 7b. It is worth to notice that the local stress distribution is not affected substantially by the load introduction path because of the low cable stiffness. A bonded connection between cable and jacket was used, but it is known from prior sensitivity tests that it does not play a significant role. It means that the load introduction path is slightly different but the effect on the stress (that is the sum of the applied and the stacking one) is negligible.

The latter figure shows the mean and peak (Tresca) stress on all DLs: the average stress computed by the SRT is always below the allowable value (with a safety factor, SF, ~1.6), while the peak stress is acceptable only for the first two DLs.

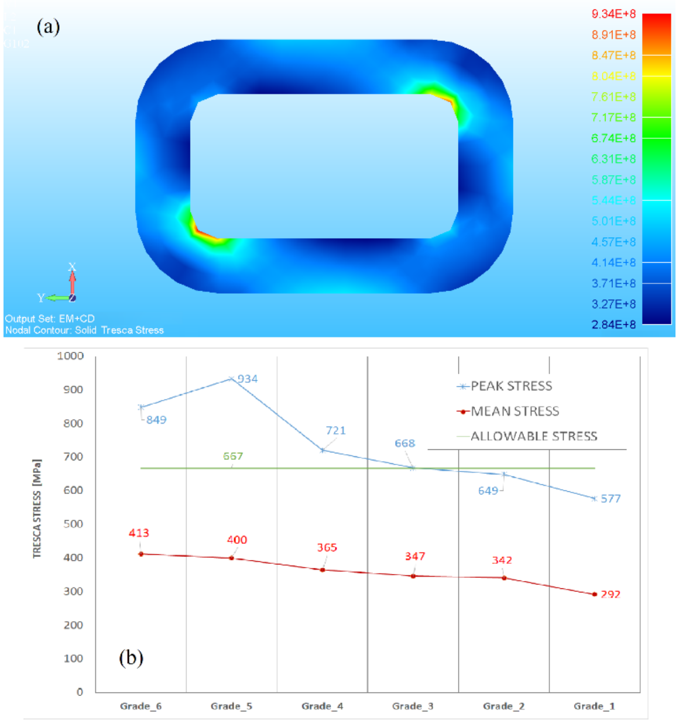

Fig. 7. (a) Computed Tresca stress distribution inside the most loaded steel jacket. (b) Tresca stress, peaks and mean values, related to each DL.

Nevertheless these peaks are extremely focused on a small portion of the material, and are relevant only for the fatigue analyses, out pf the scope of the present work.

V. CONCLUSIONS AND PERSPECTIVE

The mechanical analysis of the 2016 ENEA WP design for the EU DEMO TF coils has been performed using an advanced hierarchical workflow (defined in this study as the Stress Recovery Tool).

The maximum computed stress in the casing is located close to the OISs junctions, where the presence of sharp edges causes an unrealistic stress concentration of about 800 MPa (Tresca stress), widely exceeds the allowable stress value of 500 MPa. However thanks to a careful design, that means the introduction of proper fillets, these stress peaks could be reduced.

Concerning the WP, the detailed analysis of the slice at the inboard equatorial plane showed that the stress peaks are always located at inner jacket fillets. The stress value exceeds the allowable one with the exception of the first and second double layer. However they are relevant only for fatigue analyses. The mean stress value of each DL is instead lower than the allowable one, with a minimum safety factor of about 1.6.

Fatigue assessment, together with a detailed stress linearization, is a very important future step to be performed, because of the very high stress peaks: it will be important to evaluate their re-distribution during cyclic loading.

REFERENCES

[1] F. Romanelli, “EFDA, Fusion Electricity. A roadmap to the realisation of fusion energy,” pp. 1–75, 2012.

[2] D. Maisonnier and J. Hayward, "Technological and engineering challenges of fusion." *Proceedings of the 2nd IAEA Technical Meeting on First Generation of Fusion Power Plants*, Austria. 2007, pp. 1-7.

[3] N. Taylor and P. Cortes, “Lessons learnt from ITER safety & licensing for DEMO and future nuclear fusion facilities,” *Fusion Eng. Des.*, vol. 89, no. 9–10, 2014, pp. 1995–2000.

[4] L. Zani, C. M. Bayer, M. E. Biancolini, R. Bonifetto, P. Bruzzone, C. Brutti, D. Ciazynski, M. Coleman, I. Duran, M. Eisterer, W. H. Fietz, P. V. Gade, E. Gaio, F. Giorgetti, W. Goldacker, F. Gomory, X. Granados, R. Heller, P. Hertout, C. Hoa, A. Kario, B. Lacroix, M. Lewandowska, A. Maistrello, L. Muzzi, A. Nijhuis, F. Nunio, A. Panin, T. Petrisor, J.-M. Poncet, R. Prokopec, M. Sanmarti Cardona, L. Savoldi, S. I. Schlachter, K. Sedlak, B. Stepanov, I. Tiseanu, A. Torre, S. Turtu, R. Vallcorba, M. Vojenciak, K.-P. Weiss, R. Wesche, K. Yagotintsev, and R. Zanino, “Overview of Progress on the EU DEMO Reactor Magnet System Design,” *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, Jun. 2016, Art. no. 4204505.

[5] F. Giorgetti, A. Chiappa, M. E. Biancolini, and F. Nunio, “Application of a new tool for fast stress recovery to DEMO TF coil system*,” Proceedings of the International CAE Conference 2016*, Parma, Italy, Oct. 17–18, 2016, pp. 1-13.

[6] M. E. Biancolini, “Evaluation of equivalent stiffness properties of corrugated board*,” Composite structures,* vol. 69, no. 3, Jul 2005.

[7] M. E. Biancolini, C. Brutti, F. Giorgetti, L. Muzzi, S. Turtù, A. Anemona, “A new meshless approach to map electromagnetic loads for FEM analysis on DEMO TF coil system,” *Fusion Eng. Des.*, vol. 100, Nov. 2015, pp. 226–238.