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Mechanical analysis of the ENEA TF coil proposal for the EU DEMO fusion reactor

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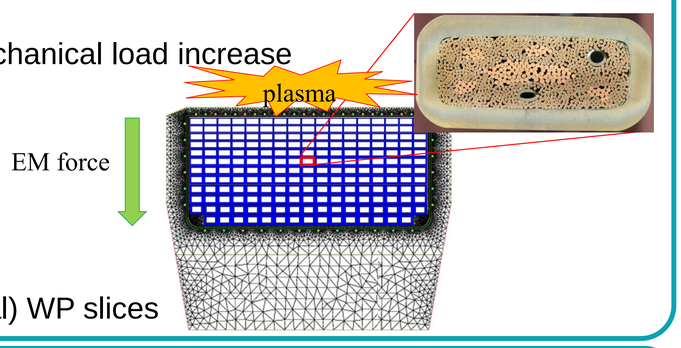
Introduction

- Design of the superconducting magnet system of the European DEMO fusion reactor currently undergoing in the EUROfusion Magnets Work Package (WPMAG)
- Three alternative winding pack (WP) options are being proposed
- WP#2, proposed by ENEA, features a layer-wound WP design adopting a wind-and-react conductor with rectangular cross section with high aspect ratio
- Very high operating current (70.8 kA) + magnetic field up to 12 T → huge electromagnetic (EM) Lorentz forces acting on each of the 202 conductor turns in a TF coil
- Forces are withstood
  - locally by the steel jacket of the conductor: thickness increases with the radial distance from the plasma to balance the mechanical load increase
  - globally by a thick stainless steel casing in which the WP is encapsulated.



AIM of the WORK

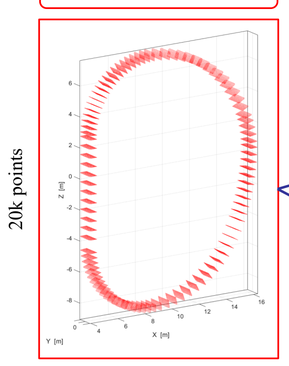
- Assess the capability of all the TF components to withstand the EM loads without any structural failure
- → detailed mechanical analysis on the 2016 version of the WP#2 design option
- **Stress-Recovery Tool**, developed in the past years at University of "Tor Vergata", Rome, is applied:
  - Finite Element Analysis (FEA) of a whole magnet with coarse WP model with smeared (homogenized) properties
  - displacements computed on the smeared WP then used as boundary conditions for a refined FEA of some selected (critical) WP slices

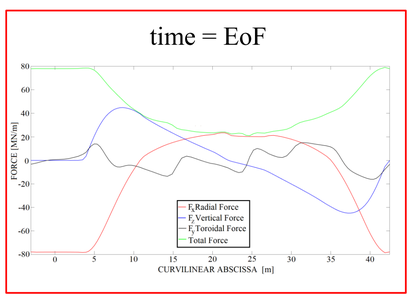
Multiphysics Hierarchical Analysis Workflow

The proposed workflow is based on a hierarchical approach and allows to fast recover the stress state in every WP component and in every TFC section.

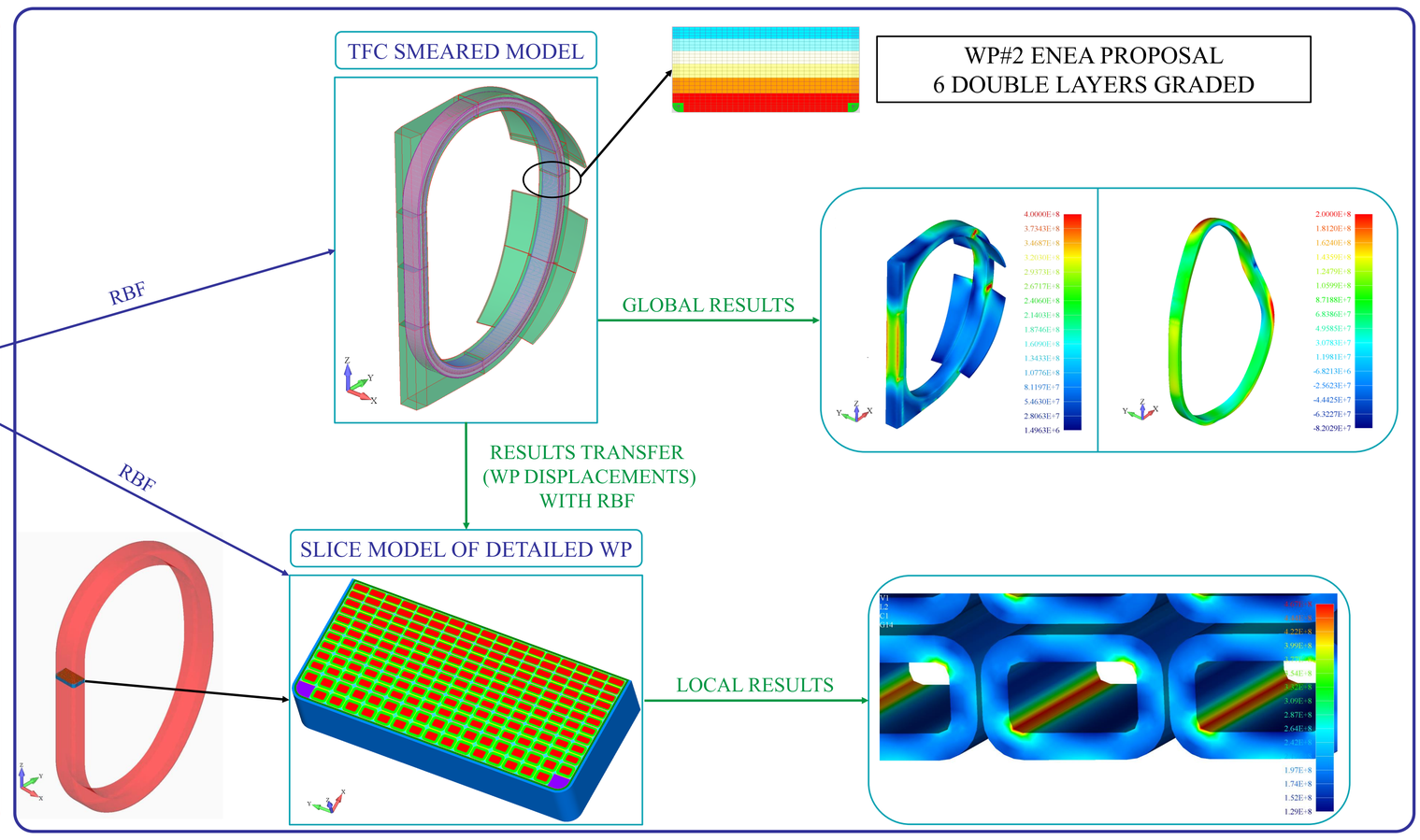
EM FIELD

TOSCA SOFTWARE → SOURCE FIELD





PROPOSED WORKFLOW



FE MODELS

- All the analyses performed with FEMAP (v 11.0.1) as pre/post processor and NX Nastran (v 8.5) as solver.
- TFC Smeared Model BCs :
  - Cyclic symmetry.
  - Gravity support.
  - Cool Down and EM loads.
  - Contacts imposed between Casing and WP
- Detailed WP Slice Model BCs :
  - X, Y, Z displacements (from smeared TFC analysis) applied to lateral surfaces to simulate the contact interface between WP and Casing.
  - Normal displacements to top/bottom surfaces to simulate the interaction with the adjacent material.
  - Cool Down and EM loads

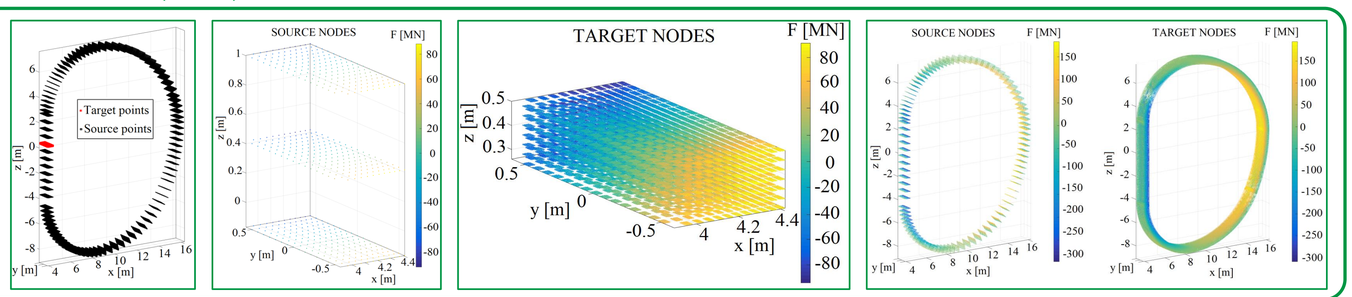
FE MODEL	NODES	ELEMENTS
Smeared TFC	487k	318k
Detailed WP Slice	259k	204k

WP Slice Model height is 0.25 m with 6 rows of elements.

RADIAL BASIS FUNCTIONS (RBFs) INTERPOLATIONS

- Radial Basis Functions (RBFs) allow to interpolate a scalar function known at a set of given points (source points).
- Due to node mismatch a meshless procedure is needed.
- RBF interpolation used to transfer displacements (from smeared TFC model to WP detailed slice) and to apply the EM loads to cables nodes.

$$s(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i \cdot \underbrace{\varphi\left(\left\|\boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{k}_i}\right\|\right)}_{\text{RADIAL BASIS}} + \underbrace{h(\boldsymbol{x})}_{\text{POLYNOMIAL}}$$

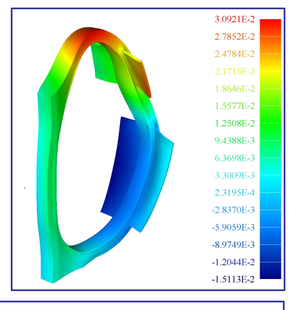


Results

GLOBAL RESULTS

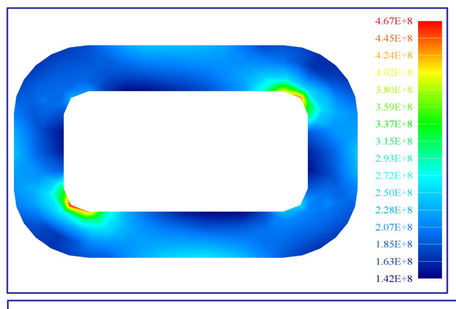
Displacement	Casing	WP
Radial max [mm]	-9.74	-12.99
Radial min [mm]	-62.21	-59.06
Toroidal max [mm]	30.92	30.15
Toroidal min [mm]	-15.11	-10.59
Vertical max [mm]	3.75	-0.46
Vertical min [mm]	-33.75	-28.20

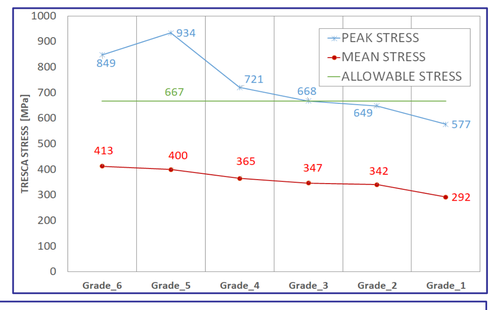
Max WP Radial stress [MPa]	Max WP Toroidal stress [MPa]	Max WP Vertical stress [MPa]
-90	200	-150



Casing critical points are the OISs junction with a Tresca stress of 800 MPa (500 MPa allowable) and the at the sharp edge of Inner Leg whit a Tresca stress of 750 MPa (allowable 667 MPa).
Smeared WP stresses used to locate critical position for the local analyses.

LOCAL RESULTS





The stress peaks (used for fatigue analysis) are always located at inner Jacket fillets, with a stress value higher than the allowable one (667 MPa), except that for the first and second double layer. Mean stress values of each layer is lower than the allowable value, with a minimum safety factor of about 1,6.

Conclusions

1. Stress Recovery Tool successfully applied to the mechanical analysis of the ENEA proposal of the TF coil for the EU DEMO.
2. The stress level are above the allowable limits in some critical locations of the Casing.
3. The mean stress levels of conductor jackets are lower than the allowable values.
4. Stress peaks (DL6 to DL3) are greater than the material limits.
5. For stress peaks a fatigue analysis is required.

References

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[3] I. Babuška and J. M. Melenk, "The partition of unity method," Int. J. Numer. Methods Eng., vol. 40, no. 4, pp. 727–758, 1997.
[4] F. Giorgetti, A. Chiappa, M. E. Biancolini, and F. Nunio, "Application of a new tool for fast stress recovery to DEMO TF coil system," *International CAE Conference 2016*, Conference Proceedings.

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