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Analysis Approaches to Resolve Structural Issues of the European DEMO Toroidal Field Coil System at an Early Design Stage

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Analysis approaches to resolve structural issues of the European DEMO Toroidal Field Coil System at an early design stage

A. Panin, W. Biel, Ph. Mertens, F. Nunio, K. Sedlak, L. Zani, M. Coleman

***Abstract*—Because of its ambitious goals, the DEMO project faces many technical challenges. The mechanical performance of the superconducting toroidal field coil (TFC) system is mostly determined by the high electromagnetic (EM) forces. A structural evaluation of the TFC of the EU DEMO 2014/2015 baseline configurations for three winding pack (WP) options is presented. The emphasis is focused on the parametric study with the use of simplified numerical modeling. Physical interpretation of the numerical results makes the system mechanical behavior transparent and directly leads to the design recommendations. An express approach is proposed to reconstruct the detailed conductor stress-state from the homogenized winding. This allows for sorting out the WP designs with respect to their robustness against acceptance criteria while giving a way to their improvement. Analysis workflow for the TFC system stress analysis is proposed. A semi-analytical procedure allowing for the coil pre-dimensioning prior to the 3D numerical simulations is briefly described. Its distinguishing feature is an optimization of the layered winding by grading the radial and toroidal conductor walls separately thus arriving at the requirement of the minimum space for the coil winding.**

***Index Terms*—nuclear fusion; DEMO project; magnet system; electromagnetic analysis; structural analysis;**

I. Introduction

The superconducting toroidal field coils system (TFC) is one of the key systems of the European DEMO project. Its mechanical performance is mostly determined by the extremely high electromagnetic (EM) forces. Use of cryogenic steels whose structural performance is excellent at low temperatures and drastically degrades with temperature rise demands for strict structural codes to preclude material plastification associated with heating [1, 2]. The aim of the present design stage is a choice of physical parameters for the systems including the TFC. The proper system design should provide its structural integrity. Due to multiple design iterations fast engineering estimations of the structure strength accompanied with the design recommendations are demanded [1].

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The TFC system (2014/2015 baseline) is formed by the sixteen identical D-shaped coils. The in-plane EM forces occur due to an interaction of the coils' currents with the EM fields produced by the TF coils and the out-of-plane forces occur when the TFC current interacts with the poloidal fields. The coils are wedged inside to support the centering in-plane forces that reach their maximum at the wedged coil inner leg portion and mostly determine the winding pack (WP) strength and design. At the outboard region the coils are interconnected via some outer intercoil structures (OIS). They form stiff rings that resist the out-of-plane forces and restrain coils' tilting.

The presented TFC analysis includes calculation of the in-plane EM forces (chapter II) and the subsequent sensitivity study featuring the TFC simplified numerical models with the homogenized WP (chapter III). Even in absence of information on the poloidal coils system scenarios, this parametric study allows for ruling out improper designs while giving a way to their improvement (chapter IV). The recommended analysis workflow featuring the coil pre-dimensioning based on a simple semi-analytical approach is discussed in chapter V.

II. TFC Electomagnetic Analysis

Three WP designs were studied. The ANSYS [3] FE EM model uses combination of linear tetrahedral elements for a winding targeted for the Lorentz forces calculation with the primitive elements to model the EM fields of surrounding coils. Two types of nodal force transfer between the coupled EM and structural models were used: the "node-to-node" for the identical meshes, and the force transfer between dissimilar meshes [4]. The total current through the TF coil is 19.1 MA, the magnetic field on TF conductor reaches ~13.3 T and the distributed radial compression reaches ~120 MN/m (Fig. 1).

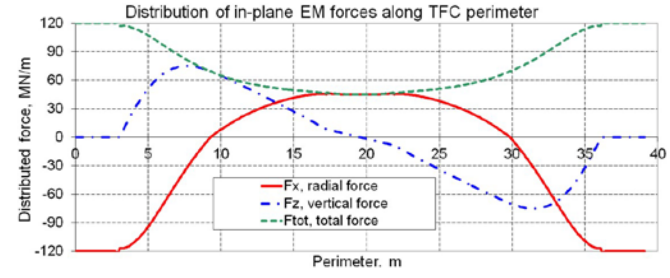

Fig. 1. Distribution of the in-plane EM forces along the TF coil perimeter

III. Winding Pack Homogenezation

Since the WP represents the periodical structure it can be treated in the global TFC structural analysis as a media with effective thermo-mechanical characteristics. These properties are defined with the detailed FE model of the WP periodical cell [5]. Ten unique problems with proper boundary conditions are solved to define the Young's modules, shear modules and Poisson's coefficients at the room temperature (RT) and 4 K. The averaged directional thermal contraction is calculated in the temperature range from the RT to 4 K. The cable stiffness is neglected. A periodical cell for one double layer of the graded winding is shown in Fig. 2.

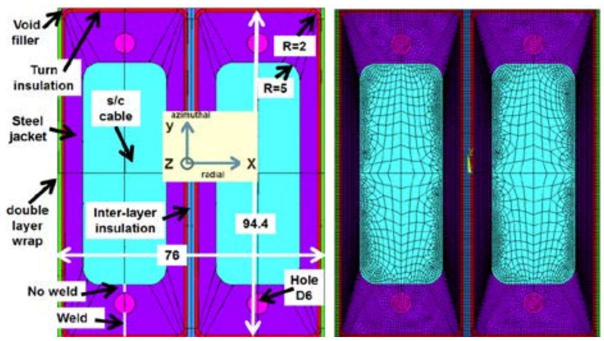

Fig. 2. 3D FE model for calculation of WP#1 homogenized properties

Important mechanical considerations can be made already at this stage, prior to the 3D TFC modeling. The WP stiffness in the winding direction determines the vertical load shear between the casing and the winding at the coil inboard. The compression in the conductor radial walls that transmit the cumulative radial EM load from the inner layers to the outermost layer is correlated with the winding radial stiffness. The toroidal walls transmit the cumulated out-of-plane forces and, in addition, take the wedge toroidal compression at the coil inboard together with the coil casing. The walls' compression is correlated with the WP toroidal stiffness.

IV. Sensitivity Study of Simplified Toroidal Coil under In-Plane Electromagnetic Forces

At the initial stage some TFC structural members like the coil pre-compression ring and the OISs are designed from scratch and need to be parametrically studied. The OISs that should prevent the coils excessive bending under the out-of-plane forces also contribute to taking the in-plane loading by wedging. They influence the coil in-plane bending at the outboard and have an impact on the required pre-compression force to avoid opening of the wedged coils. Three WP designs were studied and compared [6]. Two extreme cases of frictional coil/WP contact were studied: a friction factor of zero and of 0.3 (nearly sticking). To highlight the most important structural features and facilitate results interpretation, the coil FE model was intentionally reduced to a quasi-symmetric quarter thus neglecting asymmetry of the upper and lower OISs (Fig. 3). A tentative OIS representing the box-like-structure with ~90 mm thick walls is modeled. This layout is chosen as a compromise between a solid steel block and a single plate.

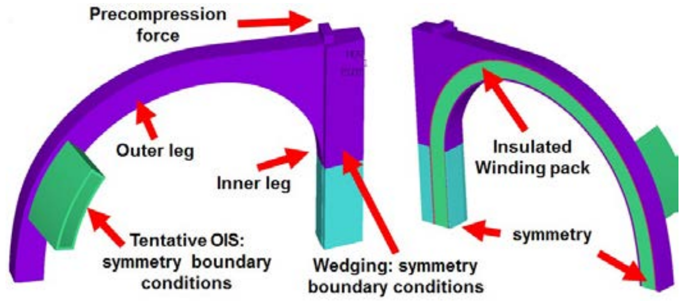

Fig. 3. Structural model of the TFC quasi-symmetric quarter used for analysis.

Symmetry boundary conditions are employed at the coil equatorial planes and at its wedged portions. The OIS loading is not of concern at this stage of parametric analysis. The static strength of the steel structures is estimated at the present stage. The ITER database was used to preselect structural materials and the applicable structural design criteria [7]. The strength properties for the structural steels at 4 K are given in Table I. The insulation strength and fatigue issues are not treated now.

TABLE I. Most important strength properties of structural steels.

Structural steel	Case inner leg, EK1/JJ1, forged	Case outer leg, EC1, cast	Conductor jacket, modified 316 LN
$\sigma_{0.2}$, MPa	1000	750	1000
σ_{ult}, MPa	1500	1000	1600
S_m, MPa	667	500	667

where: $\sigma_{0.2}$ - yield stress, σ_{ult} - ultimate strength, S_m - limiting stress intensity

A. *OIS Parametric Study*

The TFC model is studied for a one WP option under the in-plane loading. The OIS stiffness was parametrically lowered to zero (no OIS). Some important results are given in Table II. The OISs form a toroidal ring that takes a part of the centering force via tension. Its impact on the coil inward movement is negligible while the coil deformation at the outboard depends on its toroidal stiffness. The pre-compression force is applied to the coil to minimize a possible opening of the wedged coils. To facilitate modeling, symmetry boundary conditions are specified for the wedged inner legs. They prevent opening of the wedged coils and the tension in this region indicates a possible toroidal gap. Some toroidal tension between the wedged inner legs is shown in Fig. 4. Without OIS, a force of ~60 MN is required to minimize the possible gap. The OIS structure mostly prevents opening of the wedged coils even without pre-compression. So, the design of the pre-compression structure is dependent on the coil shape and the OISs stiffness.

TABLE II. Results for WP#3 in dependence on OIS toroidal stiffness.

OIS option	Nominal OIS		no OIS	
Precompression force, MN	0	60	0	60
Coil inward movement, mm	12.4	12.3	12.3	12.3
Coil outward movement, mm	34.6	32.9	72.0	67.1
Coil vertical movement, mm	18.3	19.7	7.2	10.3
WP tensile strain (inboard), %	0.22	0.22	0.23	0.23
WP tensile strain (outboard), %	0.33	0.33	0.40	0.40

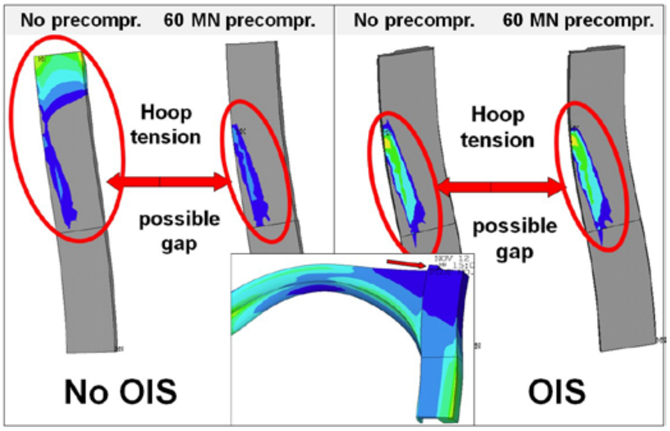

Fig. 4. Impact of the OIS stiffness on required coil precompression.

B. *Impact of WP Stiffness on Coil Structural Behavior*

Three WP options are studied (zero coil/WP friction). The main results are given in Table III. The vertical load share between the inner and outer coil legs (~53% and 47%) doesn't depend on the WP stiffness and depends only on the coil geometry. The load share between the casing and WP at the coil inboard depends on the WP stiffness. The softer the winding, the more the coil outer leg bends and moves outwards. The primary membrane stress at the coil inboard exceeds the allowable value of 667 MPa for the softest WP#3 winding.

TABLE III. COIL STRUCTURAL PERFORMANCE DEPENDING ON WP STIFFNESS.

Winding pack option	WP#3	WP#2	WP#1
WP poloidal elastic modulus, GPa	82	94	110
Net EM vertical force, MN	679	682	682
Inner/outer leg vertical load share, %	53/47	53/47	53/47
Inner leg case/WP vertical load share, %	68/32	64/36	60/40
Outer leg case/WP vertical load share, %	61/39	57/43	53/47
Coil inward movement, mm	12.4	12.3	11.1
Coil outward movement, mm	34.6	33.9	32.7
Coil vertical movement, mm	18.3	16.6	14.5
Inner leg primary membrane stress, MPa	**713**	653	637

C. *Impact of Case/WP Friction on Coil Structural Behavior*

Two extreme cases of the frictional case/WP contact have been studied for the WP#2 option. The load shear between the coil inner and outer legs does not depend on friction (Table IV). Contrary, the case/WP load shear at the coil inboard is highly friction dependent. High friction redistributes the EM vertical force between the case and winding nearly in proportion to their poloidal stiffness via the shear load at their contact interface. When the friction is low, the WP under the volumetric EM load can slide along the coil case at the coil inboard straight portion and is stretched more than the casing thus taking higher fraction of the vertical load. It results in the higher winding poloidal tension and in the smaller coil case tension. Thus zero friction gives the worst case for the WP loading. To make a conservative estimation of the conductor strength the low friction should be considered. In opposite, the case of high friction represents the worst loading conditions for the coil casing.

TABLE IV. IMPACT OF FRICTION ON COIL MECHANICAL PERFORMANCE.

Case/WP friction coefficient	0.3	0.0
Net vertical reaction force, MN	682	682
Inner/outer leg vertical load share, %	53/47	53/47
Inner leg case /WP vertical load share, %	79/21	64/36
Outer leg case/WP vertical load share, %	58/42	57/43
Coil inward movement, mm	11.7	12.3
Coil outward movement, mm	32.2	33.9
Coil vertical movement, mm	16.5	16.6
WP tensile strain (inboard), %	0.16	0.22
WP tensile strain (outboard), %	0.32	0.31
Inner leg primary membrane stress, MPa	**668**	653

D. *Strength Estimation of Coil Case (WP#2)*

To check the stresses against the structural limits [7] two critical locations in the coil case are selected (Fig. 5). The high toroidal (wedge) compression coupled with the moderate poloidal tension determines the strength of the inner leg at the equatorial plane. Stress linearization along a critical path (Fig. 5) is made according to [7]. The primary membrane stress calculated in assumption of the high friction is 668 MPa for WP#2 and slightly exceeds the allowable limit of 667 MPa. The sum of the primary membrane and bending stresses passes the structural criteria. In assumption of friction these stresses are higher for the softest WP#3 and are lower for the stiffest WP#1.

The second critical region (under the OIS) is out of the paper scope because the out-of-plane loading is not specified.

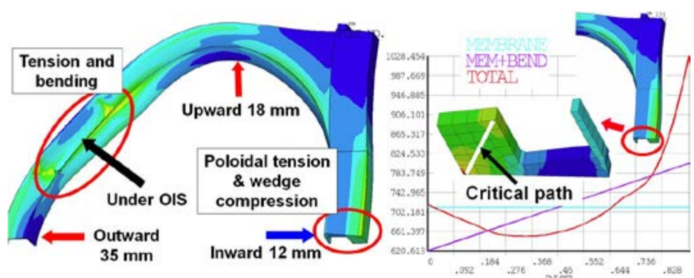

Fig. 5. Tresca stress distribution in coil case and spotted critical locations

E. *Express Approach for Detailed Conductor Analysis*

The directional stress components for the WP with effective properties (Table V) are used for the subsequent detailed conductor analysis. The main issue is the static strength of the conductor jacket. The worst combinations of the poloidal tension and the compression (radial or/and toroidal) give the highest equivalent stress in the conductor radial or toroidal walls. The conductor analysis is performed on the basis of the stresses calculated for the smeared winding and averaged over the conductor. Some post-processor procedure seeks for the critical winding locations. Note that the preceding detailed conductor analysis for each winding grade is needed to predict when these worst stress combinations violate the criteria for the steel components and for the insulation [8]. The results for the steel jacket of the outermost conductor grade (WP#2) are shown in Fig. 6 and are given in Table VI. Even with friction (optimistic case) the strength criteria is mostly

TABLE V. MAIN WP RESULTS USED FOR DETAILED CONDUCTOR ANALYSIS

Friction factor	0.3	0.0
Inner leg poloidal tension, MPa	83	140
Outer leg poloidal tension, MPa	284	304
Radial compression, MPa	84	97
Toroidal compression, MPa	144	144
Shear due to in-plane WP bending, MPa	24	23
Shear in WP cross-section (normal to winding), MPa	17	10

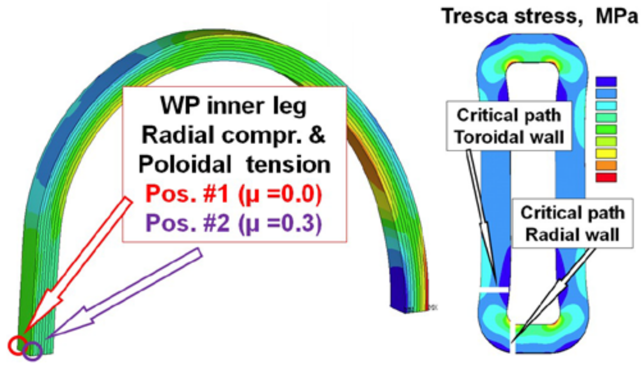

Fig. 6. Detailed analysis for conductor jacket at the coil inboard

TABLE VI. RESULTS OF DETAILED CONDUCTOR JACKET ANALYSIS

WP#2 Inner leg Pos.#2 (μ=0.3) vs. Pos.#1 (μ=0.0)				
	Friction	Allowable	Radial walls	Toroidal walls
Memrane, MPa	0.3	667	**669**	648
	0.0		**835**	**822**
Membrane+ Bending, MPa	0.3	867	**975**	844
	0.0		**1240**	**1053**

violated. Note that with the use of a relatively simple semi-analytical procedure, briefly mentioned in chapter V, one can arrive at similar conclusions prior to the 3D FE analysis. The efforts are worth a few hours and the procedure run-time doesn't exceed several minutes.

V. PROPOSED ANALYSIS WORKFLOW FOR TFC SYSTEM STRUCTURAL EVALUATION

Before launching the 3D numerical analysis, a coarse pre-dimensioning of the coils should be made. A semi-analytical code has been developed which estimates the static strength of the coil casing and the conductor jacket at the coil wedged portion under the essentially 3D stress state due to the EM loading. Both the layered and pancake winding layouts are treated by this code. Its distinguishing feature (e.g. compared with [9]) is optimization of the layered windings by grading the radial and toroidal conductor walls separately, either keeping the space allocated for the superconducting cable unchanged (may not converge to the mechanically optimized design) or arriving at the mechanically optimized design on the expense of the cable space. The minimum space required for the coil winding is defined on the basis of the pre-selected structural materials. The code has been successfully benchmarked against the 3D FE solutions for the current TFC design. The procedure has been already used to check and optimize several winding layouts for the new TFC layout associated to 2015 DEMO updated operation point. Its detailed description is out of the scope of this paper but is planned to be published soon.

Then the simplified 3D numerical parametric modeling under the in-plane loading comes into play. Note that a well-known analytical technique is to be engaged to provide the "moment free" D-shaped coil geometry under the in-plane loading (e.g. [10]). Structural elements like the OISs are to be modeled as simple tentative structures. The outcome of the sensitivity study performed is a clear understanding of the impact of different factors (like friction, OIS stiffness) on the coil mechanical behavior. Using the 3D directional results for the smeared winding, the express detailed conductor analysis can be performed. Note that the coil stress state at the coil inboard wedged portion is mostly determined by the in-plane forces. Design changes are the result of this analysis stage.

After the coil design is optimized in respect to the in-plane loading the impact of the out-of-plane forces on the coil lateral bending is to be studied. In parallel, the optimization of the conductor layout is to be performed.

VI. CONCLUSIONS

Parametric FE structural analyses of the intermediate design of the EU DEMO TFC system under the in-plane electromagnetic loading have been performed. The impact of the friction at the coil/winding interface, the impact of the outer intercoil structure, and the impact of the winding stiffness on the coil structural behavior has been studied and some important conclusions for the coil strength estimations have been drawn. The design recommendations with respect to the required coils pre-compression have been made. It has been shown that all the options of the TFC winding studied violate the static strength criteria.

An analysis workflow for the structural evaluation of the TFC system has been proposed. A semi-analytical procedure allowing for the coil pre-dimensioning prior to the 3D numerical simulations is briefly described. Its distinguishing feature is an optimization of the layered windings by grading the radial and toroidal conductor walls separately thus arriving at the requirement of the minimum space for the coil winding. The procedure has been successfully benchmarked against the 3D FE solutions for the current TFC design and has been used to pre-select some winding arrangements for the next TFC layout.

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REFERENCES

[1] Olaf Neubauer, et al., Strategies of Numerical Modeling in Component Development for Fusion Devices, IEEE Transactions on Plasma Science (2014), Vol. 42, No. 3, pp. 682-689, doi:10.1109/TPS.2013.2282179

[2] Łukasz Ciupiński, et al., Limit analysis of W7-X critical magnet system components with consideration of material serration effect, Fus. Eng. Des. 86 (2011), pp. 1501-1505, doi:10.1016/j.fusengdes.2011.03.008

[3] ANSYS, Inc. Release 14.5

[4] A. Panin, et al., Structural Analysis of a Prototype Fast Shutter for ITER cCXRS Diagnostic, IEEE Transactions on Plasma Science (2012), Vol. 4, issue 3, pp. 746-752, doi:10.1109/TPS.2012.2182782

[5] Borovkov A.I., et al., FE Analysis of Effective Mechanical and Thermal Characteristics of Micro Heterogeneous Toroidal Field Coils, IEEE Transactions on Magnetics, Vol. 28, pp. 927-930, 1992.

[6] L. Zani, et al., Overview of progress on the EU DEMO reactor magnet system design, presented at MT24 confer., to be published in IEEE Trans. Appl. Supercond. (2016)

[7] ITER Magnet Structural Design Criteria Part 1, Part 2

[8] P. Titus, A. Panin, A. I. Borovkov, Evaluation of Insulation Shear Stresses in the ITER Central Solenoid, 17th IEEE/NPSS Symposium, Fusion Engineering, San Diego, California, Oct. 6-10, 1997, vol. 2, pp. 689-692

[9] J.-L. Duchateau, et al., Conceptual integrated approach for the magnet system of a tokamak reactor, Fus. Eng and Des. 89(2014), pp. 2606-2620, http://dx.doi.org/10.1016/j.fusengdes.2014.06.012

[10] R. J. Thome, J. M. Tarrh, MHD and Fusion Magnets, Field and Force Design Concepts, John Wiley & Sons, 1982