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Structural Analysis of Fusion Magnets: Engineering Zooming on the Superconductor Strength

Anatoly Panin[a], Wolfgang Biel[a], Philippe Mertens[a], Francois Nunio[b], Louis Zani[c]

[a]*Institute of Energy and Climate Research - Plasma Physics, Forschungszentrum Jülich GmbH, D52425 Jülich, Germany*
[b]*Commissariat à l'Energie Atomique et aux Energies Alternatives, CEA Saclay, 91191 Gif-sur-Yvette, France*
[c]*Commissariat à l'Energie Atomique et aux Energies Alternatives, CEA Cadarache, 13108 St-Paul Lez Durance, France*

Fusion is foreseen to be a source of practically unlimited and clean energy in future. High magnetic fields required for optimal performance of a fusion reactor pose serious issues with the structural integrity of its magnet system. A reasonably simplified and essentially parametric modeling is efficient during conceptual design. Following the initial coils' pre-dimensioning and pre-optimization, the simplified global numerical structural models come into play. Structural periodicity of the multi-turn windings is usually utilized by their homogenization. The global 3D modeling allows for direct estimation of the structural strength of the massive coil casing. An equally important issue determining the coil design is the strength of the winding conductor, namely its metallic jacket and the conductor insulation. Calculation tool that promptly spots critical locations all over the homogenized winding and performs a detailed "express" analysis of the conductor strength in the found locations has been developed. This procedure significantly facilitates and accelerates the design flow. Main assumptions of this engineering procedure, its merits and limitations are discussed. Examples from the European DEMO project for which the procedure was successfully used illustrate the method. Note that the approach can be easily fit to different multi-physical numerical models featuring homogenization of their periodical components.

Keywords: fusion, magnets, structural integrity, homogenized windings, strength mapping, detailed analysis

1. Introduction

This paper is a logical continuation of the previous works [1, 2] describing engineering approaches to analyze structural issues of the tokamak magnets during conceptual design phase. This stage necessitates reasonably simplified and essentially parametric modeling to achieve to a high extent pre-optimized design configurations with relatively "inexpensive" and efficient analysis tools.

For the paper consistency the main structural problems of the toroidal field coils (TFC) that have been discussed in [1] are briefly recollected in Chapter 2. The coils' semi-analytical pre-dimensioning and pre-optimization [2] that logically precedes a 2D/3D numerical structural analysis is also briefly discussed and its main features are highlighted. Section 3 gives more insight into homogenization technique that uses a structural periodicity of a multi-turns winding pack (WP) to calculate its thermo-mechanical properties. The main features of the detailed "express" conductor analysis in the winding critical locations that is based on results of a global analysis of the TFC featuring homogenized WP [1] are discussed.

A developed tool that promptly spots the critical locations all over the homogenized winding (that may feature a graded layout) thus significantly facilitating and accelerating design/analysis flow is discussed in Section 4. Examples from the European DEMO project illustrate the method. Section 5 summarizes the main features, merits and limitations of the proposed engineering approach.

author's email: a.panin@fz-juelich.de

2. TFC structural issues and coil pre-dimensioning

The in-plane electromagnetic (EM) forces arising in the WP due to the TFC energizing reach their maximum at the coil inboard and the unbalanced radial net force is often supported by wedging of the coils' inner legs. High wedge compression in the coils' casing and winding coupled with their vertical tension (coil in-plane expansion) leads to serious strength problems (Fig. 1a). Since these highly stressed coil portion is located between the central solenoid and plasma it is the most "costly" coil region in a sense of the available radial space for supporting structures. That is why it is determining the coil static strength. At the outboard the coil mostly suffers the fatigue problems due to the out-of-plane forces causing its cyclic lateral bending and

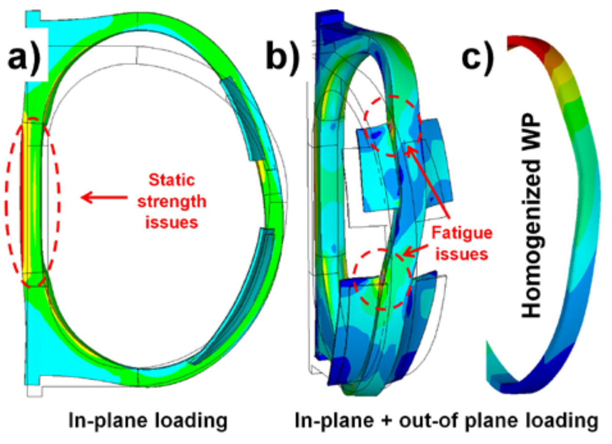

Fig. 1. TFC FE model featuring homogenized winding

tilting (Fig. 1b). Since space limitations at the coil outboard are more relaxed, the issues are settled by stiffening the coil casing and the outer intercoil structures (OIS).

A coil pre-dimensioning that precedes the CAD modeling and 2/3D FE analysis saves time and computational efforts. The semi-analytical tool described in [2] not only estimates the static strength of the TFC casing in the most stressed region [3] but also treats the conductor jacket in detail. This allows for mechanical optimization of the layered WP layouts by grading the conductor jacket radial and lateral walls separately.

The approach has certain limitations. Only the primary membrane stresses in the conductor walls are calculated. An additional safety on the walls' bending has to be used [4]. It is essential for the conductors featuring a large outer radius and a small inner one that usually experience high wall bending under compression.

Additional safety on the possible coil casing/WP sliding is also used. Usually it is assumed that the coil casing and WP share the vertical load in proportion to their stiffness (casing/WP sticking). Since their actual frictional interaction is difficult to predict the reasonable practice is to calculate two extreme cases: contact with high interface friction vs. no friction [e.g. 5]. The latter case gives the most vertical load on the WP. The pre-dimensioning tool is designed to calculate both cases and to use the worst case for the casing and for the winding.

3. Winding homogenization and zooming back

After the initial coils pre-dimensioning the 3D parametric FE structural models are used. Structural periodicity of a multi-turn winding is utilized by its homogenization. To define the winding smeared orthotropic thermo-mechanical properties the detailed FE models of the WP periodical cells are used [e.g. 6]. A number of unique problems are solved for a periodical cell (usually, thin slice of the insulated conductor) in the uniform field of each component of stress tensor. The homogenization procedure implies infinitely many periodical cells so that the deformation of each periodical cell should be compatible with the neighboring ones. Fig. 2 gives examples of the detailed and homogenized periodical cells in the uniform fields of the radial and shear stresses. The homogenized graded winding and periodical cells for different grades developed for the 2015 TFC 2015 layouts of the European DEMO project [7-9] are represented in Fig. 3.

During 3D TFC modeling the homogenized winding transmits the EM forces to the coil casing and effectively takes part in the load share according to its stiffness. The directional stresses calculated in a smeared winding have little mechanical meaning (especially for graded layouts when different layers have different properties). The conventional sub-modeling technique when the displacements from the global model are applied to the boundaries of the detailed one is not valid. Figs. 2c and 3d show that even in a field of the uniform stress (pure shear) the detailed conductor model (jacket, insulation, soft cable) and the smeared one (same mesh, calculated orthotropic properties) deform differently under the same boundary conditions to satisfy compatibility conditions with the neighboring conductors. Tool to examine the detailed conductor stress state basing on the homogenized WP results is required.

An engineering way to resolve the problem is to use a procedure inverse to the homogenization [1, 10]. Six stress components retrieved from the smeared winding are averaged over the volume of a periodic cell (poloidal slice - one element along the WP) that represents an insulated conductor turn (Fig. 4). The conductor FE model used for homogenization is engaged to get the detailed conductor response to each uniform (averaged) directional stress (Fig. 4b). The boundary conditions to satisfy compatibility with the adjacent conductors are the same as for the homogenization. On the top of the mechanical stresses the WP free thermal deformation due to the coil cooldown should be considered. Finally, the component results are superimposed.

Note that these boundary conditions imply that the neighboring conductors are also in the same fields of uniform stresses. Moreover, for the graded winding when the layers are wound with different conductors the compatibility between conductors of different layers

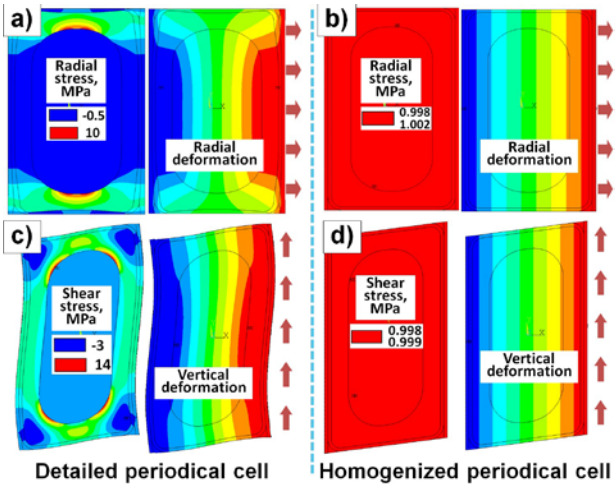

Fig. 2. Unit radial stress (a, b) and unit shear stress (c, d) over volume of a periodical cell

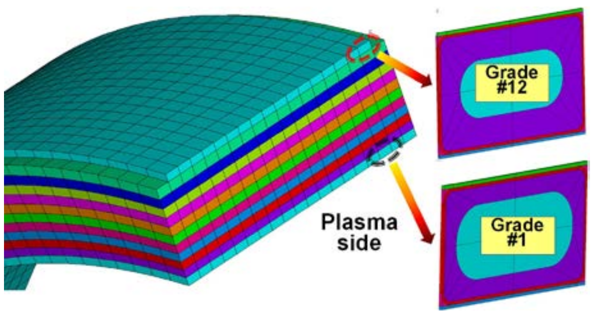

Fig. 3. Homogenized layered WP for DEMO

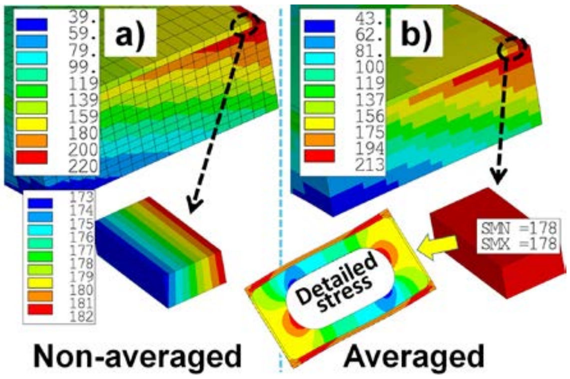

Fig. 4. Stress component (poloidal tension) averaged (a) and non-averaged (b) over the periodical cell (a single FE)

cannot be strictly satisfied (see Fig. 3). The same concerns the conductors at the winding sides that contact the coil casing via the ground insulation.

The important is that the stresses given by this non-conservative "express" approach should certainly satisfy strength criteria otherwise the coil design need to be further amended. This is an absolutely necessary but not a sufficient condition because consideration of the stress gradients will certainly result in the higher stresses in one of the jacket walls compared to the case of the uniform stresses. Some conservatism has to be engaged by putting a reasonable safety factor on the stress gradients. The same concerns the conductors located at the WP sides or for graded WP layouts. Other approaches to estimate the conductor strength are discussed in Section5.

4. Procedure for spotting WP critical locations

The main stress components calculated for a homogenized winding may indicate some conductor issues, like a combination of the high wedge or radial WP compression coupled with its poloidal tension that mostly determines the Tresca stress in the jacket walls (coil inboard portion). Another example is the coil in-plane and out-of-plane bending that results in the insulation inter-laminar shear stress. This intuitive way allows to spot only obvious problematic locations while, e.g. the critical regions where the insulation shear stress is coupled with the compression or tension are not easy to find. The graded layered winding designs make the problem even more complex.

To spot the WP critical locations an ANSYS APDL procedure has been developed. It is based on the "express" conductor analysis dealing with the averaged winding results (Section 3) and scans over the whole winding recalculating from the globally calculated WP results to the detailed conductor stresses. The use of a dedicated mesh when a single FE is attributed to each conductor turn (Figs. 3, 4) facilitates the search and averaging of stresses over the conductor volume. Note that such a procedure can be easily fit to other software.

Several strength problems have to be addressed [4]. The jacket static strength is determined by such integral values as the linearized equivalent stresses over a critical path (Fig. 5a). The jacket cyclic life depends on the stress concentration in critical nodes. The insulation strength is also determined by certain stress components in critical locations (inter-laminar shear, through-thickness compression and tension, e.g. Fig. 5b).

As a preparatory step, the detailed conductor model (Section 3) is studied under the uniform unit stress components. The stresses at the predefined candidate critical paths or nodes (reasonably many conceivable locations) due to these unit directional loads are calculated. The calculated responses (stresses) are written to a dedicated "qualification" file for each specified path or node. Note that for the jacket static strength these responses are the linearized stress components over jacket walls while for the insulation (and for jacket fatigue) they are the peak nodal stresses.

Then sets of the winding elements attributed to a single conductor turn (repetitive cell) are searched along the winding. The stress components derived from the homogenized winding are averaged over such sets. The conductor responses to the unit loads are read from the prepared file and are scaled to these averaged directional stresses. Then a required combination of stress components is constructed (e.g. Tresca stress) and checked against the criteria. This is done for each predefined conductor path (or node) and the critical one resulting in the maximal value of the combined stresses determines the conductor strength at this WP location.

Note that for the layered windings featuring conductor grading a set of the "qualification" files for all WP layers is required and each winding layer is checked separately with the use of a relevant "qualification" file.

Fig. 5 shows some candidate locations for the conductor jacket static strength and for the insulation static/cyclic strength used to analyze the European DEMO 2015TFC layout featuring the graded winding pack [7]. A special jacket failure index is used for mapping the winding in respect to its strength. In the case of the jacket static strength the failure index represents the ratio of the calculated linearized Tresca stress over the conductor wall to the allowable static limit (Fig. 6a). The safety is defined for both the linearized primary membrane and membrane plus bending stresses whatever is more critical. Because the WP was already pre-optimized considering the coil static strength at the coil inboard [2, 7], the violation of the strength criteria is found only at the coil outboard where the WP poloidal tension due to the coil in-plane and out-of-plane bending dominates. The jacket Tresca stress

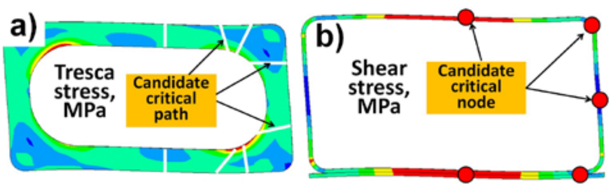

Fig. 5. Candidate critical paths for jacket and critical nodes for insulation used for conductor "qualification"

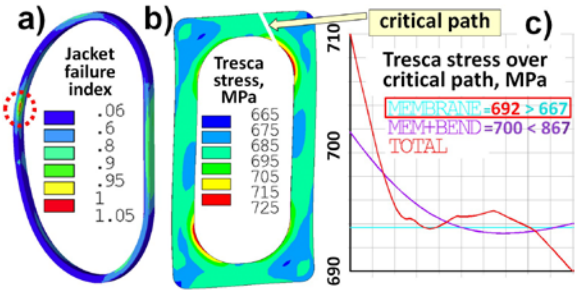

Fig. 6. Express analysis of the jacket static strength at the critical location where the failure index exceeds 1

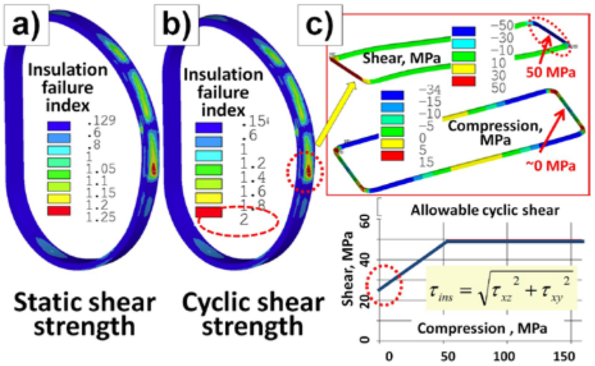

Fig. 7. Express analysis of the insulation cyclic shear strength at the defined critical location

distribution and the jacket critical path are shown in Fig. 6b. Fig. 6c indicates that the primary membrane stress violates criteria for the jacket steel (modified and aged 316 LN - 667 MPa) while the sum of the membrane plus bending stresses (867 MPa) is well below the allowable limit.

Fig. 7 represents the WP mapping in respect to the conductor insulation shear stress coupled with the compression [4]. Only moderate level problems with the conductor insulation static strength are found (Fig. 9a). Coil re-shaping can help by reducing its in-plane bending. The real issue is the cyclic shear stress (Fig. 7b) due to the coil bending and partly torsion caused by the out-of-plane EM loading when the insulation failure index amounts to 2 (twice allowable value). Efforts are required to decrease the coil lateral bending and torsion by either stiffening the OIS or by increasing the coil bending stiffness. Other insulation issues like the peak compression or tension acting normal to the insulation plane are addressed in the same way.

5. Approach discussion

The described engineering approach allows for the prompt mapping of the homogenized WP to highlight the conductor mechanical issues like the conductor jacket and the conductor insulation static/cyclic strength. Dealing with the stresses averaged over the volume of the conductor turn, this procedure doesn't take into account the stress gradients over conductor. It also doesn't treat the coil casing/WP frictional interaction in detail. This certainly results in the underestimated stresses in one of the conductor walls. This means that at this early design stage the stresses calculated with the "express" approach have to necessarily satisfy the strength criteria. Otherwise the coil/conductor design should be properly improved and then further recalculated. Since this is not a sufficient condition some design safety on the stress gradients should be added to arrive at some "promising" TFC layout.

For the final or pre-final design phases more accurate winding analysis is required. Even now a fully detailed WP modeling when the WP frictionally interacts with the casing is not that straightforward, especially regarding the results post-processing. It seems reasonable to model a homogenized winding that includes a detailed portion at the potentially dangerous regions revealed by the winding "express" zooming. Since the detailed and smeared winding models deform quite differently (Fig. 3), the detailed WP portion should be long enough to get rid of the end effects at its center. As a rule of thumb the "unaffected" stress-state in the detailed portion is expected at a distance of the WP cross-section size. A convergence study is required to define a correct length of the winding detailed portion.

Acknowledgments

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