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Mechanical pre-dimensioning and pre-optimization of the tokamaks' toroidal coils featuring the winding pack layout

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The structural integrity of the superconducting magnets that are key elements of a fusion reactor must be ensured. At an early design stage relatively simple calculation tools can greatly facilitate design optimization.

The main objective of this paper is the mechanical pre-dimensioning of the tokamak toroidal field coils prior to their 3D numerical modelling. A calculation tool that reasonably estimates the mechanical strength of the coils structural components under the dominating electromagnetic forces at the coil critical location is described. The novelty of the approach is that it treats not only the massive coil casing but also the winding pack conductor jackets under an essentially 3D stress state. The semi-analytical procedure features pre-optimization of the coil windings. The minimum space requirements for the coil structural components are defined. The procedure has been successfully benchmarked against the numerical solutions and has been used to pre-dimension the toroidal coils for the current 2015 DEMO design.

Keywords: fusion magnets, electromagnetic loads, structural performance, semi-analytical pre-dimensioning.

1. Introduction

Successful operation of Demonstration Reactors is a key step in the fusion development. High magnetic fields produced by the superconducting magnets are crucial for optimization of a fusion reactor performance. The main structural issues of the toroidal field coil (TFC) system are briefly overviewed in Chapter 2.

Combinations of calculation approaches, reasonable modelling simplifications and clever prioritization at each analysis phase facilitate design optimization by relatively simple and "inexpensive" calculation tools [1]. The mechanical pre-dimensioning of the magnets that is extremely useful and time saving at an early design stage is described in Chapter 3. The novelty of the approach is that it deals not only with the mechanical strength of the coil casing in the coil critical location (e.g. [2]) but also treats in detail the winding pack wound with the cabled conductor under an essentially 3D stress state. The procedure features pre-optimization of the layered windings by grading the radial and toroidal walls of the conductor separately. Minimum space required for the coil at the inboard is defined. The procedure has been successfully benchmarked against FE solutions and used to pre-dimension the toroidal coils for the ongoing 2015 European DEMO activity.

2. TF coil system structural issues

Typical TFC system (Fig. 1, top) comprises a number of coils arranged symmetrically around the torus axis. At the inboard the coils are wedged to support the centripetal Lorentz forces due to the TFC energizing. These in-plane forces (Fig. 1, bottom) acting normal to the winding centerline cause significant wedge compression in the coil case at the inner leg and expand the coil both radially and vertically. In respect to the in-plane loading the most critical coil region is at the equatorial plane of its inner leg where the huge wedge compression is coupled with the coil vertical tension (Fig. 2). The matter is usually aggravated by the lack of space for supporting structures. At the outboard the coils are connected via the outer intercoil structures that resist coils cyclic tilting due to the out-of-plane forces due to interaction of the coils currents with the magnetic fields of the central solenoid, poloidal coils and plasma (Fig. 2). The latera1 coils' deflection and fatigue are usual issues for the coil outboard. The strength of the coil case and conductors is of concern (Fig. 2)

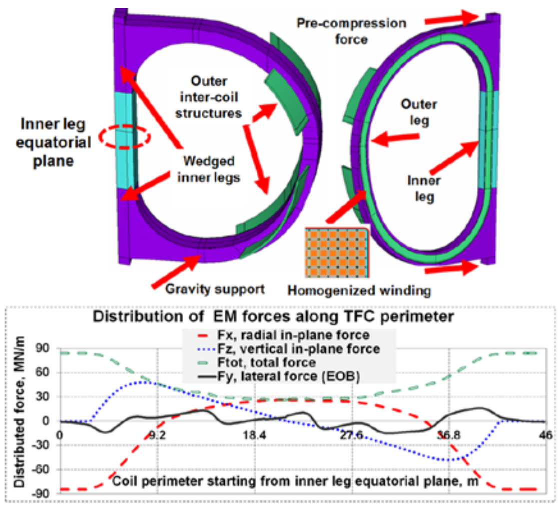

Fig. 1. Example of TF coil structure.

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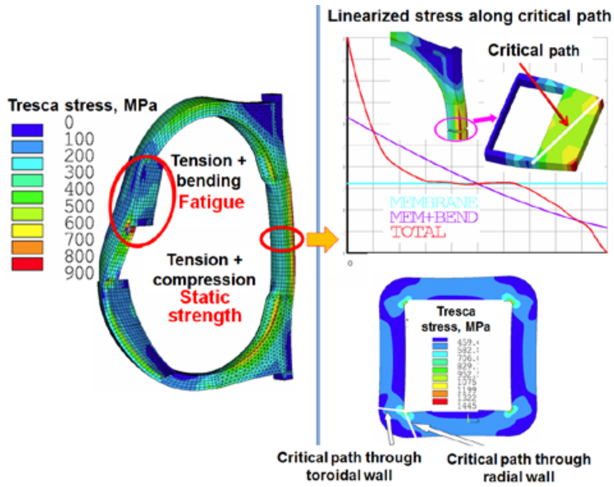

Fig. 2. Tresca stress in the coil due to EM loading.

3. TFC pre-dimensioning and pre-optimization

3.1 Electromagnetic estimations for TFC

Typical TFC cross-section is shown in Fig. 3. The TF coil can be considered like a set of the conducting shells [3]. The maximum toroidal magnetic field at the equatorial plane of the inner leg is:

$$B^{\max} = \mu_0 N_{coil} I_{coil} / (2\pi R_{in})$$

where: $\mu_0 = 4\pi \cdot 10^{-7}$, N_{coil} - number of coils, I_{coil} - current through each coil. The maximum distributed pressure force in the winding and the maximum cumulated pressure from the winding acting on the coil case are expressed as:

$$F_{EM} = 1/2\, B^{\max} I_{coil} \text{ and } P_{EM}^{WP} = F_{EM} / H_{WP}$$

The vertical bursting force acting on the coil half normal to its equatorial plane is calculated as:

$$F_z^{coil} = \pi \left(B^{\max}\right)^2 R_{in}^2 \ln\left(\frac{R_{out}}{R_{in}}\right) \frac{1}{\mu_0 N_{coil}}$$

The vertical force taken by the coil inner leg can be assumed as $F_z^{inner} \approx 1/2\, F_z^{coil}$. The force share between the coil case F_z^{SS} and the winding F_z^{WP} can be calculated from F_z^{inner} in proportion to their stiffness when no case/WP poloidal sliding is assumed.

3.2 TFC stress-state: equatorial plane of inner leg

The coil case can be considered as a ring under the uniform external pressure P_0 coming from the WP (Fig. 4, right). This pressure causes the significant wedge compression σ_{fi}^{case}. The case vertical stress is determined by the EM vertical force on the case and is defined as $\sigma_z^{SS} = F_z^{SS} / A_{SS}$ where A_{SS} is the case area.

The WP is considered as a bulk homogenized structure having the orthotropic properties [4]. Loaded by the volumetric EM forces it presses on the ring (case) and follows its inward movement. This inward movement of the wedged coils also results in the winding lateral compression σ_y^{WP} (Fig. 4). Its vertical stress is determined by the vertical EM force taken by the winding and is defined as $\sigma_z^{WP} = F_z^{WP} / A_{WP}$ where A_{WP} is the winding area.

Let's denominate $P_{EM} = F_{EM} / 2R_2\alpha$ and $k = 2F_{pull} / F_{EM}$. Then the uniform pressure on the ring (accounting for F_{pull}) is: $P_0 = \dfrac{F_{EM} - 2F_{pull}}{2R_2\alpha} = P_{EM}(1-k)$.

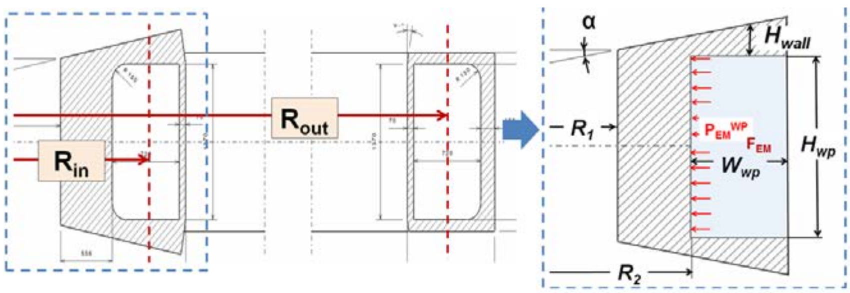

Fig. 3. Typical TFC cross-section at the equatorial plane (left) and sketch of the simplified inner leg cross-section (right).

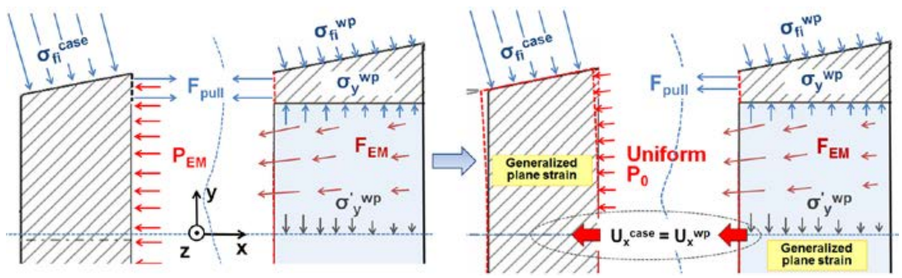

Fig. 4. Sketch of the model problem.

The ring inward movement under the external pressure coming from the winding (not accounting for F_{pull}) in assumption of the generalized plane strain conditions is:

$$u_x^{EM} = -P_{EM}\frac{R_2}{E^{SS}}\left(\frac{R_2^2+R_1^2}{R_2^2-R_1^2}+\nu_{SS}\right),\quad \text{where:}\quad E^{SS},\nu^{SS}\text{ -}$$

steel Young's modulus Poisson's ratio.

The ring inward movement under P_0 with account for its toroidal contraction due to F_z^{SS} can be written:

$$u_x^{WP} = u_x^{case} = u_x^{EM}\left(1-k\right)+u_x^{Z},$$

where: $u_x^{Z} = -\nu_{SS}\frac{\sigma_z^{SS}}{E^{SS}}R_2$, $\sigma_z^{SS} = F_z^{SS}/A_{SS}$, A_{SS} - case area. Denoting $C_1 = 2\tan(\alpha)/H_{WP}$, the winding lateral compressive strain due to its radial movement is written:

$$\varepsilon_y^{WP} = u_x^{WP}C_1 = -\nu_{xy}\frac{\sigma_x^{WP}}{E_x^{WP}}+\frac{\sigma_y^{WP}}{E_y^{WP}}-\nu_{yz}^{WP}\frac{\sigma_z^{WP}}{E_y^{WP}}$$

where: σ_x^{WP} is the x component of the winding radial stress due to the volumetric EM loading, $\sigma_z^{WP} = F_z^{WP}/A_{WP}$ and A_{WP} is the winding area. If we denote: $\varepsilon_y' = \nu_{xy}\sigma_x^{WP}/E_x^{WP}$, and $C_2 = E_y^{WP}$ (winding Young's modulus) then:

$$\sigma_y^{WP} = \left(\varepsilon_y^{WP}+\varepsilon_y'+\varepsilon_y''\right)E_y^{WP} =$$

$$= \left\{C_1\left[u_x^{EM}\left(1-k\right)+u_x^{z}\right]+\varepsilon_y'+\varepsilon_y''\right\}C_2 \qquad (1)$$

On the other hand

$$\sigma_y^{WP} = \frac{F_{pull}\cos\alpha}{W_{WP}\tan\alpha} = kP_{EM}/C_3,\ \text{where:}\ C_3 = \frac{W_{WP}\tan\alpha}{R_2\alpha} \qquad (2)$$

If we equate the expressions (1) and (2) then:

$$k = \frac{\left[C_1\left(u_x^{EM}+u_x^{z}\right)+\varepsilon_y'+\varepsilon_y''\right]C_2C_3}{P_{EM}+C_1u_x^{EM}\cdot C_2C_3} \qquad (3)$$

Having the parameter k defined, one can calculate the coil and WP inward movement $u_x^{case} = u_x^{WP}$, the case hoop stress σ_{fi}^{case} and the winding lateral compression σ_y^{WP}. The radial stress in the winding σ_x can be assumed to increase linearly from zero at its plasma side to P_{EM}^{WP} at the winding outside. To account for the distribution of σ_x and for a change of E_y^{WP} through the winding (graded WPs) more general form of the expression (3) is written:

$$k = \sum_{i=1}^{Ngrade}\left[C_1\left(u_x^{EM}+u_x^{z}\right)+\varepsilon_y'\left(i\right)+\varepsilon_y''\left(i\right)\right]\cdot$$

$$\cdot\frac{C_2\left(i\right)C_3\left(i\right)}{P_{EM}+C_1u_x^{EM}\cdot\sum_{i=1}^{Ngrade}C_2\left(i\right)C_3\left(i\right)} \qquad (4)$$

Thus, all important stress components in the case (hoop and vertical stresses - the radial one can be neglected) and in the orthotropic WP (radial, lateral and vertical ones) are available for the strength estimations.

3.3 Benchmarking of main results

Fig. 5 shows results of benchmarking of the main stress components in the homogenized winding calculated with the semi-analytical tool against the 3D FE calculations. For the 2014 DEMO layout a very good agreement was found. For the 2015 layout the lateral stresses in the winding calculated with the tool turned out to be higher than those given by FE analysis. The matter is that for this layout the coils' wedging is not engaged all over the WP width (Fig. 5, bottom) and the winding is less compressed at the plasma side. This feature is planned to be implemented in the tool.

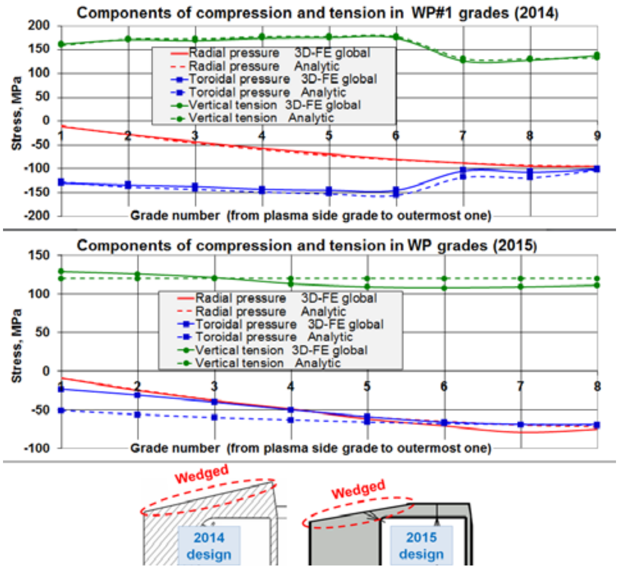

Fig. 5. Distribution of important stress components over the winding grades (2014 & 2015 DEMO TFC layouts).

3.4 Winding stresses: from global to local

The calculated vertical tension and hoop compression in the coil case can be reasonably considered as the maximum and minimum principal stresses. This makes it possible to construct directly the equivalent Tresca stress to be compared with the allowable primary membrane stress for the case structural steel [5]. For the homogenized winding the calculated stresses need to be recalculated to the conductor walls that mostly take radial and lateral compression coupled with the conductor vertical tension. The procedure looks like:

- The radial stress assumed to increase linearly through WP is calculated for each WP grade and recalculated to the conductor radial walls.
- The lateral stress is calculated for each WP grade and recalculated to the conductor toroidal walls.
- To construct the Tresca stress the compressive stresses in the conductor walls are coupled with the

vertical tension calculated for each WP grade and recalculated to the conductor walls.

- The calculated Tresca stress in the conductor walls is checked against the allowable primary membrane stress for each conductor grade [5].

Critical locations were found for the 2014 WP layout where the calculated conductor stresses exceed the limit. The "express" reconstruction of the conductor stress-state in this location [1] revealed the same problem (Table 1).

Table 1. Linearized Tresca stress over the conductor jacket walls vs. allowable stress (2014 TFC design, WP#2 option).

	Radial wall	Toroidal wall	Allowable stress
Membrane, MPa	**669**	648	667

3.5 Winding pre-optimization and TFC pre-dimensioning

- For the initial WP layout the important stress components are calculated in the coil case and homogenized winding.
- The Tresca stress is constructed for the case and for conductor walls (all grades) and compared with the allowable primary membrane stresses.
- If the strength limits in the conductor walls are violated the mechanical optimization by grading the radial and toroidal conductor walls separately starts.
- Since the radial stress doesn't practically change with grading the radial conductor walls are optimized first. The "structural steel" is redistributed between the radial walls of each grade regarding changing radial pressure to satisfy strength criteria for each grade. The "left structural steel" is redistributed between the toroidal walls.
- The new orthotropic winding properties are calculated. The changed WP toroidal stiffness results in a change of the WP toroidal compression that, in turn, impacts on the case/WP radial movement.
- Basing on newly calculated stresses the available structural steel is further redistributed between the toroidal conductor walls with the aim to satisfy strength criteria. Several iterations are usually needed (each requires recalculation of the winding properties) to converge. Note that "mechanically pre-optimized" design may not be feasible from manufacturing/assembly viewpoint.

There are two optimization options available:

1. The space allocated for the superconducting cable is kept unchanged resulting, possibly, in not fully mechanically optimized layout
2. The full mechanical optimization on the expense of the space for the superconducting cable.

The conductor stresses calculated for the 2015 WP layout prior to 3D FE analysis proved to violate the conductor stress limits. More space for the coil supporting was requested. For the changed coils the FE analysis revealed no membrane stresses in the conductor violating criteria as it was predicted while the conductors must be further optimized regarding their wall bending (Table 2).

Table 2. Linearized Tresca stress over the conductor jacket walls vs. allowable stresses (2015 TFC design).

	Radial wall	Toroidal wall	Allowable stress
Membrane, MPa	591	583	667
Membrane +bending, MPa	**891**	858	867

4. Conclusions

TFC pre-dimensioning and pre-optimization at an early design stage was proved to be extremely effective. A calculation tool that reasonably estimates the coil mechanical strength under the dominating EM loading has been developed, benchmarked and used for coil pre-dimensioning and pre-optimization in the frame of the ongoing 2015 DEMO activity.

The approach novelty is that it treats the winding pack conductor in detail under 3D stress-strain state. This makes possible an effective pre-optimization of the layered windings by grading the radial and toroidal conductor walls separately. After the winding is mechanically pre-optimized the requirements for the minimum coil space at its inner leg are defined.

Acknowledgments

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