TFC-PREDIM: a FE dimensioning procedure for the TF coil system of a DEMO tokamak reactor

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The equatorial plane of the inner leg of a toroidal field (TF) coil is the most stressed part of the TF coil system and optimal usage of the radial space in this region is crucial for the design of the DEMO tokamak reactor. A procedure for initial dimensioning (pre-dimensioning) of this region developed earlier [1] is based on a simplified 2D geometry of the TF coil cross-section and a semi-analytical approach to estimate stresses in the TF coil case and the conductor jackets with limited capabilities for optimization. This work presents a new procedure named TFC-PREDIM which features a detailed 2D finite element (FE) generalized plane strain model. The model gives very accurate results within a short calculation time and allows additional options for layout optimization. The FE model for the cross-section is generated automatically from the input geometrical parameters of the given layout allowing any of the conductor design options currently investigated for DEMO. The post-processing of the results is also automated, consisting in the determination of the maximum values of the membrane and membrane+bending Tresca stresses for each conductor jacket and for the TF coil case. Two strategies for the optimization of the cross-section are presented: minimization of the TF coil radial build with a predefined maximal toroidal field and maximization of the maximal toroidal field for a predefined radial space.

Keywords: DEMO, Tokamak, FEA, fusion, magnets

1. Introduction

A TF coil represents a winding pack (WP), made of a set of wound conductors inserted into a massive coil case (Fig. 1). Each conductor consists of a superconducting cable enclosed in a steel jacket (conduit) and wound by insulating tape (Fig. 1). The jacket and the TF coil case serve as the structural support for the cable mainly against operational electromagnetic loads (EM).

The radial extension occupied by the TF coil system at the equatorial plane of the inner leg defines how much space is left for the central solenoid (CS) coil on one side and for the blanket system on the other. Therefore, it is important to use this space effectively and the design of a TF coils system always starts from the dimensioning of this particular cross-section.

Fig. 1 From left to right: DEMO TF coil system, TF coil inner leg equatorial plane cross section, portion of a WP cross section.

A zero order approximation for a DEMO radial build is provided by the PROCESS system code [2] which defines the available radial space for the TF coil case and the winding pack (WP) at the inner leg, considering a simplified stress model and operational EM loads. Before conducting further analyses an actual design of the WP has to be developed which includes the specification of the number of conductors, cross sectional dimensions of the cable, jacket and insulation. Sometimes this can be performed automatically by system codes like SYCOMORE [3] but their capabilities, especially for the mechanical optimization, are still limited to a set of simplified analytical equations insufficient for the detailed description of the geometry.

The mechanical design of the WP consists in an estimation of the required wall thickness for the conductor jackets. To produce an initially mechanically pre-optimized WP layout a special “pre-dimensioning” procedure was developed [1]. The procedure relies on a simplified 2D semi-analytical approach to determine membrane stresses in the toroidal and radial conductor jacket walls under operational EM loads. It has a capability of optimization of a WP layout by variation of the conductor jackets wall thickness to minimize the radial built while satisfying a structural strength criterion on the membrane stress.

In this paper a new pre-dimensioning procedure TFC-PREDIM is described. It relies on the same principles for stress calculation as the previous one [1]: 2D cross section at the equatorial plane of the inner leg, generalized plane strain assumption and analytical approximation of the in-plane EM forces, but also has several advantages. It features a detailed fully parametrically defined 2D FE geometry of a coil cross-section which produces more accurate results within a short calculation time. Not only the membrane, but also the membrane+bending stresses are evaluated automatically for all possible stress classification lines along the jacket walls for each conductor. The model is benchmarked against 3D calculations and the results are in a very good agreement. The fully parametrical definition of the geometry, accurate results and a short execution time allow an effective optimization of the design layout.

Compared to the previously mentioned procedure, this one also opens new possibilities of minimization of the total radial build (varying both the WP and the TF coil case radial dimensions, not the WP dimension only). The present procedure provides as well a maximization of the toroidal magnetic field at the axis for a given radial build, the latter being a new strategy adopted by the EUROfusion magnets work package (WPMAG) in 2019.

2. Structural analysis of the inner leg equatorial plane region

2.1 Stress state at the inner leg region

The operational EM loads acting on a TF coil can be sub-divided into the in-plane forces (acting in the plane of the coil) and the out-of-plane forces. The in-plane forces are created by the interaction of the TF coil currents with the toroidal field. The out-of-plane forces are the result of the interaction of the TF coil currents with the poloidal field (Fig. 2).

Fig. 2 A sketch of operational EM forces acting on the upper half of a TF coil.

As mentioned previously, for the initial dimensioning the straight portion of the inner leg equatorial plane is addressed as the most vital part for pre-optimization. For this region only the in-plane forces are taken into account since the out-of-plane forces have negligible influence on this region [1]. Due to the negligible effect of the out-of-plane forces and a low number of the TF coil energization cycle count aimed for a power plant the fatigue is not a concern for the inner leg. Therefore further analyses consider only the static strength of the TF coil case and the conductor jackets.

The stress state at the straight leg during the operation is very close to the generalized plane strain approximation [4] (Fig. 2). For the 2D cross section at the equatorial plane the in-plane forces are further decomposed into two parts: the line-distributed forces exerted directly by the cables on the jacket cable space (act in the cross section plane) and the vertical separating force (acts perpendicular to the cross section plane).

It is assumed that the WP does not slide inside the TF coil case in the poloidal direction, based on analyses of previous DEMO configurations with low and high friction factors [5]. In this case the vertical separating force at the inner leg is distributed between the TF coil case and the WP proportionally to their stiffness, determined mainly by their steel cross-section areas. The force exerted by the cables accumulates with each layer and is reacted to by the radial walls of the winding pack. This force is further transferred to the TF coil case and reacted by the wedge. Due to wedging some part of this force is also counteracted by the toroidal walls of the winding pack.

As can be seen, the load distribution between the WP and the TF coil case is quite complex and depends on their respective stiffness making the dimensioning process challenging.

2.2 Parametric model generation

Using the ANSYS parametric design language (APDL), a parametric procedure was developed for the automatic generation of the 2D FE models of the inner leg equatorial plane cross-section (Fig. 1, middle) with conductors of standard geometries with any number of layers and of conductors in a layer.

Two winding technologies are currently under investigation for DEMO coils [6]: pancake (CEA[1]) and layered winding (SPC[2], ENEA[3]). The pancake winding technique is performed using the same conductor geometry for every layer. The layered winding gives the advantage of using different conductor jacket wall thicknesses depending on the load acting on a given layer (i.e. grading), reducing the amount of steel and the radial build compared to the pancake winding. Fig. 3 shows all the three options of the conductor jacket cross-section geometry for DEMO TF coils.

Fig. 3 Possible conductor jacket cross section geometries from left to right: SPC (layered), ENEA (double-layered), CEA (pancake).

The SPC conductor jacket is welded from two rolled profiles. This enables the usage of the largest possible inner radius to reduce the stress concentration and adjustment of the thicknesses of toroidal and radial walls independently for each layer. The ENEA and CEA conductor geometries are less flexible: only the aspect ratio and the wall thickness (equal for both toroidal and radial walls) can be manipulated since the conductor is compacted from a circular tube. As a pancake winding the CEA WP is wound using only one type of conductor geometry, while the geometry of every pair of ENEA WP layers can be adjusted independently.

The SPC design represents the most general case of the conductor geometries with eight parameters required for the cross-section generation: cable space width/height, jacket width/height, jacket outer/inner radii, turn/layer insulation thickness. The other two geometries from Fig. 3 can be generated accordingly using the same set of values. When these parameters are defined for each layer of a WP, the cross-section for each conductor is generated one by one to build the WP cross section. APDL components for each conductor are defined during the creation for further operations such as load application and post processing. The cross-section of the TF coil case is created in the same fashion, based on the main geometrical parameters. Meshing parameters such as the number of element divisions in the conductor walls are also provided to generate a mapped mesh of desired density. The coordinate systems for the insulation elements are automatically aligned to properly define the orthotropic behavior [7].

2.3 Calculation of electromagnetic forces

The line distributed force exerted by each cable of a TF coil is determined by using the Biot-Savart law and the principle of superposition. Only the cables in the inner leg region are taken into account, neglecting the influence of the ones in the outer legs of the TF coils. The cables are approximated as long thin wires. The location for each conductor of the TF coil is provided by the APDL components created during the geometry generation.

To find the force on a cable with the coordinates *x* and *y* at its cross-section center, one has to traverse all other conductors from all TF coils and sum up the magnetic field contributions for each of them at the point (*x*,*y*). The center position of an arbitrary conductor ($\tilde{x}_i, \tilde{y}_i$) is defined as:

$$\begin{aligned}\tilde{x}_i &= x_i \cos(n_{coil}\alpha) - y_i \sin(n_{coil}\alpha)\\ \tilde{y}_i &= x_i \sin(n_{coil}\alpha) + y_i \cos(n_{coil}\alpha)\end{aligned} \qquad (1)$$

where

x_i, y_i - the center position of the ith conductor at the TF coil cross section for which the geometry is generated;

n_{coil} - the TF coil number where the conductor is located;

$\alpha = \dfrac{2\pi}{N_{coils}}$ - the angle between the coils.

The magnetic field and line-distributed force components at the point (*x*,*y*) are derived as follows:

$$\begin{aligned}B_x^{(x,y)} &= -\sum_{N_{coils}}\sum_{N_{cond}}\left(\frac{\mu_0 I_{cond}}{2\pi r_i}\frac{\Delta y_i}{r_i}\right)\\ F_y^{(x,y)} &= B_x^{(x,y)} I_{cond}\\ B_y^{(x,y)} &= \sum_{N_{coils}}\sum_{N_{cond}}\left(\frac{\mu_0 I_{cond}}{2\pi r_i}\frac{\Delta x_i}{r_i}\right)\\ F_x^{(x,y)} &= -B_y^{(x,y)} I_{cond}\end{aligned} \qquad (2)$$

where,

$\Delta x_i = x - \tilde{x}_i, \Delta y_i = y - \tilde{y}_i, r_i = \sqrt{\Delta x_i^{\ 2} + \Delta y_i^{\ 2}}$

The total vertical separating force acting in a TF coil equatorial plane can be approximated by the formula for a thin toroidal current sheet [8], where the force is independent of the shape. To find the force acting only at the inner leg the formula is modified by an additional factor:

$$F_z^{Inner\ leg} = k\frac{\mu_0\left(I_{total}N_{coils}\right)^2}{4\pi N_{coils}}\log\left(\frac{R_{in}}{R_{out}}\right) \qquad (3)$$

where

R_{in}, R_{out} are the radial coordinates of the WP center line at the inner and outer leg of the TF coil;

k – the coefficient which defines the fraction of the force that is taken by the inner leg, for a bending free TF coil equals to 0.5. In the present analysis, it is taken as 0.55 based on the results of previous 3D analyses [5].

2.4 FEA modeling and Post processing

For the structural FE analysis, generalized plane strain elements are used. The model includes only a half of the TF coil equatorial plane inner leg cross section thanks to the symmetry (Fig. 4, left).

Fig. 4 2D FE model (left), radial force applied as hydrostatic pressure (MPa/m, right).

Since the superconducting cable is not fixed inside the jacket, it will only transfer the EM force to one side of the cable space, detaching from the other. This loading pattern is similar to the hydrostatic pressure created by liquid inside a vessel under gravity. Thus, the forces calculated by (2) are applied as hydrostatic pressure [7] (Fig. 4, right) using surface effect elements, which allows to use a physically representative loading pattern while saving on the element count. The pressure on each surface element of the cable space is defined based on its location:

$$P = P_I + xP_J + yP_K + zP_L \tag{4}$$

where

$P_J = \frac{m}{V} g_x, P_K = \frac{m}{V} g_y, P_L = \frac{m}{V} g_z$ - the "fluid" density multiplied by the projection of the (gravitational) acceleration, in our case the EM force components are $F_x = mg_x, F_y = mg_y, F_z = mg_z$;

P_I - a constant part, which is found by taking that pressure on the surface of the "liquid" as zero $P_I = -\left(x_0 P_J + y_0 P_K + z_0 P_L\right)$. To simplify the calculations volume occupied by the cable is assumed as a half of the cable space.

The vertical separating force is calculated by (3) with a half of the value applied. The rotation angle around the X axis is zero due to symmetry, the rotation angle around Y axis is assumed to be zero due to negligible bending at the straight leg region [9]. Zero normal displacements are imposed for the wedged boundary (frictionless sliding) and for the symmetry boundary. Friction between the winding pack and the case does not make much of a difference for the plane problem due to the very soft embedding layer, therefore frictionless contact between the winding pack and the TF coil case is assumed. The cooldown from 293 to 4K is also taken into account.

To verify the structural integrity according to the ITER magnet structural design criteria for the conductor jackets, a post processing procedure was developed which produces a set of stress classification lines (SCL) through the cross section of the jacket walls. For each conductor cross-section a shortest distance path from the inner to the outer surface of the jacket is created for each node on the inner surface (Fig. 5, right).

Fig. 5 Tresca stress contours (MPa) for the TF coil case cross section (left) and for a conductor (right) with automatically generated stress classification lines.

The linearized values of the membrane and the membrane+bending Tresca stresses are calculated for each path and the maximum values among all paths for each conductor are used for the assessment. For further optimization purposes the values of the membrane Tresca stresses at the toroidal and radial walls (see Fig. 5, right) are calculated for each conductor layer. Using these values one can estimate if the wall thickness is appropriate for a given layer. For the TF coil case assessment a representative SCL is defined for which the membrane and the membrane+bending Tresca stresses are calculated (Fig. 5, left).

The total time required for model generation, calculation and post-processing is less than 10 minutes for the mesh shown on Fig. 4 on a modern workstation. The short execution time enables different options for the parametric optimization, which are discussed further.

2.5 Results comparison of 2D to 3D modeling

The 2D modelling procedure was compared to a 3D modelling approach for a 2015 DEMO design with a graded SPC WP. The 3D analysis was conducted using a global model which included the WP with homogenized material properties and then using the sub-modeling approach for a portion of the inner leg with the detailed geometry of the WP (Fig. 6) [7].

Fig. 6 3D inner leg sub-model for the 2015 DEMO TF coil.

The 2D analysis was conducted with two sets of loads. For the first set the vertical separating force and the bending moment are imported from the equatorial plane of the inner leg and the line-distributed EM forces for each conductor are imported from the global EM model. The second set of loads is calculated using the expressions (2) and (3). The total loads for the 3D sub-model and 2D models are presented in Table 1. The comparison of the membrane stresses for toroidal and radial walls for the conductors from the second row is shown in Table 2.

Table 1 Total loads for the 3D sub-model and 2D models

Total Loads	**3D model**	**2D model, imported loads**		**2D model, calculated loads**	
Vertical, MN	275.3	275.3	0%	274.6	-0.3%
Radial, MN/m	-88.1*	-86.0	-2.4%	-85.1	-3.4%
Bending moment, MN·m	-2.47**	-2.47**	0%	-	-

*Averaged through the whole length
**Extracted from the equatorial plane relative to the cross section centroid

Table 2 Stress comparison of the toroidal and radial SCLs for each conductor grade for the 3D and the 2D approaches

Grade #	**Toroidal wall membrane stress**					**Radial wall membrane stress**				
	3D model stress, MPa	**2D model, imported loads**		**2D model, calculated loads**		**3D model stress, MPa**	**2D model, imported loads**		**2D model, calculated loads**	
		Stress, MPa	**% difference to 3D**	**Stress, MPa**	**% difference to 3D**		**Stress, MPa**	**% difference to 3D**	**Stress, MPa**	**% difference to 3D**
1	328	333	1.4%	368	11.8%	331	325	-1.9%	360	9.0%
2	367	374	1.8%	407	10.5%	345	334	-3.3%	365	5.9%
3	417	416	-0.3%	447	7.2%	363	359	-1.1%	386	6.5%
4	465	461	-0.8%	490	5.4%	392	384	-1.9%	408	4.3%
5	484	485	0.1%	510	5.3%	427	414	-3.1%	434	1.6%
6	483	486	0.6%	508	5.0%	467	449	-3.7%	465	-0.5%
7	485	490	0.9%	508	4.6%	503	484	-3.7%	496	-1.5%
8	482	491	1.8%	506	4.9%	531	513	-3.4%	520	-2.1%
9	473	483	2.1%	495	4.6%	550	533	-3.1%	537	-2.4%
10	478	492	3.0%	501	4.6%	552	536	-2.8%	538	-2.5%
11	495	513	3.7%	517	4.4%	576	564	-2.1%	561	-2.6%
12	551	565	2.4%	565	2.4%	614	611	-0.5%	607	-1.2%
Case	658	636	-3.3%	613	-6.9%	-				

The results show a very good agreement between the 3D model and the 2D model with the imported loads (<4% difference). The 2D model with the calculated loads performs a bit worse with TF coil strength is underestimated by 7% and up to 12% stress overestimation for the plasma side conductors. This is mainly due to the zero-bending assumption: the conductors located closer to plasma will be subjected to vertical compression due to bending, which marginally offsets the vertical tension.

Therefore it is concluded, that the accuracy of the generalized plane strain assumption with the loads calculated by the expressions (2) and (3) is enough for the initial dimensioning. The main advantage of this approach is a fast execution which does not require the preparation and solution of the global EM and structural models.

3. Design optimization

3.1 Geometry parametrization

The optimization strategies are described for an SPC-like layout as for the most general case when both radial and toroidal conductor walls can have a different thickness. Fig. 7, left shows the main geometrical parameters of the model. The generation of a layout starts from the plasma side of the WP. The number of layers and conductors in a layer are predefined. The toroidal dimension of the WP cross section W_{wp} is fixed during optimization, which can lead to a clash with the wedged side of the case. In this situation, W_{wp} has to be decreased and the process restarts from the beginning.

The main geometrical parameters of a conductor cross-section are shown on Fig. 7, right. The outer toroidal dimension of a conductor W_{out} is calculated by dividing the WP toroidal dimension W_{wp} by the number of layers and subtracting the insulation thickness.

An initial layout is designed for a certain value of the toroidal field B_{max} at $R_{plasma\ side}$. The cable space area A_{cs} for each layer conductor is predefined by the initial layout depending on the nominal current, superconductor type and field value at that layer [10].

Fig. 7 Main geometrical parameters of the model (left), geometrical parameters of a conductor cross section (right).

The toroidal wall thickness T_t and radial wall thickness T_r are the optimization parameters which determine the strength and stiffness of a given conductor layer and will be varied on each iteration. Other geometrical values from Fig. 7, right are derived as follows:

$$W_{in} = W_{out} - 2T_r$$
$$H_{in} = \frac{-W_{in} + \sqrt{W_{in}^2 + (\pi - 4)A_{cs}}}{2(\pi/4 - 1)}$$
$$H_{out} = H_{in} + 2T_t \qquad (5)$$

The last optimization parameter is the case radial extension H_{case} which determines the strength and stiffness of the case. Other values like the insulation, embedding and plasma facing plate thicknesses are provided as an additional input.

The final set of the optimization parameters consists of the toroidal and radial wall thicknesses for each layer T_r^i, T_t^i, the cable space area for each layer A_{cs}^i, and the radial extension of the TF coil case H_{case}.

3.2 Minimization of the radial build with a pre-defined maximum toroidal field

It is assumed that the position of a conductor layer does not change significantly during the optimization process, therefore the change in the cable space area A_{cs} due to the change in toroidal field in this region is not required A_{cs}^i and therefore it is excluded from the set of optimization parameters. For a graded design it is quite natural to assume that the conductor wall thickness should increase from the plasma side towards the machine center due to increase in the accumulated radial load and the toroidal pressure. A linear variation of the wall thickness along the layer number can therefore be taken as a first estimation:

$$T_r^i = a_r \cdot \left(n_{layer}^i - 1\right) + T_r^1,\ a_r \geq 0$$
$$T_t^i = a_t \cdot \left(n_{layer}^i - 1\right) + T_t^1,\ a_t \geq 0 \qquad (6)$$

The wall thicknesses for the first layer T_r^1 and T_t^1 can usually be set to the minimal feasible value and now only three optimization parameters are left: a_r, a_t and H_{case}. The optimal values can be quite easily determined by several manual iterations: on each iteration the values of the membrane stress for the toroidal walls, radial walls and TF coil case are obtained, indicating where the steel fraction should be changed.

Summarizing, the optimization algorithm looks as follows:

- Define the number of conductors and the width of the WP W_{out}
- Based on the required field B_{max} at $R_{plasma\ side}$ define the required total current and derive the required cable space area for each layer of conductors A_{cs}^i
- Take an initial estimation of the wall thicknesses for each layer of conductors T_r^i, T_t^i (e.g. by (6)) and the case radial extension H_{case}.
- Calculate the derived parameters for each layer of conductors using the expressions (5) and build the FE model

- Solve the FE model and check the membrane and membrane+bending stresses for the radial and toroidal walls as well as for the case (see SCLs on Fig. 5).
- Change the thickness of the radial and/or toroidal walls depending on the membrane and membrane+bending stresses (e.g. by changing a_r, a_t from (6)); do the same for the case radial extension
- Repeat the steps 4-6 until the convergence is reached

Most of the time the accuracy of this approach should be enough. Otherwise manual fine tuning of individual layers or the in-built ANSYS parametric optimization capabilities can be used subsequently with the wall thicknesses for each conductor set as a design variable.

3.3 Maximization of the toroidal field for a pre-defined radial build

In this case the aim is not to minimize the radial build but to increase the maximal toroidal field B_{max} as much as possible while still satisfying the strength criteria and fitting into the radial space defined by PROCESS. This will require to increase both the cable space area to provide higher current and the steel fraction in the cross-section for support against the increased EM forces.

The process starts from a layout already optimized for a certain maximum toroidal field value B_{max}, defined by the parameters of each layer: T_r^i, T_t^i, A_{cs}^i and H_{case}. On the first iteration the nominal conductor current I_{cond} is slightly increased. The cable space area A_{cs}^i for each layer has to be increased too by adding more superconducting material, stabilizer and/or helium fraction depending on the value of the field at the given location. A special function which correlates the effective current density (current divided by the total cable space area) vs toroidal field value $\rho\left(B_t^i\right)$ has to be defined for this purpose. For the 2019 layout a simple linear approximation is assumed, based on the values from the previous design [10]. The toroidal field decreases almost linearly from $B_{\max} \approx \mu_0 N_{coils} I_{coil} / (2\pi R_{in})$ (the equivalent current sheet model) at the first layer (plasma side) to zero at the last layer. Thus, knowing the location of a conductor, the required cable space area for each layer of the WP is calculated as $A_{cs}^i = I_{cond} / \rho\left(B_t^i\right)$.

Then the layout is generated and optimized using the above-mentioned procedure to achieve the minimal radial build satisfying the strength criteria by variation of the parameters T_r^i, T_t^i and H_{case}. The conductor current I_{cond} is then increased again and the process is repeated until the allowable radial space is reached.

Thus, the previous optimization algorithm is modified by adding an addition external loop at the step 2, where $A_{cs}^i = A_{cs}^i\left(I_{cond}, B_t^i\right)$.

3.4 Example of an optimized layout

An example of the achieved parameters for an optimized SPC layout for the 2018 design is shown in Table 3. Table 4 shows the wall thicknesses for each conductor grade (T_r^i, T_t^i) and the case nose thickness (H_{case}) as well as the maximum stresses for each grade and the margin below the ITER criteria (667 MPa for membrane and 867 MPa for membrane+bending stress for modified and aged 316LN steel with 1000 MPa yield stress at 4K).

Table 3 Main parameters of the initial output by PROCESS and optimized WP layout parameters

Main parameters	PROCESS output, July 2018	Optimized layout
$R_{plasma\ side}$, mm	4263	
R_{out}, mm	16475	
$R_{plasma\ axis}$, mm	9073	
N_{coils}	16	
I_{coil}, MA	14.92	17.88
H_{wp}, mm	958	545
H_{case}, mm	382	735
$H_{wp} + H_{case}$, mm	1340	1340
B_{max}, T	11.99	14.13
$B_{plasma\ axis}$, T	5.26	6.31

Table 4 Wall thicknesses and stresses for the optimized WP layout

Grade	Wall thickness, mm	Max. membrane	Max. membrane

#			Stress		+bending stress	
	Toroidal	Radial	MPa	%, below criterion	MPa	%, below criterion
1	5.0	5.0	546	18%	602	31%
2	5.0	5.0	560	16%	746	14%
3	5.0	5.0	573	14%	760	12%
4	5.0	5.0	584	12%	751	13%
5	5.0	5.6	596	11%	737	15%
6	5.0	6.0	604	9%	726	16%
7	5.2	6.4	607	9%	710	18%
8	5.4	6.8	608	9%	717	17%
9	5.6	7.2	608	9%	724	17%
10	5.8	7.6	606	9%	732	16%
11	6.0	8.0	603	10%	733	16%
12	6.2	8.4	600	10%	732	16%
13	7.0	8.8	588	12%	776	10%
14	10.0	12.0	578	13%	700	19%
H_{case}	735		572	14%	584	33%

3.5 Insulation strength assessment

There are two potential issues related to the static insulation strength at the equatorial plane of the inner leg which may affect currently investigated winding pack designs.

The first issue may arise due to some conductor jackets walls bending from the compression into the soft insulation. This creates secondary tension stresses normal to reinforcing plane (Fig. 8).

Fig. 8 Insulation tensile strain normal to reinforcing plane

ITER magnet structural design criteria specify the allowable tensile strain of 0.02% in the absence of specific data, or 1/5 of the ultimate tensile strain otherwise. The limits may be locally exceeded by secondary and peak stresses if it can be demonstrated that local cracking/debonding will relieve the stresses. The maximum normal tensile strain is around 0.2% (11 MPa). With such high values it may be impossible to meet the criterion of 0.02%, therefore further tests are required to check if such a design is acceptable.

Another issue may be high static shear stresses in the insulation if the conductor jacket walls are too thin. Fig. 9 shows comparison of the ITER static shear stress insulation criterion for the optimized layout (Table 4) and for the same layout with the wall thickness if 4 mm for the first three layers of conductor jackets. The allowable shear stress for the criterion changes from 42.5 MPa at zero compression up to 68.6 MPa at the compression of 58 MPa.

Fig. 9 The values of static shear stress insulation criterion for 4mm (left) and 5mm (right) jacket walls thickness.

Conclusions

The paper describes a new FE procedure, TFC-PREDIM, for the structural assessment and pre-optimization of the TF cross-section layout of a tokamak. The modeling part consists of an analytical EM force calculation and FE analysis using the generalized strain approximation. The FE model is generated parametrically using APDL, which gives the advantage of fast assessment of different design options. The new method presented allows faster iterations with sufficent accuracy as compared to the 3D modelling.

The procedure also enables the efficient optimization of a given WP layout: two possible optimization strategies for DEMO TF coil are presented. An example of the optimized layout for the 2018 design with increased toroidal field is presented.

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