Magnetostructural assessment of DEMO TF coils with ENEA Winding Pack configuration

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Abstract. The present paper deals with a multiphysics study of the DEMO Toroidal Field (TF) coils with Winding Pack (WP) layout proposed by the Italian agency ENEA. The latest WP configuration, so far designed adopting the Wind&React technique, is composed of 202 Nb3Sn rectangular conductors, with steel jacket thickness progressively increased from the plasma-facing side, arranged in 6 double layers. Each conductor is designed to carry an operative current of 73.4 kA (14.8 MA for one TF coil) and to ensure the requirement of 12 T of magnetic peak field. The electromagnetic (EM) Lorentz forces have been preliminary evaluated with a magnetostatic 3D analysis at different instants of plasma scenario and then used to perform the 3D structural assessment of the TF coil. For both models (i.e., electromagnetic and mechanical), the WP has been represented as a homogenized material with the cyclic symmetry boundary conditions, allowing to reduce the computational effort. In the structural model, a preliminary design of outer inter-coil structures and gravity support have been included allowing them to identify critical locations in a reliable way. In addition to the EM loads at different plasma scenario instants also the cooling down has been considered as loading condition. The stress assessment on the steel Casing was performed, exploiting the stress linearization along several paths chosen in the most critical locations.

1. Introduction

In the path toward the realization of a commercial fusion power plant, DEMO (DEMOngstion fusion reactor) is expected to produce net electricity for the grid after 2050 [1]. Nowadays, the DEMO design is in the pre-conceptual phase, and after the 2020 Final Review it will enter the Conceptual Design Phase. Among the several work packages, the WPMAG has the challenge of designing the poloidal and toroidal magnet systems. As far as the Toroidal Field (TF) coils are concerned, several Winding Pack (WP) options are being pursued and developed in parallel, as reported by the authors of [2,3]. Among the various WP layouts proposed, the one object of the present paper (WP#2) has been proposed by the Italian agency ENEA, and adopts a Wind&React technology. The conductor is made of a rectangular CICC (cable in conduit conductor), with high aspect ratio, low void fraction, and arranged in Layers [4]. Following the 2018 release of PROCESS system code, the WP#2 was updated to be compliant with the new requirements [5]. The resultant layout upgrade consists of 6
graded Nb₅Sn Double Layers (DLs) with 202 turns, operating with a current of 73.4 kA and a total radial size of 607 mm (see Figure 1).

A total current of ~14.8 MA, carried by each TF coil, generates the 12 T as a magnetic peak field on the conductor, as required.

The TF steel Casing has the arduous task to withstand the huge EM loads generated by superconductors and to ensure the structural integrity of all TF components at the same time. Due to geometry complexity and the non-axisymmetric load distribution, the behavior of the TF coil is challenging to be analyzed, even resorting to a Finite Element (FE) model. For these reasons in recent years, several simplified multiphysics tools (i.e., EM and structural) were developed. In [6], the stress on the Jacket thickness is evaluated, integrating the analytically computed EM loads on the WP cross-section. The Tresca stress, used for the optimization procedure, is the sum of the above-mentioned stress plus the hoop one. In [7], the authors dealt with a semi-analytical approach, combining the empirical assumption with analytical modeling. The EM loads were evaluated within the ANSYS environment while the stress state is reconstructed considering the plane-strain condition. Another possible way to face such a problem is presented in [8]. Starting from the TF coil model with homogenized WP, it is possible to retrieve local stress results through a hierarchical approach. Resorting to radial basis functions interpolation, the EM loads, calculated with the TOSCA (Opera-3D) software, are then applied on both local and global models with the procedure exposed in [9]. The same methodology was adopted in [10] to evaluate the structural integrity of the Divertor Tokamak Test Facility (DTT) TF coils.

The work presented in this paper dealt with the electromagnetic and structural assessment of the TF coil featuring WP#2 layout. Concerning the DEMO TF baseline geometry, in this paper, the Outer Inter-coil Structures (OIS) and Gravity Support (GS) were preliminarily designed and considered in the structural calculation, in order to increase the reliability of the results. The EM Lorentz forces used in the structural analyses were evaluated at different instants of a single null plasma scenario during normal operations. All the FE calculations presented in this paper relied on the smeared WP assumption and were performed within the ANSYS suite.

2. Preliminary design of OIS and GS

The 3D global model of the TF coil was updated to the baseline geometry of 2018 in order to fit with the ENEA WP layout requirements, which mainly consists of WP resizing operations. Besides, the OIS and the GS were preliminarily designed and considered in the simulations to achieve more realistic results.

As far as the OIS are concerned, their main aim is to connect the adjacent TF Casing to reduce the lateral deflection of the structure when out-of-plane EM loads are applied. The chosen shape of OIS consists of simple curved plates with 300 mm of thickness and located in the available space between 2019 vacuum vessel ports [11], as depicted in Figure 2.

The gravity supports GS provides the vertical strength of the structure against the weight and to out-of-plane EM loads as well (see Figure 3). A certain amount of radial displacement is instead guaranteed in order to allow a relatively free deformation of the TF during the Cooling Down (CD). This requirement often leads to the choice of a structure made of parallel plates [13].

The pre-dimensioning of the GS was conducted based on the results presented in [14]. To avoid interference with poloidal field coil number six and based on the results in [15], the radial distance of the GS from the machining center was chosen equal to 8300 mm. The present GS design is composed of 25 steel plates (see Figure 3), whose dimensions are resumed in the next table (Table 1).

The weight of the six poloidal field coils and the central solenoid is not considered in the subsequent structural analysis.
Figure 1. TF coil cross-section view at the equatorial plane from [12].

Figure 2. OIS position in the available space between the vacuum vessel ports.

Figure 3. Overview of gravity support placed below the TF coil.

Table 1. GS and components dimensions

| Component           | Number | Dimensions [mm] |
|---------------------|--------|-----------------|
| Plates              | 25     | 1900 x 1545 x 36 |
| Inter-plates spaces | 24     | 1900 x 1545 x 21 |
| Upper block         | 1      | 1545 x 1404 x 200 |
| Lower block         | 1      | 1545 x 1404 x 200 |
| Gravity Support     | 2300   | 1545 x 1404     |

3. Electromagnetic analysis
The 3D electromagnetic loads acting on the TF coils at the different instant of plasma scenario were evaluated through the electromagnetic model, presented in this section.

Figure 4. TF cross-section: an overview of the layered homogenized WP.

Figure 5. DEMO magnet system with nomenclature.
The poloidal magnet system dimensions, nomenclature (depicted in Figure 5), and currents were applied according to the single null reference scenario equilibrium [16]. All the magnets were considered as homogeneous media, and the TF was subdivided in order to represent the different WP layers (Figure 4) and to obtain a high quality mapped mesh. The EM forces were computed at two different instants of the scenario: at TF energization, namely when the current flows only in the TF coils and the forces act only in the plane, and at the End of Flat-top (EoF) instant, when the poloidal EM field summed to the toroidal one contribute to generating the out of plane forces. Considering Figure 5 nomenclature and clockwise rotation as positive, the values of the currents, as extracted from [16], are reported in Table 2. The plasma current at EoF is equal to 17.8 MA, while the TF one is 14.82 MAt.

| Current [MAt] | CS3U | CS2U | CS1 | CS2L | CS3L | PF1 | PF2 | PF3 | PF4 | PF5 | PF6 |
|--------------|------|------|-----|------|------|-----|-----|-----|-----|-----|-----|
| -5.9         | -29.1| -58.2| -29.1| -12.4| 2.32 | -5.9| -6.1| -3.6| -8.9| 10.3|

The analyses were performed with the ANSYS APDL, making use of the SOLID97 element type. The periodicity of the model allowed to consider only 1 of the 16 sectors, with an angular span of 22.5°. The domain was represented with half elliptical cross-section, with semi-minor and semi-major axes equal to 20 m and 30 m, respectively. On the region's outer surface, well extended beyond the size of the magnets, the far field flux condition was applied, while the imposed conditions on the lateral surfaces follow the flux type that depends on the considered scenario instant. The element size for the coils was set equal to 10 cm in order, which leads to a mesh model with 2.4 million nodes and guarantees the required accuracy.

4. Structural analysis
The 3D global model of the TF coil aims to compute deformation and stresses on the steel Casing, and its TF structures (see Figure 6), and to highlight possible critical stress locations.

![Figure 6. TF coil Casing with OIS and GS overview.](image1)

![Figure 7. Material distribution and mesh detail of TF Casing and WP at the inboard equatorial plane.](image2)

As mentioned before, the geometry and loads periodicity permits to analyze only one TF sector applying the cyclic symmetry conditions on the boundaries. This task was accomplished through a set of Constraint Equations (CE), applied to the Casing nodes in the wedge region and external OIS faces, linking the movement of the relative nodes in a cylindrical reference system.
The material distribution is depicted in Figure 7, together with an overview of the mesh model of Casing and WP at the equatorial plane section. As previously said, the WP is represented as a homogenized orthotropic material. This choice is required to reduce the global computational effort of the model, while the global stiffness of the system is still guaranteed. Despite the stresses on the WP components that cannot be evaluated in this case, this approach allows well to estimate the stress distribution on the steel Casing. The smeared orthotropic thermo-elastic properties were retrieved with the method illustrated in [17], which is based on the equivalence of energy encapsulated in the heterogeneous and homogeneous media. This homogenization procedure was performed for each of 6 DLs, because of different amount of steel and of superconductors from plasma-facing to machine axis, and considering both room and cryogenic temperatures. The smeared material properties used in the FE model are summarized in Table 3.

|       | DL 1  | DL 2  | DL 3  | DL 4  | DL 5  | DL 6  |
|-------|-------|-------|-------|-------|-------|-------|
| E_x   | 26.9  | 27.2  | 31.8  | 32.1  | 35.6  | 36.0  | 38.1  | 38.5  | 40.1  | 40.5  | 41.0  | 41.4  |
| E_y   | 11.3  | 11.3  | 13.9  | 13.9  | 16.7  | 16.7  | 19.4  | 19.4  | 22.0  | 22.0  | 24.2  | 24.2  |
| E_z   | 57.8  | 59.7  | 69.9  | 72.3  | 79.8  | 82.6  | 87.3  | 90.3  | 93.5  | 96.7  | 97.8  | 101.0 |
| G_xy  | 0.9   | 0.9   | 1.6   | 1.6   | 2.6   | 2.7   | 3.7   | 3.8   | 5.0   | 5.2   | 6.1   | 6.3   |
| G_yz  | 7.5   | 7.7   | 9.2   | 9.5   | 11.0  | 11.3  | 12.7  | 13.1  | 14.2  | 14.6  | 15.4  | 15.9  |
| G_zx  | 14.5  | 15.0  | 17.4  | 18.0  | 19.5  | 20.3  | 20.9  | 21.7  | 22.0  | 22.8  | 22.7  | 23.4  |
| ν_xy  | 0.25  | 0.25  | 0.26  | 0.26  | 0.27  | 0.28  | 0.29  | 0.29  | 0.30  | 0.31  | 0.32  | 0.32  |
| ν_yz  | 0.06  | 0.06  | 0.06  | 0.06  | 0.06  | 0.07  | 0.07  | 0.07  | 0.07  | 0.07  | 0.07  | 0.07  |
| ν_zx  | 0.13  | 0.13  | 0.13  | 0.13  | 0.13  | 0.13  | 0.12  | 0.12  | 0.12  | 0.12  | 0.12  | 0.12  |
| α_x   | 1.07  | 1.07  | 1.07  | 1.07  | 1.08  | 1.08  | 1.08  | 1.08  | 1.09  | 1.09  | 1.09  | 1.09  |
| α_y   | 1.19  | 1.19  | 1.19  | 1.18  | 1.18  | 1.18  | 1.17  | 1.17  | 1.17  | 1.16  | 1.16  | 1.16  |
| α_z   | 1.03  | 1.03  | 1.03  | 1.03  | 1.03  | 1.04  | 1.04  | 1.04  | 1.04  | 1.04  | 1.04  | 1.04  |

The model set up required different operations, among all the WP element orientation, aimed to apply the orthotropic homogenized properties correctly. For this purpose, a cylindrical coordinate system was created in the curvature center of each TF segment, while three Cartesian coordinate systems were imposed on the three straight segments of the coil. Also, for the G10 insulation in the wedge region, two coordinate systems were required to orient the orthotropic insulation properties correctly. The elements of ground insulation required the creation of several coordinate systems. This process was accomplished through an APDL snippet used inside Workbench. As for the smeared properties, the isotropic and orthotropic materials properties, depicted in Figure 7, were extracted from [17]. The analysis was performed within the ANSYS Workbench environment, making use of SOLID185 linear elements. The size of the model is about 515k mesh nodes.

Contact elements were required to simulate the sliding between the WP and the steel Casing, and between Casing-wedge and insulation on the left side. On the right side of the wedge, a bonded contact was applied. The non-symmetric contact at Casing wedge is considered to reproduce better real working conditions of G10 panels, bolted on the side of each TF coil for electric insulation purposes. For sliding contact, a friction coefficient of μ = 0.2 was adopted.

As far as the loading conditions concern, in addition to the cyclic symmetry GS bottom surface was fixed. The considered load steps for the analysis are:

- Deadweight
- Cooling down, bringing the structure from room temperature (293 K) to 4 K (cryogenic temperature)
- EM loads at TF coil energization
- EM loads at EoF of single null scenario
The cooling down was simulated, applying a constant temperature of 4.2 K to the Casing, the WP, and the OIS. Concerning the GS, its bottom surface is linked to the ground at room temperature (293 K). For this reason, a temperature variation (from room to cryogenic temperatures) along the GS height was considered. The EM forces were applied to the mesh nodes of smears DLs inside ANSYS Mechanical, resorting to the External Data module and a direct force assignment.

5. Results

5.1. EM analysis results
In this section, the results related to the EM analyses are exposed. In Figure 8 and Figure 9, the magnetic field contour is depicted respectively at TF energization and EoF instants of plasma scenario, respectively, in a lateral view of the model.

![Figure 8. Total EM field contour at TF energization instant of scenario in a lateral view](image1)

![Figure 9. Total EM field contour at EoF instant of scenario in a lateral view](image2)

The magnetic field, as a function of the radial distance at the equatorial plane and evaluated at the TF energization instant of scenario, is shown in Figure 10. As can be observed, the peak field values are about 12 T and therefore is compliant with the requirement mentioned above.

An overview of the EM forces per unit length, evaluated on the normalized TF curvilinear abscissa (i.e., poloidal direction), is given in Figure 11, at TF energization and EoF. It should be noted that the lateral forces (toroidal direction) arise only at EoF when poloidal coils are activated, and plasma is burning. It can also be observed that the radial force is slightly higher than 80 MN/m in the inner leg, while the sum of vertical forces in the upper and lower TF portion is almost balanced, with values of 258.1 MN and -257.4 MN respectively.

Besides, the curves of vertical and radial components of the forces are very well overlapped at both instants, as expected, because the poloidal magnet system contributes to generating only the out of plane component of the forces (toroidal direction).
5.2. Structural analysis results
In this section, the results related to structural analyses will be shown. The displacements of the whole structure (Casing + WP + OIS + GS) is presented in Figure 12 for the worst instant, namely at EoF. The maximum value (i.e., about 68 mm) occurs in the structure upper part, with a lateral deflection, due to out of plane forces, of approximately 33 mm. In Figure 13, the stress intensity distribution is shown in the same scenario instant. The yielding stress of 316L(N) stainless steel at 4 K is $S_y=1000$ MPa [17] and is considered as a limit value in the contour map of Figure 13. All zones depicted with purple color are above the stress limit and are then considered for a more in-depth investigation.

Following the ITER design criteria [18], the stress linearization will be performed in the steel Casing critical location. The primary membrane ($P_m$) and primary membrane plus bending ($P_{m+b}$) stresses,
evaluated along chosen paths, were compared with the related limits. In particular, $P_m$ and $P_{m+b}$ must be lower than $S_m$ and $1.3 \cdot S_m$, where $S_m$ is $2/3 \cdot S_y$. Considering that $S_y = 1000$ MPa, $P_m$ and $P_{m+b}$ will be equal to 667 MPa and 887 MPa, respectively. It must be said that thermal stresses are not considered in the linearization procedure because they are considered as secondary stresses.

As can be observed from Figure 13, the critical locations are on the plasma-facing side, in the upper and especially in the lower bend zones. It can also be observed that the stress is mainly concentrated on one side of the lower bend, because of the out of plane force effect. The lower bend, together with the equatorial plane, can be considered the critical zones where the stress linearization has to be performed. The chosen paths at the equatorial plane can be observed in Figure 14, while the results of the stress linearization are collected in Table 4. The paths were numbered from 1 to 13.

![Figure 14](image1.png)

*Figure 14.* Path location on steel Casing and numeration for stress linearization at the equatorial plane

![Figure 15](image2.png)

*Figure 15.* Path location on steel Casing and numeration for stress linearization at lower Casing bend.

The linearized stress values at the inner leg equatorial plane, as it can be noticed from Table 4, are always below the primary membrane and primary membrane plus bending stress limits.

| Path | $P_m$ [MPa] | $P_{m+b}$ [MPa] |
|------|-------------|-----------------|
| Path 1 | 401,4 | 441,6 |
| Path 2 | 479,3 | 506,1 |
| Path 3 | 384,2 | 424,4 |
| Path 4 | 409,6 | 417,3 |
| Path 5 | 378,2 | 400,8 |
| Path 6 | 510,0 | 577,9 |
| Path 7 | 439,8 | 457,3 |
| Path 8 | 396,0 | 418,1 |
| Path 9 | 364,3 | 375,9 |
| Path 10 | 505,3 | 587,6 |
| Path 11 | 421,8 | 462,7 |
| Path 12 | 494,9 | 539,3 |
| Path 13 | 485,8 | 556,3 |

Similarly, the paths in the Casing lower bend location, shown in Figure 15, were numbered from 14 to 16, and the detailed results are reported in Table 5. As it is possible to notice, the stresses are often higher than the prescribed limits (values highlighted in red), only at EoF instant.
Table 5. Summary of stress linearization along with Casing lower bend paths at EoF

| Path | Pm [MPa] | Em [MPa] | Pm+b [MPa] | Em+b [MPa] |
|------|----------|----------|------------|------------|
|      | Energization | EoF | Energization | EoF |
| Path 14 | 619,1 | 875,3 | 833,6 | 1185,1 |
| Path 15 | 595,50 | 789,5 | 967,4 | 1174,1 |
| Path 16 | 599,30 | 850,3 | 798,0 | 1142,9 |

Besides, it can be stated that at TF energization instant (only in-plane EM forces) the stresses are lower, the allowable value. It means that a reduction of TF deflection, due to out of plane forces, could be helpful to reduce the stress state.

Taking into account the foregoing considerations, a further simulation, with limited lateral deflection in the lower Casing bend zone, was assessed. The linearized stresses for paths 14 to 16 at EoF, are resumed in Table 6. In the same table are also reported the results related to the case without deflection limitations.

Table 6. Summary of stress linearization along with Casing lower bend paths at EoF

| Path | Without deflection limitations | With deflection limitations |
|------|---------------------------------|----------------------------|
|      | Pm [MPa] | Em [MPa] | Pm+b [MPa] | Em+b [MPa] |
| Path 14 | 875,3 | 1185,1 | 678,5 | 889,2 |
| Path 15 | 789,5 | 1174,1 | 554,6 | 934,0 |
| Path 16 | 850,3 | 1142,9 | 668,9 | 868,6 |

Limiting the TF lateral deflection, as can be observed, enhances the stress state and the linearized stresses return below or near the allowable limits. In fact, only membrane stresses of paths 14 and 16 are respectively 1.7% and 0.3% over the prescribed limits.

The lateral deflection of the steel Casing could be minimized by introducing additional Inter-Coil (IC) structures in the inner TF region. A possible solution can be to adopt inner IC structures similar to those inserted between ITER TF coils [19]. Another possibility is to resort to a solution analogous to that proposed for DTT [20], in which the TF coils are bolted in the upper and lower parts of inner leg.

6. Conclusions

In the present paper, the magnetostructural assessment of DEMO TF coil featuring WP#2 layout, was performed. The geometry and loads periodicity allowed to restrict the study to only one of the 16 sectors (22.5°) for both EM and structural analyses.

From 3D EM analysis, performed with ANSYS APDL, were evaluated the EM loads at two instants of the single null plasma scenario: at TF energization and at the end of flat-top. All the coils were considered as homogeneous media and, the TF coil was also subdivided to represents the different WP double layers. The EM analysis results showed that the requirement of 12 T as a magnetic peak field is fulfilled.

The EM Lorentz forces were then extracted and used in the structural model, to assess the strength of the TF and its structures.

For the 3D model of the TF coil, the DLs were represented as a homogeneous media. The equivalent thermo-mechanical orthotropic properties were evaluated for each DLs, being the amount of steel and superconductor strands different for each DLs. The use of smeared properties, to represent the WP, allows to drastically reduce the required computational effort, maintaining at the same time equivalence from a global stiffness point of view.

Concerning the applied loads, four different load steps were considered: dead weight, cooling down, EM loads at Energization and EoF.

The total deformation of the Casing is equal to 68 mm at EoF, and occurs in the upper part of the structure, with a lateral deflection of about 33 mm. As far as the stresses concern, the critical locations
were found at the inboard lower bend zone and equatorial inboard section. The stress linearization was performed, and the obtained primary membrane and primary membrane plus bending stresses were compared with the allowable values. It can be stated that in the inboard equatorial region, the stresses are below the prescribed limits, while in the lower bend region are often above the allowable values, especially at EoF instant, when the out of plane EM loads generate a lateral deflection of the structure. This suggests that a reduction of the lateral TF bending could help to reduce the stress state in the critical locations.

A further structural analysis, in which the lateral deflection of Casing lower bend was limited, showed that the reduction of the lateral TF lateral bending contribute to reduce the stress state. The linearized stresses are in this case below or very close to the allowable values. To minimize this effect different solutions for inner inter-coil structures can be adopted and introduced, such as those proposed for ITER or DTT TF coils.

Much complex is to follow the path of a TF shape change, being related to several factors, as for instance its strict relation with required plasma shape. Also the “bending free” shape (in-plane bending minimization) have to be considered to design a TF coil, together with the presence and the dimensions of in-vessel components and external poloidal coils. Lastly cannot be neglected the technological issues related to the realization of these massive TF coils.

Acknowledgments
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.
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