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An Electromagnetic and Structural Finite Element Model of the ITER Toroidal Field Coils

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Abstract

The ITER magnet system consists of 18 toroidal field (TFCs) coils, a central solenoid (CS), 6 poloidal field (PFCs) coils and a set of correction coils. The TF coils provide the required toroidal magnetic field of ≈ 5.3 T at the plasma radius R=6.2 m mainly needed to confine the plasma [1]. Since the magnets are under manufacturing [2], non-conformity-reports (NCR) and/or deviation requests (DR) can be provided by the manufacturers. Fast checks on the impact of those design updates on the structural behavior of the system are needed before accepting their implementation [3]. With this aim a detailed finite element model of the TF system has been developed and it is described in this paper. It is a three-dimensional cyclic symmetric finite element model giving a representation of the two types of coils characterizing the TF magnet: one TF coil type A (the one which supports the six poloidal field coils) and one TF coil type B (the one which supports four out of six poloidal field coils and the central solenoid).The model allows computing the magnetic field during the operating scenario of the magnet and the related Lorentz forces acting on the TF coil system. It also permits to simulate how the TF system will mechanically behave during operation. Updates of the FE mesh can be easily implemented since the model has been built in a modular way, small sub-components of the system can be isolated and geometrically updated if needed. This is the key feature of the model which has allowed to study in a very fast way possible NCR's and DR's produced during the manufacturing. An intensive usage of the ANSYS® APDL language has been implemented in such a way that the entire analysis cascade can be ran in a completely automatic way. Due to its versatility, this tool has become the reference TF coils model in the ITER Magnet division.

1. Methodology

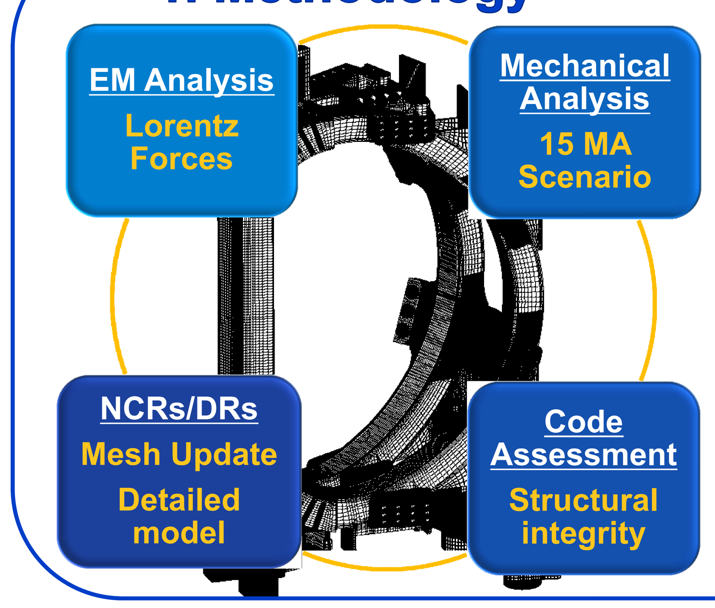


Table 1. Magnet operating 15 MA Scenario

15 MA ITER Scenario	
TFO	TF Coils current (only)
SOD	Initial magnetization
SOP	Start of Plasma
XPO	X point formation
SOF	Start of Flattop
SOB	Start of Burn
EOB	End of Burn
EOC	End of Current
EOP	End of Plasma

2. Electromagnetic Analyses

EM Analyses to simulate Normal Operating Conditions. Lorentz Forces acting on the TF winding pack (WP) are evaluated directly as nodal loads on TF WP mesh

2.1 Electro Magnetic Model

6 PFCs, CS, Plasma, and 18 TFCs. ANSYS® multi-physics tool to perform static analyses based on Scalar potential formulation.

Figure 1a. Electro Magnetic FE model

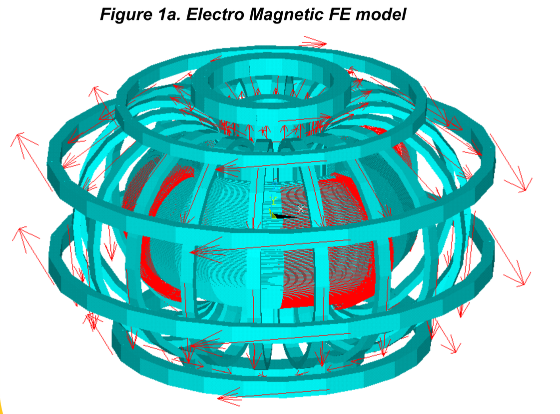
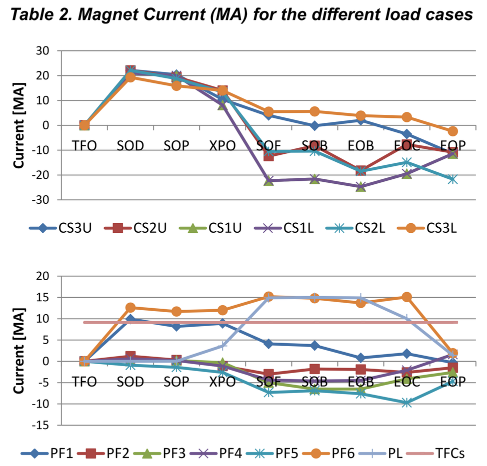


Table 2. Magnet Current (MA) for the different load cases



2.2 Electro Magnetic Results

Output: B_{field}, **Current Density** and Nodal **Lorentz Forces** on TF WP.

Figure 1b. Toroidal Force density in EOB

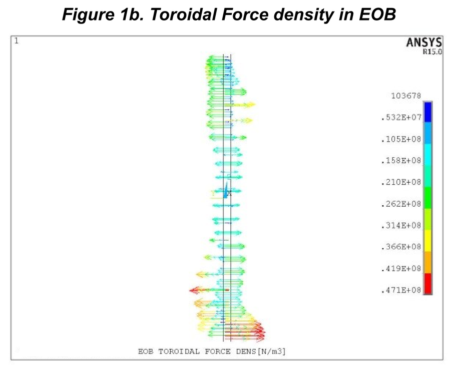


Table 3. Resultant loads on 1 coil for the different load cases

	FRAD (MN)	FTOR (MN)	FVERT (MN)	MRAD (MNM)	MTOR (MNM)	MVERT (MNM)
TFO	-398.8	0.0	0.0	0.0	-4.2	0.0
SOD	-398.8	1.4	0.0	44.7	-4.2	0.0
SOP	-398.8	2.1	0.0	-8.9	-4.2	0.0
XPO	-398.8	5.6	0.0	1.9	-4.2	0.0
SOF	-398.8	15.0	0.0	-41.4	-4.2	0.0
SOB	-398.8	15.5	0.0	-83.6	-4.2	0.0
EOB	-398.8	15.0	0.0	-77.4	-4.2	0.0
EOC	-398.8	12.7	0.0	-78.6	-4.2	0.0
EOP	-398.8	2.2	0.0	-28.1	-4.2	0.0

3. Mechanical Analyses

A 3D **finite element model** of the TF system representing two TF coils is built. An **ANSYS® APDL** [6] set of macros allow to run the entire cascade of analysis in a full automatic way.

Visual Basic (VB) scripts have been developed in order to automatize the post-processing of the results up to the mechanical assessment performed according to the applicable codes [4].

3.1 Mechanical Model

40° cyclic symmetric FE model representing two TF coils, one **TF coil type A** and one **TF coil type B**, including:

- ❑ Pre compression ring (**PCR**):
- ❑ Gravity Support (**GS**):
- ❑ Wedging:
- ❑ Upper/lower Shear Keys (**IIS**):
- ❑ Upper/lower outer inter-coil structure (**OIS**)
- ❑ Upper/lower interm. outer intercoil structure (**IOIS**)
- ❑ Winding Pack (**WP**)/ TF case
- ❑ Pedestal Ring + Bearings

Figure 2a. Mechanical FE Model (overview of the mesh)

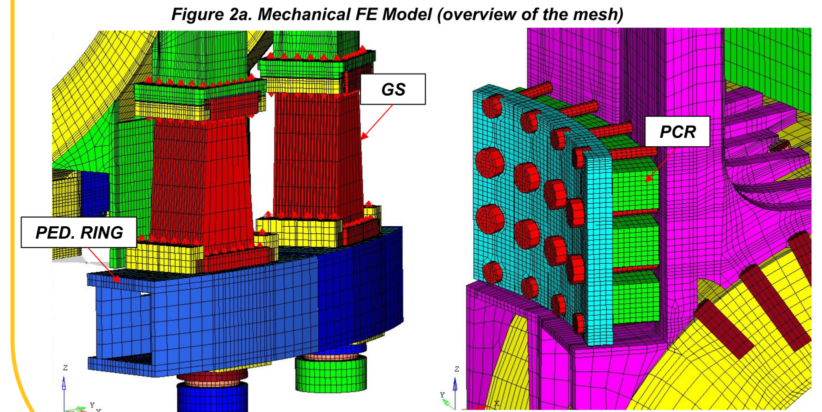
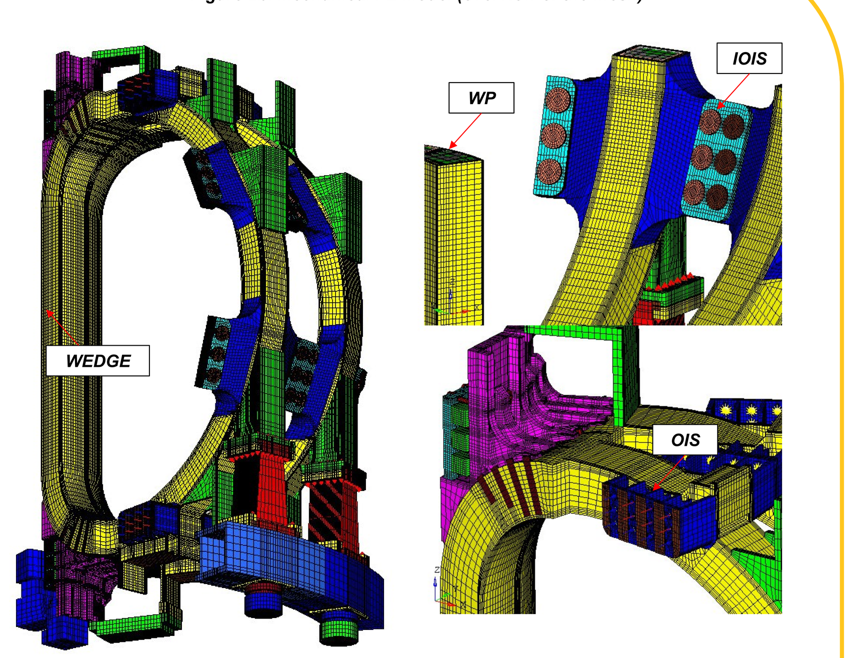


Figure 2b. Mechanical FE Model (overview of the mesh)



All **non liner interfaces** modeled
All **bolted connection** modeled.
ANSYS® APDL procedure allows running the FE model considering 2 coils model with **9-fold** Symmetry or a single coil model representing only type A (or type B) coil with **18-fold** symmetry.

3.2 Mesh Features

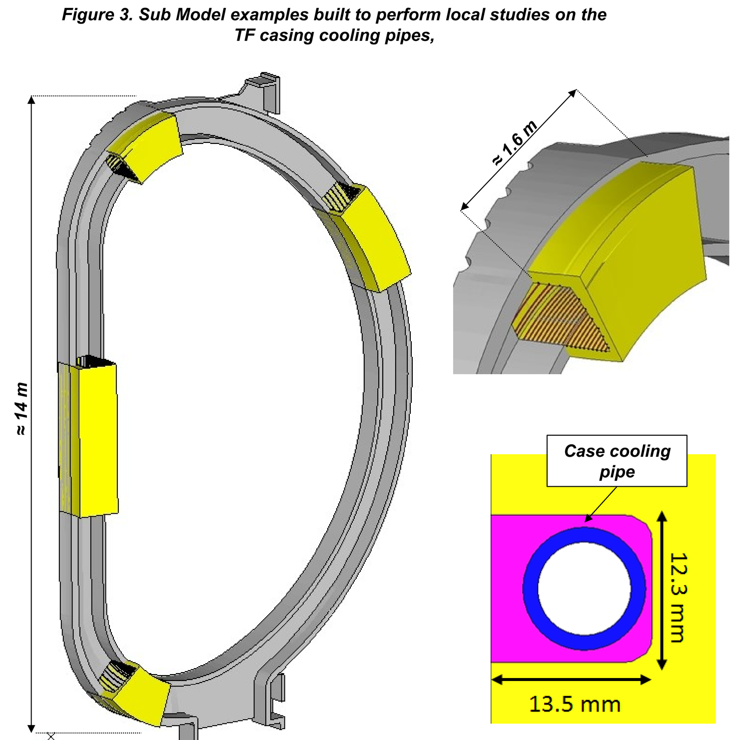
General Features

- ❑ 586,000 **nodes**/572,000 **elements**
- ❑ **Element types**: Solid + beam + links + MPC
- ❑ **Contact** elements for non-linear interfaces
- ❑ Bolt **preload** via **pretension** elements

Mesh Updates

- ❑ **Modular mesh** (derived from [7]) → easy re-meshing of components/ small regions
- ❑ Quasi-automatic procedure based on TCL language (inside Altair Hypermesh® software [8]) in order to implement **mesh updates**
- ❑ **Mesh morphing** techniques can also be used via Altair Hypermorph® module [8].
- ❑ Model built considering a number of cutting planes which allows an easy implementation of **sub-modeling** techniques [6].

Figure 3. Sub Model examples built to perform local studies on the TF casing cooling pipes,



3.3 Loading Conditions and Post-Processing of Results

Loading Conditions:

- ❑ **LS1**: TF dead weight + pre-loading of the PCR (70 MN as total radial force).
- ❑ **LS2**: dead weight of the PFCs and CS (as vertical interface loads).
- ❑ **LS3**: Cooldown from RT to 4 K everywhere (except for GS where local gradient is considered, top at 4 K bottom at RT).
- ❑ **LS4** to **LS12**: Energization load cases (see table 1)

(PFCs and CS not modeled, EM vertical loads as interface loads.)

Post-Processing:

Great effort in **managing output** data in an automatic way:

- ❑ Full **automatize procedure** able to describe the behavior of the system and to verify its structural integrity.
- ❑ ANSYS® output data (produced via **APDL** scripts) are managed via **Visual Basic** (VB) scripts to generate the required number of standardized output information (i.e. tables, graphs, pictures).
- ❑ A VB library including all needed material data (and related code assessment rules) has been built in order to automatically verify the **structural integrity** of the system against the applicable codes described in [4] (an example is shown in Table 5).

Main outputs:

- ❑ Global **contour plots** (an example is shown Figure 4)
- ❑ **Displacements** and maximum values of **stresses** on a number of locations (an example is shown Figure 5),
- ❑ Interface loads on each component (an example is shown Table 4).
- ❑ **Resultant** loads on each bolt/pin
- ❑ Automatic **Stress linearization** and easy implementation of additional supporting line segments
- ❑ **Code Assessment** for metallic components and bolted connections (an example is shown in Table 5).

Figure 4. Example of displacements [mm] and stress [MPa] global contour plot on TFC type B for EOB loading conditions

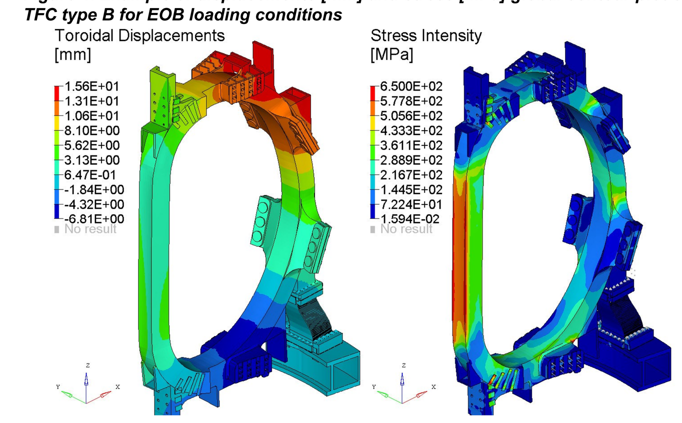


Table 4. Example of a standard output for the reference design representing the Toroidal Force distribution [MN] on different TFC interfaces

	LS1 DW	LS4 TFO	LS5 SOD	LS6 SOP	LS7 XPF	LS8 SOF	LS9 SOB	LS10 EOB
Radial EM Force (F)	0.0	398.8	398.8	398.8	398.8	398.8	398.8	398.8
Toroidal F = F(Radial F)	0.0	1142	1142	1142	1142	1142	1142	1142
Toroidal F by PCR	220.4	168.7	168.9	169.1	169.6	170.8	171.1	170.3
Toroidal F Upper IIS	-72.4	-89.8	-90.7	-91.7	-93.8	-87.7	-88.0	-81.9
Toroidal F Lower IIS	67.3	81.1	80.4	79.3	77.3	82.6	81.4	87.2
Toroidal F on Upper OIS	-26.5	-5.2	-5.6	-6.0	-6.9	-4.9	-5.0	-2.6
Toroidal F on Upper IOIS	-12.6	8.4	8.9	9.2	10.1	6.9	6.5	3.6
Toroidal F on Lower IOIS	-16.3	3.9	3.6	3.0	1.9	4.0	3.3	5.8
Toroidal F on Lower OIS	-26.5	-5.3	-5.7	-6.1	-7.0	-5.3	-5.4	-3.1
Toroidal F in Cryo Ring	-1.8	-1.9	-2.0	-2.0	-2.1	-1.7	-1.7	-1.3

Figure 5. Example of a standard output for the reference design representing the toroidal displacements [m] of the TF winding pack as a function of the location expressed as poloidal angle for the different loading conditions,

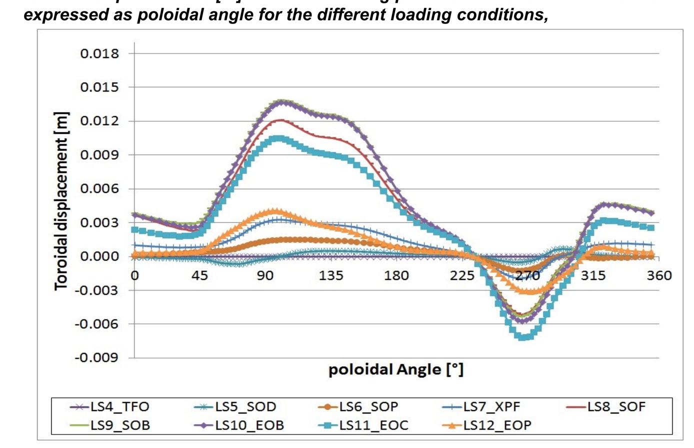


Table 5. Example of a standard output for the reference design representing a summary of the minimum safety factor (safety factor higher than 1 means that the rule is satisfied) on the most critical bolt of each connection applying static stress assessment rules for bolted connection

	LS4 TFO	LS5 SOD	LS6 SOP	LS7 XPF	LS8 SOF	LS9 SOB	LS10 EOB	LS11 EOC	LS12 EOP
UOIS	4.8	4.8	4.8	4.8	3.4	3.1	3.1	3.8	4.8
UIOIS	6.7	6.3	5.7	4.7	2.5	2.2	2.3	2.7	3.9
LIOIS	13.9	12.2	13.6	7.9	2.7	2.4	2.3	2.6	7.7
LOIS	4.8	4.8	4.8	4.8	4.9	4.9	4.9	3.8	4.9
GS	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6

4. Conclusions

As a global conclusion, the tool presented here due to its versatility and its high level of automation is widely used in the ITER Magnet division in order to support the manufacturing of the magnets. Design changes arising from NCRs and/or DRs can be easily implemented and checked before acceptance in order to assess their impact on the mechanical behavior of the system. A number of additional studies have been also carried out with it in order to investigate particular operating conditions to which the magnets could be temporarily subjected during the ITER lifetime, confirming the soundness of the magnet design for the foreseen operating conditions.

5. References

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