The SMC (Short Model Coil) Nb_3Sn program: FE analysis with 3D Modeling

C. Kokkinos, J. C. Perez, M. Karppinen, P. Manil, F. Regis, M. Guinchard, M. Bajko

***Abstract*—The SMC (Short Model Coil) project aims at testing superconducting coils in racetrack configuration, wound with Nb_3Sn cable. The degradation of the magnetic properties of the cable is studied by applying different levels of pre-stress. It is an essential step in the validation of procedures for the construction of superconducting magnets with high performance conductor. Two SMC assemblies have been completed and cold tested in the frame of a European collaboration between CEA (FR), CERN and STFC (UK), with the technical support from LBNL (US). The second assembly showed remarkable good quench results, reaching a peak field of 12.5T.**

This paper details the new 3D modeling method of the SMC, implemented using the ANSYS® Workbench environment. Advanced computer-aided-design (CAD) tools are combined with multi-physics Finite Element Analyses (FEA), in the same integrated graphic interface, forming a fully parametric model that enables simulation driven development of the SMC project. The magnetic and structural model is described and the results are compared with the experimental data from the strain gauges, which monitor the mechanical strain of the structure.

***Index Terms*—Finite element analysis, parametric model, Nb_3Sn, superconducting accelerator magnet.**

I. INTRODUCTION

THE mechanical structure [1] of the SMC (Fig. 1) comprises an iron yoke surrounded by an aluminum alloy shell, and includes four loading pads that transmit the required pre-compression from the outer shell into the two coils. The outer shell is pre-tensioned with keys that are inserted using pressurized stainless steel bladders [2]. Two aluminum alloy rods provide the axial loading at the coil ends. The outer shell, axial rods, and coils are instrumented with strain gauges, which allow precise monitoring of the loading conditions during the assembly and the testing of the magnet.

Several software packages have been used to analyze the magnetic and mechanical design of the SMC project, as they have been reported in [3]-[6]. New available features in the software packages and in their interfaces, provided the possibility to develop a new modeling approach to simplify the geometry creation, link the programs and facilitate the file management. It was decided to test this implementation on the well-known SMC model.

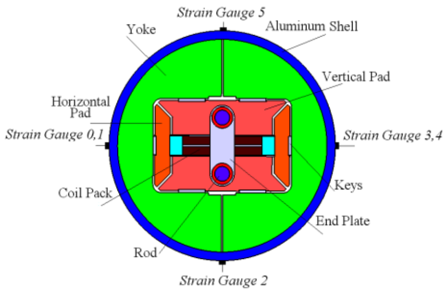

Fig. 1. Schematic view of the SMC including the strain gauges position on the shell. The results on the shell, presented in this paper, for SMC1 and SMC3 are from strain gauge 0 and 3 respectively. Both measure in the azimuthal direction.

The goal of the new Finite Element Model (FEM) described in this paper, is to combine advanced CAD tools with Finite Element Analysis (FEA) software, in the integrated design environment of ANSYS® Workbench (Fig. 2).

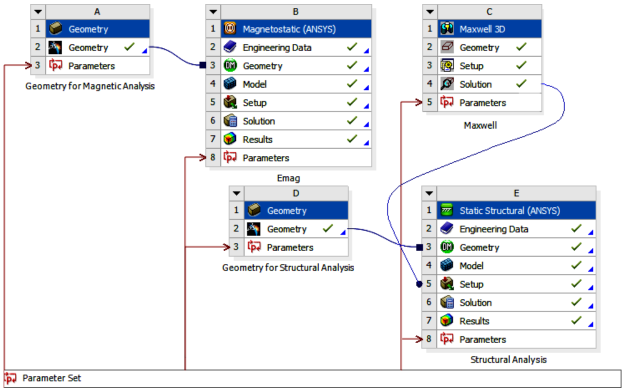

Fig. 2. Schematic view of the integrated design environment. The geometry is designed in CATIA® and ANSYS® DesignModeler, the magnetic analysis is accomplished in ANSYS® Emag and ANSOFT® Maxwell and the structural in ANSYS® Workbench.

This method allows:

1) controlling all used software from the same platform.
2) easy and safe file management.
3) bi-directional interface and integration of the CAD tools.
4) managing and sharing all parameters through a table shared by all applications. The platform updates simultaneously all applications composing the project, in case of a parameter change, reducing the time of performing design iterations.
5) direct linkage and data exchange between software.

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The results presented in this paper concern:

1) the initial test results of the assembly, containing a dummy-coil to investigate the general behavior of the mechanical structure and validate the FE-model.
2) the first assembly of the SMC, called SMC1, which was tested in October 2010, with poor quench results.
3) the second assembly, called SMC3, which was tested in June 2011, and provided satisfactory quench results [1].

II. FINITE ELEMENT MODEL

A. CAD Tools

All parts of the SMC assembly, except for the coil block, are parametrically designed in CATIA® and imported into DesignModeler®, along with their parameters. From Workbench® it is possible to simultaneously update all parts modeled in CATIA® using the CADNexus® CAPRI CAE Gateway plug-in that enables a bidirectional linkage between the two software.

The parametric model of the coil block, consisting of the insulated conductors, the island, the spacers and the end-spacers, is designed in DesignModeler®, using the already imported CATIA® parts as reference. DesignModeler® is also used for the boolean and body operations, the definition of multi-body parts, and the definition of the enclosing region, used in the magnetostatic analysis.

The coil block's parameters from DesignModeler® are added to those imported from CATIA®. A complete summary table (Fig. 2) in the integrated design environment of ANSYS® Workbench is formed.

The ability to combine parts and parameters from both CAD tools provides an efficient way for extensive parametric studies of the SMC.

B. Magnetic Analysis

The magnetic analysis is accomplished both in ANSYS® Emag and in ANSOFT® Maxwell to compare results with different mesh densities, element types, solution setups and algorithms. The same parameters are shared, in terms of current excitation, geometry, number of strands and turns. The SMC cable properties are described in [3].

The model in Emag® (Fig. 3) consists of a very fine, 20-nodes elements, hexahedron mesh, whereas in Maxwell®, the mesh density is much coarser, consisting of tetrahedrons, generated by an adaptive analysis (Fig. 3) until the energy error [7] is less than the target of 0.1 %.

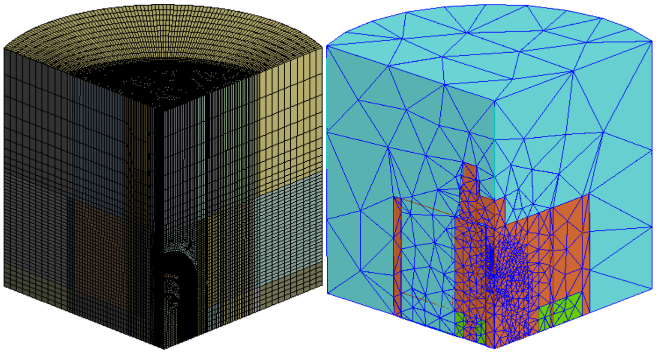

Fig. 3. 3D magnetic model mesh in Emag® and Maxwell®. Only the 1/8th of the assembly is modeled, due to symmetry reasons.

The different mesh type and density between both magnetic and structural model (Fig. 4) enables the optimization of the meshing process according to the given analysis and its physics preference. Macros are needed to transfer the Lorentz forces from Emag® to the structural analysis, which makes the procedure complex and time consuming. Utilizing the implementation of Maxwell® in Workbench®, the Lorentz forces are transferred in the structural analysis as body force densities, via the direct linkage between the two analyses (Fig. 2).

The coil block region, in all analyses, has a very fine mesh (Fig. 4) to ensure the correct mapping and interpolation of the Lorentz forces in the element nodes, from the magnetic to the structural model.

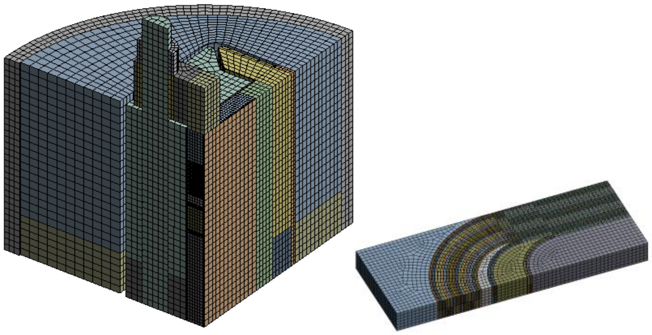

Fig. 4. 3D structural model mesh in ANSYS®.

The high field region (B_{max}) is located in the first turn, in the middle of the straight section. The software show a very good agreement in terms of the computed magnetic peak field, having a maximum difference of 0.2% (Table I). The measured inductance of the two SMC3 coil packs is 1.8 mH in comparison to 2 mH computed with Maxwell®.

TABLE I SMC MAGNETIC RESULTS COMPARISON

Parameter	Unit	ANSYS EMAG®	ANSOFT Maxwell®
I_{ss}	kA	13.99	13.96
B_{max}	T	12.59	12.57
Inductance	mH	2.09	2.01
Stored Energy	kJ	193	196
No.of Elements	/	289044	105670

C. Structural Analysis

The goal of the parametric 3D structural analysis in ANSYS® Workbench is the simulation of the mechanical behavior of the structure, including four main load steps: (i) transverse pre-load at 293 K, by utilizing the horizontal and vertical pads, (ii) axial pre-load at 293 K, using the longitudinal rods, (iii) cool down to 4.2 K, and (iv) powering up to the nominal current (I_{ss}) of 14 kA.

The chosen assembly parameters ensure that the stresses in the middle of the straight section of the Nb_3Sn coil, where the peak magnetic field is located, remain close to the assumed safe limit of 150 MPa (Fig. 5, Table II, Table III) and that the coil remains in compression, at all times.

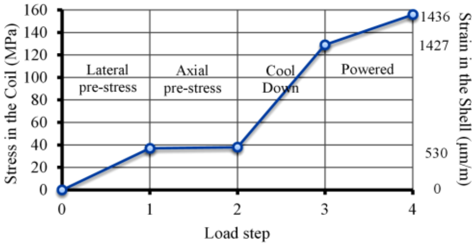

Fig. 5. Correlation between the stress in the coil, in the middle of its straight section, and the strain in the shell (values computed in strain gauge 0 (Fig. 1)) for SMC3 (Table III).

Since the conductor is potted to the island, spacers and end-spacers, bonded contact is assumed between the elements of the coil pack. Sliding contact is defined between the magnetic and non-magnetic parts of the pads and the yoke. The contact elements used elsewhere are considered frictionless. All contact definitions include surface-to-surface elements, with asymmetric behavior [8] and augmented Lagrange formulation [8]. In particular, the target surfaces are modeled using the TARGE170 [9] element type and the contact surfaces with CONTA174 [9]. Modifications or improvements of the contact status will be done after a detailed analysis of the last assembly test. The isotropic material properties for the magnet components are described in [4].

SMC3 had very low axial pre-stress compared to SMC1 and different cable insulation thickness. The main results concerning the coil (mid-plane, equivalent Von-Mises stress and lateral strain), the shell (equivalent Von-Mises stress, azimuthal strain in strain gauge 0 (Fig. 1)) and the rod (mid-plane, stress and strain in axial direction) are reported in Table II and Table III.

TABLE II SMC1 3D STRUCTURAL MODEL MAIN RESULTS

(*Stress in MPa, Strain in µm/m*)

Item	**Lateral pre-load**		**Axial pre-load**		**Cool Down**		**I_{ss}**	
	σ	ε	σ	ε	σ	ε	σ	ε
Coil	35	-1264	30	-1114	120	-2327	134	-2654
Shell	82	481	84	500	178	1375	178	1384
Rod	0	0	145	2066	257	3258	278	3530

TABLE III SMC3 3D STRUCTURAL MODEL MAIN RESULTS

(*Stress in MPa, Strain in µm/m*)

Item	**Lateral pre-load**		**Axial pre-load**		**Cool Down**		**I_{ss}**	
	σ	ε	σ	ε	σ	ε	σ	ε
Coil	39	-1264	39	-1258	129	-2854	156	-3533
Shell	88	531	88	531	182	1427	182	1436
Rod	0	0	3	46	94	1193	116	1477

The strain in the shell (Table II, Table III) increases by almost 900 µm/m during the cool down, whereas the peak stress remains constant during powering. This indicates that the assembly pre-loads counterbalance the magnetic forces. The increase of the peak stress in the coil, during powering depends on the given pre-stress (Table II, Table III).

III. MODEL VALIDATION

A. *Dummy-Coil*

Before carrying out the first assembly of the SMC with a real coil, the structure was assembled including a dummy-coil, machined out of a solid block of 2017A aluminum alloy. The study of the structure's mechanical behavior at room and cryogenic temperature provided knowledge for future tests, in terms of the expected strain values. The measured data were used to validate the FE-model.

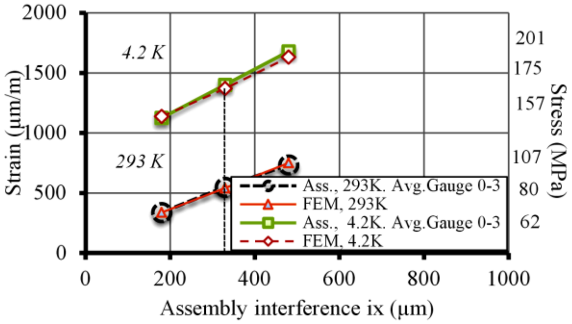

Fig. 6. Correlation between azimuthal strain and stress on the shell (assembly values are the average from strain gauge 0,3 (Fig. 1)) as a function of the assembly horizontal interference i_x.

The limitation of about 150 MPa, in the middle of the coil's straight section, is satisfied with a strain of about 520 µm/m and 80 MPa stress on the shell, at room temperature, corresponding to about 1400 µm/m and 175 MPa at cryogenic temperature (Fig. 6). For future tests, the strain and stress increment on the shell, during cooling-down, is expected to be about 900 µm/m and 95 MPa respectively.

B. *SMC1*

The azimuthal strain on the shell, in strain gauge 3 (Fig. 1) is presented in Fig. 7.

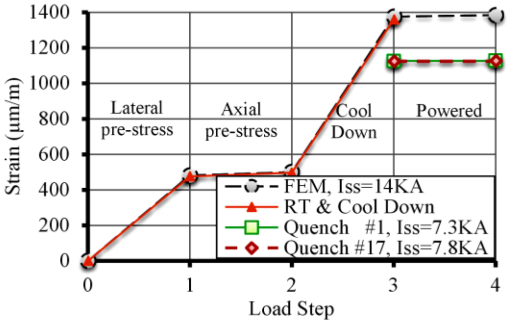

Fig. 7. SMC1: Azimuthal strain on the shell (strain gauge 3) during the magnet operating cycle, from assembly to 100% of the Lorentz forces.

As expected from the assembly test with the dummy-coil (Fig. 6), the strain in the shell increases by almost 900 µm/m during cooling-down. A drift of 230 µm/m (Fig. 7) in the measured values was observed between the end of the cooling down procedure until the beginning of the first training quench. The FE model follows the strain variation tendency, but this reduction in the strain is not predicted, possibly due to the frictionless model. The calculated and the measured strain values, at room and cryogenic temperature, are compared in Table IV.

TABLE IV SMC1 RESULTS COMPARISON

Component	293 K		4.2 K	
	FEM	Test	FEM	Test
Shell	500	496	1375	1360
Rod	2066	2064	3258	3240

C. *SMC3*

The assembly, instrumentation, cold powering tests and test results of SMC3, are extensively described in [1]. Similar to Fig. 7, the azimuthal strain on the shell, in the region of strain gauge 0 (Fig. 1) is presented in Fig. 8.

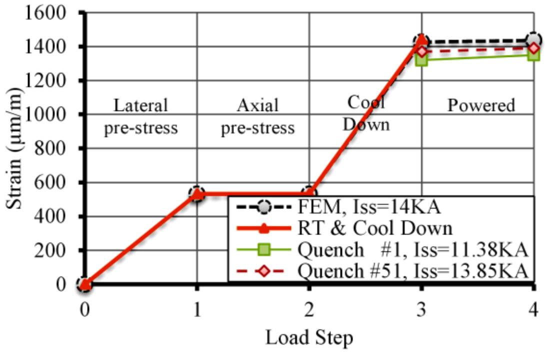

Fig. 8. SMC3: Azimuthal strain on the shell (strain gauge 0 (Fig. 1)) during the magnet operating cycle, from assembly to 100% of the Lorentz forces.

The strain in the shell increases, as expected, by almost 900μm/m during cooling-down. It is important to notice that in the 48 hours elapsed between the end of the cooling down process and the first training quench, a loss in the measured strain of 120 μm/m is recorded. This reduction corresponds to a loss of 9 MPa of the stress in the middle of the coil's straight section, according to the FEM. The total reduction in the strain on the shell between the end of the cooling down process and the first training quench was significant lower in SMC3 than in SMC1. This can be explained by the larger amount of horizontal pre-stress in SMC3.

From the first to the last training quench, a gain of 50 μm/m can be observed. The effect of friction is clear (Fig. 8) causing stick/slip behavior and surface adhesion effect, often referred-to as ratcheting.

Fig. 9 shows the lateral strain, in strain gauge 1 (Fig. 10) on the island. The friction effect results in a total gain of 70 μm/m of the strain between the end of the cool down process and the last training quench

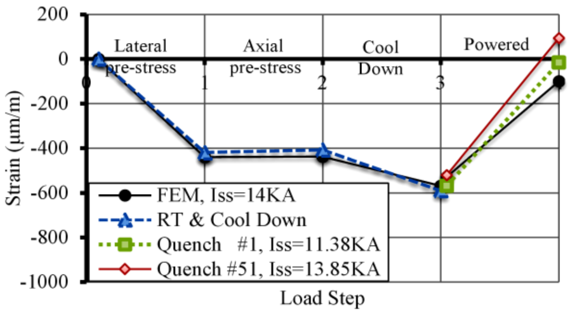

Fig. 9. SMC3: Lateral strain on the island (strain gauge 1 (Fig. 10)) during the magnet operating cycle, from assembly to 100 % of the Lorentz forces.

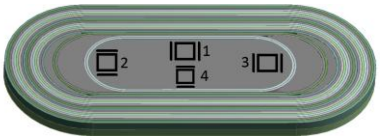

Fig. 10. Schematic view of the SMC coil. The results presented in this paper, for SMC3, are from Coil 2, upper layer [1], strain gauges 1 and 4, which measure in the lateral and axial direction respectively.

The calculated and the measured strain values, at room and cryogenic temperature, are compared in Table V.

TABLE V SMC3 RESULTS COMPARISON

Component	293 K		4.2 K	
	FEM	Test	FEM	Test
Shell	532	533	1430	1443
Rod	45	41	1193	-
Island (Str. Gau.1)	-437	-409	-570	-590
Island (Str. Gau.4)	256	281	-232	-275

IV. CONCLUSION

The integrated 3D design of the SMC assembly, featuring the magnetic and structural FE analysis besides the advanced CAD Tools, has been presented. The goal to build a powerful, fast and accurate system of all used software along with their imported parameters, in an integrated design environment, has been achieved. The results between the magnetic and structural analysis and the measured, from the strain gauges, values during all tests of the SMC, have been cross-checked and proved to have a good relation. The differences observed are possibly due to the frictionless model. Further improvement of the 3D design includes friction definition and examination of the contact status in the coil block, which is a reason for magnet quenches. SMC3 showed an excellent performance of Nb_3Sn coils, reaching a peak field of 12.5T.

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