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3D FEM Modeling of the Coil Ends of the LHC Main Dipole

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3D FEM Modeling of the Coil Ends of the LHC Main Dipole

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***Abstract*— A 3D finite element mechanical model has been developed to simulate the complex geometry of the extremities of the coils for the LHC main dipoles. The final aim is to evaluate the possible impact of coil defects on quench performances. In this paper we describe the first part of the work that has been carried out. This covers an analysis of the contribution of the mechanical properties of the different materials to the rigidity of the coil heads and the experimental validation of the model. For such validation we compared the computed stiffness with the values observed during production measurements in industry. The numerical results are in good agreement with the measured; some discrepancies in the intermediate zone of the end point out also in which direction the modeling should be refined.**

***Index Terms*— Accelerator magnets, mechanical engineering**

I. Introduction

THE LHC Main Dipoles are 15m long twin aperture superconducting magnets based on classic cosθ 2 layers coil design. The contracts for the production of 1248 units have been equally split among 3 firms (Cold Mass Assemblers) [1]. Each aperture consists of 2 identical poles. Every pole consists of one inner and one outer layer connected in series. The extremities of the coils are wound by placing the cable on composite (epoxy-fiber glass, G11) machined end spacers (Fig. 1 and Fig. 2) [2]. The extremities of the coil (called ends or also heads) have a very complex topology and the local magnetic and mechanical behavior needs to be studied with a full 3D approach. The aim of this work has been to develop a 3D FEM mechanical model to try to reproduce the mechanical behavior of this region and to validate it by means of the extensive experimental data now available. The work has been triggered by the observation that few produced coils were affected by cracks in the head spacers. The final aim would be to define which is maximum flaw that can be accepted without impairing the magnet performance also taking into consideration possible evolution with fatigue. To provide an accurate description of the loads, at which each end spacer is submitted, and their cycles during the LHC life an accurate FEM modeling is necessary.

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II. The 3D FEM Model

The model was built using the ANSYS code [3] and it reproduces half of the non connection side pole extremity, this head being symmetric. The topology of the model is built reading the coordinates of the key-points, which define the volume geometry, from 3 ASCII files that are directly derived from the program used to design the end spacers. The volumes are automatically generated starting from these points providing the solid models as shown in Fig. 3 (inner layer) and in Fig. 4 (outer layer). To mesh the model, 20 nodes elements were used and the mesh was optimized to reduce the number of elements degenerating into tetrahedral shapes. The region of mesh singularities were confined to zones of lower interest far from the superconducting winding. The model constrains the outer surface of the pole in radial direction while it is azimuthally compressed by applying a displacement or a pressure along the mid plane, thus simulating the conditions during the production control measurements.

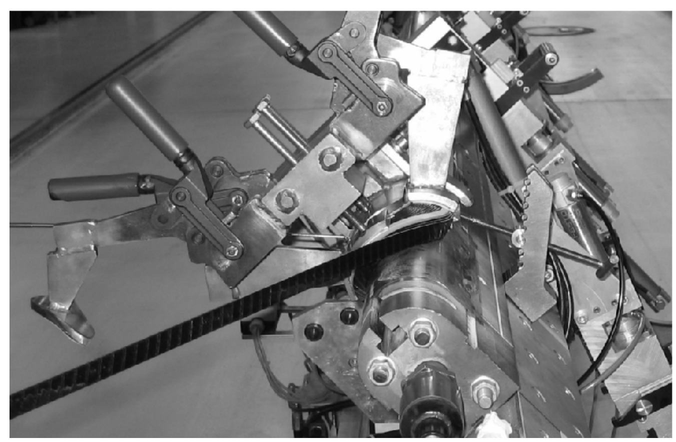

Fig. 1. Winding of coils heads.

III. The Experimental Measurements

In order to validate the model it was decided to use the mechanical measurements carried out at the 3 Cold Mass Assemblers. These measurements are performed by closing the coils' heads in a rigid cavity and measuring the pressure along the coil mid plane. The data acquisition is performed by an ad hoc developed pressure sensor composed by a matrix of sensitive points. This feature provides a very detailed map of the pressure distribution. The measurements are performed on poles and it is possible to change the dimension of the cavity in order to measure the head in a set volume smaller or larger than the nominal one. The measurements used in this work have been performed on 31 different poles and with various cavity conditions providing a total of more than 120 measurements.

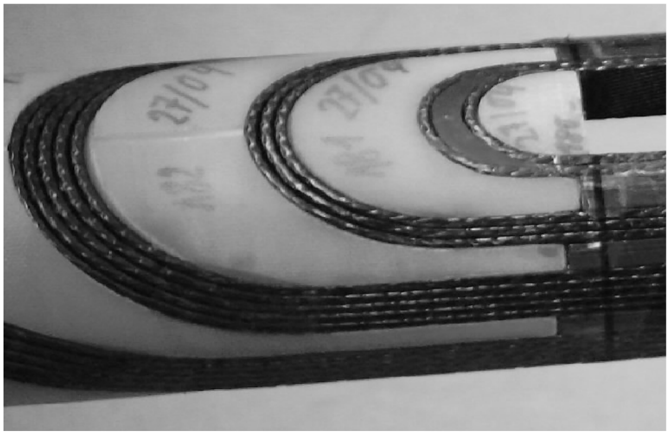
Fig. 2. Detail of inner layer coil non connection side head

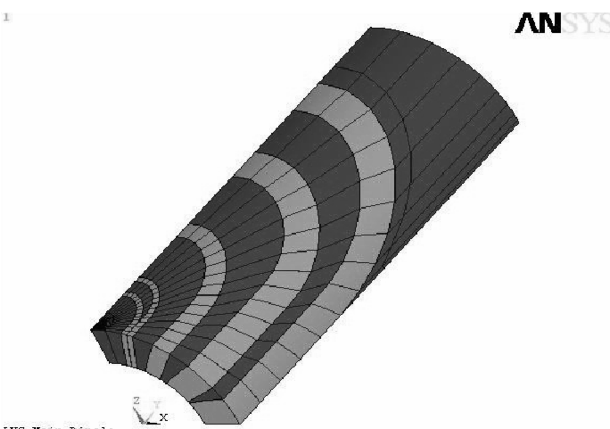

Fig. 3. The inner layer model extracted from the pole model. In light color the superconducting windings, in dark the composite spacers.

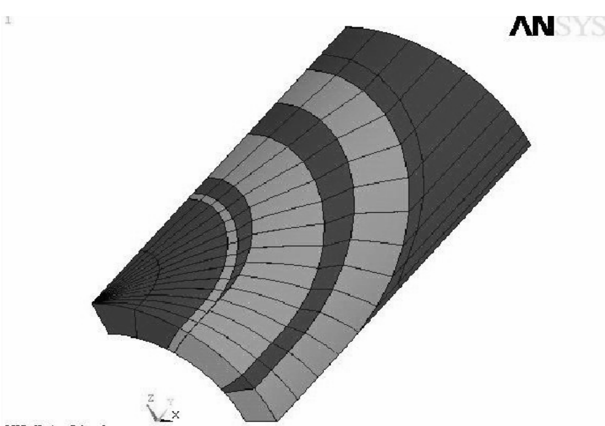

Fig. 4. The outer layer model extracted from the pole. In light color the superconducting windings, in dark the composite spacers.

The measurements are averaged in 5 zones of 35 mm each which cover almost completely the 180mm of the pole head length. Each zone is the average of the values acquired via 42 sensitive points. Zone 1 is the zone of the head near the straight part, while zone 5 is the one placed near the end of the coil, under the last saddle shaped spacer. A typical outcome of such measurements (in term of pressure profile) is shown in Fig. 5 where it is worth remarking the reduction in dimension of the coil towards the extremity. These measurements are used during collared coils assembly in order to compute the shims that have to be implemented to guarantee the adequate pre-stress in the heads after collaring.

The end spacers have dimensions that can vary inside the tolerances range (typically +/- 0.05 mm) and the process of producing the coils (winding and curing) also contributes to the variation of the coils size. These two contributions are the source of the variation of the recorded pressure profile from one coil to another. Therefore in this work we will not try to reproduce the pressure distribution in its absolute values as reported in Fig. 5, but we will try to verify if the model provides adequate evaluation of the stiffness in the 5 measuring regions. The local (azimuthal) stiffness is defined here as the variation in azimuthal pressure load [MPa] for a compressive displacement of 0.1mm of the pole mid-plane.

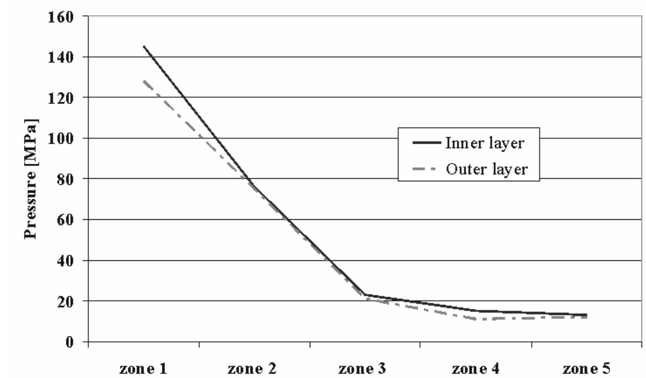

Fig. 5. Example of measure azimuthal pressure profile along the pole mid-plane. Measurement reported in the 5 averaging zones.

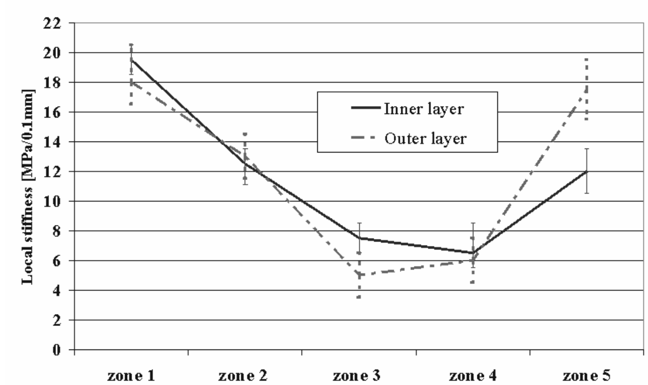

Fig. 6. Head coil azimuthal stiffness (MPa/0.1mm) in the 5 averaging regions measured along the coils' heads.

The results of the measurements are reported in Fig. 6 where the average values and the spread are shown for each region. The reported curves correspond to an average pressure on the coil of 140 MPa in zone I, 95 MPa in zone II, 30 MPa in zone III, 20 MPa in zone IV and 30 MPa in zone V.

The stiffness of the coil changes very much (up to a factor 5) along the coil head demonstrating that is not possible to perform any meaningful 2D mechanical analyses of this region.

IV. Computation Results: Linear Model

The first series of computations were carried out using linear properties for all the materials. Two main components constitute the heads: the spacer and the superconducting winding. The spacers are machined in G11 epoxy-fiber glass pipes and the raw material has been submitted to mechanical tests in order to measure the Young Modulus in 3 directions. The data are reported in Table I [4]. It is worth remarking the difference in azimutal modulus between the material used to produce the inner layer spacers and the one used for the outer layer. This difference could be probably linked to differences in the resin/glass ratio and its compaction. Concerning the superconducting windings, an average azimuthal E-modulus (Eθ), computed along the loading curve from 30 MPa to 180 MPa, has been used. This method provides a value of 10500 MPa for the inner layer and 9000 MPa for the outer. For the radial modulus we used a value of 13000 MPa. For the direction along the cable itself (Ez) a value of 3900 MPa has been assumed being this value, the lowest for which it has been possible to obtain numerical convergence of the model. At the moment measurements of the Ez modulus for a stack of cable are not available. In order to follow the bending of the cable and therefore the change in direction of the material properties (Fig. 7) it has been necessary to set up a macro that redirects the element axis according to the cable direction. Such macro rotates the element axis on the base of the volume vertex coordinates. The model has been uniformly compressed along the head length and the change in compressive load for 0.1 mm of extra displacement has been evaluated.

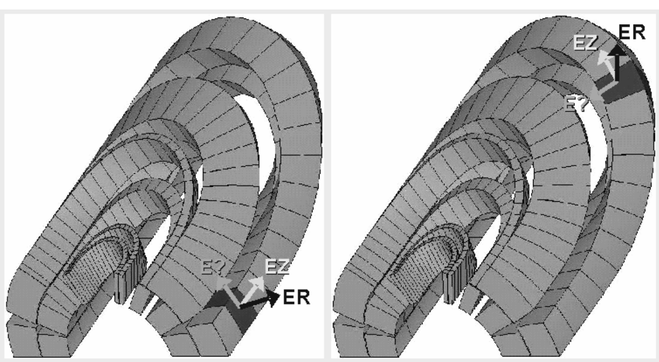

Fig. 7. Orientation of the material and elements reference axis along the superconducting windings.

TABLE I
MECHANICAL PROPERIES OF G11 USED FOR THE END SPACERS

	Spacer inner layer	Spacer outer layer
E radial [MPa]	32000	32000
E azimuth [MPa]	15000	12000
E long [MPa]	13000	13000

The results are shown in Table II and they show that the agreement between the experimental data and computational results is quite poor. It is nevertheless possible to use this linear model to evaluate the importance of the different material properties for each of the 5 regions, evaluating the sensitivity of the stiffness parameter to the change in material properties.

TABLE II
RESULTS FOR THE LINEAR MODEL

Zone	Inner layer coil local stiffness [MPa/0.1mm]		Outer layer coil local stiffness [MPa/0.1mm]	
	Exp. Results (min/max)	Computed value	Exp. Results (min/max)	Computed value
I	18/22	23	17/19	20
II	11/14	22	11/14	17
III	6/9	17	4/6	14
IV	5/8	17	5/8	14
V	10/14	20	16/19	17

The results obtained are shown in Fig. 8 and Fig. 9 for what it concerns the outer layer. The values are normalized to the assumed nominal values for the Eθ and Ez and also the stiffness is normalized to the corresponding computed values. In Fig. 8 it is evident how the importance of the modulus Eθ decreases towards the end of the pole. In fact there is a decreasing sensitivity of the results to this parameter as we move from region 1 to 5: in zone 1 doubling the Eθ modulus corresponds to multiplying the local stiffness by 1.5 while for the same change in zone 4 we get only a 20% increase. On the contrary for the modulus Ez we can see that the two more sensitive regions are the ones where the cable bends and the material properties are rotated of 90º respect the region 1. Zone 1 seems nevertheless to be sensitive to the Ez modulus for low values of this parameter and after to saturate.

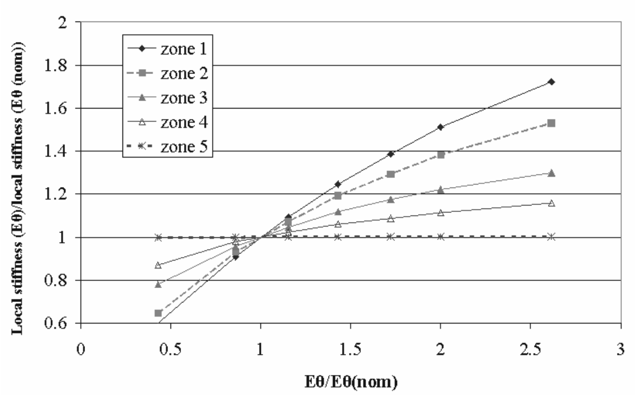

Fig. 8. Sensitivity of the local azimuthal stiffness in function of the azimuthal Young modulus (Eθ).

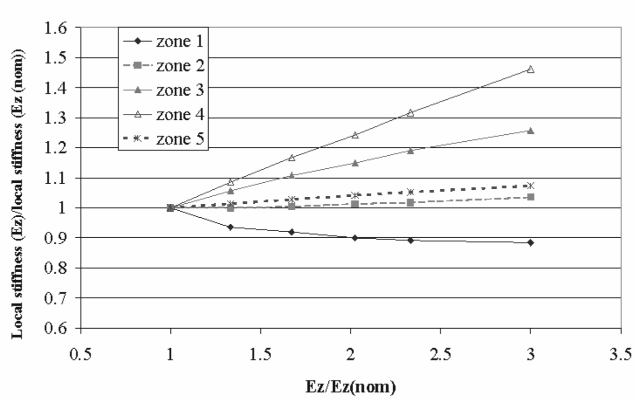

Fig. 9. Sensitivity of the local azimuthal stiffness in function of the cable longitudinal Young modulus (Ez).

V. Computation Results: Non Linear Model

In order to improve the quality of the results it is possible to use a better description of the Eθ modulus introducing the real modulus that is not linear and it increases with the load. The methodology followed is via ANSYS MELAS [5] option that allow defining multilinear materials. Unfortunately this option does not allow dealing with anisotropic materials therefore it has been decided to use the Eθ value for all the 3 directions. The curves of Eθ used are based on the set of measurements performed routinely on the coil straight part by the Cold Mass Assemblers. In the heads the copper wedges, that in the straight part allow to correctly position the cables. are substituted by the extremities of the G11 end spacers. It is therefore necessary to modify the measured data in order to eliminate the contribution of the copper to the material rigidity The curves used are reported in Fig. 10. As consequence of the stiffening of the modulus Eθ with increasing load, it has been now necessary to charge the model with the same load distribution, along the mid-plane pole length, that was obtained during the measurements. The average measured load has been used (zone I 140MPa, zone II 95 MPa , zone III 30 MPa, zone IV 20 MPa, zone V 30 MPa).

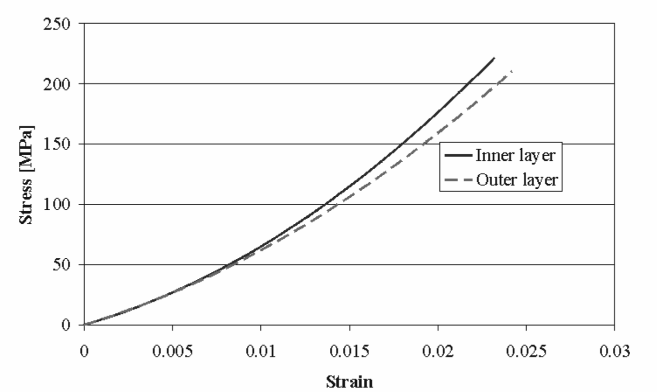

Fig. 10 Azimuthal modulus (Eθ) for the inner layer and the outer layer insulated superconducting coil block, derived from measurements on the coil straight part after eliminating the contribution to the rigidity of the copper wedges.

The results obtained are reported in Table III and they show that:

- The agreement with the experimental results is much improved respect to the previous model
- The agreement is better for the outer layer than for the inner one. For the inner layer the computed values overestimate the stiffness of the structure.
- The agreement in the zone I is quite good for both layers and it becomes worst in the region III and IV where the cables bend.

VI. Conclusion and Future Activities

A 3D mechanical model of the LHC pole heads has been developed. It has been demonstrated how the various materials contribute, with different importance, to the stiffness of the pole head itself, being the azimuthal properties of the superconducting cable stacks the dominant element in the regions I and II while the Ez modulus (along the cable direction) acquires more importance in the regions 3 and 4. A model that takes into account the non linear mechanical behavior of the superconducting coil provides better results, but it assumes that the materials are isotropic and therefore accuracy is lost in the zones III and zone IV.

TABLE III
Results for the Non-Linear Model

Zone	Inner layer coil local stiffness [MPa]		Outer layer coil local stiffness [MPa]	
	Exp. Results (min/max)	Computed value	Exp. Results (min/max)	Computed value
I	18/22	19.5	17/19	15
II	11/14	17.5	11/14	12
III	6/9	14	4/6	7
IV	5/8	13	5/8	8.5
V	10/14	18.5	16/19	14.5

The use of the present modeling has been restricted to the behavior of the pole at room temperature before assembly. Further modeling will be implemented to simulate the behavior of the pole head inside the magnet, during cooling down and in excitation. In order to improve the accuracy of the model it is necessary to

- Refine the boundaries between coil blocks and end spacers
- Perform measurements to qualify the mechanical properties of a cable stack along the direction of the cables (Ez). Such measurements shall be performed pre-loading the cable stacks at different levels of azimuthal compression in order to measure the stiffening of the block when the load increases. The measurements have to be carried out both under compression and under tension; the last being necessary to have a full set of data for the model with electromagnetic forces.

Acknowledgment

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