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The Use of a New Modular Approach in the Mechanical Design of Superconducting Magnets

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[1] ***Abstract*— This paper focuses on the mechanical design of superconducting magnets with a new modular approach developed by a mechanical research laboratory (the LMT-Cachan). The structure of superconducting magnets exhibits many frictional contact zones, the loading conditions are complex and the results must be more and more accurate. The use of classical finite element method can be heavy and difficult. So a new modular approach, described here in, can treat the same problem with more efficiency and with a less numerical cost.**

***Index Terms*—Numerical method, E.F. Computations, Contact, Friction, Design.**

I. Introduction

THE design of superconducting magnets requires to compute significant and complex numerical problems. Large size of the problems (three dimensional meshes) and the necessity to take into account many no linearities (frictional contact zones, mechanical behaviours, etc.) generate difficulties of resolution and convergence when classical finite element methods are used as the industrials codes. So, the LMT-Cachan has developed a new modular approach making it possible to compute with efficiency an assembly of three-dimensional structures with a large number of contact zones. The COFAST3D approach is based on both a decomposition of the structure and a particular iterative resolution scheme. Recently, the STCM used this new method to design superconducting magnets. In this paper, we will present the main aspects of both the approach and the treatment of contact problems. The approach is applied to the design of superconducting magnet and we will show the reduction of the numerical cost with regards to the classical FE method Within the framework of the design of superconducting magnets at the STCM, we will present several applications and the accuracy of the approach, such as Nb3Sn magnet (Fig. 1).

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II. COFAST3D Approach Description

The COFAST3D approach is based on both a formulation and a strategy which have been adapted to the use of parallel computers [1][2]. The partitioning of the structure is performed so as to break down the problem from its global formulation. A partitioning involves two distinct mechanical entities: substructures and interfaces. Each substructure is considered as a separate structure on its own which only communicates with its adjoining interfaces. Interfaces, in the other hand, constitute the key elements to this approach; they are two-dimensional entities which exhibit their own individual behavior and which can be represented in a mixed manner on the displacement and force fields defined on both sides of the interface.

When only perfect connections are considered, this algorithm can be obtain by other approach such as Glowinski and Le Tallec [3]. In the case of frictional contact conditions it is not very far from the augmented Lagragian algorithms as presented in Simo and Laursen [4]

A. Decomposition of the structure

When considering an assembly of various components using linkage elements (coils, wedges, collars, etc.), a decomposition can be introduced (see Fig.2). The components are separated, and the interfaces (γ^{12}) generated serve to model the connections existing between these elements: contact, friction, etc. For this study, each component is a substructure (Ω^1). To reduce again the size of the model, some components can also be separated into substructures. A displacement field W^1 and a surface force density field F^1 permit to describe the interactions between substructures and interfaces.

B. Substructure

Since a given substructure (Ω^1) communicates only with interfaces (γ^{12}), the problem to be solved consists of finding the couple of stress and strain $\{\sigma^1, \varepsilon^1\}$ that satisfies the following equation:

Cinematic admissibility with the displacement on the interfaces (Ω^1):

$$U^1\Big|_{\partial\Omega^1} = W^1, \text{and "regular" in } \Omega^1 \quad (1)$$

Equilibrium equation under the force field on the interfaces:

$$\forall U^* \in U^{1,0} = \left(U^*|_{\partial\Omega^1} = 0, \text{"regular"}\right)$$

$$\int_{\Omega^1} Tr[\sigma^1.\varepsilon(U^*)]\, d\Omega = \int_{\Omega^1} fd.U^*\, d\Omega + \int_{\partial\Omega^1} F^1.U^*\, dS \quad (2)$$

Constitutive law:

$$\sigma^1 = K.\varepsilon(U^*)\,(K: \text{Hookes's operator}) \quad (3)$$

where *fd* is the prescribed body forces, U^* the displacement field being sought in Ω^1, σ^1 the stress field being sought in Ω^1, and $\varepsilon(U^*)$ the strain field generated by the displacement U^*.

C. *The interface*

The problem to be solved on one interface consists of finding the force and displacement fields on both sides that satisfy the behaviour of the modeled connection. The problem on the interface γ^{12} can then be expressed as a constitutive relation:

$$R(W^1(M), F^1(M); W^2(M), F^2(M)) = 0$$
$$\forall M \in \gamma^{12} \quad (4)$$

For example the relation that described a perfect connection between two substructure Ω^1 and Ω^2 is:

$$W^1(M) = W^2(M), \text{continuity of displacement} \quad (5)$$

$$F1(M) + F2(M) = 0, \text{equilibrium of forces} \quad (6)$$

In the case of a contact connection between Ω^1 and Ω^2:

$$\pi F^1(M) = \pi F^2(M) = 0 \quad (7)$$

if separation:

$$N(W^1(M) - W^2(M)) \geq 0 \text{ and}$$
$$NF^1(M) = N(F^2(M) = 0 \quad (8)$$

if contact:

$$N(W^1(M) - W^2(M)) = 0 \text{ and}$$
$$NF^1(M) + N(F^2(M) = 0 \quad (9)$$

where π is the tangential projection operator and N denotes the external unit vector.

D. *Iterative scheme*

The iterative resolution scheme employed is based on the Large Time Increment method ("LATIN" method) proposed by Ladevèze (in 1998) [1]. The LATIN method separates out the problem's difficulties; it enables avoiding the simultaneity of the global and non-linear aspects. Thus, it incorporates the mechanical properties of the equations in order to divide equations in two groups:

- Local in space variable, and possibility non-linear, equations
- Linear and possibility global in space variable equations

These groups serve to define two subspaces of elements s, which denotes the set of unknowns for the entire problem. Since the only non-linearities being studied are those defined on the interfaces and in order to obtain independent global linear problems on each substructure, the two subspaces are to be defined as follows:

Ad = { $s \in S$ satisfying $\forall\Omega^1$:
- the cinematic admissibility, as in (1)
- the equilibrium equation, as in (2)
- the constitutive law on Ω^1, as in (3)}

Γ = { $s \in S$ satisfying $\forall\gamma^{12}$
- constitutive relation, as in (4)}

The used algorithm consists of finding a solution element that satisfies both the behaviour of the subtrucutres (s Ad) and the behaviour of the interfaces (s Γ). Each iteration give an approximate solution whose accuracy is know. The problem to calculate the solution that satisfies the first subspace (Ad) is a classical linear for each substructure (E.F. is well used). The problem to calculate the solution that satisfies the second subspaces (Γ) is a local non-linear in each point of each interfaces. In the case of static friction or perfect contact, the solution is explicit. The LATIN method and the numerical implementation are described in [2] and [1]. A complete presentation of the COFAST3D and the LATIN method is well described in [5].

III. Application to Design Superconducting Magnets : the Cross Section of the Superconducting Quadrupole Magnet

A. *Presentation of the mechanical design*

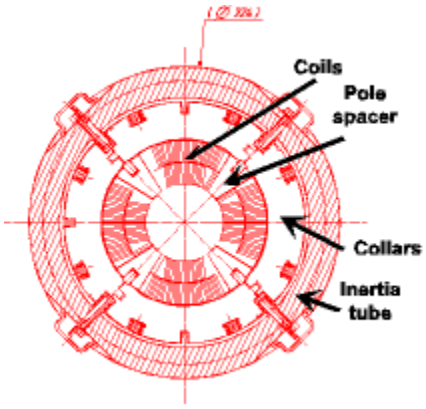

Fig. 1 : Cross section of the Nb3Sn quadrupole magnet.

The magnet coils is be produced according to the “wind, react & impregnate” technique. Prior to winding, the un-reacted Nb_3Sn cable will be wrapped with a mineral fiber tape. Upon winding completion, the whole coil will be subjected to the heat treatment required for Nb_3Sn compound

formation (typically: 660 ºC for 240 hours). After heat treatment, the coil will be vacuum-impregnated with epoxy resin. It is worth mentioning that an alternative insulation scheme is being investigated by DAPNIA/STCM, that may eliminate the need for a vacuum-impregnation, but the design and the computations reported here correspond to the standard (mineral fiber tape + epoxy resin) scheme [6]

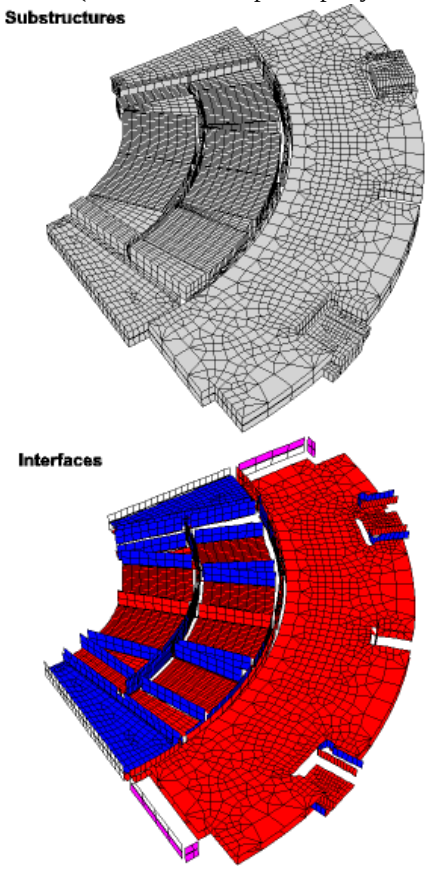

Fig. 2 : Substructures and interfaces of the mechanical model of the cross section of the Nb3sn quadrupole magnet. The grey interfaces corresponding to the unilateral or bilateral contact, the black interfaces for the perfect connection and white interfaces for the symmetry conditions.

As in LHC arc quadrupole magnets [7], the coils will be restrained by laminated, 2-mm-thick, austenitic steel collars locked around them by tapered keys. However, unlike in LHC arc quadrupole magnets, there will be no iron yoke and the collared-coil assembly will be centered directly within a precisely-machined, steel inertia tube delimiting the region of liquid helium circulation. A sketch of the quadrupole magnet cold mass is shown in Fig.1.

We shall now report on a mechanical computations, which have been carried out to dimension the coil support structure. The objectives of the mechanical design are: (1) all parts of coils should remain in compression at nominal current, (2) peak stress in coils should be less than 150 MPa at all time, and (3) collar deflections and stress under various loading conditions should not exceed those of the LHC arc quadrupole magnets.

B. Description of the model

The model under study is restricted to $1/4^{th}$ of the quadrupole magnet cross section. It includes two levels of collars; two keys, four stripping keys, the insulation, the angular and polar wedges and the conductors blocks. Friction is considered on all contact zones. In Fig.2, the substructures and the interfaces are illustrated and a 3D mesh of the structure has been developed.

The mechanical loading can be divided into three different parts corresponding to the history of the superconducting magnet assembly and operation:

- pre-loading applied during assembly process
- Cool down from 293K and 4.2K
- and the Lorentz forces application during energization

The magnet assembly corresponds to a two step collaring process. The first step was modeled by applying surface forces onto the bottom of the collar keyways along the pole axes. Then, the second step was described by prescribing gap between the sides of the keys and the stripping keys. Its correspond to the insertion of the keys into collar keyways.

Cooling is modeled by an applied thermal body force over the entire structure. The temperature distribution throughout cool-down was assumed to be uniform.

Afterwards, the Lorentz forces can be modeled by a pre-computed body force field on the coil. Two types of Lorentz forces are induced in the TESLA final focusing quadrupole magnets. The first type was due to the quadrupole magnetic field versus the current, and the second was due to the solenoid magnetic field versus the current in the end parts of the quadrupole.

C. Results

The three successive loads have been applied to the structure. So, we analyze the final state (energization). Some results are illustrated in Fig.3.

At 14000 A and without solenoid magnetic field, all parts of coils remain under compression. The external collar radius must be increased to minimize the collar deflection. With this new radius value, the deflections was similar to the LHC Arc Quadrupole (d_{radial} = –0.013 mm for $d_{réf}$ = –0.010 mm).

The peak stress in collars remains under the ultimate stress (σ_{VM} = 1000 MPa for σ_{ult} = 1600 MPa).

At 14000 A and with solenoid magnetic field, all parts of coils remain under compression. The radial deflection was high (d_{radial} = ±0.2 mm). So, a mechanical support will be added to prevent any damage or to restrain coil deflection.

The peak stress in te collar remains under the ultimate stress(σ_{VM} = 1250 MPa for σ_{ult} = 1600 MPa).

D. Comparison with the use of standard contact tools

Other computations were made with a standard Element Finite Code, in particular with standard contact tools [8]One complete simulation requires several hours with a lot of

difficulty to obtain the convergence of the solution. Conversely, with the COFAST3D method, the computation requires only few minutes, with more sophisticated 3D mesh (2D for the standard contact tools). Some comparisons were made with an industrial E.F. code in [2].

E. Comparison with the experimental data

An experimental device was developed to check the accuracy of the numerical model during the first two steps; the collaring process and the cool down at 77K. Four fiber glass epoxy blocks make up the 200-mm long device. Two hundred collars, and eight tapered keys were used. Each block was instrumented with two strain gauges and one capacitive sensor.

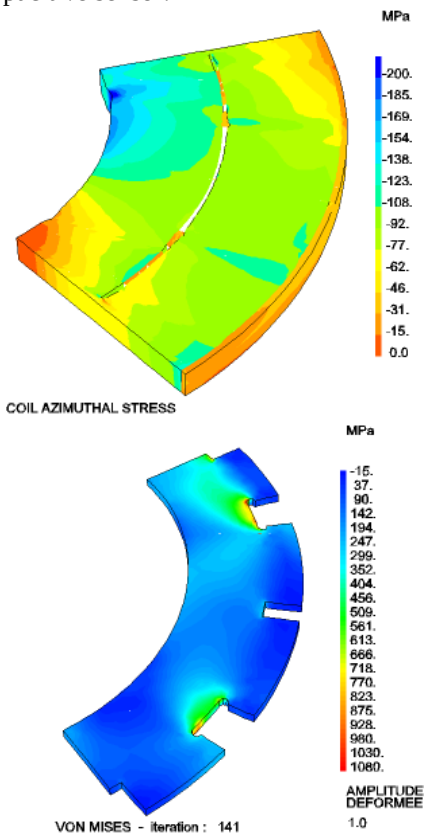

Fig.3. Azimuthal stress distribution in quadrupole magnet coils and Von Mises stress distribuion in quadrupole magnet collars at 14000 A and with solenoidal field

At the end of the collaring process, the strain measured is -0.754 % versus -0.725 for the simulated strain. And after the cool down, the model estimates the loss of prestrain to 0.114% to be compared to the experimental loss of prestrain to 0.132%.

Other experimental data are also used to verify and to confirm the good agreement of the numerical results, in particular for the main LHC quadrupole [9].

IV. Conclusions

When one compares the different results obtained at different step of the studied loading, the numerical model and the modular approach can be used, not only to check, but also to predict the behaviour of the structure with different loading.

So, this new modular approach gives more efficiency and less numerical cost than a standard E.F. approach used in an industrial code.

So, a 3D analysis of the coil end regions of the quadrupole magnet are modeled with the new modular approach (see Fig.4.). It was intended to understand the quench behaviour by analyzing the mechanical state under several loading.

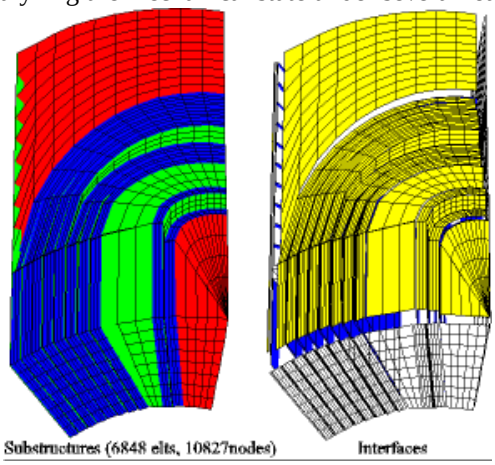

Fig.4. Substructures (6848 elts and 10827 nodes) and Interfaces of the end parts model

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