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Development of an integrated thermo-mechanical simulation environment for quench analyses in HTS cables for fusion

M. De Bastiani, R. Bonifetto, V. Corato, D. P. Boso, R. Zanino, A. Zappatore

***Abstract*—In the last years several experimental campaigns have been carried out to assess the performance of High Temperature Superconducting (HTS) cables for nuclear fusion applications. In such experiments it has been often observed that cable performance in terms of critical current (I_c) degrade, mainly after quenches. The nature of the degradation is not completely assessed, but secondary strains given by temperature increase are considered to be its responsible. To confirm such statement it is necessary to develop a tool capable of reproducing the quench effects both from the thermal and from the mechanical points of view, aiming at retrieving the induced strain field in the conductor itself. The aim of this work is presenting the development of a simulation environment which embeds both the required features mentioned above. The thermal-hydraulic (TH) aspects of the quench are analysed here with the H4C code, developed at Politecnico di Torino and spreadly validated against several quench campaigns in SULTAN. The output of the H4C code represents an optimum set of inputs for a detailed mechanical model of the cable. For this reason a python API has been developed making the H4C code communicate with ANSYS, used to compute, on the base of the temperature profiles in input, the consequent strain field. The simulation environment developed has been applied to a slotted core HTS conductor to check its functionalities, showing good agreement with the physical expectations.**

***Index Terms*—HTS cables, nuclear fusion, quench, numerical modeling, FE analysis, Thermo-mechanics.**

I. Introduction

In the last years an increasing interest on the use of High Temperature Superconducting (HTS) cables for nuclear fusion application has been registered [1], [2], [3], [4] and several different cable concepts have been presented, such as those proposed by ENEA [5], [6], Swiss Plasma Center [7], Karlsruhe Institute of Technology [8], Advanced Conductor Technology [9], Commonwealth Fusion Systems [10] and North China Electric Power University [11]. A certain number of the above mentioned cables have been already tested and several of them showed performance degradation after quench. The reduction of the critical current (I_c) in HTS tapes due to strain is a well known effect [12], [13] and it is assumed that the observed I_c degradation during HTS cable quenches may be induced by secondary strains arising from the sharp, localized temperature rise. The secondary strains which are arising during the cable quench cannot be measured, so that, to verify their real impact on the cable performance degradation, it is necessary to have a tool capable of reconstructing the strain field during a quench. To do so it is fundamental to rely on a tool which properly reproduces the cable temperature evolution and distribution along the transient and uses it as input to a mechanical model which evaluates the subsequent cable deformation, from which the strain field can be retrieved. In this work, the development of a simulation environment which embeds the above mentioned features is presented. The thermal-hydraulic modeling is based on the H4C code [14], developed at Politecnico di Torino with the aim of simulating from the electrical and thermal-hydraulic point of view transients in HTS conductors and already validated against experimental data [15]. The H4C code is a multi-region 1D finite element model which is able to simulate quenches in HTS conductors accounting for both the current redistribution within the cable and all the thermal-hydraulic aspects, providing, at the end, reliable and well detailed temperature profiles along the cable regions. Such profiles may be used as temperature field within a mechanical model to compute the induced strain field. For this purpose, a python API based on the PyMAPDL package [16] has been developed, that: (i) builds the geometry and mesh, (ii) suitably interpolates the thermal load coming from the H4C on the mechanical model, (iii) applies boundary conditions (BCs), (iv) solves the problem (using the ANSYS solver [17]) and (v) post processes the obtained results. As for the H4C, also the mechanical model is parametric and can be adapted to different cable geometries. After the description of the simulation environment, its test on two hypothetical quenches in the slotted core ENEA conductor is presented, assessing its physical coherence and the impact of different BCs and contact type on the final results.

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II. TH modeling of quenches with H4C code

The H4C code has been developed with the aim of modeling TH and electrical transients in HTS cables for fusion and has been already extensively adopted for modeling quenches in such cables [18] and even in full coils [19]. This code solves, along the cable axis, a set of 1D coupled equation: (i) heat diffusion in each solid region, (ii) mass, momentum and energy conservation in each fluid region and (iii) a diffusion-like equation for the current distribution in each electrical region. The number of regions is completely arbitrary and

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it can be adjusted according to the cable design at hand, being, differently with respect to LTS cables, not appropriate to consider the solid as a single region, due to the stronger temperature gradients arising in the conductor cross section, especially in fast transients such as quenches [20]. On the base of the above, and of the already mentioned validations, the H4C code can reliably reproduce the quench evolution in several different HTS cable concepts, considering both TH and electrical aspects. Eventually, the code output will contain, among others, the evolution of temperature profiles in each fluid and solid regions, which are considered to be the best available input for a thermo-mechanical model aiming at assessing the possible I_c permanent degradation due to strain.

III. Development of a Thermo-mechanical simulation environment based on H4C code and ANSYS

The thermo-mechanical simulation environment should be able to interact automatically with the H4C code to get the inputs and which may be as flexible as the H4C in adapting to different cable designs. For this reason a python API based on PyMAPDL package has been developed. The PyMAPDL python package has been directly developed by ANSYS as a python-ANSYS interface which allows to embed the workflow of a ANSYS simulation, based on the APDL parametric language, suitably translated in different python classes and methods, in a python script. This allows the developer to use both the the capabilities of ANSYS in solving mechanical problems, as well as those of python, which can help in data manipulation, preparation, visualization and automatization of repetitive tasks. Indeed, through python scripts it is easy to interact with the H4C outputs while through the PyMAPDL package it is possible to prepare and solve the mechanical model. The main advantage of this approach is the possibility of building fully parametric models to cope with different cable designs, with the same flexibility of the H4C code. In principle the developed API may also interact with the 4C code [21], being therefore applicable to LTS cables (and magnets) as well. The scheme reported in Figure 1 summarizes the logic of the developed API. As reported in the scheme, the

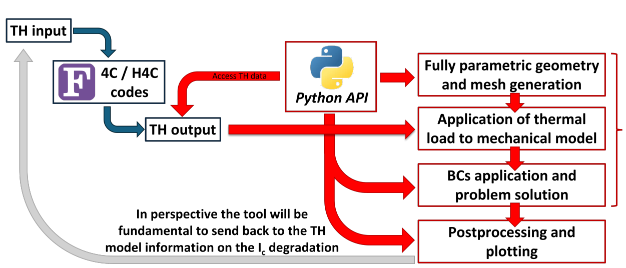

Fig. 1. Schematic representation of the API logic implemented, highlighting the interaction with the TH model and the main subroutines of the mechanical one: the TH (and electrical) model is first run and then the computed temperature field is used as input to the independent mechanical simulation.

python API interacts with the TH model outputs to collect the relevant information and produces the fully parametric geometry and mesh to be used in the mechanical analysis. Such a mesh is also user-defined in terms of dimensionality, refinement and type, bases on the problem at hand. In the case of the cable quench analysis, a 3D mechanical model is adopted, but the API is capable of producing 2D meshes as well, if required. Once the mesh is built, the API applies to the mechanical model the thermal loads obtained from the TH model. In the case of the cable analysis, the 1D axial temperature profiles of each solid region of the cable are forced in the corresponding regions of the mechanical model. As a consequence, the temperature within each region (e.g. stacks, core, jacket, etc.) will be uniform on the cross section. Since no unique correspondence between the axial node location in the 1D thermal model and in the 3D mechanical one is guaranteed, an interpolation between the two grids is performed.Boundary conditions are then fixed, according to the simulated case, and the problem can be solved using the Mechanical APDL solvers. In this model . This step, as well as each of two previous ones, may be run in parallel to reduce the computational time thanks to the native MPI structure of the Ansys environment. The last feature of the API is the possibility of directly post process the results in the same environment with the PyVista [22] and the Matplotlib [23] python packages. In perspective, thanks to this embedded post-processing feature, it will be possible to update the I_c axial profile in subsequent simulations: if permanent degradation is found, the TH model inputs will be modified accordingly, possibly accounting for the cumulative degradation.

No co-simulation is foreseen between the two models, namely they do not interact at each single time step: they are executed in cascade. First the thermal-hydraulic and electric simulation is carried out with the H4C code, and then the temperature field evolution computed is used as input to an independent thermo-mechanical simulation. This clearly reduces the computational time, while also preserving the physical content since, despite the strain induces I_c degradation, the SC will be affected by thermal strain only when the quench is already in progress: therefore, the current mainly flows already outside the SC, being unaffected by the reduction of the I_c.

IV. Preliminary test case

To test the functionalities of the new simulation environment, it has been applied to model the thermal strain generation in an ENEA-like slotted core HTS CICC during two possible different quenches in SULTAN configurations. The considered cable geometry is reported in figure 2.

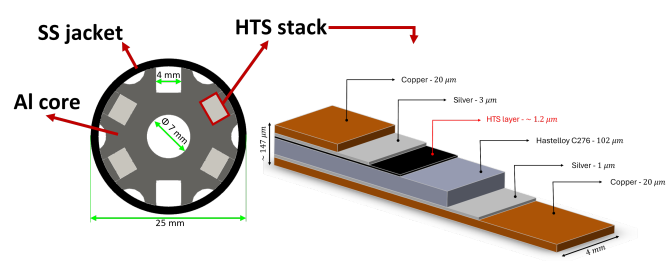

Fig. 2. Geometrical configuration of the cable adopted for the test cases.

The two quenches have been modeled with the H4C code, simulating the heating of the helium at the inlet of the ENEA slotted core conductor considering the 10.9 T SULTAN background field and a transport current of 15 kA. The different temperature profiles obtained depend on the different instant in which the curren has been discharged in the two cases. Indeed, in the ”cold” case the current has been discharged once the total sample voltage reached the threshold of 500 mV, while in the ”hot” one it has been discharged once the hottest sensor measured a temperature of 200 K. So, the difference is only given by the time interval between the quench initiation and the start of current discharge. In figure 3, the computed temperature profiles along the axis of SC stacks are shown for the two cases, labelled as “cold” and “hot” referring to the hotspot temperature reached in the two simulations before dumping the sample current. The H4C code produced the same profiles also for the other regions considered, namely the cable core and the jacket.

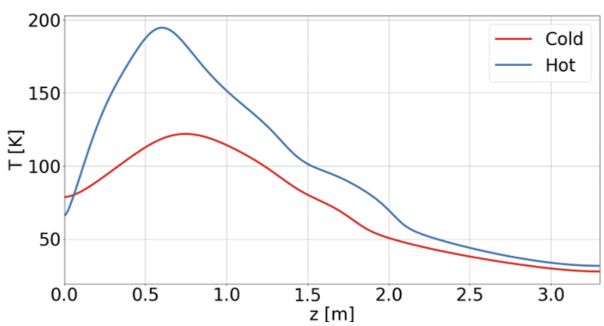

Fig. 3. Temperature profiles in the SC stacks in the two analysed cases.

A. Evaluation of the HTS stack equivalent properties

From the mechanical point of view the most complex object to be modeled is the SC stack, composed by different tapes each characterized by a layered structure, as shown in figure 2. To reduce the computational cost, here each SC stack has been modeled as an entity homogenized on the cross section, therefore neglecting the possibility of tapes to slide one on the other. This approach is coherent with the fact that the displacement driver (the temperature), computed by the TH model, is the same for all the tapes of the same stack and no twisting was applied to this cable; consequently, the latter are deformed in the same way. However this requires to find out equivalent mechanical properties (from those of the tapes) to be adopted for the homogenized stack. A traction test on the tape has therefore been simulated, considering the mechanical properties of each single tape layer, which are reported in table I. The copper, the silver and the hastelloy are modelled considering a bilinear isotropic hardening to include also the plastic behavior; the HTS layer, on the contrary, has been considered a purely elastic material. The adopted material properties have been taken from [24]. The bilinear hardening modeling has been adopted since, despite its simplicity, it fits well the experimental data available for tapes [25],[24].

To avoid the detailed discretization of each single layer of the tape, its structure has been described making use of ANSYS SOLSH190 elements, characterized by continuum solid element topology and with eight-node connectivity with three degrees of freedom at each node: translations in the nodal x, y, and z directions. Moreover, an internal layered section can be defined in the element setting the number, thickness and material properties of the single layers. This approach allows reducing the numbers of degrees of freedom, while preserving the information on the tape layered structure, keeping under control the computational cost, as already presented in [24].

TABLE I
MATERIAL PROPERTIES OF THE DIFFERENT LAYERS OF THE HTS TAPE.

Material	E [GPa]	Y [MPa]	T [GPa]
Copper	85.0	350.0	4.0
Hastelloy	180.0	1225.0	7.5
Silver	90.0	225.0	22.0
REBCO layer	150.0	n/a	n/a

One edge of the modeled tape segment (5 cm) has been bonded, while on the other edge a sequence of prescribed axial displacements has been imposed. The forces computed at the bonded edge allowed to retrieve the stress induced for each prescribed axial strain, simply averaging the force on the tape cross section. Then the results have been linearly interpolated to build an equivalent bilinear hardening model of the tape, to be used for the homogenized stack. The obtained results are reported in figure 4. This approach clearly neglects the interaction between the tapes, which may be non-negligible in case of twisting, bending and temperature gradient on the stack: in such cases the detailed modeling of the tapes and their contact would be required. However, being the tested conductor not bended and untwisted with no temperature gradient on the stack cross-section, we decided to remove this additional complexity, to properly focus only on the single effect given by the temperature field.

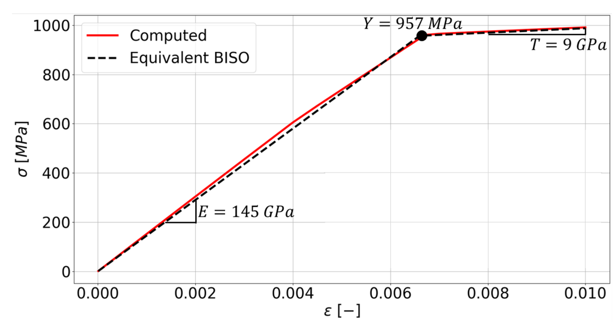

Fig. 4. Computed equivalent stress-strain curve of the REBCO tape and parameters of the interpolating equivalent bilinear hardening model.

The equivalent mechanical behavior of the tape is strongly influenced by the material properties of the hastelloy substrate, which is the thickest layer in the tape, acting as mechanical support of the entire tape.

B. Simulation setup

To model the strain induced in the superconductor by a prescribed temperature profile, it is not sufficient to consider the stack alone, but the entire model of the cable is required. Therefore, the full cable model has been developed including the Al 6063 core and the stainless steel jacket. The material properties are reported in table II. For the Al 6063 the material properties have been taken from [26], as well as for the stack thermal expansion coefficient, which was not previously estimated in the tape homogenization procedure. The steel properties, on the contrary, have been taken from the ANSYS material property database [17], since it is very similar to literature available data.

TABLE II
MATERIAL PROPERTIES CONSIDERED IN THE MECHANICAL CABLE MODEL.

Material	**E [GPa]**	**Y [MPa]**	**T [GPa]**	α $[K^{-1}]$
Al 6063	80.0	50.0	0.9	$2.34 \cdot 10^{-5}$
Steel	210.0	n/a	n/a	$1.35 \cdot 10^{-5}$
Stack	145.0	957.0	9.0	$1.37 \cdot 10^{-5}$

To properly simulate the mechanical behavior of the cable it is of key importance to select the boundary conditions (BCs) and the contact type, mainly between the stacks and the core. Setting proper BCs is not trivial due to the complex joint structures which sustain the cable in SULTAN. Indeed, the cable is, at one end, bonded to an electrical joint, while on the other end it is connected to a second cable with a U-shaped joint, which is a less strong mechanical binding with respect to that at the opposite end. However, as a first approximation, two extreme cases have been considered:

- both cable edges fully bonded (FB) (displacement in all three directions imposed to 0).
- U-shape connection edge free to expand (FE), while the opposite edge is fully bonded.

However, due to the flexibility of the U-shaped joint, the real result will be closer to the case with the U-shape joint edge free to expand. In addition to the BCs, the type of contact between the stacks and the core and between the core and the jacket is important to be analyzed as well. Indeed, due to the different thermal expansion of stacks, core and jacket, modifying their mutual interaction will affect the final strain field. The contact friction between these two elements is, however, an unknown parameter, and for this reason two extreme cases have been considered:

- standard contacts (SCo) with very low friction coefficient ($\mu = 0.01$): stacks and core basically free to expand independently,
- bonded contacts (BCo): stacks and core completely soldered together.

Given the different BCs, contacts and quenches considered, a total of six cases have been analyzed from the mechanical point of view (see table III, containing also the label of each different case). The case with fully bonded edges and standard contacts has been omitted since no major differences with respect to the case with bonded edges and contacts are present. Indeed, globally the displacement is limited by the BCs and the considered temperature profile do not cause strong differential displacement between core and stacks.

C. Results

The final objective of the model will be to monitor the induced thermal strain and use this data to evaluate the possible irreversible I_c degradation. The axial strain obtained in the six analysed cases is reported in figure 5. The strain peak

TABLE III
SUMMARY OF THE SIX DIFFERENT CASES ANALYSED FROM THE MECHANICAL POINT OF VIEW WITH CASE LABELLING ADOPTED.

Case label	Quench case		BCs		Contact Type	
	Cold	Hot	FB	FE	SCo	BCo
Cold - Fully bonded	X		X			X
Hot - Fully bonded		X	X			X
Cold - Free Edge (SC)	X			X	X	
Hot - Free edge (SC)		X		X	X	
Cold - Free Edge (BC)	X			X		X
Hot - Free Edge (BC)		X		X		X

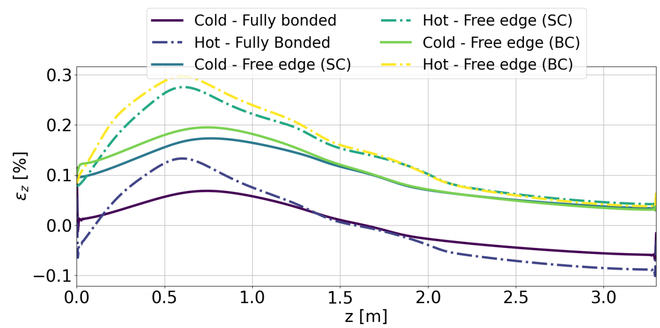

Fig. 5. Axial strain computed in the HTS stacks for the six analysed cases.

is proportional to the temperature one, confirming that the I_c degradation probability increases with the quench hot spot temperature. The BCs have quite a large impact on the strain field in the cable. This confirms the importance, in validation and prediction perspective, to establish the most appropriate BCs to represent the condition at hand. Also the contact type is important: assuming that the stack is bonded to the cable core, the strain peak of the former increases due to the larger deformation of the core which pulls the stack harder with respect to its normal, free expansion. It is therefore advisable to limit as much as possible the bonding between stacks and core, e.g. avoiding the soldering. At the same time the difference between the bonded contact and standard contact cases is not so big meaning that even if the real friction between the stack and the core is not known the model can provide a good insight on the strain field. The justification of the larger strain in case of bonded contact is found on the increase of the stack axial displacement (locally pulled by the core, which expands more than the stack) with respect to standard contacts case as can be seen in figure 6 (a) and (b).

V. CONCLUSIONS

In several experimental campaigns permanent I_c degradation has been observed in HTS cables for fusion after quenches, probably due to the induced thermal strain. To try and confirm this speculation, a detailed thermo-mechanical model has been developed and presented in this work. The integrated simulation environment is based on the H4C code and Ansys, mastered by a python API. The details of the development have been presented and then the newly developed model has been used in some test cases showing coherence

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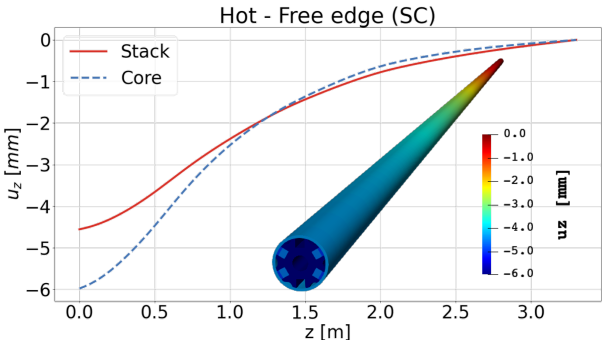
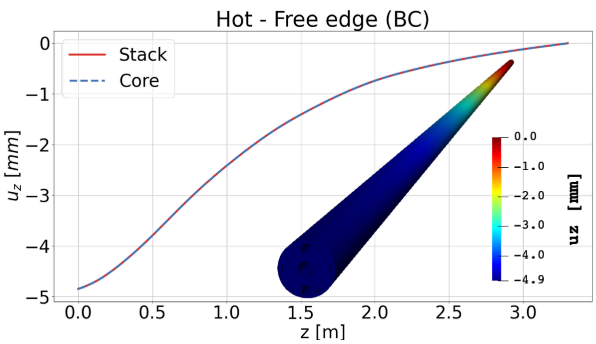


(a)



(b)

Fig. 6. Axial displacement profiles in core and stacks in the hot case considering (a) standard contacts and (b) bonded contacts. Maps of axial displacement in the cable is plotted as well.

with the physical expectations. In perspective the model will be updated including the contribution given by cooldown and Lorentz's forces and then validated against experimental data. Moreover, more detailed models of the tape, fully considering their layered structure, are currently under development in support of the model validation against experimental data.

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