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FINITE ELEMENT MODEL TO STUDY THE DEFORMATIONS OF Nb_3Sn WIRES FOR THE NEXT EUROPEAN DIPOLE (NED)

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The Next European Dipole (NED) activity is aimed at the development of a large-aperture, high-field superconducting magnet relying on high-performances Nb_3Sn conductors. Part of the NED program is devoted to the mechanical study of a new generation of Nb_3Sn wires and to predict and describe their behavior under the severe loading conditions of the cabling process. The deformation resulting from the cabling process was simulated through mechanical analyses by Finite Elements (FE). The ensuing results of FE analyses are presented, allowing the wire behavior under simple uni-axial loads to be described. They are compared to cross section micrographs of deformed wires.

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Finite element model to study the deformations of Nb_3Sn wires for the Next European Dipole (NED)

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***Abstract*— The Next European Dipole (NED) activity is aimed at the development of a large-aperture, high-field superconducting magnet relying on high-performances Nb_3Sn conductors. Part of the NED program is devoted to the mechanical study of a new generation of Nb_3Sn wires and to predict and describe their behavior under the severe loading conditions of the cabling process. The deformation resulting from the cabling process was simulated through mechanical analyses by Finite Elements (FE). The ensuing results of FE analyses are presented, allowing the wire behavior under simple uni-axial loads to be described. They are compared to cross section micrographs of deformed wires.**

***Index Terms*—NED, Nb3Sn wires, FE analysis.**

I. Introduction

THE aim of the Next European Dipole (NED) project [1] [2] is developing a high-field (~ 15 T) and large aperture superconducting magnet made of high-performance Nb_3Sn conductors. For achieving the highly demanding requirements of NED, a high critical current density strand (~ 1500 A/mm^2 at 4.2 K and 15 T) and a sub-element diameter of 50 µm are requested in order to ensure both high performance and stability. However, Nb_3Sn strands are known to be very sensitive to stress and strain. Their critical current degradation, during the cabling process to form a Rutherford cable, represents a genuine issue. In addition, the individual barriers of the sub-elements, which have typically a thickness of few µm, can easily be sheared during cabling and not be anymore tight to avoid tin diffusion into copper stabilizer during the reaction heat treatment. Such a contamination is likely to cause a sharp drop in the RRR of the strand, thus dampening drastically its dynamic stability. Therefore it is of prime importance to adopt a strand design which will minimize the cabling damage to both sub-elements and barriers. Important design parameters, like spacing between sub-elements, barrier thickness or sub-element layout, can be considered for an optimal strand design. However, hundreds of meters of strand should be available to allow for crucial cabling tests. Instead, although a flat deformation of a strand by rolling is not equivalent to a real cabling test, the flat deformation approach was tried on NbTi [3] and Nb_3Sn [4] strands. When comparing filament distortion, a fair correlation between deformed and cabled strands was found for both materials. Considering that a flat deformation of a strand is much easier to realize than that of cabling, a simulation of a flat deformed strand by a mechanical model could be an effective tool for probing the expected mechanical behavior of a given Nb_3Sn strand design to cabling. It can then be used for selecting an adequate strand design. In this work, a FE mechanical model is proposed to assess the expected mechanical behavior of Nb_3Sn strands under a one-directional deformation. The simulation results are compared to the micrographs of strand samples flat-deformed by means of rollers.

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II. FE Methodology

With the aim of simulating via Finite Element (FE) analysis the mechanical behavior of a Nb_3Sn wire subjected to a severe plastic deformation, it is very important to clearly understand the choices made in the modeling phase, so that we can correctly interpret the results.

The first key issue is related to the mechanical properties of the various materials composing the wires. Indeed, we verified that the results of the FE analyses are widely affected by the choice of material properties, namely by the elasto-plastic stress-strain curves used to represent such deformations. For this reason, we decided to use bi-linear stress-strain curves (see Fig. 1), the simplest description of a complex plastic behavior. Needing only three parameters, the Young modulus (E), the yield strength (YS) and the second slope (H), it enables keeping the FE model behavior under control and isolating the basic influence of each parameter on the final results. These mechanical properties have been experimentally assessed through microhardness and nanohardness measurements [5] and validated by tensile tests. Nanoindentation is a tool to measure not only hardness at a very local scale (lateral resolution is in the nanometric range and total indentation depths as small as 20 nm are resolved by the instrument), but also to measure local elastic properties of the individual phases based on the recorded force-

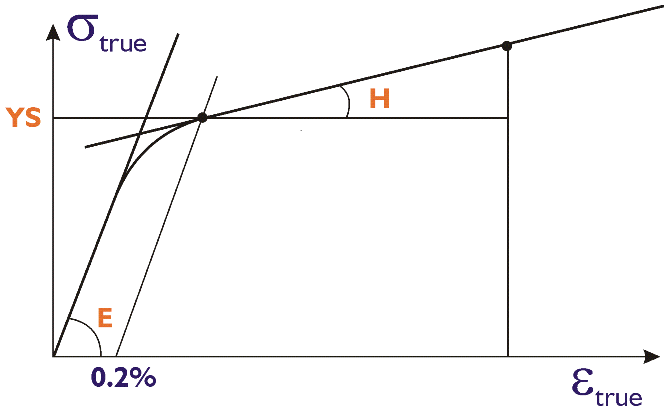

Fig. 1. Bilinear stress-strain curve used to represent the plastic behavior of the materials composing the wires.

displacement behavior.

The second key point is the choice of the most adequate 2D FE representation of the wire deformation. A 3D model, in fact, would have been too time consuming for the calculation campaign we intended to launch. In general, a 2D mechanical modeling of solid structures offers three options for solving the analysis: plane strain, plane stress or generalized plane strain. Let *z* designate the wire axis. A plane strain 2D model represents an infinitely long structure, in which the material is then constrained orthogonally to the cross section (*x-y* plane), resulting in zero strain in the longitudinal direction (ε_z=0). The volume being conserved, there is no cross section reduction during deformation. Conversely, in a plane stress condition, the stress in the longitudinal direction has to be zero throughout the section (σ_z=0). This second option allows a free elongation of the wire normally to the cross section. The main drawback is that the strain in the longitudinal direction is not constant, as it is in the real case, since different parts of the wire cannot have relative movements in that direction. As a consequence, the calculated area reduction due to longitudinal elongation can be overestimated. What we found is that the cross section reduction calculated by FE analysis with the plane stress option is much larger than the one measured. For instance, for a 28% deformation on diameter, the measured elongation is 0.5%, whilst the one inferred from the area reduction given by FE calculations would lead to 10%. The conclusion is that the plane strain option gives better results than the plane stress one, that is ε_z=0 is a better approximation of ε_z=0.5% than ε_z=10%.

From this point of view, the best option would seem to be the third one, the generalized plane strain option, which assumes a finite deformation domain length in the *z* direction, as opposed to the infinite value assumed for standard plane strain. This feature allows the 2D representation of a "fiber" in which the amount of deformation of all cross sections are identical throughout its length (ε_z=const.). Allowing the imposition of a longitudinal strain, it correctly handles the reduction in section of wires during deformation. We found that this option is in slightly better agreement with measurements than the plane strain option, but this difference is not enough to justify the much longer run time needed for the analysis (almost a factor 10). Running all the FE analyses in plane strain option, we need to keep in mind that the transverse deformations and in-plane strain components will be slightly overestimated.

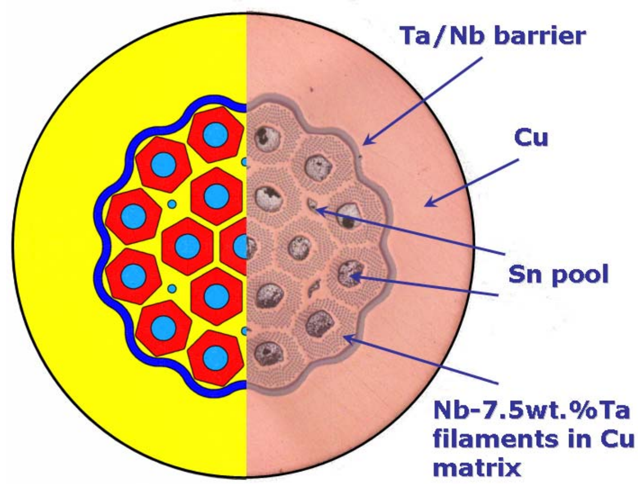

Fig. 2. ALSTOM/CEA Nb_3Sn internal tin wire shown together with its FE model. White represents copper, dark grey is tantalum, light grey is tin and grey is a homogenized material representing the Nb-7.5wt.%Ta filaments in Cu matrix. The wire diameter is 0.825 mm.

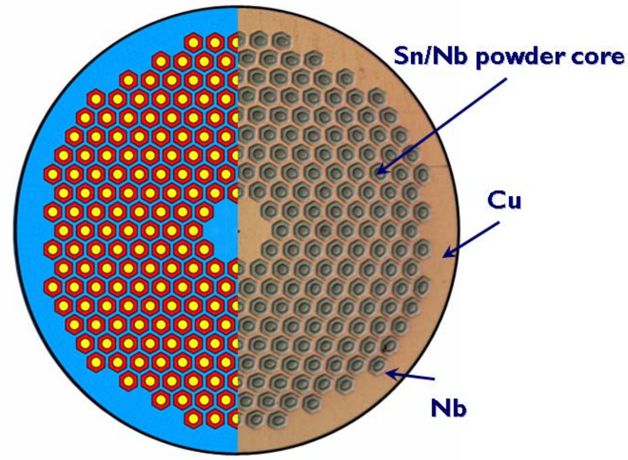

Fig. 3. SMI/NED PIT wire shown together with its FE model. White represents Sn/Nb powder core, light grey is copper and dark grey is niobium. The wire diameter is 1.25 mm.

The next step is to choose an element having plasticity, large deflection, and large strain capabilities. All the FE calculations shown in this paper have been carried out using the FE code ANSYS [6] and its PLANE182 element. Moreover, all the models suppose a perfect bonding between different materials, and neither sliding nor detaching is allowed. Furthermore, no kind of breakage is taken into account: when rupture or mixing up of material occur, the mechanical system changes, as well as the properties of the materials involved, and the FE model is no more representative of this new structure.

Finally, the loading of the FE model is very simple: using the ANSYS contact tool, two rigid and parallel planes in contact with the external surface of the wire have been generated through CONTA172 and TARGE169 elements. Whilst one of the planes is kept fixed, the other is gradually lowered, resulting in a uni-axial compression of the wire in the

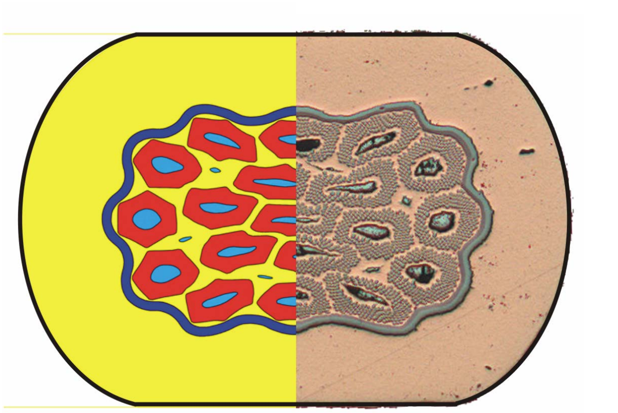

Fig. 4. ALSTOM/CEA Nb_3Sn internal tin wire after a 24% reduction in diameter. The observed deformation is shown together with the FE analysis result.

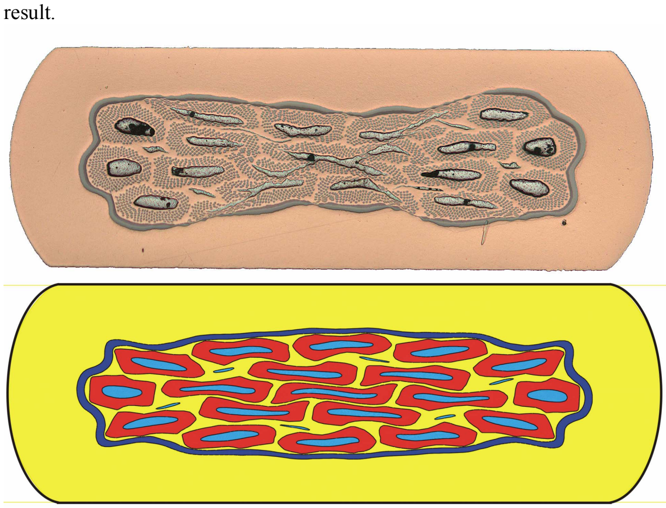

Fig. 5. ALSTOM/CEA Nb_3Sn internal tin wire after a 48% reduction in diameter. The observed deformation is shown together with the FE analysis result.

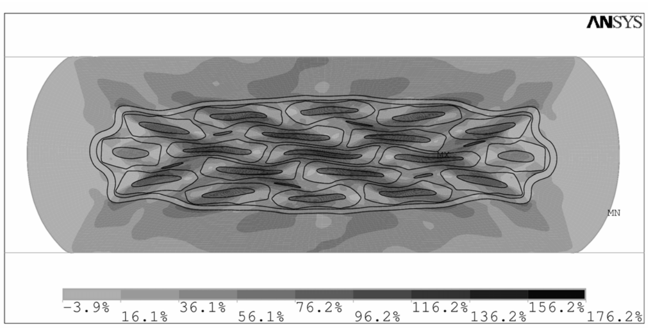

Fig. 6. Total strain in the *x* direction of the ALSTOM/CEA Nb_3Sn internal tin wire after a 48% reduction in diameter.

y direction.

III. Wire Models

A. ALSTOM/CEA Internal Tin Wire

The model was first applied to an old internal tin wire manufactured by Alstom/MSA for CEA/Saclay [7] and shown in Fig. 2. This wire is made up of 19 sub-elements and 6 additional Sn sources surrounded by a Ta/Nb diffusion barrier isolating the stabilizing copper on the outside. Each sub-element is made up of Nb-7.5wt.%Ta filaments arranged in a pure-Cu matrix around a Sn pool. Fig. 2 shows also the FE model for this analysis; it is made up of 4 different materials: copper is represented in white, the Nb/Ta barrier in dark grey, tin in light grey, and finally grey is a homogenized material representing the filamentary areas. The properties of this homogenized material were found by running a sort of virtual experiment, that is: a plastic analysis simulating a stress-strain measurement on a significant part of the sub-element system where a uni-axial force in tension is applied to the system and the corresponding displacement is retrieved. Each step of this analysis corresponds then to a point in the stress-strain plane, allowing outlining a new bi-linear stress-strain curve for the homogenized material.

B. SMI/NED PIT Wire

The layout of the SMI/NED PIT wire is shown in Fig. 3. It is made up of hexagonal cells regularly arranged within a copper matrix. Each cell is made up of a hexagonal copper tube surrounding a niobium tube which is hexagonal on the outside and circular on the inside, filled up with a powder mixture. Fig. 3 shows also the FE model for this analysis: white represents the powder core, light grey is copper and dark grey is niobium. The main difficulty in this modelization was to assess relevant properties to the powder core, as they cannot be directly measured. To do so, we ran several models changing the parameters of the bilinear curve of this material until we found the best agreement between calculations and observed deformations.

IV. Results and Discussions

First, let us consider the deformation of the ALSTOM/CEA wire. Fig. 4 shows the wire after a 24% reduction in diameter together with the deformed picture coming from the FE analysis. Note that the left and right sides are not symmetrical because the starting position of the wire is rotated by 15° with respect to the model in Fig. 2. The agreement is very good, the calculated shape of the external barrier is very similar to the observed one and also the overall dimensions of FE analysis and micrograph match pretty well. One of the mostly critical parameters is the strain in the *x* direction (*i.e.* perpendicular to the direction of compression). When compressing the wire, the thickness in the *y* direction reduces and strain ε_y is mainly negative (only small regions in the external copper are in tension). The main consequence is that, due to Poisson's ratio, most parts of the wire will be in tension in the *x* direction. At a certain value of diameter reduction, this tension overcomes the elongation at fracture and parts of the wire break. This effect is clearly visible in Fig. 5, corresponding to a 48% reduction in diameter of the wire. The FE analysis, which does not take into account any kind of ruptures, presents a plastically deformed shape which is no more in agreement with what is observed. Evidently, the regions of the wire which are the most strained in tension break up and mix with one another. It is clear that the FE model cannot adequately represent this new wire layout with different mechanical properties. In any case, the FE analysis is still helpful in understanding what are the regions having the highest risk factor, *i.e.*, the ones having the largest ε_x values. Fig. 6 shows the total strain in the *x*

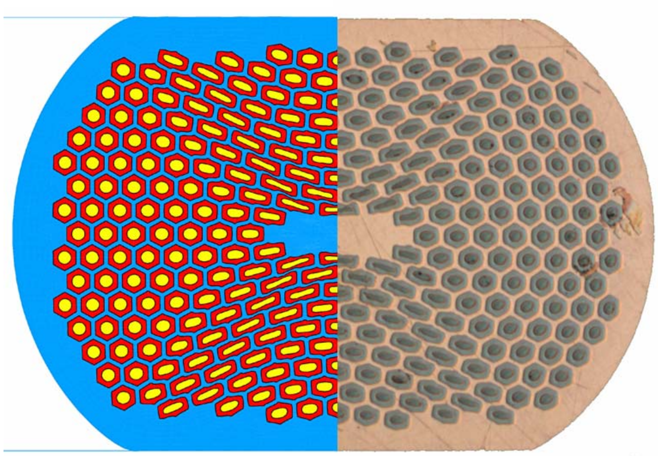

Fig. 7. SMI/NED PIT wire after a 24% reduction in diameter. The observed deformation is shown together with the FE analysis result.

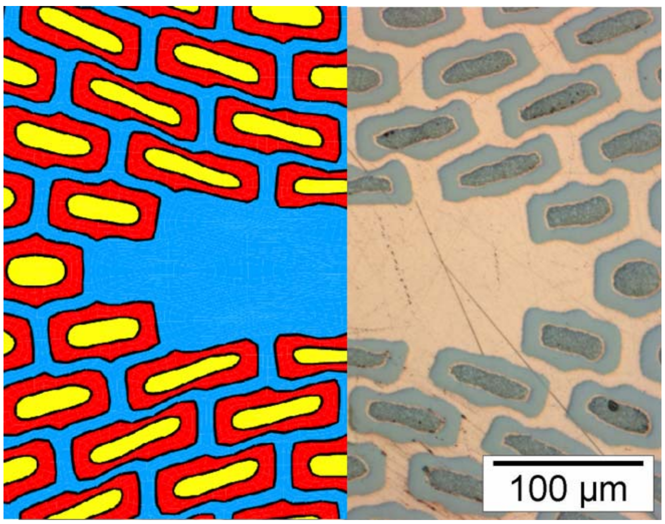

Fig. 8. SMI/NED PIT wire after a 24% reduction in diameter enlarged in the around the center of the wire. The observed deformation is shown together with the FE analysis result.

direction of the ALSTOM/CEA wire after a 48% reduction in diameter. The tin of the central sub-elements is the most strained material, having values of ε_x well over 100%, and up to a maximum value of 176%. These conditions are obviously not sustainable by tin, which appears to break. Also the Ta/Nb barrier can be expected to break. Already, after a 24% reduction in diameter it is strained up to 30%, the maxima being located at the top and bottom parts, where the initial undulation seen in Fig. 2 appears to be straightened. Even if these values are a bit overestimated, it was predictable that further reducing the diameter would result in wire breakages in these areas, as observed on the deformed wire.

The PIT/SMI wire can also be very well simulated by our FE analysis. Fig. 7 shows the wire after a 24% reduction in diameter. The match is not perfect, but the calculations give a suitable description of the overall behavior of the real wire. Two shear planes tilted by about 45° with respect to the *x* axis can be easily identified. They divide up the *x*-*y* plane into four regions: the regions on both sides are almost unaffected by the deformation, whilst the top and bottom regions are the most strained, especially near the center of the wire. In Fig. 8 an enlargement of the previous picture around the center of the wire is shown. It is possible to appreciate that there is a sort of "bumping" effect on the central tubes which is well predicted by the FE analysis.

V. Conclusion

We demonstrated that FE analysis is a powerful tool to simulate severe plastic deformations of wires. It can be adopted to predict the mechanical behavior during cabling of different wire designs, with the aim to find an optimum design minimizing cabling damages. The only limit lies in the fact that possible ruptures are not included in the FE model: we can only determine the regions which, having overcome their elongation at fracture, are possible candidates for breakages.

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