Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Cryogenics 46 (2006) 569–580

Cryogenics

www.elsevier.com/locate/cryogenics

Homogenisation methods for the thermo-mechanical analysis of Nb_3Sn strand

Daniela P. Boso [a,*], Marek Lefik [b], Bernhard A. Schrefler [a]

[a] *Department of Structural and Transportation Engineering, University of Padua, Via Marzolo 9, 35131 Padua, Italy*
[b] *Chair of Geotechnical Engineering and Engineering Structures, Technical University of Łódz, Al.Politechniki 6, 93-590 Łódz, Poland*

Abstract

An accurate estimation of the strain state of a strand inside a coil is a crucial point in the prediction of Nb_3Sn conductor performance, since Nb_3Sn based strands show a strain-dependence of their critical parameters. To perform a numerical analysis of a superconducting coil it would be impossible to operate a spatial discretization fine enough to take into consideration each single material. Therefore, we make use of homogenisation methods, so that the strand (or the triplet or higher order bundles) can be schematized as an equivalent homogeneous material.

This paper presents a general overview of different ways to approach a study of superconducting strands using homogenisation techniques. We aim to point out that there is not a "unique best approach", but different methods have to be chosen depending upon the microstructure of the strand. Three kinds of strands are taken into consideration to exemplify the various techniques: the strand from European Advanced Superconductors (EAS), from Furukawa (FUR) and from Outu Kumpu (OUK) company. For the three strands the thermal strain due to the cool-down from reaction temperature to the coil operating conditions is calculated, making use of the effective properties obtained via the various approaches.

Keywords: Thermal strain; Multifilament superconducting strand; Self-consistent and asymptotic homogenisation; Multiscale modelling; Finite element technique

1. Introduction

It is well known that superconducting (SC) strands containing Nb_3Sn filaments are strain sensitive, i.e. the critical current and temperature depend on the strain state. A pioneering work on Nb_3Sn strain sensitivity can be found for example in [1]. In this work, we focus our attention on Cable In Conduit Conductors (CICC) that, more than others, experience thermal strain.

Because of its brittleness, Nb_3Sn compound cannot be extruded and drawn (as for example NbTi), but requires special manufacturing processes: a billet including un-compounded precursors of Nb_3Sn is assembled and processed until the desired wire size is obtained. After that, according to ITER present design [2], more than one thousand wires are twisted together following a multilevel twisting pattern and inserted in a metal jacket which carries the magnetic loads and confines the liquid helium (Cable In Conduit Conductors). The cable is then wound to obtain the SC coil and finally (Wind and React technology) the entire coil is heated up to the reaction temperature (923 K) to allow Sn atoms to diffuse and react with Nb atoms to form Nb_3Sn precipitates. The coil is kept for several hours at 923 K because the progression rate of the reaction is rather slow. At the end, the coil is cooled down to room temperature and then to its operating conditions (about 4.2 K).

It is clear that the strand inside the cable is not strain free, because of the different thermal expansion coefficients of the various materials of the composite. Moreover, the

---

[*] Corresponding author. Tel.: +39 049 827 5627; fax: +39 049 827 5604.
E-mail addresses: boso@dic.unipd.it (D.P. Boso), emlefik@p.lodz.pl (M. Lefik), bas@dic.unipd.it (B.A. Schrefler).

0011-2275/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cryogenics.2006.01.005

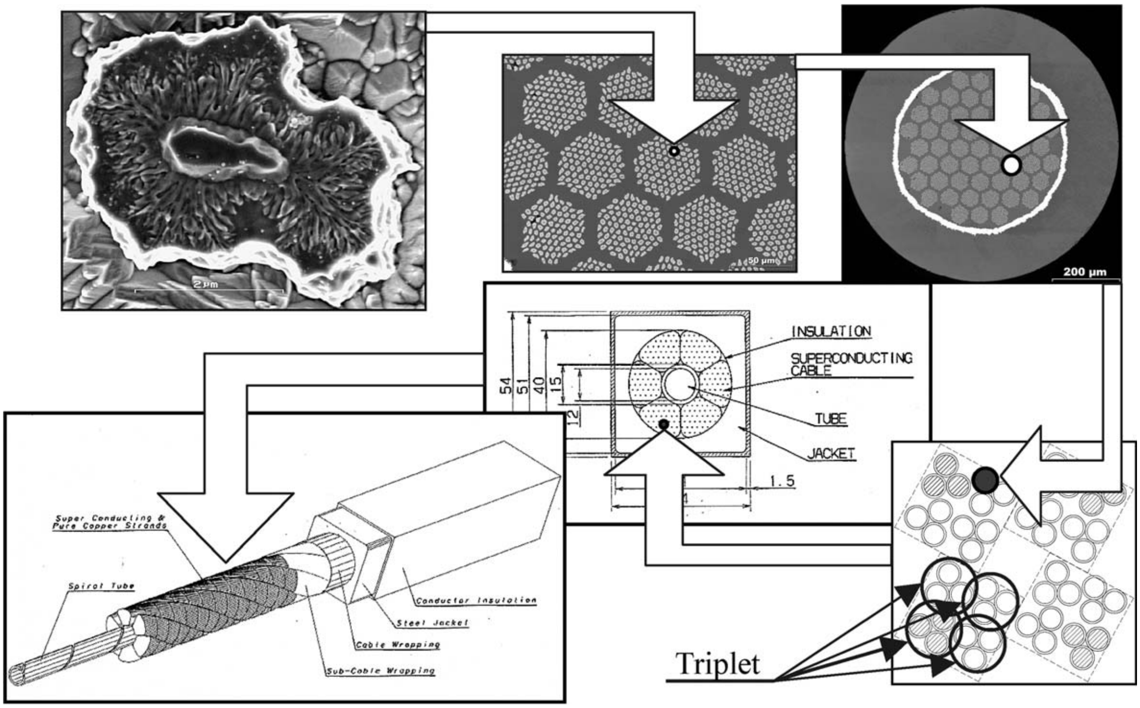

Fig. 1. Hierarchical structure of ITER cable. It is assembled according to a multilevel twisting process: three multi-filamentary strands (upper row, on the right) are twisted into a triplet, then four triplets are again twisted to obtain a bundle, four of these bundles are twisted again to obtain a higher order bundle (lower row, on the right), then four of them are twisted together to obtain the last but one cabling stage: the petal. Six petals (lower row, in the middle) are then twisted around a spiral tube and inserted into a jacket to obtain the final cable (Cable In Conduit Conductors). Upper row images: courtesy of P.J. Lee, University of Wisconsin—Madison Applied Superconductivity Center.

thermal strain is only part of the initial strain, because the helicoidal geometry of the wires inside the cable and of the filaments inside the wire causes an additional strain [3]. Finally, when the magnetic field is applied, electromagnetic forces act as a bending load on the wires, which behave like continuous beams supported by the contacting wires in their neighbourhood. In this way a bending strain is added to the initial strain. This seems to be one of the main causes of the observed degradation of the performances of the cabled strand in comparison with those of the un-cabled one. Therefore, an accurate estimate of the strain state of the strand inside a coil experiencing magnetic loads is clearly a crucial point in the prediction of Nb_3Sn conductor performances.

Superconducting coils can be regarded as very good examples of hierarchical structures (Fig. 1), where lower levels take part in the global behaviour. To perform a numerical analysis of a SC cable or coil (via the finite element method for example) it would be impossible to operate a spatial discretization fine enough to take into consideration each single material: the filament diameter is a few micrometers long and the coil main dimension is about 13 m. To investigate the higher levels of the hierarchical structure we propose to make use of homogenisation methods, so that the strand, or the triplet or higher order bundles (depending upon the level of the structure being studied) can be schematized as an equivalent homogeneous material.

This paper presents a general overview of different ways to approach a study of superconducting strands using homogenisation techniques. The main goal is to obtain the thermal and mechanical characteristics of the equivalent homogeneous material starting from the initial material properties and their geometrical layout inside the strand. We aim to point out that there is not a ‘‘unique best approach’’, but different methods have to be chosen depending upon the microstructure of the strand.

Three kinds of strands are taken into consideration to exemplify the approaches: the strand from European Advanced Superconductors (EAS), from Furukawa (FUR) and from Outu Kumpu (OUK) company (Fig. 2).

For the three strands, the thermal strain due to the cool-down from reaction temperature to the working conditions is calculated, making use of the effective properties obtained via the various approaches.

2. Homogenisation methods

Existing homogenisation methods can generally be divided into two broad categories depending upon the composite characteristics.

Considering the definition of the effective properties of composites with *linear* constitutive behaviour, if the microstructure is sufficiently regular to be considered periodic, the effective properties may be determined in terms of unit cell problems with appropriate boundary conditions. On