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Electro-mechanical behaviors of composite superconducting strand with filament breakage

Xu Wang [a,b], Yuanwen Gao [a,b,*], Youhe Zhou [a,b]

[a] Key Laboratory of Mechanics on Environment and Disaster in Western China, The Ministry of Education of China, Lanzhou, Gansu 730000, P. R. China
[b] Department of Mechanics and Engineering Science, College of Civil Engineering and Mechanics, Lanzhou University, Lanzhou, Gansu 730000, P. R. China

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ABSTRACT

The bending behaviors of superconducting strand with typical multi-filament twist configuration are investigated based on a three-dimensional finite element method (FEM) model, named as the Multi-filament twist model, of the strand. In this 3D FEM model, the impacts of initial thermal residual stress, filament-breakage and its evaluation are taken into accounts. The mechanical responses of the strand under bending load are studied with the factors taken into consideration one by one. The distribution of the damage of the filaments and its evolution and the movement of the neutral axis caused by it are studied and displayed in detail. Besides, taking the advantages of the Multi-filament twist model, the normalized critical current of the strand under bending load is also calculated based on the invariant temperature and field strain functions. In addition, the non-negligible influences of the pitch length of the filaments on both the mechanical behaviors and the normalized critical current are discussed. The stress-strain characteristics of the strand under tensile load and the normalized critical current of it under axial and bending loads resulting from the Multi-filament twist model show good agreement with the experimental data.

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1. Introduction

As the basic structure generating the magnetic confinement for the fusion plasma in the International Thermonuclear Experimental Reactor (ITER), the cable-in-conduit-conductors (CICCs) cable consists of thousands of superconducting strands with a strong strain sensitivity due to the main superconducting material Nb_3Sn [1]. In the operating condition, the strand works under strong magnetic field (12 T) and low temperature (4 K) [2]. Due to the current carried herein and the change of the temperature, the strand is always subjected to the bending (Lorentz force) and axial (thermal expansion) deformation, which will lead to the degradation of the superconductivity. However, the complex structure of the strand and the brittleness of the Nb_3Sn make it difficult to predict the strain of the filaments.

Experiments investigating the performance degradation of the strand under bending deformation have been conducted frequently [3–10]. Typically, Nijhuis et al. [3,4,7] studied the critical current of several types of strands under bending load on TARSIS facility. From these investigations it can be seen that the normalized critical currents of LMI, SMI and VAC strands follow exactly the model with low interstrand resistivity developed by Ekin [1]. Takayasu et al. [9] developed a bending device to apply the pure bending load on the Nb_3Sn strands and the bending effects on the critical current of five different strands were investigated. Lately, Allen et al. [10] characterized the pure bending behavior of two Nb_3Sn strands by the device using a beam style sample holder. In this experiment, the performance degradation of the internal tin strand is more serious than the bronze route strand. Meanwhile, when unloading completely, the performance of the bronze route strand recovers completely, while the internal tin strand shows significant permanent degradation. The filament cracking in the strand was also observed [11–14]. The study developed by Sheth et al. [11] indicated that the cracking of Nb_3Sn filaments in the ITER Toroidal Field (TF) bronze-process strand and ITER TF internal tin strand increase with the increasing number of loading cycles up to 0.6% strain, and the locations of the cracks are mostly adjacent to voids. While, the strain distribution and the fracture situation cannot be predicted through the experimental methods quantitatively.

In order to investigate the electro-mechanical coupling behaviors of the strand and cable, the relevant numerical simulations and theoretical researches on their mechanical properties were also performed [9,15–25]. In 2005, Mitchell [15] calculated the thermal residual stress of several strands occurring during man-

* Corresponding author. Fax: 0086 931 891 4359.
E-mail address: ywgao@lzu.edu.cn (Y. Gao).

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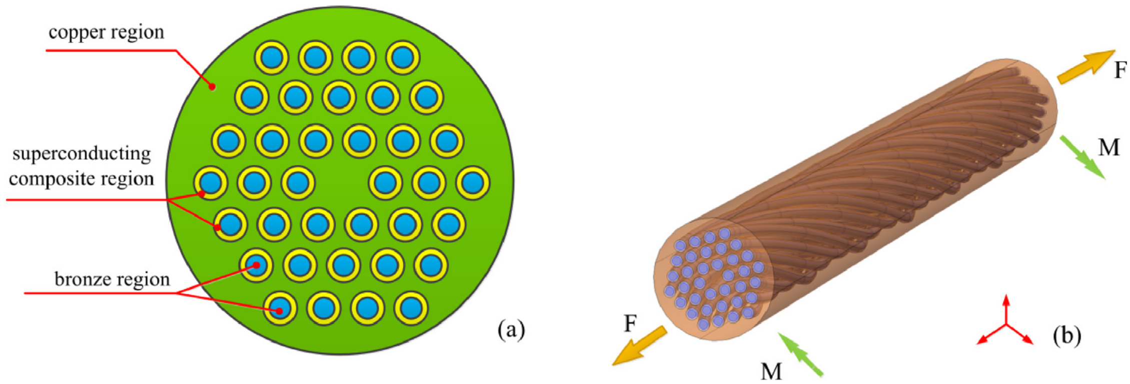

Fig. 1. Schematic of the Multi-filament twist model: (a) cross section view; (b) global view.

ufacturing process with a simple several cylinders model. For the LMI strand, the results of this model shows a compressive behavior of the matrix materials, copper and bronze, in the temperature rising phase, while a tensile one of them in the cooling stage. The behaviors of other materials (Nb in the temperature rising phase and Nb_3Sn after heat treatment) are opposite to the matrix material and stabilizer. Boso et al. [16] calculated the tensile behavior of several strands with the FEM simulation. In the simulation, the authors select the representative volume element of the filaments region in each strand through the picture of the cross section of the strand, and replace these composite regions with a continuous material consisting of the representative volume elements through the homogenized method. It should be noted that although this model only considers the tensile case, it could also be applied to calculate the bending behavior of the strand. However, the damage of the filaments is not taken into consideration. Takayasu et al. [9] developed an integrated model to analysis the bending behavior of the strand. In this method, the neutral axis shift, current transfer length, filament breakage and the uniaxial strain release are taken into consideration, and these considerations make the calculated normalized critical current closer to the experimental data. However, the parameters describing these behaviors are fitting ineluctably.

Recently the authors developed a three-dimensional Multi-filament twisted FEM model and investigated the axial mechanical behaviors of strand under cyclic loading [26,27]. In this paper, taking the LMI strand as an example, we generalize the 3D multi-filament FEM model for the study of the bending behavior and electric properties of the strand. Based on this model, firstly we investigate the influence of the thermal residual stress, the damage and the pitch length of the filaments on the bending behavior of the strand. Then we discuss the damage evolution in the strand and the movement of the neutral axis caused by it. Finally, the normalized critical current of the strand is calculated through the strain resulting from the FEM model and the suitable scaling law. The paper is organized as follows: the 3D model of the strand is briefly introduced in Section 2. The simulating results discussion of the mechanical behaviors including the influence of different factors on bending behaviors of the strand, the sensitive analyses of the Weibull modulus and the pitch length of the filaments and the fracture situation are shown in Section 3. Section 4 displays the related calculation of the normalized critical current of the strand, and the conclusions are drawn at last in Section 5.

2. Multi-filament twist model

The Multi-filament twist model is developed according to the real structure of the LMI strand, as shown in Fig. 1. In the manufactured LMI strand, the superconducting filaments are twisted together into 36 filament groups and embedded into the bronze matrixes. Then wrapped with the corresponding barrier materials (Nb and Ta for LMI strand), these composites are twisted and embedded into the copper stabilizer. Thus, in the Multi-filament twist model, we build 36 helical cylinders representing the bronze matrixes, denoted as the "bronze region" shown in Fig. 1. It should be noted that the barrier materials in the LMI strand have the same structure with the bronze matrix, therefore, in order to save the computation time and space, the bronze matrix and the corresponding barrier materials are incorporated into one matrix region. Meanwhile, due to the small volume fraction of the barrier materials, we still name these matrix regions as bronze regions. Around these bronze regions, there are corresponding 36 superconducting regions representing for the filament groups in the strand. At last, these composite regions are embedded into the copper region which stands for the copper stabilizer in the strand. The area of these regions and the pitch length of the filaments are decided according to references [3,15,28], and the main geometrical and mechanical parameters of the components in the LMI strand are listed in Table 1. The cross section and global view of the Multi-filament twist model is shown in Fig. 1.

The adjacent surfaces of all the components in the model are tied each other to make sure that there is no relative displacement between each other. Meanwhile, to meet the real experiment condition, the rotational freedom of the two end faces of this model is limited. In the simulation, the three-dimensional eight-node elements (C3D8R) in ABAQUS are used, and the ABAQUS/Explicit is adopted as the solver.

2.1. The important influence factors in strand model

2.1.1. Initial thermal residual stress

During the drawing and heat treatment of the LMI strand, there exists a strong thermal residual stress system due to different thermal expansion properties of materials. Before heat treatment, due to the drawing process, the Nb and Ta in the initial strand are in tension, while the copper in compression, resulting from the elastic behaviors of Nb and Ta. Then heating the initial strand up to 923 K, the content of tin in the bronze changes along with a complete relaxation of the thermal strain and annealing of the work hardening. Meanwhile, the filaments are Nb up to 923 K and then Nb_3Sn with no thermal strain. Then cool it to the room temperature (293 K) or the operating temperature (4.2 K). Due to the different thermal expansion coefficients and the complex structures of the materials in the strand, the thermal residual stress will occur during this process. We calculate this thermal residual stress system by the models of Mitchell [15] and Boso et al. [16], and apply the results into the Multi-filament twist model.

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