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Modeling for mechanical response of CICC by hierarchical approach and ABAQUS simulation

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HIGHLIGHTS

- We develop an analytical model based on the hierarchical approach of classical wire rope theory.
- The numerical model is set up through ABAQUS to verify and enhance the theoretical model.
- We calculate two concerned mechanical response: global displacement–load curve and local axial strain distribution.
- Elastic–plasticity is the main character in loading curve, and the friction between adjacent strands plays a significant role in the distribution map.

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ABSTRACT

An unexpected degradation frequently occurs in superconducting cable (CICC) due to the mechanical response (deformation) when suffering from electromagnetic load and thermal load during operation. Because of the cable's hierarchical twisted configuration, it is difficult to quantitatively model the mechanical response. In addition, the local mechanical characteristics such as strain distribution could be hardly monitored via experimental method. To address this issue, we develop an analytical model based on the hierarchical approach of classical wire rope theory. This approach follows the algorithm advancing successively from $n+1$ stage (e.g. $3\times3\times5$ subcable) to n stage (e.g. 3×3 subcable). There are no complicated numerical procedures required in this model. Meanwhile, the numerical model is set up through ABAQUS to verify and enhance the theoretical model. Subsequently, we calculate two concerned mechanical responses: global displacement–load curve and local axial strain distribution. We find that in the global displacement–load curve, the elastic–plasticity is the main character, and the higher-level cable shows enhanced nonlinear characteristics. As for the local distribution, the friction among adjacent strands plays a significant role in this map. The magnitude of friction strongly influences the regularity of the distribution at different twisted stages. More detailed results are presented in this paper.

1. Introduction

ITER superconducting cable, known as Nb_3Sn cable in conduit conductors (CICCs) for the International Thermonuclear Experimental Reactor (ITER), is with typical multi-stage twisted configuration: three multi-filamentary strands are twisted into a triplet, and then several triplets are again twisted to obtain a bundle. A few of these bundles are twisted again to form a higher order bundle, then several them are twisted together to obtain the last but one cabling stage: the petal. Six petals are then twisted around a spiral tube and inserted into a jacket to obtain the final cable. During operation, both transverse electromagnetic load and axial thermal shrinkage act on CICC with such multi-level structure [1]. And the generated internal stress and strain distribution subsequently affect the CICC's superconducting performance [2]. This mechanics-superconductivity dependence is mainly due to the strain sensitivity of Nb_3Sn, the basic superconductor material in CICC [3,4].

Two mechanical responses for the operating loads are concerned. One is global displacement–load curve that is the direct indicator of CICC's mechanical performance. Another is local axial strain distribution, dependent on the degradation. Modeling for the responses is the basis of quantitative evaluation of the superconducting performance. To address this issue, CICC model coils tests [5–8] and some idealized simulation works [1,9–11] have been conducted recently. The tough part is how to describe the complex trajectory of strands and multiple interactions among them. However, accurate descriptions of CICC's geometry and corresponding mechanical behavior are scarce in the previous works. This is why although experimental tests have detected some shortfalls of additional performance, the simulations fail to predict

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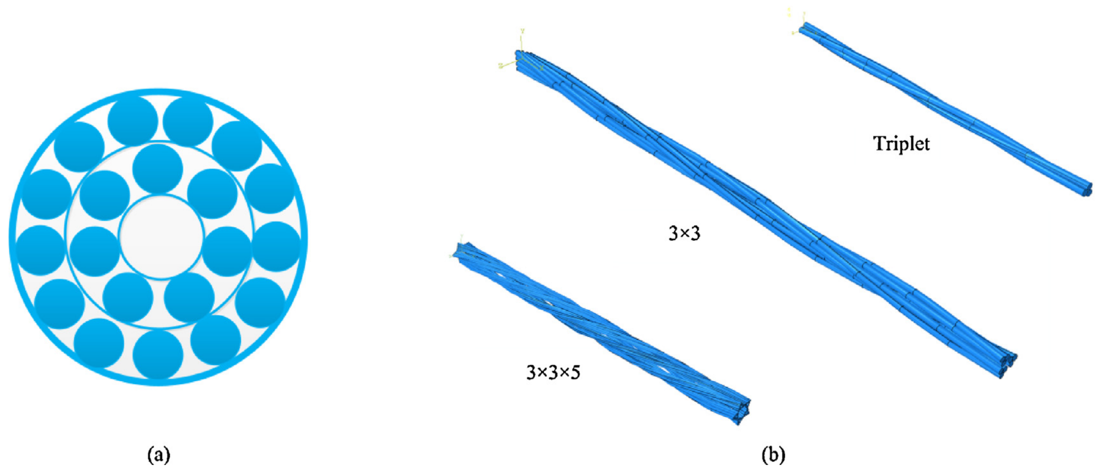

Fig. 1. Illustration of configuration of (a) traditional cable and (b) CICC.

this degradation. Therefore, the modeling work, approaching the real situations encountered during operation, is strictly necessary to address key issues on CICC.

Based on this consideration, a finite-element model (MULTIFIL) [12–14] employing the entangled materials approach [15] is successfully applied in the simulation of CICC mechanics. This mechanical model allows describing the evolution of strains and stresses within each strand and simulating the conductors' service life from manufacturing to operating conditions. Nevertheless, the FEM is not conducive to apply in variable parameter case and larger-scale CICC due to a huge amount of calculations. Another numerical approach has been performed via several types of finite-element models (continuum model, beam-gap model and beam-shell model) in different software environments (ABAQUS, LS-DYNA and MSC. Mark) [16]. Some analytical estimations of these different models are also given, according to the well-known wire rope theory stretching and twisting. Nemov et al. [16] also present the comparison between the analytical and numerical results of the different models. To the author's knowledge, the global mechanical response such as the displacement–load curves is the focus of attention. Thus, the investigation on local stress and strain distribution map is insufficient [16]. Besides, Qin et al. [17,18] develop a theoretical mechanical model (CORD) for a superconducting cable based on wire rope theory. CORD can predict the local strain and stress state of all individual wires, including inter-strand contact force and the associated deformation. However, CORD covers the loading cases of axial tension and torsion except for bending. However, bending is proven to be the main deformation in CICC during operation and should be considered in mechanical analysis to gain more practical significance [19].

In the view of the flaws of the existing works, we realize a theoretical model proposed earlier for calculating the response of electrical cables subjected to bending load [20]. This previous model is primarily based on hierarchical approach of classical wire rope theory [21], taking into account multi-order helical structure and frictional effects. This approach has a clear physical significance and sequential algorithm. So it is considered facilitating application and saving computing time. However, what this model only considers is the traditional electrical cables, which have substantially different configuration and loading situation with the CICC.

Our model is developed from this hierarchical approach of classical wire rope theory, and improved for addressing the CICC mechanics. In order to validate and enhance this model, ABAQUS simulation is employed. Then, these models are utilized for the

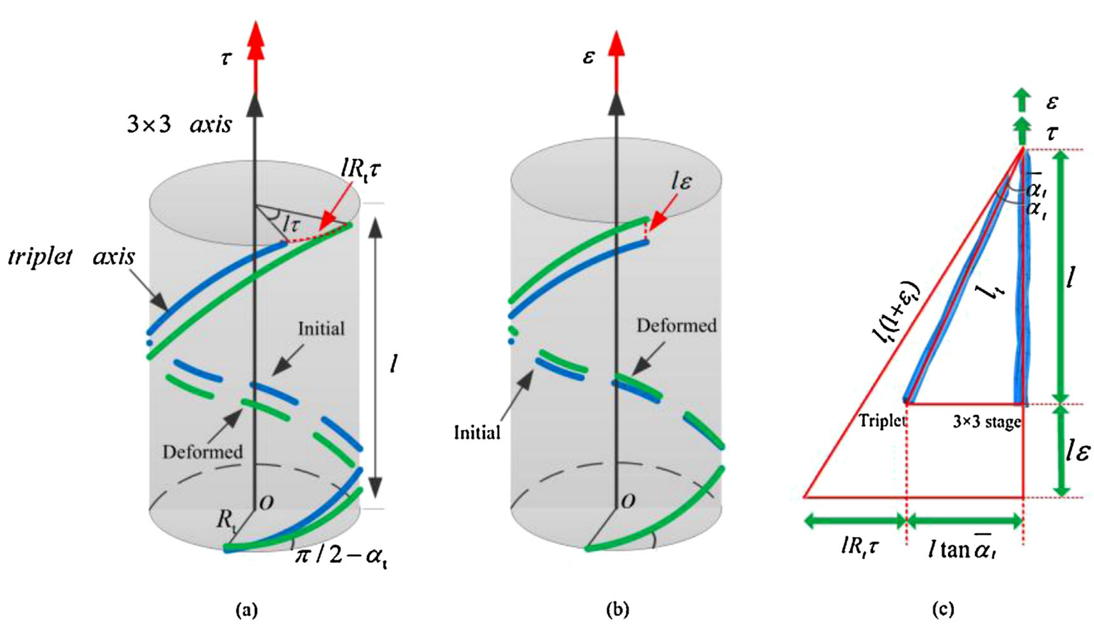

Fig. 2. Mechanical analysis of 3 × 3 stage under (a) torsion, (b) axial tension and (c) combined deformation.