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Numerical study for ITER superconducting cable of correction coils

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ABSTRACT

The superconducting cable with multi-stage twisted wires is the main component of ITER conductor. This paper proposes the numerical models to describe the pattern of the correction coils (CC) cable and analyze the mechanical properties during cabling. The current models give approximate simulation of space structure and stress–strain curve for the cable. The models could provide theory analysis for design of cable pattern and improve the cabling method.

1. Introduction

ITER is a joint international research and development project [1,2] that aims to demonstrate the scientific and technical feasibility of fusion power. The ITER magnet system is made up of four main sub-systems: The 18 Toroidal Field coils, referred to as TF coils; the Central Solenoid, referred to as CS; the 6 Poloidal Field coils, referred to as PF coils; and the correction coils, referred to as CCs. All coils with different dimensions used Cable-In-Conduit Conductors (referred to as CICC). The key-point in CICC is superconducting cable.

The pattern of a superconducting cable is important for cabling, and the modeling for the pattern with multi-stage twisted wires is necessary. For example, we can choose the appropriate diameters of dies and rollers according to the simulation. The modeling spatial structure of strands is important for more accurate simulation of structure void statistics, strain effect, AC losses, current distribution, quenching, etc. Several models [3–6] have been carried out to analysis the cable pattern. Mechanical properties of sub-cable or cable are also very important for cabling. Large tension on strands and cable can cause undesired single strand elongation or damage during cabling. Unsuitable axial tension on the strands can cause differences in spring-back strain of the strands from different materials, possibly resulting in kinks and unengaged triplets. At present, few researcher has attention on the mechanical properties of the cable. Nemov et al used two models to solve the problem of determining the superconducting cable stress–strain state under tensile and twisting loads [7]. The first approach is based on the theory of rope. The second approach is to solve the general elasticity theory equations with appropriate boundary conditions. In the two models, the strand is supposed to be homogeneous and isotropic with a constant Young's modulus. Bajas et al. develop one finite element model for CIC conductors, which describe the distribution of axial strains, obtained form simulation results of both thermal and Lorentz loadings [8]. A new mechanical model (CORD) is developed to describe the strain and stress distribution for cable, sub-cable and single wire under axial force, twist moment and bending moment by Qin [9,10].

The ITER CC cable is enclosed in a (stainless steel) conduit and the void fraction is about 36%, shown in Fig. 1. The cables for the ITER CC are made up of four stages of NbTi based strands. The final cable is compacted by rolling. During this operation, the fourth-stage sub-cables deform into 5 trapezoidal/triangular shapes that are referred to as petals. The final stage cable is wrapped with a stainless steel strip that provides mechanical protection during jacketing and eases handling. Already in the phase of cable manufacture, the strands are subjected to stress in order to control the cabling process and in addition, stress and strain distributions are created in the strands. The stress level for cabling is important to guarantee a good quality cabling pattern but at the same time, too high stresses can affect the transport properties.

In this paper, the 3D numerical method is used to simulate every stage of the CC cable. From the model, we can get the space structure of every strand, the space pattern and cross-section of every stage. The mechanical property of CC sub-cable is analyzed by the mechanical model (CORD). We could get some useful information from the model results for CC cabling. In Section 2, we give the general descriptions of the 3D model and mechanical model. In Section 3, we present the model results and comparison to the experiments. We discuss the mechanical properties of the single strand and cable. The models can provide the approximate

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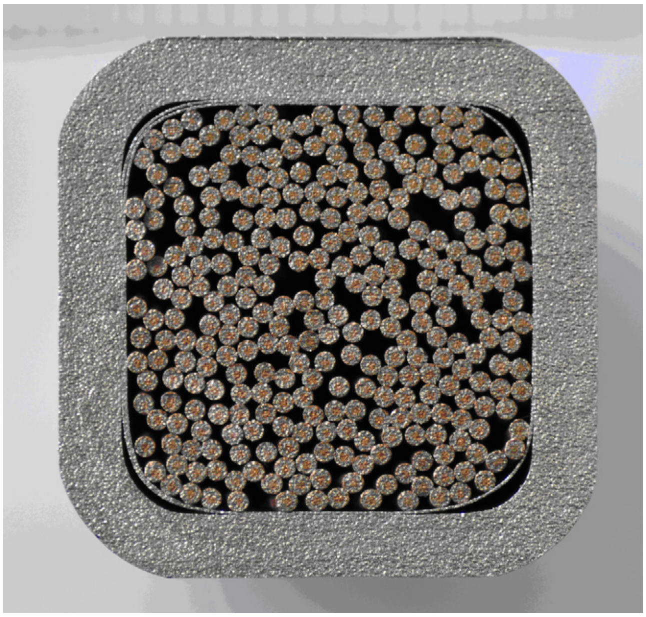

Fig. 1. Cross-section of CC conductor.

structure, stress and strain distribution in a cable. The simulation results are not only important for cable manufacture but may even be more essential for cable and conductor analysis.

2. Numerical model description

In this section, the 3D model and mechanical model are described. All symbols used in this section are listed in the following table.

List of symbols	
d	diameter of single strand
p_i	twist pitch of the ith stage of cable
s	variable parameter, length of cable
r_i	twist radius of the ith stage of cable
D_i	diameter of the ith stage of cable
ξ_i	twist starting angle of the ith stage of cable
N_p	array of cable pattern
n_i	element of N_p
$X_{i,j}$	X-coordinate of the jth strand in the ith stage of cable
$Y_{i,j}$	Y-coordinate of the jth strand in the ith stage of cable
$Z_{i,j}$	Z-coordinate of the jth strand in the ith stage of cable
$\kappa_p, \kappa_b, \kappa_t$	curvature components

2.1. Space structure model

We construct the space structure for every stage of CC cable in this section. We assume that the X–Y–Z coordinate system is right-hand standard coordinate system.

The CC cable pattern N_p is $3 \times 4 \times 5 \times 5$. The parameter equation of triplet can be obtained [6],

$$\begin{cases} X_{11} = r_1 \cos(\theta_1 + \xi_1) + \dfrac{d}{2} \cos \beta \\ Y_{11} = r_1 \sin(\theta_1 + \xi_1) + \dfrac{d}{2} \sin \beta \\ Z_{11} = s \cdot \cos \alpha_1 \end{cases}, \quad (1)$$

where $r_1 = 2/3d \sin \pi/3$, $\theta_1 = s \cdot \sin \alpha_1 / r_1$, $\alpha_1 = \arctan 2\pi r_1/p_1$, $\alpha_1 \in (0, \pi/2)$, $\beta \in [0, 2\pi]$.

The parameter equations of every single strain in the ith ($i > 1$) stage can be obtained by the transfer matrix [6],

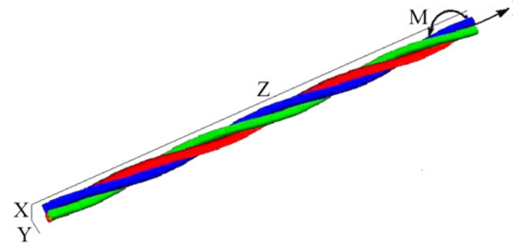

Fig. 2. Loading acting on rod.

$$\begin{pmatrix} X_{i1} & X_{i2} & \cdots & X_{im} \\ Y_{i1} & Y_{i2} & \cdots & Y_{im} \\ Z_{i1} & Z_{i2} & \cdots & Z_{im} \end{pmatrix} = A \begin{pmatrix} X_{i-1,1} & X_{i-1,2} & \cdots & X_{i-1,m} \\ Y_{i-1,1} & Y_{i-1,2} & \cdots & Y_{i-1,m} \\ Z_{i-1,1} & Z_{i-1,2} & \cdots & Z_{i-1,m} \end{pmatrix} + \begin{pmatrix} r_i \cos(\theta_i + \xi_i) \\ r_i \sin(\theta_i + \xi_i) \\ 0 \end{pmatrix} I \quad (2)$$

and

$$\begin{pmatrix} X_{i,j} \\ Y_{i,j} \\ Z_{i,j} \end{pmatrix} = \begin{pmatrix} \cos \gamma_i & -\sin \gamma_i & 0 \\ \sin \gamma_i & \cos \gamma_i & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X_{i,j-m} \\ Y_{i,j-m} \\ Z_{i,j-m} \end{pmatrix}, \quad (3)$$

where $m = n_1 \cdot n_2 \cdots n_{i-1}$, $j = m + 1, m + 2, \cdots, m \cdot n_i$, $\gamma_i = 2\pi/n_i$, and I is the identity matrix with $1 \times m$.

The transfer matrix [5,6] is

$$A = \begin{pmatrix} \sqrt{1 - \sin^2\theta_i \sin^2\alpha_i} & 0 & 0 \\ -\dfrac{\sin\theta_i \cos\theta_i \sin^2\alpha_i}{\sqrt{1 - \sin^2\theta_i \sin^2\alpha_i}} & \dfrac{\cos\alpha_i}{\sqrt{1 - \sin^2\theta_i \sin^2\alpha_i}} & 0 \\ \dfrac{\sin\alpha_i \cos\alpha_i \sin\theta_i}{\sqrt{1 - \sin^2\theta_i \sin^2\alpha_i}} & \dfrac{\sin\alpha_i \cos\theta_i}{\sqrt{1 - \sin^2\theta_i \sin^2\alpha_i}} & \cos\alpha_i \end{pmatrix},$$

where $\theta_i = s \cdot \sin \alpha / r_i$, $\alpha_i = \arctan 2\pi r_i / p_i$, $\alpha_i \in (0, \pi/2)$.

2.2. Mechanical model

Every stage of CC cable is subjected to axial force during cabling (Fig. 2). The mechanical model is considered in this section.

In the cartesian coordinate system (X–Y–Z), the Z-axis coincides with the center line of the cable. The local coordinate system is formed by Frenet frame (p–b–t) with unit principal normal, binormal, and tangent vectors, shown in Fig. 3.

The single wire in the cable can be considered as one thin rod. Now, a thin wire loaded with the force is considered, shown in Fig. 4. F_p, F_b, and F_t are sectional force components of wires, and M_p, M_b, and M_t are sectional moment components of wires. F_x, F_y, and F_z are the components of the external line load, and M_x, M_y, and M_z are the components of the external moment.

The equilibriums for the thin rod loaded can be obtained from [11,12]:

$$\frac{dF_p}{ds} - F_b\kappa_t + F_t\kappa_b + F_x = 0, \quad (4)$$