Influence of bending strain on the critical properties of jacketed Nb$_3$Sn strands for ITER

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Abstract. The tests analysis of the International Thermonuclear Experimental Reactor (ITER) model coils showed lower performances than expected. For that reason, a specific program has been launched in Europe for investigating the influence of bending strain on the transport properties of high-performances Nb$_3$Sn strands inside cable-in-conduit conductors when experiencing significant Lorentz forces. To this purpose, an experimental campaign has been initiated on single Nb$_3$Sn strands jacketed inside a 0.2 mm thick stainless-steel (SS) tube in order to be tested in mechanical ITER Toroidal Field (TF) Coils relevant conditions. In this article we describe in a first part the procedure investigated at CEA to impose a controlled pure bending strain upon jacketed stands and we present the results of the qualification tests carried out in the ENEA facility to assess the reliability of the chosen method. In a second part we propose a new model to simulate the strands behaviour experiencing bending strain together with an initial compressive strain. To understand our results, a key parameter considered is a specific weighting function relying on strand interfilament current redistribution capacity. At the end, this model enables us to explain more reliably the experimental results but also shows discrepancies which requires further improvements and extra refinements.

1. Introduction

The analysis of the results of the tests carried out on conductor samples and model coils in the framework of the R&D programme for ITER showed that the critical performances of the Nb$_3$Sn conductors are lower than expected [1,2,3]. In that context a specific programme was launched in EU to address the impact of bending strain on critical performances of Nb$_3$Sn superconducting strands. For that, a dedicated a CEA-ENEA collaboration was launched, aimed at defining a method to apply a pure controlled bending strain on SS-jacketed strands and at measuring their critical properties. After this operation, adapted models were used to tentatively explain the behaviour of Nb$_3$Sn strand experiencing strong bending in conditions close to those of the ITER TF Coils conductors.

2. Bending application method development

The bending application method is based on a sample transfer from a heat treatment (HT) mandrel to a measuring mandrel. It requires first a suitable strand jacketing procedure, achieved at ENEA, and second a definition of bending application method together with an adapted procedure to validate it, mostly achieved at CEA. It includes design and manufacture of specific supports, adapted tooling and selection of a process. Globally, the choice was made between four options resulting from the
combination of jacket removal at strand ends (before or after HT) and bending strategy (diameter increase or reduction for the measurement mandrel). Discrimination between these options was performed by relative critical current properties comparisons (tests made at ENEA at 4.2K). Clear differences were observed between each option results (see figure 1).

**Figure 1.** Critical current degradation percentage after bending with raw results (dots) and averages (lines). RI/D and UA/B are options with Radius Increase/Decrease and Unjacketing After/Before HT).

The option with jacket removal before HT and bending application by increasing mandrel diameter (RI-UB) was finally selected. An exhaustive description of the method development is available in [4].

3. Analysis

3.1. Intrinsic strain (unbent conditions)

In order to assess a consistent strand-jacket interaction, the effective longitudinal strain (i.e. the strain needed to match the jacketed strand critical current experimental value), called $\varepsilon_I$, was deduced from comparisons between results on bare strands and on SS-jacketed strand (see table 1). The strand considered is produced by OST and its critical properties parameters were extracted from [5].

| batch # | $\varepsilon_I$ (%) average | $\sigma$ (%) | $\varepsilon_I$ (%) maximum | $\varepsilon_I$ (%) minimum |
|---------|-----------------------------|--------------|-----------------------------|-----------------------------|
| 1       | -0.67                        | 0.01         | -0.655                      | -0.685                      |
| 2       | -0.645                       | 0.01         | -0.63                       | -0.66                       |

The average $\varepsilon_I$ is in agreement with fully-bonded model (around $-0.7\%$). The difference between the two batches is thought to be due to HT.

3.2. Bending strain study

3.2.1. Models description

First, a basic model considered is the classical Ekin one [6]. Schematically the bending effect is supposed to drive a strain field map in the strand cross section, changing thus the critical properties of each filament depending on its position. In that model, two parameters are free: the intrinsic longitudinal strain and the neutral axis position (usually invariant). However one hypothesis must be set on the interfilamentary current redistribution capacity by mean of a comparison between filament twist pitch (TP) to an average current transfer length L defined as:

$$ L = d \frac{0.1 \rho_T}{\frac{n}{\rho_n}} $$
where \( \rho_T \) is interfilamentary transverse resistivity, \( \rho \) the Iₙ criterion, d the strand diameter and n the transition index (or n-value). For Nb₃Sn, L is typically 10 times the diameter (here 8 mm) quite close to the OST strand TP used in our experiment. So for this basic model both TP cases can be considered with corresponding critical current ratios calculation formulas:

\[
\frac{I_C}{I_{C0}} = \frac{1}{\pi R^2} \int \frac{J_C(\varepsilon(x, y))}{J_{C0}} \, dxdy \quad \text{or} \quad \frac{I_C}{I_{C0}} = \frac{1}{R} \int \frac{J_C(\varepsilon(x))}{J_{C0}} \, dx
\]

for TP \( \gg L \) or TP \( \ll L \) respectively.

Where \( R \) is the strand filamentary zone (FZ) radius, \( \Sigma \) the FZ surface, \( \Gamma \) a FZ radius defined by all points at minimum \( J_C \) for each filamentary trajectories (i.e. circles included into \( \Sigma \)). \( I_{C0} \) and \( J_{C0} \) refer to the unbent strand. Globally this basic model considers either fully connected or isolated filaments (for long or short TP hypothesis respectively).

In this work we developed a model, called weighted distribution model (WDM), which is somehow a generalization of the classical one as it allows all intermediate possibilities for current redistribution capacity, in other words all possible values for interfilamentary resistivity. For that, the \( I_C \) ratio calculation is modified with help of a specific weighting function \( H \) convoluted with \( J_C \) as:

\[
\frac{I_C}{I_{C0}} = \frac{1}{\pi R^2} \int \int H(\lambda, \theta, r, \theta) J_C(\varepsilon(r, \theta)) \, rdrd\theta \quad \text{with} \quad H(\lambda, \theta, r) = \frac{\pi}{\lambda(1-e^{-\frac{\theta_{eff}}{\lambda}})} e^{-\frac{(\theta_{eff}+\theta)}{\lambda}}
\]

Here \( \{\theta_{eff}, \omega\} \) is \{0,1\} or \{\pi, -1\} if minimum \( J_C \) is respectively for \( \theta = 0 \) or \( \theta = \pi \). In fact, this new model generalizes the basic one as for \( \lambda \) close to zero (or infinite) we find back the short (or long) TP hypothesis described before. An important point is that \( H \) is defined to remain physically meaningful, with a \( \lambda \) parameter that can be interpreted as relevant to an effective angle \( \theta_{eff} \) inside which current redistribution can occur (for intermediate values of \( \rho_T \)). The influence of self field is also considered in WDM. A global illustration of this model principles can be seen in figure 2.

![Figure 2. Geometrical illustration of WDM. In left picture a radius \( \Gamma \) is shown with \( J_C \) minimum at A (one filament in dashed). In center picture \( H \) curves are shown for 3 typical \( \lambda \) values. Right figure is \( \theta_{eff}(\lambda) \), defined here as the angle for which a ratio \( \eta \) of \( H \) integral is reached.](image)

Those two models are applied to the experimental data and results can be seen in figure 3. Fitting curves for all TP hypotheses have been selected keeping invariant neutral axis and intrinsic longitudinal strain.
Figure 3. Illustration of simulation of final chosen method experimental results using both classical model (dashed) and WDM (solid black). All samples experienced the same HT conditions.

The basic model hypotheses (short or long TP) obviously shows important discrepancy with experimental results. Finally WDM, by enabling to physically describe intermediate configurations that better match with results (here the average only), turns out to be the more adapted model for our analysis even though large room for improvement remains (such as increasing trend of $I_c$ degradation with magnetic field). For that, investigations are planned, among which the consideration of geometrical effects (field-filament angle, filament distribution...), or making precise strain field map calculations (3D models...) or better defining H function through electric network modelling. Future tests at intermediate bending strain will also clarify the possible influence of zones where $J_c=0$.

Conclusion
A method for applying a pure controlled bending on long lengths of jacketed Nb$_3$Sn strands was successfully developed by CEA and ENEA, particularly adapted to ITER operating conditions and usable on many strands types. Besides, a new model for bent strands properties simulations (weighted distribution model or WDM) allowing to consider all interfilamentary redistribution configurations was proposed. Experiments showed this model as the more adapted one for pre-stressed Nb$_3$Sn strands simulation. However remaining discrepancies with data call for improvements. Some extra refinements are planned on this subject (geometrical effects, 3D calculations, weighting function...).

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