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Comparison of a Contact Mechanics Model with Experimental Results to Optimize the Prediction of Transverse Load Effects of Large Superconducting Cable-In-Conduit-Conductor

Luisa Chiesa, and Makoto Takayasu

***Abstract*—A model based on contact mechanics concepts has been developed to analyze and quantitatively evaluate mechanical transverse load effects on superconducting strands in a cable-in-conduit-conductor (CICC). The model estimates the number of contact points and the effective contact pressures between the strands in a cable. Experimental measurements confirmed the model, which was then used to evaluate mechanical transverse load effects on the critical current degradation of sub-sized cable samples of Nb_3Sn wires. It is proposed to use a set of experimental transverse load test data of the smallest stage cable (triplet) in order to predict transverse load degradations of the critical current of a large full size CICC cable. This paper will review the model to estimate the degradation caused by the transverse load effect and discuss the results of several cable configurations. The analysis provides suggestions for future design evaluation of mechanical behaviors of large Nb_3Sn CICC cable magnets during operations.**

***Index Terms*—Contact mechanics, Cable-In-Conduit-Conductor (CICC), critical current, transverse stress, Nb_3Sn, superconducting cable.**

I. INTRODUCTION

SUPERCONDUCTING magnets for fusion energy applications use cable-in-conduit conductors (CICC). The electromagnetic interaction between current and magnetic flux in a CICC results in a significant Lorentz force accumulating across the cross section of the conductor. Several types of forces act onto the cable during cool down (axial) and operations (bending and transverse loads). Those effects are believed to be the cause of the unexpected degradations seen in large CICC magnets such as the ITER model coil magnets [1]. Experimental and modeling investigations have been performed for pure and periodic bending and transverse load effects in an effort to understand and mitigate possible degradations in the ITER magnets [2-6]. This paper discusses how experimental results on different Nb_3Sn (Oxford ITER pre-production) samples (single strand, 3-strand and 45-strand cables) were used to develop a new model to evaluate effective transverse loads in a Nb_3Sn cable.

The transverse load pressure due to the electromagnetic Lorentz force is often referred to as "averaged pressure" because it is determined from the force divided by the projected area of the sample cross-section. This averaged pressure does not take into account the actual area pressed and the local effects that might occur within the strand. In a cable composed of many strands, the real pressure acting on a strand is a combination of the angle between crossing strands, the number of their contacts and the force. Using the projected area of the wire or the cable is an oversimplified way of estimating the pressure exerted on strands and it can be much smaller than the actual contact pressure experienced by each strand.

In this paper we describe the salient characteristics of a model to evaluate the deformation of the cables under a load according to the theory of contact mechanics. This model quantitatively evaluates the effective contact pressure between strands and predicts the critical current behavior of full size cables under the natural Lorentz transverse load during operations. It is proposed to use a set of experimental transverse load test data of the smallest stage cable (triplet) to evaluate the transverse load effects on performances of full size superconducting cables.

II. EXPERIMENTAL RESULTS

The details of the experimental setup are described in [7]. Three different samples were tested: a single strand, 3-strand and 45-strand cables. To simulate the same electromagnetic conditions felt by strands in a full size cable, it was necessary to apply a mechanical load to the sub-cables. The normalized critical current as a function of mechanical load (force averaged over the cross section of the sample) is represented in Fig. 1. The experimental setup allowed for a direct measure of the load applied and the displacement through a load cell and extensometer. All samples show an initial plateau and subsequent degradation. The change in critical current is reversible up to a certain load conditions after which permanent degradation is observed. It is worthwhile noticing that single strand and 3-strand cable have no significant bending or axial strain effects but show a significant

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degradation caused by the transverse load effect. This indicates that the transverse load effect is important in the overall performance of CICC cables. Additionally, the single strand sample shows a more gradual degradation for the same amount of mechanical load applied. This is obvious because the load in the case of a single strand is distributed over the entire length pressed and it is not localized at the contact points as in the 3-strand and the 45-strand samples. It is believed than the 3-strand sample would show a similar behavior as the single strand if its twist pitch was longer allowing for a better distribution of the load through almost parallel strands contacts.

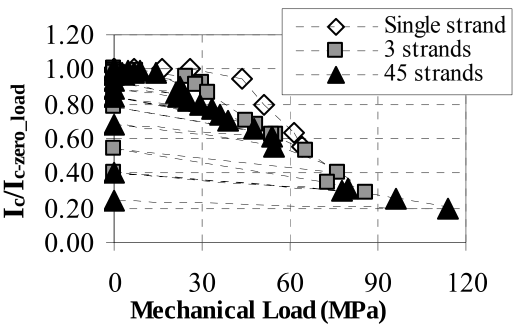

Fig. 1. Measured normalized critical currents as a function of applied mechanical load for three different samples.

III. Model Main Concepts

In this section the main concepts used for the model will be briefly described. More details on the model can be found in [8]. The goal of the model is to estimate the critical current of a full size cable taking in consideration the Lorentz load accumulation across its cross section (Fig.2).

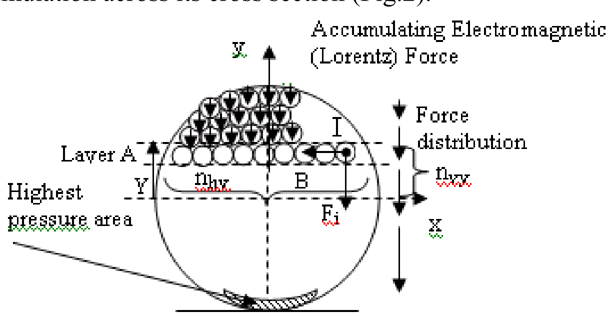

Fig. 2 Electromagnetic force effect on strands in a CICC and parameters used in the analysis.

To evaluate the critical current caused by the transverse Lorentz load it is necessary to estimate the effective contact pressure felt by the strands in a cable. The pressure at the contact point is the ratio of the force at that point divided by the area of the contact. In order to find the local force we can use the total force applied (mechanical or electromagnetic) divided by the number of contact points. Estimating the number of contact points is essential to this approach and it will be discussed later in this section. To estimate the area of contact, contact mechanics concepts are used [9]. Contact mechanics between crossing cylinders is mathematically treatable only for elastic materials. Superconducting strands are elasto-plastic materials and more work in estimating the real behavior of strands under load is being performed [10].

The normalized critical current I^*_c in the case of a fully twisted cable can be written as (1):

$$I_c^* = \frac{I_c}{I_{c0}} = \frac{2\cdot\pi\cdot(1-v_f)\cdot\cos\vartheta}{N_s\cdot\pi\cdot a^2}\int_{-R_{cable}}^{0} I^*_{c-single}(p_{cy})\cdot y\,dy \quad (1)$$

where a is the strand radius, N_s the number of strands, θ the average angle between strands and the cable axis and v_f the void fraction.

In a fully twisted cable each strand is assumed to spiral along the cable axis, and in a twist pitch length it will go back to its original location. In a twist pitch length, each strand will experience the highest Lorentz load at some point so that the currents of strands on the same annulus will transport the same current *I(r)* corresponding to the minimum critical current experienced in a twist pitch length. No current sharing among strands is assumed in a twist pitch length (true for a chrome plated wire cable). The integral in equations (1) is evaluated using Gaussian integration. It is calculated using Microsoft Excel®. To evaluate the contact pressure p_{cy}, the strand currents are required, and the current is a function of the pressure, so an iteration process was used to perform the critical current calculations. To evaluate the currents used in the iterative process, the total transverse force acting on a horizontal plane layer A at location Y, F_{LFy}, caused by the strands above the layer A and the strands of the layer-A (Fig. 2) is given by (2):

$$F_{LFy} = \int_{Y}^{R_{cable}} \Delta f_{LFy} = \frac{2\cdot B\cdot N_{sc}}{\pi\cdot a^2\cdot N_s}\cdot(1-v_f)\cdot\cos\vartheta\cdot \cdot\int_{Y}^{R_{cable}} I_{c-single}(p_{cy})\cdot\sqrt{R_{cable}^2-y^2}\,dy \quad (2)$$

where N_{sc} is the number of superconducting strands (the function $I_{c-single}(p_{cy})$ is described later in this section). For a 5-stage cable the number of contacts in a contact plane between bundles per unit length, N_{hy} is a function of the total number of contacts N_T where N_{si} is the number of strands in a stage i and the number of strands on a plane y, n_{hy}:

$$N_{hy} = (N_T / N_s)\cdot n_{hy} \quad (5)$$

$$n_{hy} = 2\cdot(1-v_f)\cdot\cos\vartheta\cdot\sqrt{(R_{cable}^2-y^2)}\cdot 2a/\pi\cdot a^2 \quad (6)$$

$$N_T = k_2\cdot k_3\cdot k_4\cdot k_5\cdot N_1 + k_3\cdot k_4\cdot k_5\cdot N_2 + k_4\cdot k_5\cdot N_3 + + k_5\cdot N_4 + N_5 \quad (7)$$

$$N_i = 2\cdot k_i\cdot 4\cdot(1-v_f)\cdot\cos\vartheta\cdot N_{si}/(\pi^2\cdot L_{pi})\ i = 1...5 \quad (8)$$

Estimating the number of contacts in a cable with more than a thousand strands twisted together is not a simple task. The assumption made in our analysis is that only the perpendicular cross-contacts between two strands (perpendicular to the field) need to be accounted for because those are where the highest forces are felt from a particular strand. For example when a transverse load is applied to a 3-strand cable it is noted that there are six places of strand-to-strand contact points that support the load in one twist pitch length as shown in Fig. 3(a). The other contacts can be disregarded because the forces at these points are much smaller. The next stage could be composed of three, four or five bundles of 3-strand cables. In the case of five bundles (Fig. 3(b)) the number of bundle-to-bundle contact places is 10. In general, the contact places between sub-bundles are given by $2{\cdot}k$ where k is the number of bundles. The total number of strand-to-strand contact points given by (7) at the bundle crossing contact place will be a function of the number of strands in that bundle.

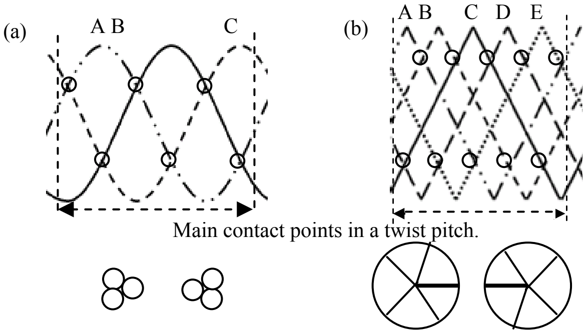

Fig. 3 (a) Contact points in a triplet and (b) a 5-bundle cable after swaging.

The function $I_{c\text{-}single}(p_{cy})$ is the critical current as a function of the contact pressure p_{cy} (estimated knowing the number of contacts in a contact plane per unit length on N_{hy}). It can be obtained from the experimental results of the smallest stage (triplet) of a full size cable and is used in (2) to calculate the cable critical current. A triplet is the smallest stage of typical CICC cables and its behavior is more representative of transverse load effects between strands in a cable than a single strand loaded uniformly along its length. It is noted that in a 3-strand cable the effects of thermal contraction and bending are negligible; therefore the degradation mechanism observed in the experiment (Fig. 1) is most probably due to the applied mechanical transverse load.

The contact pressure p_{cy} is the ratio of the contact force F_{cy} on a strand at a particular location y, divided by the contact area S_c ($p_{cy}=F_{cy}/S_c$). The contact force F_{cy} is the ratio of the force acting on a layer divided by the contact points in the layer ($F_{cy}=F_{LFy}/N_{hy}$).

The effective contact area (ellipse) for crossing strands is described by (9):

$$S_c = \pi \cdot \eta \cdot \xi \qquad (9)$$

where $\eta = \alpha \cdot \left(F_c \cdot K_D / E^*\right)^{1/3}$, $\xi = \beta \cdot \left(F_c \cdot K_D / E^*\right)^{1/3}$ and $1/E_i^* = 2(1-\nu^2)/E$

The Young's modulus E is the only unknown parameter and it is used as fitting parameter in our analysis. This parameter is chosen so that the calculated displacement predicts reasonably well the measured displacement [7]. E varied between 1 and 4 GPa which was similar to previously measured values [11].

The critical current of a fully twisted cable, (1), allows simulating superconductor performances of various CICC cables. For the model analysis, the critical current behavior $I^*_{c\text{-}single}(p_{cy})$ on the transverse pressure for a given wire is required to evaluate (1). In the following analyses the experimental $I^*_{c\text{-}single}(p_{cy})$ obtained at the background field of 12 T for the 3-strand sub-cable experiment with a Young's modulus of 3 GPa (solid line in Fig. 4(a)). This assumption was justified by the fact that the experimental data of the 45-strand cable were very well predicted by the 3-strand data (Fig. 4(b)). Those results are very encouraging because they suggest that experimental results of the smallest stage of a CICC could be used to estimate the behavior of a larger size cable subjected to a certain transverse loads. In our analysis the variation of magnetic fields across the cross section of the cable is disregarded. The purpose of the model analyses is to provide a general idea of the effects of transverse load.

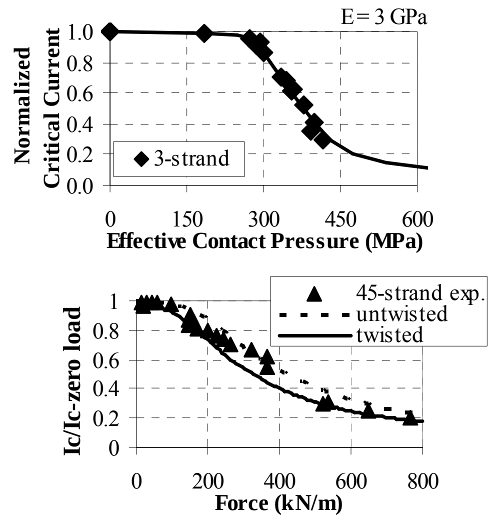

Fig. 4 (a) 3-strand data and fitting curve used to predict the behavior of the 45-strand sample (b).

IV. Model Analysis for Full Size Cables

The model results show that for a full size cable with the original cable pattern proposed for the TF coil in ITER (cabling pattern 3x4x4x4x6 and twist pitches 65, 90, 150, 270, 430 mm), the Lorentz load could account for up to 20% of degradation [8]. Those results could partially explain the large initial degradation observed in the full size model coil magnets [1]. It was also shown that to reduce the degradation caused by the transverse Lorentz load each sub-cable could be supported. For example, if the 6 petals of the last stage of the TF cable are independently supported (each one carrying 11.6 kA), the degradation would be 6% [8]. The analysis showed that the cabling pattern plays a fundamental role in the performance of full size cables. The analysis showed that lower number of bundles in a stage causes higher degradation. A cabling pattern 3x3x3x3x6 shows a 10% larger degradation than a cabling pattern 3x5x5x6 [8]. The effect of twist pitch length is of particular interest considering recent work has been focusing on optimizing this parameter to obtain the best performance [2-6]. Our model indicates that shorter twist pitches at the first stage are preferable. In the following analysis we considered the original ITER cabling pattern (twist pitches 65, 90, 150, 270, 430 mm) and multipliers of these nominal values. In Fig. 5 the results are plotted so that the nominal ITER pattern has multiplier 1x1x1x1x1. The other curves are fractions of the nominal values (0.75 being 75% and 1.25 125% of the nominal values respectively). From Fig.

5 we can see that for a given nominal current of 68 kA we expect a degradation of 20%, so that a current of 98 kA will be required to satisfy the 68 kA requirements. If we reduce the twist pitch of the first stage by 25% in turn we increase the number of contacts and reduce the effective contact pressure that the strands feel. This allows for a reduction of the degradation caused by the Lorentz load by 5% (Fig. 5 grey diamonds). An equivalent effect can be obtained by shortening the second stage by 25% (open diamonds).

It is important to notice that the model presented takes in consideration only the crossing points between strands. As for now the model does not have the capability of taking in consideration very long twist pitch in which a contact resembles a long rectangular shape as the strands were parallel. In fact if the first stage has a very long twist pitch the contact between strands is long so that the load is distributed over a larger line-contact area compared to the cross-contact case in which the area is a small ellipse. The contact mechanics approach is very different for the two cases and it will be addressed in future work. Combining the line contact mechanism with the present model will explain the better performances of long twist pitch cables recently reported [3]. Additionally, the presented model takes into account only the degradation caused by the transverse contact pressure of crossing strands due to the Lorentz load. Axial and bending strains caused by thermal contractions and by the Lorentz load are additional sources of the degradation [2-6]. Those effects are complementary and not mutually exclusive.

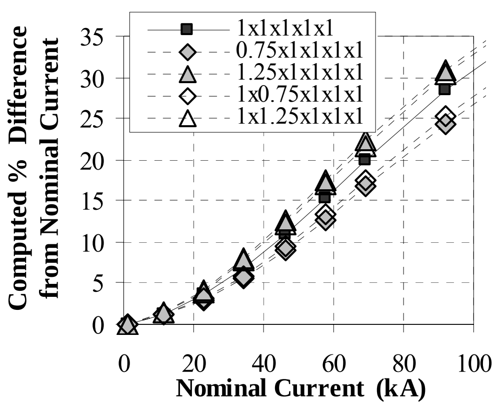

Fig. 5 Percent differences between the nominal current and the expected values considering the Lorentz load effect as a function of different twist pitch values. 1x1x1x1x1 represents the nominal ITER TF cable value. The other curves are fractions of the nominal values (0.75 being 75% and so on).

V. DISCUSSION

With the present work, we proposed a method to evaluate degradation caused by transverse electromagnetic load in large CICC. The model relies on the experimental behavior of the smallest stage of CICC (triplet) to extrapolate the behavior of full size cables allowing for the first time a quantitative evaluation of this effect. Several studies have been performed to understand the transverse load effects of bending and axial strain in CICC extrapolating single strand behavior [3-6]. Very few people performed experiments on transverse load effects [12]. This work is the first to evaluate and quantify its effects by using 3-strand data results. We believe the use of the smallest stage of a CICC to evaluate the performance of a full size cable is more representative than using a single strand.

As reported in [3], [6] a longer twist pitch in the first stage mitigates the degradation effects without causing larger AC losses. From our analysis shorter twist pitches are beneficial against transverse load. These contrasting results are due to the fact that when the first stage is longer than a certain value the contact will be more likely like a line contact (rectangular area compared to ellipse) so that the contact pressure between strands becomes smaller. Our model considers only crossing strands contacts and does not include the effect of having large enough twist pitches to allow long contacts. The expansion of the model to include long contact areas will be considered in the future. Longer twist pitches in subsequent stages cause large AC losses so that a compromise between those two choices needs to be considered. A cable with a long twist pitch in its first stage could have a shorter second stage to maintain the same amount of contact points to reduce the effect of transverse load but minimize the AC losses at the same time.

VI. CONCLUSIONS

A new model based on contact mechanics between strands was presented to explain the transverse load degradation. A method evaluating quantitatively the number of contacts and the effective contact pressure between strands has been developed. With experimental support, it has been proposed to use the 3-strand transverse-load performance data of the critical current to evaluate the degradation of a large full size cable due to Lorentz load effect. The overall degradation of a cable includes other sources such as axial and bending strains.

Future work includes more experimental studies on the critical current of sub-cables under transverse load, mechanical studies of strands and cables and finite element analysis to provide insights on how strands behave under loading conditions.

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