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EXPERIMENTAL STUDIES OF TRANSVERSE STRESS EFFECTS ON THE CRITICAL CURRENT OF SUB-SIZED NIOBIUM-TIN SUPERCONDUCTING CABLES

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ABSTRACT

A simple and reliable test method for transverse load experiments of sub-sized cables has been developed in order to study mechanical and electrical transverse load effects on superconducting cables. The device uses straight samples in a hairpin configuration. Three different size cables of a single strand, a triplet and a 45-strand cable were systematically tested. The hairpin sample device was successfully operated and provided very reliable experimental data. The unique experimental design allows great flexibility, and different size cables can be efficiently tested with minor parts changes to the sample holder. One sample can be mounted and tested in a week's time frame using a superconducting split magnet available at National High Magnetic Field Laboratory (NHMFL), Florida State University (FSU). In this paper the characteristics of the device and the measurement technique are described. The test results from the three different cables are reported and discussed.

KEYWORDS: Fusion, ITER, Cable-in-Conduit Conductors (CICC), critical current, transverse stress, Nb_3Sn, superconducting cable.

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. This transverse load is one of the causes of the unexpected degradations seen for large CICC magnets such as the ITER magnets. Efforts in measuring and modeling the transverse load effects on single strands and cables have increased over the past decade. In particular, pure and periodic bending and transverse load experiments have been performed [1-4]. This paper discusses the measurements performed on sub-sized Nb_3Sn superconducting cables and their behavior when transverse load is applied.

To reproduce similar electromagnetic load as in a full size CICC, the loading conditions of a full size cable are simulated by applying mechanical loads on sub-sized cables. The natural Lorentz load in a full size cable is too large to be produced in the limited space of an experimental magnet and with currents capability limited to ~10 kA, so that a sub-sized cable is used to reproduce similar loads in magnitude with an external mechanical load applied. Previously we used circular single-turn 36-strand cables [5, 6], however the results showed unexpectedly large initial degradations. We have developed a new device using a hairpin sample configuration. The hairpin samples were tested using a 12 T split magnet at NHMFL, Florida State University. The following is the description of the new experimental setup and the results obtained with the samples tested.

EXPERIMENTAL SETUP

FIGURE 1 shows the transverse load test sample holder setup and its working principles. The mechanical load is applied to each leg of a hairpin type sample by using a vertically moving wedge. The wedge transversally moves two matching pieces (one on each side) that are constrained vertically and can only slide horizontally. The two matching parts touch two pressing pieces where the sample is located (FIGURE 1a). To ensure uniformity of the load applied over the length of the sample, the wedge was segmented into four sections. The matching wedges are made of 316 stainless steel. All the wedge pieces were cut using EDM technique with high tolerances. Any imperfection could create an undesirable localized force accumulation. All the parts are enclosed inside a reusable single-piece case (FIGURE 1b) which was also machined with EDM and made of $TiAl_6V_4$ alloy. The case needed to be machined as a single piece to withstand the load applied during the experiment.

The main advantage of the hairpin sample design compared with the circular single-turn one described in earlier work is that the sample is straight making it easier to handle and fabricate. Furthermore the heat treatment structure is much smaller than that in the previous design (a circle 115 mm in diameter compared to a block 30x70 mm). Those dimensions allowed the use of a smaller furnace (152 mm diameter, 1.2 m length) for the heat treatment of four samples at the same time. The sample cooling conditions of the hairpin design are better since the helium vertically flows in parallel to the cable. The entire structure was made of $TiAl_6V_4$ alloy that has an excellent strain matching with Nb_3Sn and it is a strong enough material to react the forces of the experiment.

Another advantage of the design is that the same structure and many of the parts can be used to test different size cables reducing the cost for the test of multiple samples. The only components specific to a cable sample are the cable holder and the pressing piece. Samples can be easily changed (2 days to remove one sample and mount a new one) reducing the overall time of preparation.

A spacer block instead of the wedge and the matching pieces was used to maintain the void fraction during heat treatment together with some metal strips that maintained the correct space between the holder and pressing piece. The metal strips and the block were removed after heat treatment and replaced with the wedge pieces.

A single strand, a triplet and a 45-strand cable were tested. The overall length of the hairpin samples is 1.45 m including about 220 mm soldered joint at each end. The pressed length was ~130 mm for each leg on the sample (being a hairpin configuration two legs of the same sample can be tested simultaneously). Three pairs of voltage taps were mounted along the sample with two covering each leg and one covering the entire length (FIGURE 1c). The voltage taps were mounted on the samples before heat treatment and insulated by glass fiber sleeves that could resist the high heat treatment temperatures.

Strain gages were mounted on the wide side surface of the single piece case to verify the uniformity of the applied load since the wedge piece was composed of four sections. Three strain gages were mounted on the front of the case and two on the back (FIGURE 1b). A Hall sensor was mounted on the same wide surface to verify the split magnet field.

An extensometer was mounted on the wedge piece and secured on the sample case, so that, while the load is applied and the wedge displaced, the extensometer remains in position and measures the vertical displacement of the wedge (FIGURE 1d). The vertical displacements were converted to the horizontal displacement of the pressing pieces. These measurements were used to evaluate the transverse Young's modulus of the tested cables as presented in the following section.

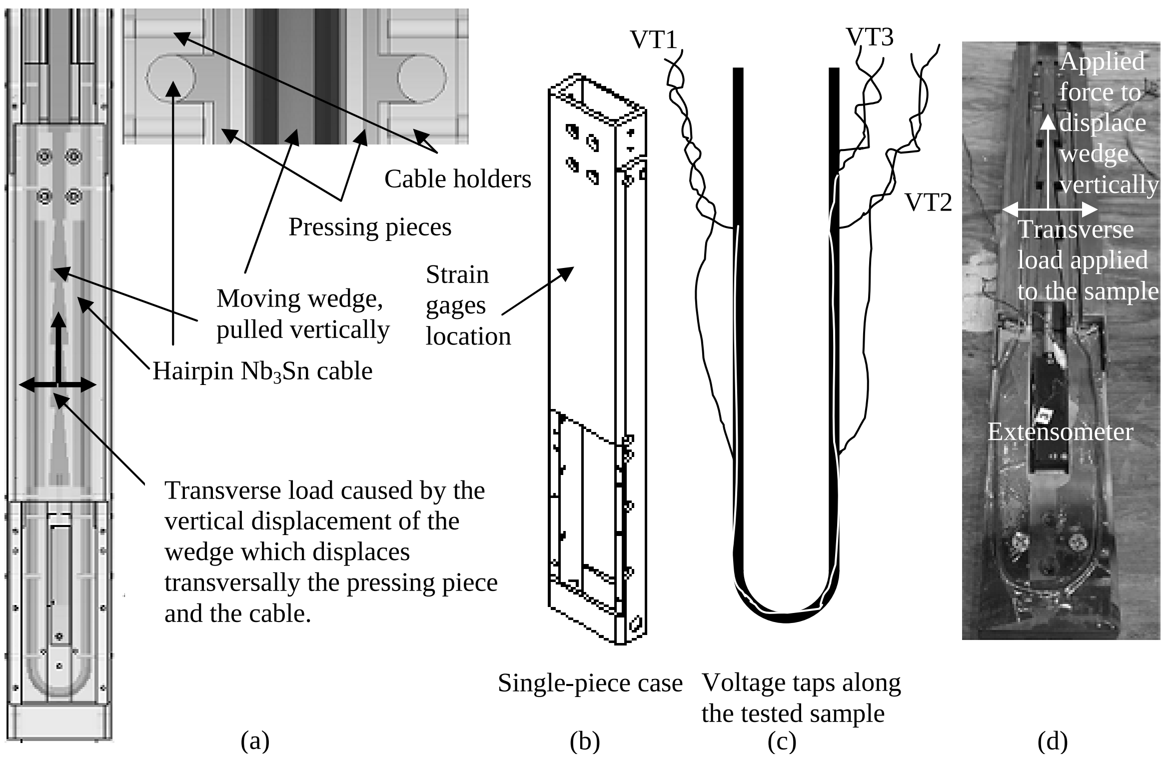

FIGURE 1. (a) Schematic view of the sample holder and how the load is applied to the sample. (b) The structural single-piece case where strain gages are located. (c) A hairpin cable with three voltage tap wires. VT1 and VT2 cover the two straight legs of the sample and VT3 is the overall sample voltage. (d) The vertical displacement of the wedge is measured with an extensometer. This vertical motion creates the outward movements of the matching pieces.

The test facility used in this experiment was at the NHMFL, FSU. The magnet system used to apply the external field was comprised of an Oxford superconducting split magnet having a 30x70 mm vertical slot where the sample was mounted. It provided the magnetic field of 12 T uniform over a 150 mm length. One of the advantages of using a superconducting magnet was the low electrical background noise level in the system (less than 0.5 μV).

Once the sample probe was inserted into the cryostat and through the bore of the magnet, the probe bottom was held in position using a remotely actuated sliding pin located at the bottom of the cryostat, that the sample holder was locked while the wedge was displaced vertically applying the load to the sample. The positioning of the sample could be adjusted within 25 mm (1 inch) to ensure a proper engagement with the sliding pin. The adjustment was obtained with the use of a bellow mounted on the top flange of the probe (FIGURE 2).

Two types of linear actuators were used for the experiments, since the single strand test required a finer sensitivity than the other two tests (3-strand and 45-strand samples). The vertical load applied on the single strand was less than 1500 N while for the other two experiments they were 3600 N and 17700 N respectively. The test setup was optimized for multi-strand samples and not single strand experiment. The single strand was tested first followed by the testing of the triplet and the 45-strand cables

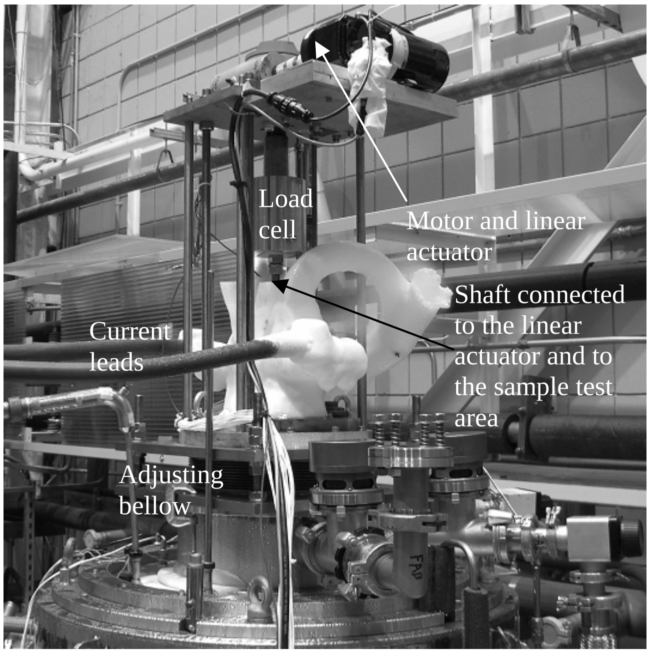

FIGURE 2. Probe inside the dewar. The picture shows the top flange with the bellow used to adjust the height of the probe so that it can be easily connected to the pin sitting on the bottom of the dewar. The linear actuator is connected to the shaft connected to the wedge at the sample area through the cylinder containing the load cell

SAMPLES TESTED AND EXPERIMETAL RESULTS

Samples description

The cables were made of an ITER pre-production internal-tin, Oxford wire. The 45-strand cable (3x3x5) was a hybrid cable meaning that the first stage triplet was composed of one copper strand and two superconducting strands, which had a total of 30 superconducting and 15 copper strands. The triplet sample had three superconducting wires with a twist pitch of 45 mm, while the 45-strand cable had the twist pitches of 45, 85, and 125 mm for each stage respectively. The void fraction for the 45-strand cable was 33% following the general guideline of the ITER project. The main properties of the samples are given in TABLE 1.

TABLE 1. Main properties of the sample used in the experiments.

J_c (12 T, 4.2 K)	1014 A/mm^2		
Diameter	0.82 mm		
Copper/non-copper ratio	1.04:1		
Number of strands	1	3	45
Average cable diameter (mm)	0.82	1.74	6.72
Cable pattern	1	triplet	(1Cu+2SC)x3x5

Results and discussion

Critical current measurements as a function of the mechanical load were performed at 12 T for all the samples. The results are shown in FIGURE 3. The critical currents were evaluated at a 10 μV/m criterion. The natural Lorentz loads for those sub-sized cables were very small compared with the applied load so they were neglected in the plot.

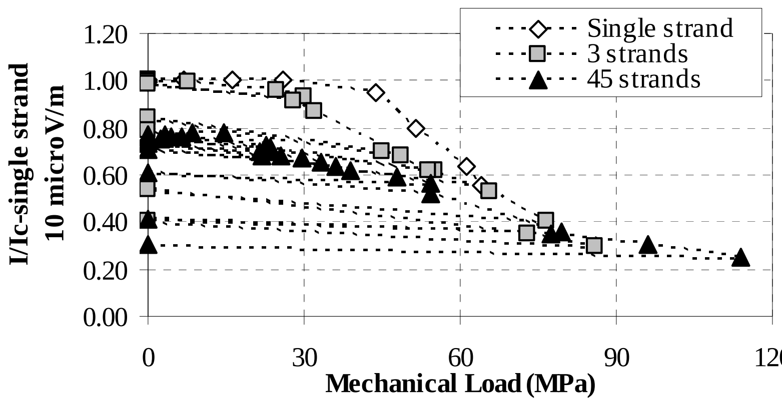

FIGURE 3. Normalized critical current (normalized to the single strand value) as a function of the applied mechanical load.

It can be seen that the initial critical currents of the single strand and triplet were their expected values while the 45-strand cable showed an initial degradation of about 23%. The degradation might be caused by thermal contractions and other unknown factors. It is believed that this degradation is not caused by the mechanical transverse load since the data showed an initial plateau followed by a significant degradation once the external loads were applied. The initial degradation was far better than our cables tested with the previous experimental setup discussed in [5, 6]. The sample fabrication process has been carried out very carefully but still unexpected damages might have occurred during the process.

As shown in FIGURE 3 all samples were tested until the critical current levels reduced as low as 30% of their initial values. It is noted that all samples show initial plateaus with constant critical currents up to a certain level of load as have been reported earlier [7]. Those plateaus were not observed in our previous tests that used the circular one-turn configuration.

The 3-strand and 45-strand samples were cyclically loaded as many times as possible considering the time constraints of the facility used. All the samples showed a permanent degradation and did not recover completely when the loads were released.

In FIGURE 4 the same data shown in FIGURE 3 are plotted as a function of the transverse force per unit length. In this plots the x-axis shows the amount of force applied on each sample. In contrast with FIGURE 3, the forces per unit length applied to the samples for a given normalized critical current are very different in values.

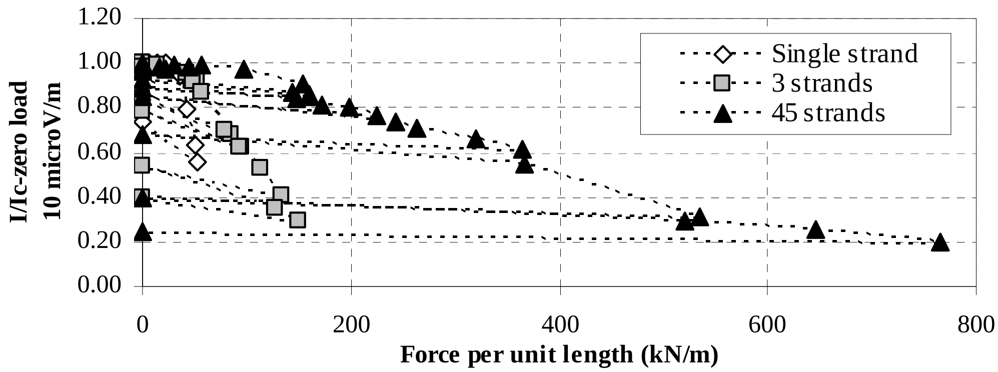

FIGURE 4. Normalized critical current as a function of force per unit length of the samples tested.

We have developed a model for transverse load effects on the critical current, presented in [8]. The model takes into account the total number of contact points in a cable, and quantitatively evaluates the effective contact pressure between strands. The details of the work and analysis equations are given in [8]. Here the experimental results of the triplet and 45-strand cables are shown with the model results.

FIGURE 5 shows the experimental results of the 3-strand cable as a function of the effective contact pressure evaluated from the model. From the plot the characteristics of the critical current as a function of the effective contact pressure was identified for the tested specific sample. The solid line in FIGURE 5 was obtained as the best fit with a fitting parameter for the Young's modulus of E = 3 GPa. This fitting curve was then used to estimate the behavior of larger cables. A triplet is the smallest stage of typical CICC cables and its behavior is more representative of contacts 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 small; therefore the degradation mechanism observed in the experiment is most probably due to the applied mechanical transverse load.

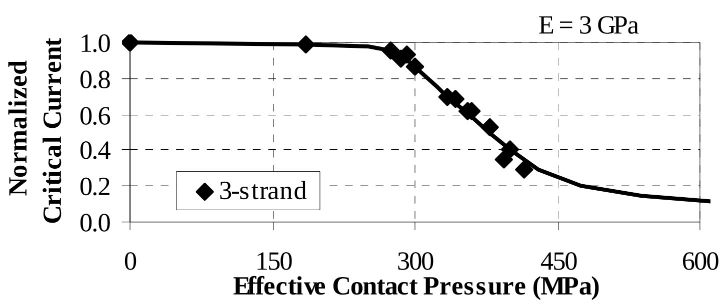

FIGURE 5. 3-strand data and fitting curve used to predict the behavior of the 45-strand sample.

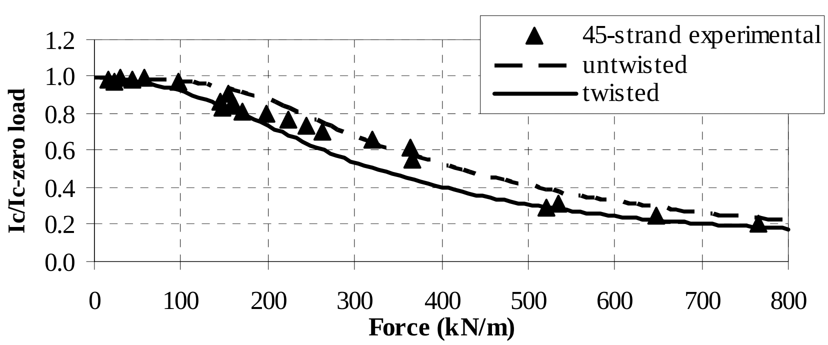

FIGURE 6. Normalized critical current as a function of force per unit length of the 45-strand sample and the calculated curves obtained from the model developed in [8].

FIGURE 6 shows the 45-strand experimental data and the two theoretical curves determined from the twisted and untwisted cable models using the 3-strand fitted curve shown in FIGURE 5 [8]. The experimental data are between the two lines obtained from the twisted and untwisted cable models. Since the pressed test section length of the sample was similar to the last stage twist pitch, the 45-strand cable could not be considered to be fully twisted. The experimental data are well matched by the model curves.

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 and expensive experiments on large CICC could be avoided.

The vertical displacement data obtained using the extensometer and the load data with a load cell were used to evaluate the transverse displacement as a function of the force per unit length for each sample, and the dynamic transverse Young's modulus was obtained from the following equation:

$$E_y = \frac{\textit{Cable diameter} \cdot \textit{Transverse Force}}{\textit{Displacement} \cdot \textit{Cable cross section}} = \frac{\textit{Transverse Force}}{\textit{Displacement} \cdot \textit{Cable length}} \qquad (1)$$

The values of the transverse Young's modulus found for those samples are similar to the values reported in the literature [9]. The transverse Young's modules are much lower than the values of solid metals composing the Nb_3Sn strands. Mechanical properties of superconductors are not very well documented in literature. More systematic approaches and experiments would be required to understand the mechanical response of the strands and cables to various sources of loads. Further studies will help understanding the critical current behaviors of a 3-strand cable as a function of the effective contact pressures. Those results could be used for large cable analyses.

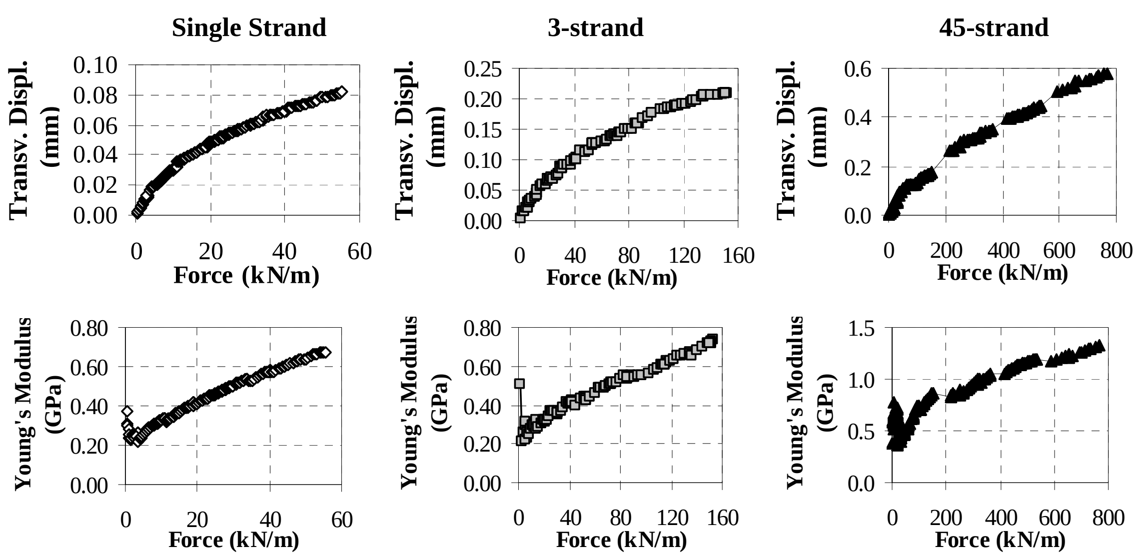

FIGURE 7. Transverse displacement and Young's modulus for the sample tested as a function of the force per unit length.

CONCLUSIONS

An experimental device developed to study the effect of transverse load on sub-sized cable-in-conduit conductor was successfully built and tested. The device used a hairpin sample and was successfully operated providing very reliable experimental data. Very few parts required to be changed for measurements after heat treatment. Most parts of the device can be reused and are independent of the sizes of various samples. The device allows simultaneous measurements of the critical current and mechanical properties of the cables in liquid helium.

Three samples were successfully tested: a single strand, a triplet and a 45-strand cable. All of them showed a significant reduction of the critical currents with increasing transverse loads. The cyclic loading tests of the critical currents showed good recoveries once the loads were released up to a certain value of the applied transverse loads. For loads higher than those values the critical current decreased sharply with increasing loads and all samples showed significant permanent degradations.

It is important to notice that the experimental transverse load test results of the single strand and 3-strand samples showed significant degradation with the transverse load. These samples experienced only the transverse load applied. The experimental results clearly showed that the transverse load is a significant source of critical current degradation and it needs to be taken in consideration while estimating the performance of large magnets.

The obtained experimental data were analyzed with the newly developed contact pressure model [8]. The 45-strand cable behavior was successfully explained by the model. In the model analysis, the critical current characteristics of the 3-strand cable for the effective contact pressure were obtained and used for the 45 strand cable analysis.

The smallest stage of a 3-strand cable could be tested and used to predict behaviors of a large CICC cable. It can minimize expensive tests and appropriately assess the overall performance of large magnets

More tests, using different types of strands and cable configurations, are necessary to improve the understandings of the contact pressure between strands and its effect on the cable performances. A more systematic approach to characterize the mechanical properties of superconductors should also be developed to fully understand the CICC cable performances.

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