# Composite Mechanical Properties of Coils Made With Nickel-Alloy Laminated Bi-2223 Conductors

William S. Marshall, *Member, IEEE*, Andy V. Gavrilin, Dylan Kolb-Bond, Kyle J. Radcliff, and Robert P. Walsh, *Member, IEEE*

***Abstract*—High-temperature superconducting magnet coils made with Sumitomo Type HT-NX are complex composite structures composed of Bi-2223 conductor filaments, silver matrix, solder, nickel-alloy laminations, polymer insulation, and epoxy or wax. The mechanical properties of these composites are required inputs to a correct stress analysis. Measurements of the desired properties are performed on representative model test specimens. Mechanical test specimens composed of several layers of insulated conductor are prepared by cutting to length, stacking and epoxy impregnation. Mechanical tests are performed in liquid nitrogen and liquid helium. Elastic constants are found from tensile strain measurements in the conductor longitudinal, or coil hoop, direction and from compressive strain measurements in the conductor transverse, or coil radial and axial directions.**

***Index Terms*—Superconducting magnets, high-temperature superconductors, mechanical properties.**

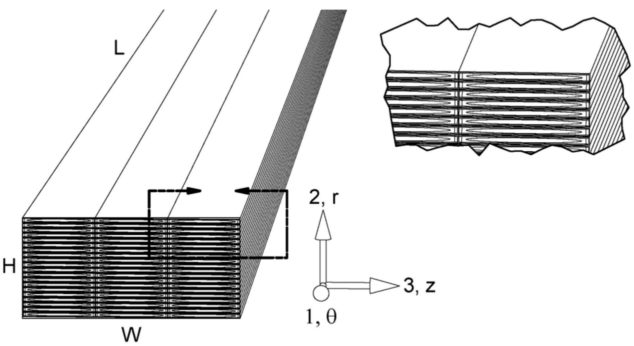


Fig. 1. Configuration of HT-NX coil composite specimen with principal directions shown.

## I. Introduction

THE maximum field that can be obtained in solenoid coils made with Bi-2223 high-temperature superconductors is mited primarily by strain in the superconducting material, rather than by current carrying capacity. Sumitomo HT-NX conductor uses nickel alloy laminations to improve the strain tolerance of the conductor.

Findings from mechanical tests of HT-NX conductor are reported in [1] and [6]. They include determination of the stress-strain curve, critical tensile strain and critical current vs. fatigue cycles and load. Mechanical testing results for Sumitomo Bi-2223 conductors has reported for bare conductor [2], and for conductors laminated with copper and stainless steel [3]. Small coils tested the influence of bending strain on critical current [4], [5]. In order to fully model the response of a coil to its magnetic and thermal loadings during normal operating and fault modes, elastic moduli and Poisson's ratios of the composite are required in the hoop, axial and radial directions [6]. A set of mechanical test specimens were made and then fitted with strain gauges. Specimens were cooled down to 77 K and 4.2 K, and loaded in tension in the hoop direction, and in compression in the axial and radial directions in separate tests. Normal and transverse strains were measured with the strain gages. Young's moduli and Poisson's ratios were calculated and then compared with rule of mixtures and finite element estimates [11].

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W. S. Marshall, A. V. Gavrilin, D. Kolb-Bond, K. J. Radcliff, and R. P. Walsh are with the National High Magnetic Laboratory, Tallahassee, FL 32310 USA, and also with the Florida State University, Tallahassee, FL 32306 USA. (e-mail: wsmarshall@magnet.fsu.edu; gavrilin@magnet.fsu.edu; kolbbond@magnet.fsu.edu; kradcliff@magnet.fsu.edu; walsh@magnet.fsu.edu).

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## II. Mechanical Test Specimens

### A. Description of Specimens

The conductor composite test specimens were made with twenty layers of three Kapton-wrapped HT-NX conductors, as shown in Fig. 1. The specimen is three layers wide to observe the effect of epoxy fill between adjacent turns. The specimen is twenty layers thick to provide sufficient room for strain gauges. The longitudinal (1) direction is analogous to the hoop direction in a solenoid coil. The radial, or short transverse (2) direction is normal to the wide face of the tapes and the axial or long transverse (3) direction is normal to the narrow face of the tapes. The cross section of the composite is 13.8 mm width x 6.3 mm thick. The samples for tensile tests are 200 mm long, and for compressive tests are 12.7 mm long. The test specimen was made as an array of unit cells, each containing a region of Bi-2223 superconductor filaments, silver matrix, nickel-alloy laminations, solder, Kapton tape and epoxy. Fig. 2 shows a cross section of the conductor composite before insulation is applied. Dimensions of each component of the tape are given in Table I.

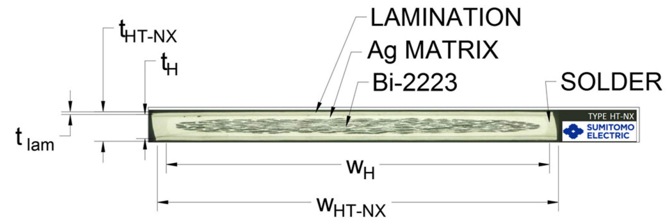


Fig. 2. HT-NX conductor constituents and dimensions. Kapton insulation is not shown.

TABLE I
SUMITOMO TYPE HTI-NX CONDUCTOR AND COMPOSITE SPECIMEN DIMENSIONS

| Component, Dimension | Symbol | Value (mm) |
|---|---|---|
| Type H conductor and silver matrix, width | $w_H$ | 4.3 |
| Type H conductor and silver matrix, thickness | $t_H$ | 0.21 |
| Type HT-NX, laminated conductor, width | $w_{HT\text{-}NX}$ | 4.5 |
| Type HT-NX, laminated conductor, thickness | $t_{HT\text{-}NX}$ | 0.31 |
| Ni-alloy laminations, thickness per side | $t_{lam}$ | 0.03 |
| Kapton insulation, thickness per side | $t_{kapton}$ | 0.025 |

### *B. Fabrication of Specimens*

The conductors were stacked into a close-fitting mold, and then impregnated with NHMFL Mix 61 epoxy, cured and then broken out.

## III. MECHANICAL TESTS AND RESULTS

### *A. Test Configurations*

A tensile test machine fitted with a cryostat and reentrant load frame enable testing in liquid cryogens. Tensile strain measurements were found by loading the 200 mm length specimens in the longitudinal (1) direction. Strain is measured in the longitudinal (1) and both transverse (2, 3) directions, with gauges shown in Fig. 3. Three strain gauges were used for the longitudinal (1) direction measurement. Two strain gauges were used for the long transverse (2) direction and one strain gauge was used for the short transverse (3) direction.

Compressive strain measurements were made by loading the 12.7 mm length specimens in the short transverse (2) direction and then measuring strain in the same direction with a pair of extensometers, as shown in Fig. 4.

### *B. Test Results – Longitudinal Tensile Loading*

The specimen was loaded twice to 5 kN at 295 K, three times to 10 kN at 77.4 K and three times to 10 kN and twice to 12 kN at 4.2 K. The stress-strain curves for the last load cycle at each temperature are shown in Fig. 5. The strain is the average value of the gauges L1, L2 and L3. The slopes of the curves are the elastic moduli, $E_{11}$, and are given in Table II.

The transverse strain in the short transverse (2) and long transverse (3) directions are graphed vs. longitudinal strain in

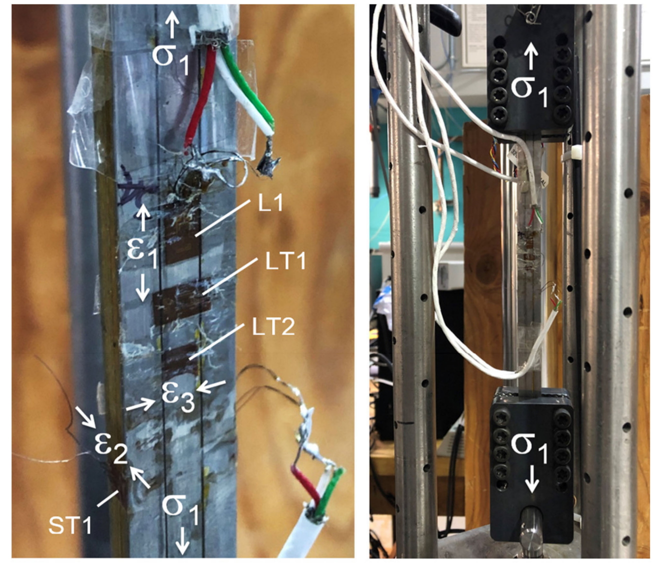


Fig. 3. Tensile specimen with strain gauges mounted (left) in load frame and grips (right). Direction of applied stress ($\sigma_1$) and measured strains ($\varepsilon_1$, $\varepsilon_2$, $\varepsilon_3$) are shown. L1 is one of three longitudinal strain gauges. L2 and L3 are placed on the back side of the sample. LT1 and LT2 are the two strain gauges in the long transverse (2) direction. ST1 is the strain gauge in the short transverse (3) direction.

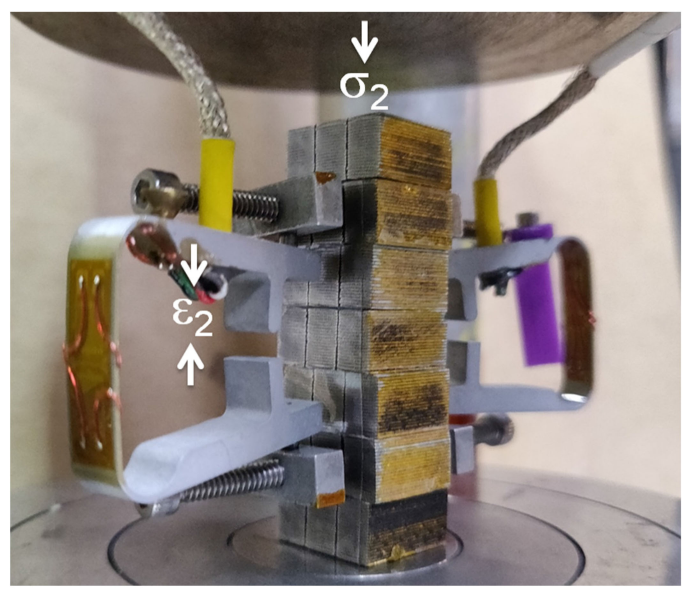


Fig. 4. Compressive specimens with extensometers mounted. Stress and strain directions are indicated.

TABLE II
SUMITOMO TYPE HTI-NX CONDUCTOR COMPOSITE ELASTIC AND SHEAR MODULI AND POISSON'S RATIOS FROM STRESS-STRAIN MEASUREMENTS

| | Units | 295 K | 77 K | 4 K |
|---|---|---|---|---|
| $E_{11}$ | GPa | 93.5 | 98.3 | 105.0 |
| $E_{22}$ | GPa | 4.4 | 10.2 | 11.1 |
| $\nu_{12}$ | | 0.50 | 0.51 | 0.46 |
| $\nu_{13}$ | | 0.35 | 0.35 | 0.37 |

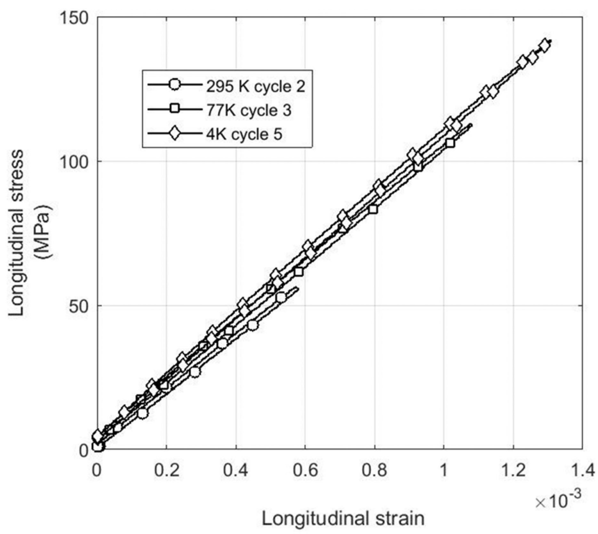


Fig. 5. Stress-strain curve in longitudinal direction at 295 K, 77 K, and 4.2 K.

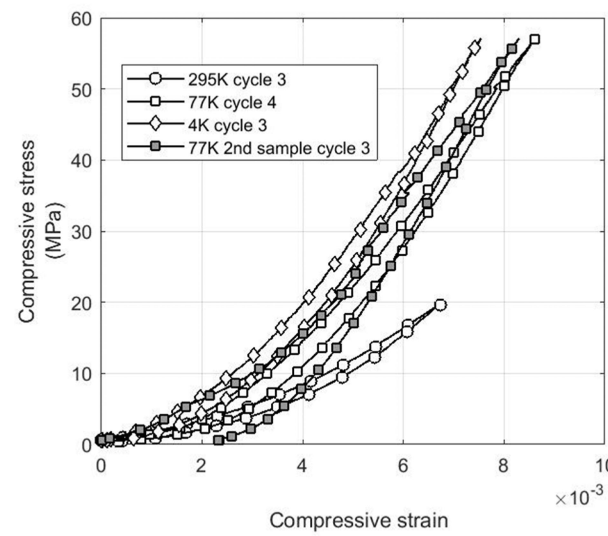


Fig. 7. Stress-strain curves in short transverse (2) direction at 295 K, 77 K, and 4.2 K.

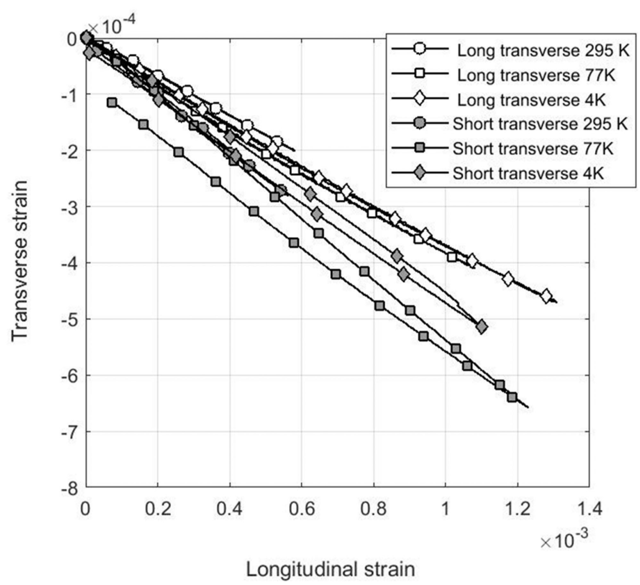


Fig. 6. Transverse vs longitudinal strains at 295 K, 77 K, and 4.2 K.

TABLE III
SUMITOMO TYPE HTI-NX CONDUCTOR COMPOSITE CONSTITUENT MECHANICAL PROPERTIES AT 295 K

| Constituent [Ref] | Cross section Area | Elastic modulus | Poisson's ratio | Shear modulus |
|---|---|---|---|---|
| Units | $mm^2$ | GPa | | GPa |
| Bi-2223 filaments [7][8] | 0.327 | 103 | 0.21 | 43 |
| Silver matrix [1][2] | 0.590 | 77 | 0.37 | 28 |
| Solder [9] | 0.040 | 50 | 0.42 | 18 |
| Ni-Alloy lamination [5] | 0.270 | 226 | 0.29 | 88 |
| Kapton [10] | 0.231 | 5.5 | 0.34 | 2 |

the (1) direction in Fig. 6. The slopes of the linear fit lines are the Poisson's ratios, $\nu_{12}$ and $\nu_{13}$ and are given in Table II.

## C. Test Results – Transverse Compressive Loading

The short transverse modulus ($E_{22}$) was found from the short transverse (2) strain response to loading in the short transverse (2) direction. The strain is the average of both gauges. The specimen was loaded twice to 3.5 kN at 295 K, twice to 9 kN and twice to 10 kN at 77.4 K and three times to 10 kN at 4.2 K. A second sample was loaded to 10 kN three times at 77 K. The stress-strain curves for the last load cycle at each temperature are shown in Fig. 7.

# IV. MECHANICAL PROPERTIES

## A. Measurements

Measured elastic moduli and Poisson's ratios from measured strains are given in Table II. For the tensile strain measurements, the moduli and Poisson's ratios are linear fits to the entire data ranges. For the compressive strain measurements, the moduli are linear fits to the data above 0.4% strain. The stress-strain curves in the range below 0.4% strain are nonlinear and indicate a low stiffness. This is likely caused by settling of the irregular mating surfaces between each of the stacked specimens as the stack is loaded.

## B. Calculation and Modeling

In Table III, the cross section areas, elastic moduli, Poisson's ratios and shear moduli of the constituents are given.

Two computed estimates of the composite moduli were made. The first was a rule of mixtures calculation using the bulk properties and cross section area fractions in Table III, combined in series and/or parallel to determine the composite properties. The second was a finite element calculation performed in ANSYS, with a model of the conductor shown in Fig. 8.

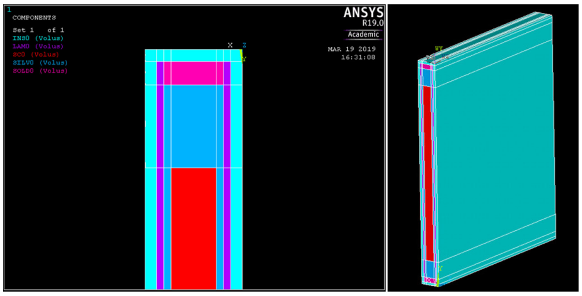


Fig. 8. ANSYS model of insulated HT-NX conductor. Each constituent is modeled as a solid rectangular area.

TABLE IV
SUMITOMO TYPE HTI-NX CONDUCTOR COMPOSITE ELASTIC AND SHEAR MODULI AND POISSON'S RATIOS FROM RULE OF MIXTURES AND FINITE ELEMENT CALCULATIONS AT 295 K

| | Units | Rule of Mixtures | Finite Element |
|---|---|---|---|
| $E_{11}$ | GPa | 99 | 93 |
| $E_{22}$ | GPa | 37 | 24 |
| $E_{33}$ | GPa | 87 | 72 |
| $\nu_{12}$ | - | 0.32 | 0.37 |
| $\nu_{23}$ | - | 0.13 | 0.49 |
| $\nu_{13}$ | - | 0.32 | 0.31 |

The resulting elastic moduli and Poisson's ratios from the calculations are given in Table IV.

## V. CONCLUSION

Mechanical properties sufficient for determining the strain state of a solenoid magnet made with Sumitomo Type HT-NX conductor were determined by measurement. Stacked composite specimens were fabricated and then load tested at 295 K, 77K and 4 K.

The measured elastic modulus in the longitudinal direction ($E_{11}$) showed good agreement with computed estimates. The measured elastic modulus in the short transverse direction ($E_{22}$) was far lower than estimated. Consequently, the Poisson's ratios ($\nu_{12}$ and $\nu_{13}$) calculated from measured moduli were also significantly different than predicted.

The high value of $\nu_{12}$ ~0.5 is a consequence of the low value of $E_{22}$, and may indicate that the amount of epoxy fill is higher in the sample than used in the predictive model.

Further work is needed to reconcile the observed disagreements between the test findings and computed values. A direct measurement of $E_{33}$ is also needed to completely characterize the composite. Future measurements should include more strain gauges in each direction to confirm that the deformation is reasonably homogeneous.

## ACKNOWLEDGMENT

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