Experimental results and Finite Element Analysis of single REBCO tape and TSTC conductor for high field magnets

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Outline

- Research activities and their importance
- Experiments on single tapes and TSTC conductors
- Modeling work on tapes and cables
  - Torsion, Bending and Lorentz load
- Next high field TSTC experiment
- TSTC conductor scale-up
- Joints and AC losses
- Future directions and conclusions
Complementary research activities of Tufts and MIT-PSFC:

- Characterization of the electrical and mechanical behaviors of HTS materials under loads relevant to magnets using *custom-made experimental devices* and *finite element analysis* (FEA) techniques in support of design and fabrication of the next generation high-field HTS magnets.

- *Development, fabrication and high-field, high-current experiments of the Twisted Stacked-Tape Cable* (TSTC).
What do we do?

Pure bending Nb$_3$Sn

Transverse load Nb$_3$Sn

Electromechanical characterization HTS

Transverse load Nb$_3$Sn

HTS Conductor Electro-Magnetic load

HTS Conductor bending

Torsion-Tension HTS
Our approach

The critical current of a superconductor is a function of load (stress & strain). For high field magnet applications the conductor will experience a variety of different loads during cable and magnet fabrication, thermal cool down, and magnet operation:

- Axial (different rates of thermal contraction)
- Torsion (twisting during cable fabrication)
- Bending (winding of magnet coils)
- Transverse compression (electromagnetic forces)
- Combined tension-torsion (magnetic hoop stress)

![Graph showing critical current as a function of axial strain](image)

We are particularly interested in **HTS TSTC conductor** to be used in the next generation high-field magnets. Our work allowed us to identify key features of TSTC for twisting, bending and transverse load.
Experiments on REBCO tapes

I. Pure Torsion

II. Mechanical Transverse Compression

III. Tension

a. Tension

b. Tension-Torsion
Experiments on REBCO tapes

I. Pure Torsion

II. Mechanical Transverse Compression (Thin Edge)

III.a Tension

III.b Tension-Torsion
Experiments on TSTC conductors

Pentagon Stacked-Tape Twist-Wind (STTW) Sample
40-Tape, 2.6 Turn, 2.6 m cable ~200 mm twist pitch
REBCO tape: SuperPower 4 mm width, 0.1 mm thick, 120 A at 77 K

Sample current DC power supply of 10 kA
(seven small power supplies in parallel)

Stacked-tape cable **twisted**
during winding in a groove
covered with **braided copper**.

Soldered, and then filled
with **Styecast** around the
braided copper.

17 T Bitter magnet

P. Noyes, NHMFL

Presentation CO-02 given at CCA 2016; Aspen, Colorado, USA, September 11 – 14, 2016.
Experiments on TSTC conductors

I-V curves

Comparison with tape data

B - I_c results

- The degradation compared to single tape data was 16% [16%, between 10 T and 17 T]
- High n-value
- No cyclic load effect (102 kN/m)

\[ J_e (8.1 \text{ mm Dia.}) = 117 \text{ A/mm}^2 \]
\[ J_e (4 \text{ mmx4mm}) = 375 \text{ A/mm}^2 \]
\[ J_e (5.7 \text{ mm Dia.}) = 239 \text{ A/mm}^2 \]
Modeling

Structural **finite element analysis**

**SOLSH190** – 3D 8-node structural *solid-shell element* with layered capabilities

**Multipoint Coupling Constraint**

**Surface-to-Surface Contact Pairs**

**Bilinear Material Properties**

<table>
<thead>
<tr>
<th>Material</th>
<th>E (GPa)</th>
<th>Y (MPa)</th>
<th>T (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td></td>
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<tr>
<td>Hastelloy® C-276</td>
<td>180</td>
<td>1225</td>
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<td>Stainless Steel</td>
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<td>Ni-5AT.%W</td>
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<tr>
<td>Copper</td>
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<tr>
<td>Electroplated</td>
<td>85</td>
<td>350</td>
<td>4.0</td>
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<tr>
<td>Rolled</td>
<td>120</td>
<td>455</td>
<td>4.5</td>
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<tr>
<td>Silver</td>
<td>90</td>
<td>225</td>
<td>22.0</td>
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<tr>
<td>REBCO/Buffer</td>
<td>150</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Aluminum</td>
<td>80</td>
<td>235</td>
<td>15.0</td>
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<tr>
<td>Copper</td>
<td>120</td>
<td>400</td>
<td>4.5</td>
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<tr>
<td>Solder (Sn60/Pb40)</td>
<td>30</td>
<td>40</td>
<td>0.1</td>
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</tbody>
</table>
Predicting \( I_c \) using FEA strain results

We can estimate critical current of tape using axial strain through width of tape.

**Analytical Relationship**

\[
I_c = I_s \int_0^w \frac{2}{w} j_c(\varepsilon_x) \, dx \quad j_c(\varepsilon) = I_c(\varepsilon) / (t_s \, w)
\]

**Experimental Data**

D. van der Laan, 2009

\[
\frac{I_c}{I_{c0}} = 0.057713 \times 10^{12} \, \varepsilon_{b\theta}^6 - 0.03979215 \times 10^{10} \, \varepsilon_{b\theta}^8 - 0.2090279 \times 10^8 \, \varepsilon_{b\theta}^4
+ 0.02385557 \times 10^6 \, \varepsilon_{b\theta}^3 - 0.1668065 \times 10^4 \, \varepsilon_{b\theta}^2 - 0.003 \times 662115 \times 10^2 \, \varepsilon_{b\theta} + 1.0
\]
Twisting of tapes with different widths

\[ \frac{I_c}{I_{co}} \]

**Tape-Width Dependence**
(analytical evaluation)

\[ \varepsilon_x = \frac{\vartheta^2}{2} \left( \chi^2 - \frac{w^2}{3} \right) \]

**I_c Degradation due to Twisting**
(analytical evaluation)

Twist-pitch \( L_p \) (\( I_c/I_{co} = 0.98 \)) \( \approx 22 \cdot 2w \) (mm)

2w tape width

Takayasu ASC2016, 2LPo2D-03
Bending behavior

No-slip model

\[ \varepsilon_b = \frac{\left(\frac{x}{\cos\alpha}\right) \sin \theta + h \cos \theta}{r_0 \cos \alpha} \]

Perfect-slip model (PSM)

\[ \varepsilon_b = \frac{x \sin \theta}{r_0} \]

HTS CICC - Tape 13 ($h = 6.7$ mm)

0.5 m diameter

Perfect-slip case

No-slip case

Experimental

FEA ($\mu = 0.02$)

FEA ($\mu = 0.2$)

FEA ($\mu = 1.0$)

Poly Fit (Exp)

Takayasu, CEC-ICMC, 2015

De Marzi, MT24, 2015

Presentation CO-02 given at CCA 2016; Aspen, Colorado, USA, September 11 – 14, 2016.
Bending diameters for different tapes width

$l_c$ degradation due to bending based on Perfect-Slip Model
(analytical evaluation)

Bending Diameter vs. Tape Width
(analytical evaluation)

$Bending\ diameter\ r_o\ (0.98\ \frac{l_c}{I_{co}}) \approx 150 \cdot 2w\ (mm)$

2w tape width
Predicting support structure for large EM loads

Stress in Width Direction

- Stress is maximum value of 95% of the elements (stress concentrations were excluded).
- Load Direction
- Thickness
- Width

Stress in Thickness Direction

- Solid Copper Core
- Solder Filled Tube

Compressive Stress (MPa)

Transverse Load (kN/m)
Next TSTC experiment at high fields-NIFS

Max. Field: 13 T
Bore: φ700 mm
Sample Current: 50 kA
Temperature: 4-50 K
Possible cable configurations

Based on SuperPower SCS4050-AP (2012), 4 mm width, 0.1 mm thickness REBCO tape. Tape critical current: 180 A at 17 T and 4.2 K.

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Tape width (mm)</th>
<th>Tape current (A)</th>
<th>Number of Tapes</th>
<th>Critical Current (kA)</th>
<th>Cable Diameter (mm)</th>
<th>Conductor Cross-Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-stage</td>
<td>4</td>
<td>180</td>
<td>40</td>
<td>7.2</td>
<td>7.4</td>
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<td></td>
<td>6</td>
<td>270</td>
<td>60</td>
<td>16.2</td>
<td>11.1</td>
<td></td>
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<tr>
<td></td>
<td>12</td>
<td>540</td>
<td>120</td>
<td>64.8</td>
<td>22.2</td>
<td></td>
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<tr>
<td>Triplet</td>
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<td>180</td>
<td>120 (40 x 3)</td>
<td>22</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>270</td>
<td>180 (60 x 3)</td>
<td>49</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>540</td>
<td>360 (120 x 3)</td>
<td>194</td>
<td>48</td>
<td></td>
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<tr>
<td>Hexa</td>
<td>4</td>
<td>180</td>
<td>240 (40 x 6)</td>
<td>43</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>270</td>
<td>360 (60 x 6)</td>
<td>97</td>
<td>35</td>
<td></td>
</tr>
</tbody>
</table>

One channel cable

3 channel cable

4 mm Tape Hexa CICC (26 mm x 26 mm)
Current and current density vs. width, thickness

Square TSTC Conductor
Stabilizer space 36% of total cross-section

Evaluation based on
4 mm width, 0.1 mm REBCO tape
Critical current : 200 A

Tape-Width Dependence
Tape thickness = 0.1 mm

Tape-Thickness Dependence
Tape width = 4 mm
Joints

I. YBCO - BSCCO Termination

II. YBCO - YBCO Termination

III. Folding-Fan Soldered Termination
AC losses characterization

Various TSTC conductors (30 SuNAM tapes)

Fabricated AC loss test samples of various TSTC conductors (sent to OSU).
(a) Stacked tapes **twisted between copper strips**, encapsulated with a 0.5” OD plexiglass tube.
(b) Tapes **stacked horizontally** in a single helical groove of OFHC rod enclosed in an OFHC sheath (0.5” OD).
(c) Tapes **stacked vertically** in a single helical groove of OFHC rod enclosed in an OFHC sheath (0.5” OD).
(d) Stacked tapes in **two helical grooves** of OFHC rod enclosed in an OFHC sheath (0.5” OD).

SuNAM (SCN04150-140819-01)
4.1 mm width
150 µm thickness
Non-magnetic stainless-steel substrate (>80 µm)

Tape critical current 200 A at 77 K in self-field (manufacturer’s data).
Conductor length: 203 mm
 Twist pitch: **200 mm**

These samples **after tests will be soldered and sent back to OSU** for the soldered sample tests, in order to investigate solder effects on AC losses.
Future directions and conclusions

- Continue EM studies of cables and use future experiments to validate modeling
- Use modeling to optimize design of HTS cable options for high field magnets
- Continue study of joints for HTS cables
- Comprehensive structural and electromagnetic modeling
- CICC fabrication development for a long conductor
- More experiments on cables at high field and 4.2 K are necessary!!! ($$$)

- Our expertise is the *electromechanical characterization* of REBCO (single tape and TSTC) using *experiments and finite element analysis*.
- The work provides critical information to design and fabricate cables and magnets for HEP/Fusion that are structurally and electromagnetically sound.
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