Axial and transverse load FEM analysis of CORC® cables and wires

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IN THIS PRESENTATION:

1. Introduction
2. CORC FEM model steps
3. CORC axial load FEM and analytical model
4. CORC axial load Optimized cable
5. CORC transverse load FEM model
6. Effect of tape gap and core diameter in transverse load
7. Conclusions
CORC FEM modeling steps

Production process

Winding different layers

Stress-Strain transfer to full CORC geometry

Bending load

Axial load

Transverse load
CORC FEM modeling steps

**Winding process**

REBCO layer strain after winding is higher on the edges and lowest in the middle due to edge effect.

**Stress-strain transfer process**

- The stress-strain is transferred to the entire CORC geometry before any other load is applied.
- To simplify the model, the loading is done in different steps.
CORC axial load

Strain across tape width and length varied with axial load

Gray colour indicates strain above critical limit
Recent Progress on CORC® Cable and Wire Development for Magnet Applications

Danko van der Laan$^{1,2}$, Jeremy Weiss$^{1,2}$, Kyle Radcliff$^{1}$, Drew W Hazelton$^3$, Tim Mulder$^4$, Alexey Dudarev$^4$, Herman ten Kate$^4$, Xiaorong Wang$^5$, and Soren Prestemon$^5$

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CORC axial load

Experiments

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CORC 6L_40~45

CORC 6L_30~35
CORC axial load

Analytical approach

\[ l = \pi D / \cos(\alpha) \]

tape strain, \( \varepsilon_t = (l_f - l)/l \)

\[ \varepsilon_{tape} = \frac{D_f}{D} \times \frac{\cos(\alpha)}{\cos(\alpha_f)} \times \left(1 - \varepsilon_a\right) \]

\[ \alpha_f = \tan^{-1}\left(\frac{\tan(\alpha) \times (1 + \varepsilon_a)}{1 - \mu \varepsilon_a}\right) \]

\( \mu = \) Poisons ratio
Axial strain factor

CORC axial load

Analytical approach

\[ l = \pi D / \cos(\alpha) \]

tape strain, \( \epsilon_t = (l_f - l)/l \)

\[ \epsilon_{tape} = \frac{D_f}{D} \times \frac{\cos(\alpha)}{\cos(\alpha_f)} - 1 \]

\[ \epsilon_{tape} = (1 + \epsilon_a)^{-\mu} \times \frac{\cos(\alpha)}{\cos(\alpha_f)} - 1 \]

\[ \alpha_f = \tan^{-1}\left(\frac{\tan(\alpha) \times (1 + \epsilon_a)}{1 - \mu \epsilon_a}\right) \]

\[ \mu = \text{Poisons ratio} \]
**Axial strain factor**

**CORC axial load**

**Analytical approach**

\[ \epsilon_{tape} = (1 + \epsilon_a)^{-\mu} \times \frac{\cos(\alpha)}{\cos(\alpha_f)} - 1 \]

\[ \alpha_f = \tan^{-1} \left( \frac{\tan(\alpha) \times (1 + \epsilon_a)}{1 - \mu \epsilon_a} \right) \]

\[ \mu = 0.343 \]
CORC FEM modeling – $I_c$ calculation

$J_c(\varepsilon)/J_c(\varepsilon_0) = 1 - a |\varepsilon_0|^{2.2\pm0.02}$  
$a = 6918$

$J_c = 0$ if $\varepsilon_{\text{intrinsic}} > 0.45%$

Tape $I_c = \min I_c$ along tape length

- Tape $I_c$ calculated in 2D plane of the tape and then calculated the $I_c$ of different sections of the tape across the tape length.
- Tape $I_c$ is determined by the weakest section of the tape

CORC FEM model comparison with experiment

Validation

FEM model can predict the cable performance

\[ \varepsilon_{tape} \approx \frac{\Delta l}{l} (\sin^2 \alpha - \nu \cos^2 \alpha) \]

\[ J_c(\varepsilon) / J_c(\varepsilon_0) = 1 - a |\varepsilon_0|^{2.2 \pm 0.02} \]
CORC FEM model $I_c/I_{c0}$ contour calculation

CORC 6L_40~45

$\varepsilon = 3.7\%$
CORC FEM modeling comparison with experiment

Axial load – Optimized cable

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<thead>
<tr>
<th>Type</th>
<th>wire</th>
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<tbody>
<tr>
<td>Former size</td>
<td>2.55 mm</td>
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<tr>
<td>Tape number</td>
<td>28</td>
</tr>
<tr>
<td>Tape width</td>
<td>2 mm</td>
</tr>
<tr>
<td>Gap spacing</td>
<td>0.33 to 0.4 mm</td>
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<tr>
<td>Substrate thickness</td>
<td>30 µm</td>
</tr>
<tr>
<td>Copper plating thickness</td>
<td>5 µm</td>
</tr>
<tr>
<td>Winding angle</td>
<td>25° to 35°</td>
</tr>
</tbody>
</table>
CORC Transverse load

Strain across tape width and length varied with transverse load

Gray colour indicates strain above critical limit
For FEM, an element considered as damaged when maximum in-plane strain is either above 0.45% or below -1.8%.

Tensile stain limit = 0.45%
Compressive stain limit = -1.8%

No irreversible degradation reported till -2% compressive strain, but Ic is almost zero near -1.8%.


Damage by tensile strain happens in the gap between tapes.
Validation

FEM data with selected criteria shows a damage response like Ic degradation

<table>
<thead>
<tr>
<th>Type</th>
<th>Wire</th>
</tr>
</thead>
<tbody>
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<td>Former size</td>
<td>2.55 mm</td>
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<tr>
<td>Tape number</td>
<td>12</td>
</tr>
<tr>
<td>Tape width</td>
<td>2 mm</td>
</tr>
<tr>
<td>Gap spacing</td>
<td>~0.33 mm</td>
</tr>
<tr>
<td>Substrate thickness</td>
<td>30 µm</td>
</tr>
<tr>
<td>Copper plating thickness</td>
<td>5 µm</td>
</tr>
</tbody>
</table>
Effect of gap spacing between tapes

- Degradation starts at lower transverse loads for cables with larger gap between tapes.
- But for cables with higher diameter the degradation curve saturates after a certain load limit.

Six-layer cable with different diameter and different gap:

- Hastelloy thickness = 30 µm
CORC Transverse load

Effect of core diameter

Three-layer cable with different diameter and same gap

- Cables with higher diameter have larger tolerance to transverse loads when the gap between tapes kept same.
Conclusion

• Detailed CORC cable FE model is built and validated for axial and transverse loads.
• CORC axial load FE model can predict multilayer cable performance.
• Analytical model for CORC axial load gives a rough estimation of CORC cable performance.
• With optimized cabling parameters, the irreversible strain limit of CORC cables and wires can be as high as 7%, which is 10 to 12 times higher than the irreversible strain limit of single REBCO tapes.
• Gap spacing and core diameter are the two critical parameters affecting CORC cable transverse load behavior.
Thank you!