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HTS 2020 Modelling

Analysis of contact behavior in CORC® cabling and under axial tension

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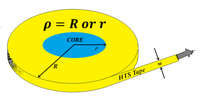
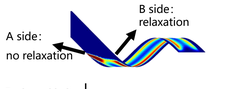
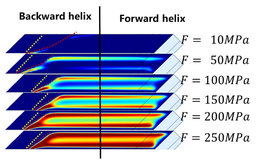
Abstract

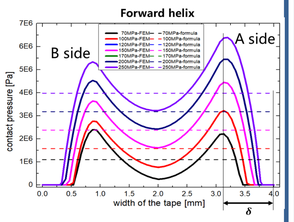
CORC® cables or wires are composed of helical wound HTS REBCO tapes in multiple layers with high flexibility. In this study, starting with the cabling process, the deformation of the tape and the initial contact force distribution between the tape and the core are described. Then axial tensile loading of the CORC® is simulated and compared with the experimental curve including its critical current degradation. The results describe the interaction between tape and core that occurs during the tensile loading. The tape and the core are extruded and friction is generated, directly causing critical current degradation. The developed analytical and FE models can predict the mechanical and electrical properties of CORC® cables.

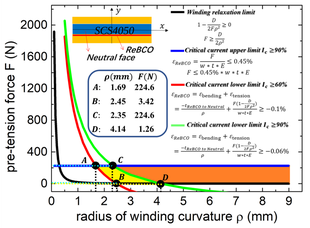
CORC cabling process











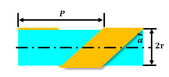
Approximate average contact force:

$$\bar{q} = \frac{F\left(1 - \frac{EI/(1-\nu^2)}{2Fr^2}\right)}{rw}$$

Edge Lifting affects depth of the tape edge:

$$\delta \approx \frac{\pi}{2}\sqrt[4]{\frac{t^2r^2}{3(1-\nu^2)}}$$

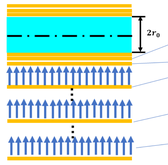
Multilayer CORC cabling process



Average one layer contact force: $\bar{q} = \frac{p}{w} = \frac{F\left(1 - \frac{EI/(1-\nu^2)}{2Fr^2}\right)}{\rho w}$

Radius of curvature: $\rho = (1 + tan^2\alpha)r$

Pitch and core radius: $tan\alpha = \frac{P}{2\pi r}$



$$p_{i\to k} = p_i \frac{(r_k/r_0)^{-1+\kappa} - (r_k/r_0)^{-1-\kappa}}{(r_i/r_0)^{\kappa-1} - (r_i/r_0)^{-\kappa-1}} \qquad \kappa = \frac{E_{hoop}}{E_{radial}}$$

This equation can calculate the ith effect the kth contact force

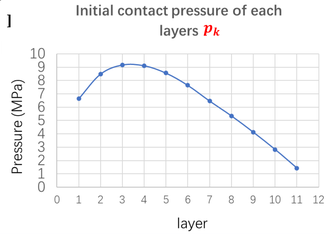
$$p_k = p_{k+1\to k} + p_{k+2\to k} + \cdots + p_{i\to k} + \cdots + p_{12\to k}$$

After 12 layers CORC cabling, this equation shows the contact force of the kth layer comes from the combination of the pressure of all outside layers.

Tape selection
- Tape thickness t [mm]
- Tape Width w [mm]

Winding method
- Core radius r [mm]
- Winding angle α [°]
- Tape Tension F [N]

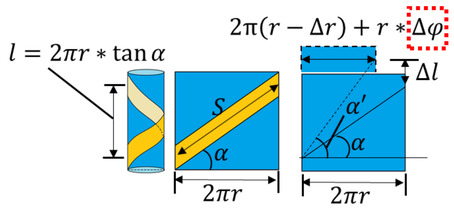
Initial contact pressure of each layers p_k



Apply contact pressure(Pa) P_i

Contact pressure define(MPa) p_k

Theory of CORC tension process

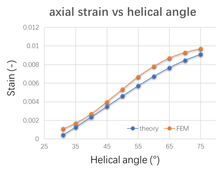


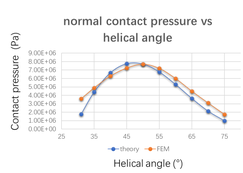
$$\varepsilon_{tape\ axial} = \frac{\Delta S}{S} = \frac{\frac{l + \Delta l}{\sin\alpha'} - \frac{l}{\sin\alpha}}{\frac{l}{\sin\alpha}}$$

$$= \frac{\Delta l}{l}\sin^2\alpha + \frac{\Delta r}{r}\cos^2\alpha + \frac{\Delta\varphi}{l} * r\sin\alpha\cos\alpha$$

1. Helical axial tension
2. Radial shrink (Poisson ratio ν)
3. torsion

Approximated as: $\varepsilon_{tape} = \varepsilon_{cable}(\sin^2\alpha - \nu\cos^2\alpha)$

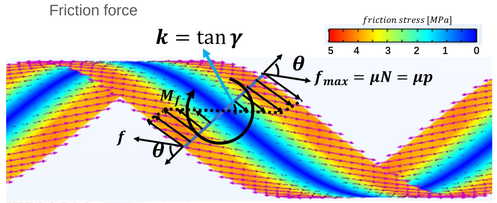




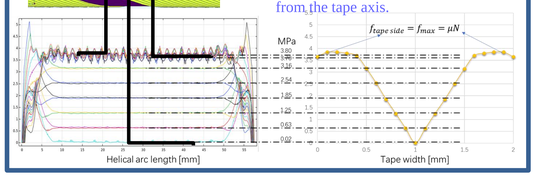
$$\varepsilon_{tape} = \varepsilon_{cable}(\sin^2\alpha - \nu\cos^2\alpha) \qquad p = \overline{\sigma_{tape}} * \rho = EA\varepsilon_{tape} * \rho$$

Helical angle (r=1.29 mm, w=2 mm, μ=0.3, ν=0.3, ε_{cable} = 1%)

Friction force



1. The friction is the largest at the edge and the least in the middle.
2. The direction of friction is different from the tape axis.



3D T-A method for CORC tension process consider contact behavior

Step-1 solid:

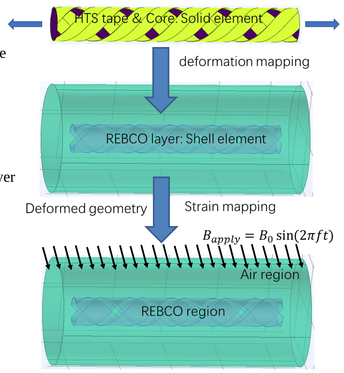
Calculate the overall strain of the cable

Step-2 shell:

Calculate the strain in the REBCO layer

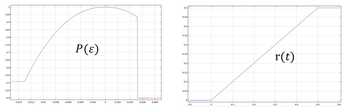
Step-3 T-A

Calculate the critical current, current distribution, magnetic field, AC loss and other electric behavior



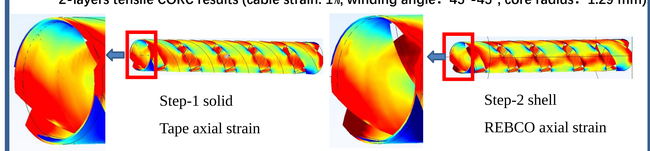
Base equation

1. T-formulation
2. A-formulation
3. Power law $J_c(\varepsilon) = J_{c0} * P(\varepsilon)$
4. AC & DC applied current and magnetic field



AC $\begin{cases} I_{apply} = I_0\sin(2\pi ft) \\ B_{apply} = B_0\sin(2\pi ft) \end{cases}$ DC $\begin{cases} I_{apply} = I_0\,r(t) \\ B_{apply} = B_0\sin(2\pi ft) \end{cases}$

2-layers tensile CORC results (cable strain: 1%, winding angle：45°-45°, core radius：1.29 mm)



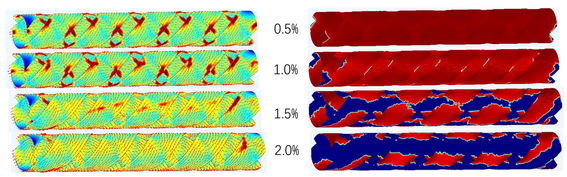
Step-1 solid
Tape axial strain

Step-2 shell
REBCO axial strain

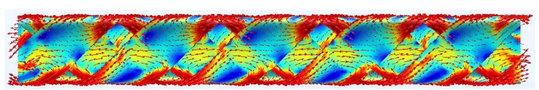
Case 1. When there is no background magnetic field, only DC transport current.

Transport current distribution [A/m²]

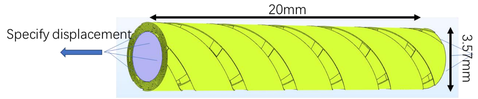
Critical current degradation J_c/J_{c0} [1]



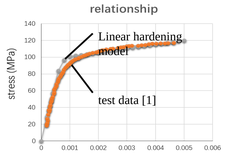
Case 2. When there is no transport current, only the current generated by the background magnet.



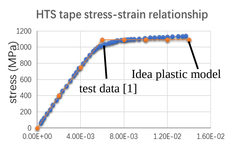
Tension model considering Initial Contact



copper core stress-strain relationship



HTS tape stress-strain relationship



$$\sigma_{ys} = \sigma_{ys0} + E_{iso}\varepsilon_{pe}$$

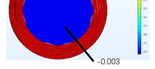
$$\frac{1}{E_{iso}} = \frac{1}{7e9[Pa]} - \frac{1}{E}$$

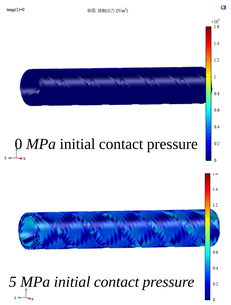
$$\sigma_{ys} = \sigma_{ys0}$$

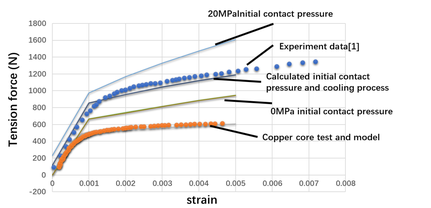
Cooling process

$$\varepsilon_{cooling} = \alpha(T - T_0)$$

$\alpha_{copper\ core}$	17.7e-6	1/K
$\alpha_{HTS-tape}$	13e-6	1/K
T	77	K
T_0	293.15	K







[1]D C van der Laan, D M McRae and J D Weiss, Effect of monotonic and cyclic axial tensile stress on the performance of superconducting CORC® wires. Supercond. Sci. Technol. 32 (2019) 054004

Conclusions

- The contact behavior of CORC® cable is studied in FE model and theoretical method.
- A CORC® axial tensile model was built. The tape strain, normal contact stress and friction force were calculated.
- The electromagnetic analysis model of CORC® cable considering the tape deformation and interlayer contact during cabling process, cooling process and axial tensile loading process was established. The validations are ongoing.