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

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HTS 2020 Modelling

OS-C3-PM 350774

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

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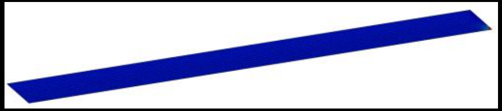
CORC FEM modeling steps

Production process



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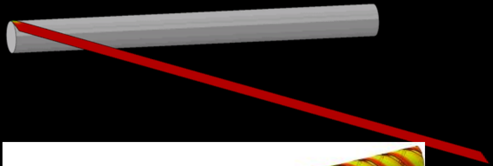
Winding different layers



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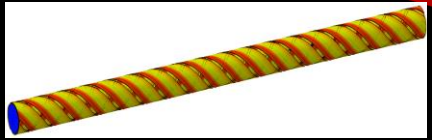
Stress-Strain transfer to full CORC geometry



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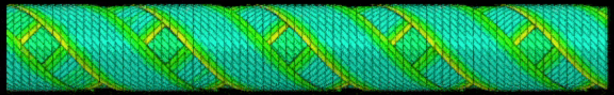
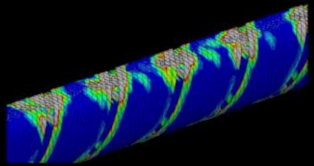
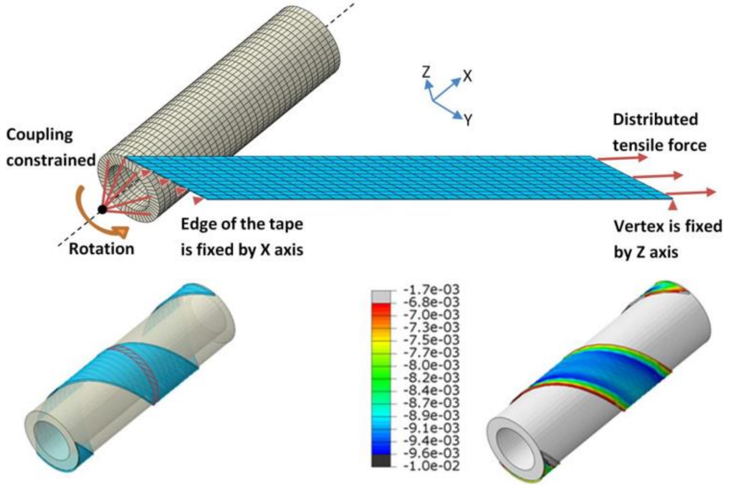
Bending load | Axial load | Transverse load





CORC FEM modeling steps

Winding process

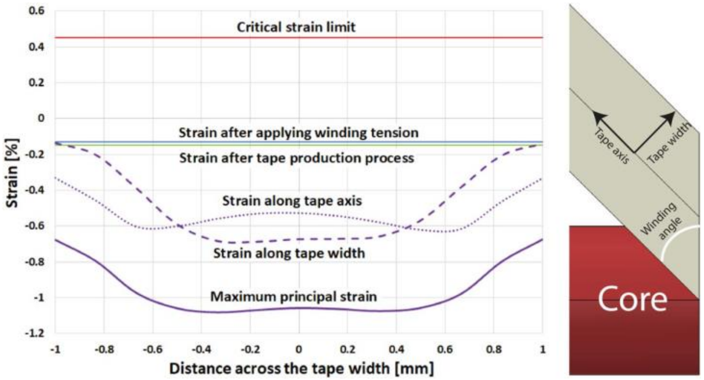


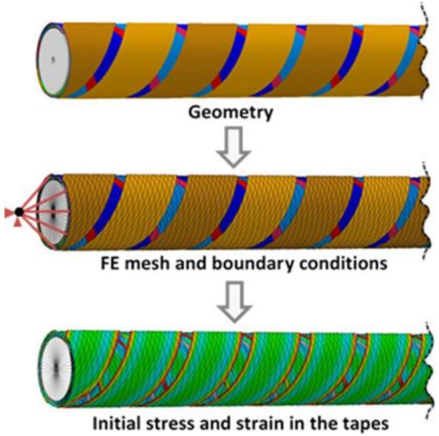
Stress-strain transfer process

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

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

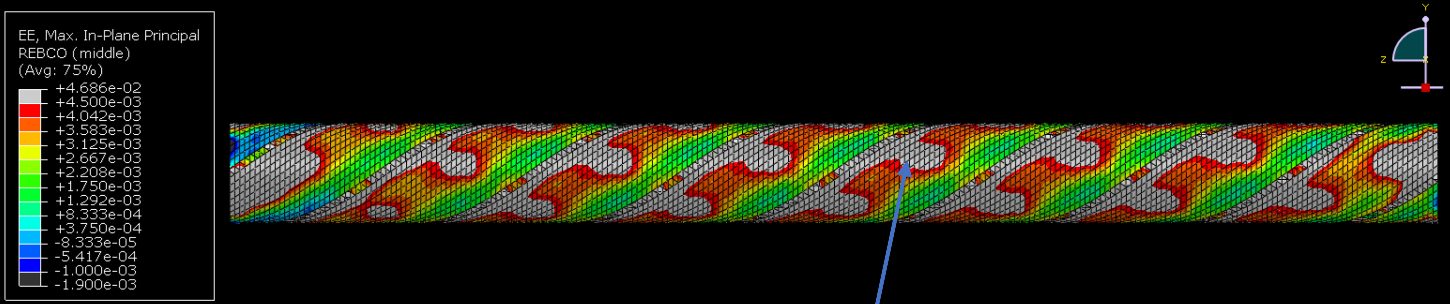




CORC axial load

FEM

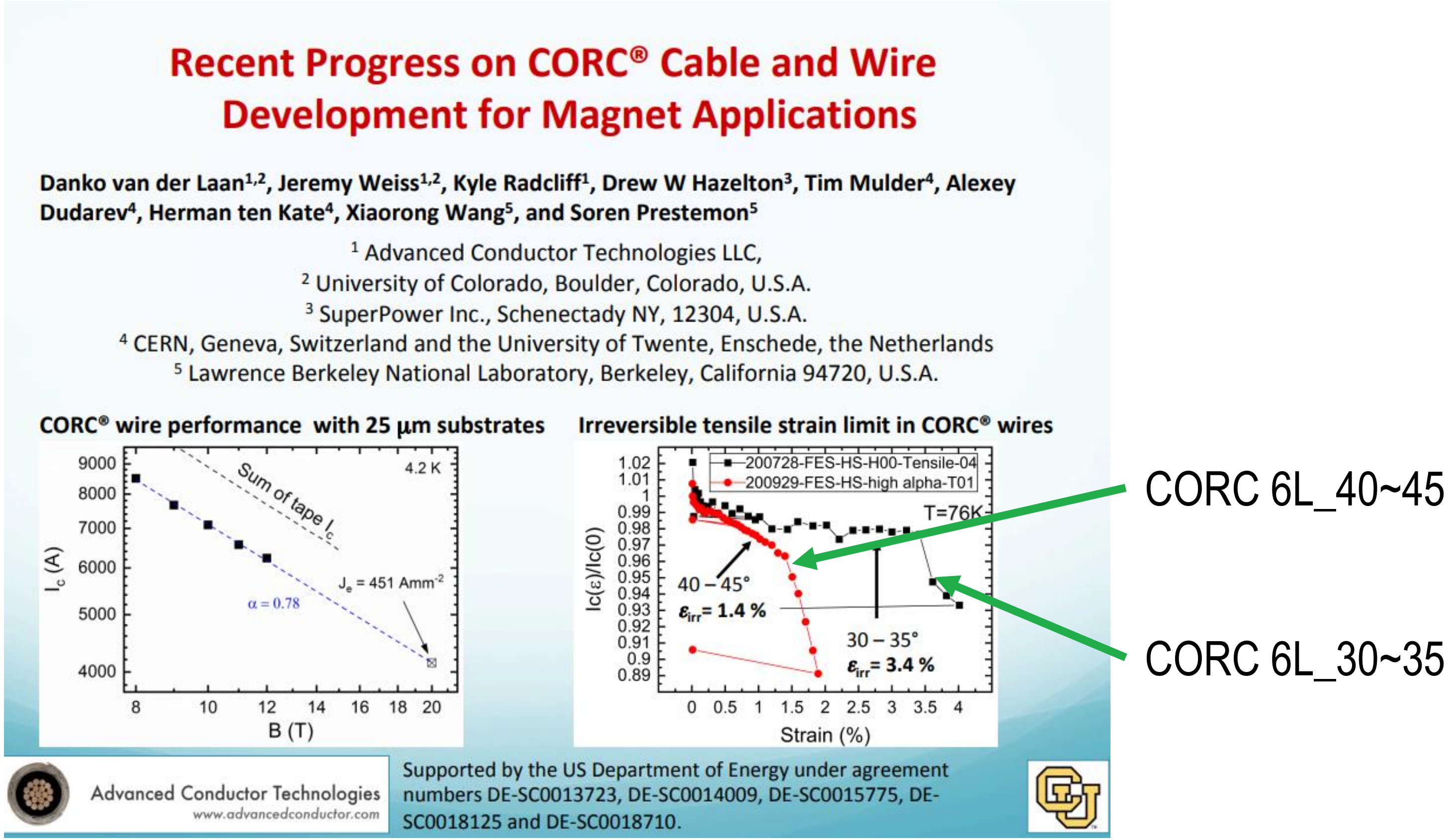
Strain across tape width and length varied with axial load



Gray colour indicates strain above critical limit

CORC axial load

Experiments



ASC2020

CORC axial load

Analytical approach

$$l = \pi D/\cos(\alpha)$$

$$\text{tape strain, } \varepsilon_t = (l_f - l)/l$$

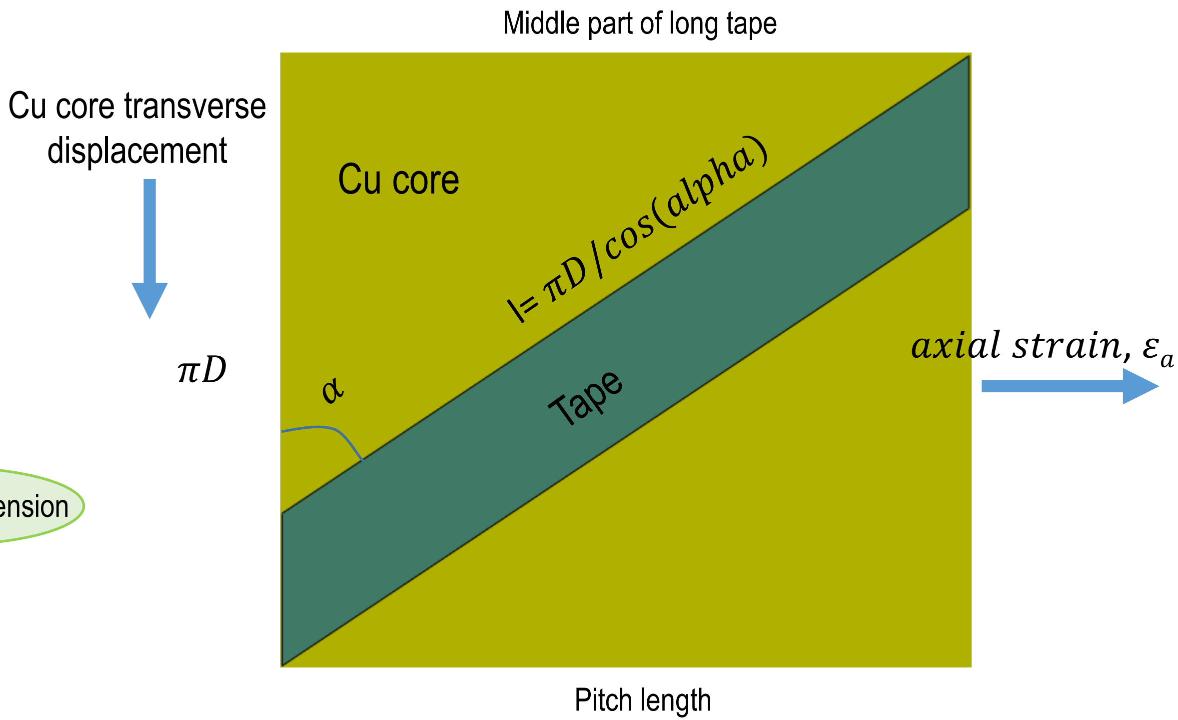
$$\varepsilon_{tape} = \frac{D_f}{D} \times \frac{\cos(\alpha)}{\cos(\alpha_f)} - 1$$

Radial shrink

Helical axial tension

$$\varepsilon_{tape} = (1 + \varepsilon_a)^{-\mu} \times \frac{\cos(\alpha)}{\cos(\alpha_f)} - 1$$

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



μ = Poisons ratio

CORC axial load

Axial strain factor

Analytical approach

$$l = \pi D/\cos(\alpha)$$

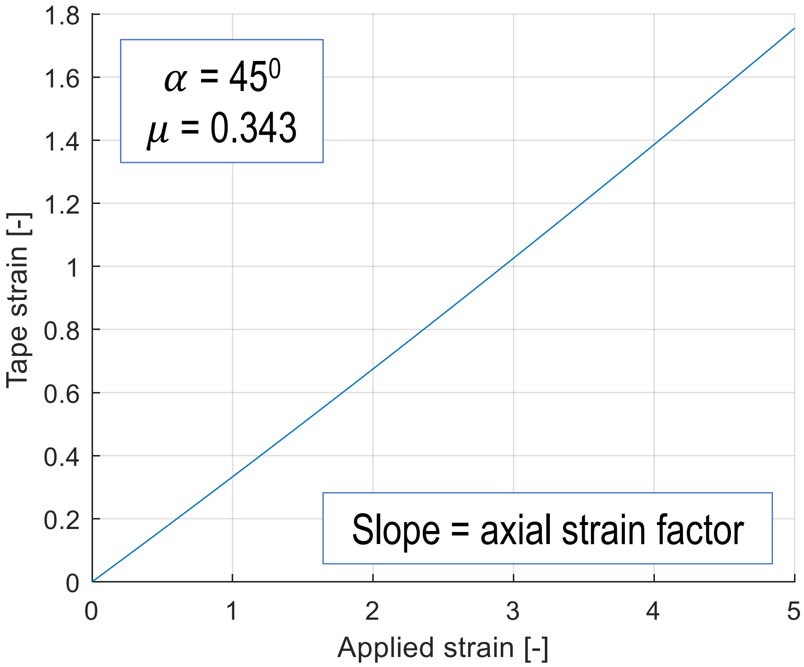
tape strain, $\varepsilon_t = (l_f - l)/l$

$$\varepsilon_{tape} = \frac{D_f}{D} \times \frac{\cos(\alpha)}{\cos(\alpha_f)} - 1$$

$$\boxed{\varepsilon_{tape} = (1+\varepsilon_a)^{-\mu} \times \frac{\cos(\alpha)}{\cos(\alpha_f)} - 1}$$

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

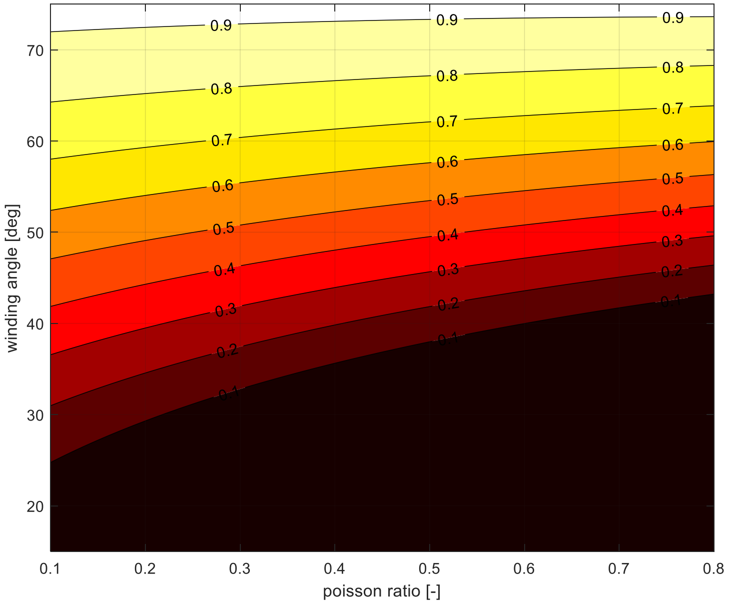
μ = Poisons ratio

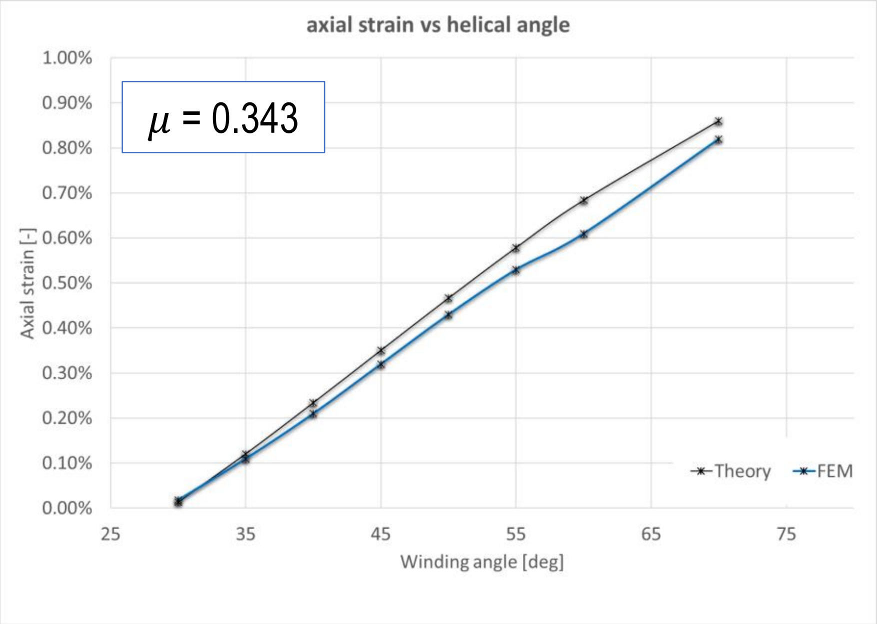


CORC axial load

Analytical approach

Axial strain factor

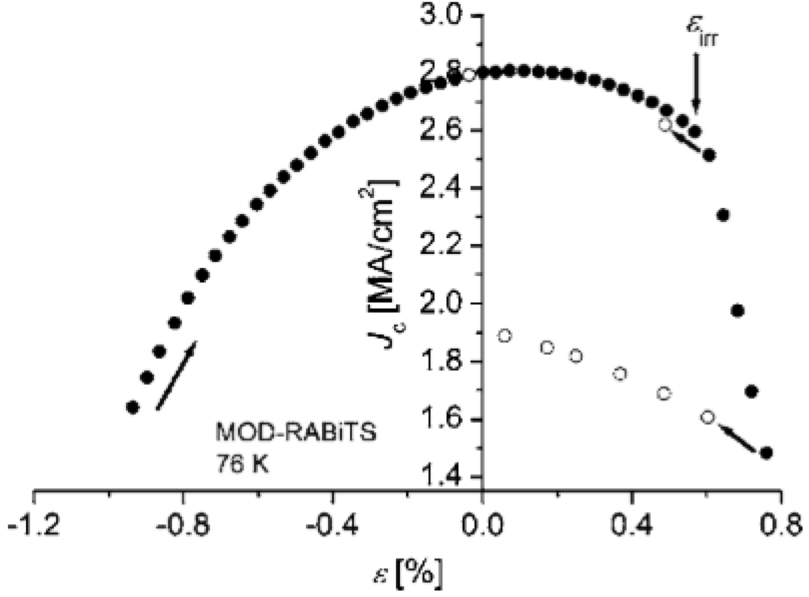




$$\varepsilon_{tape} = (1+\varepsilon_a)^{-\mu} \times \frac{\cos(\alpha)}{\cos(\alpha_f)} - 1$$

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

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 $\varepsilon_{intrinsic}$> 0.45%

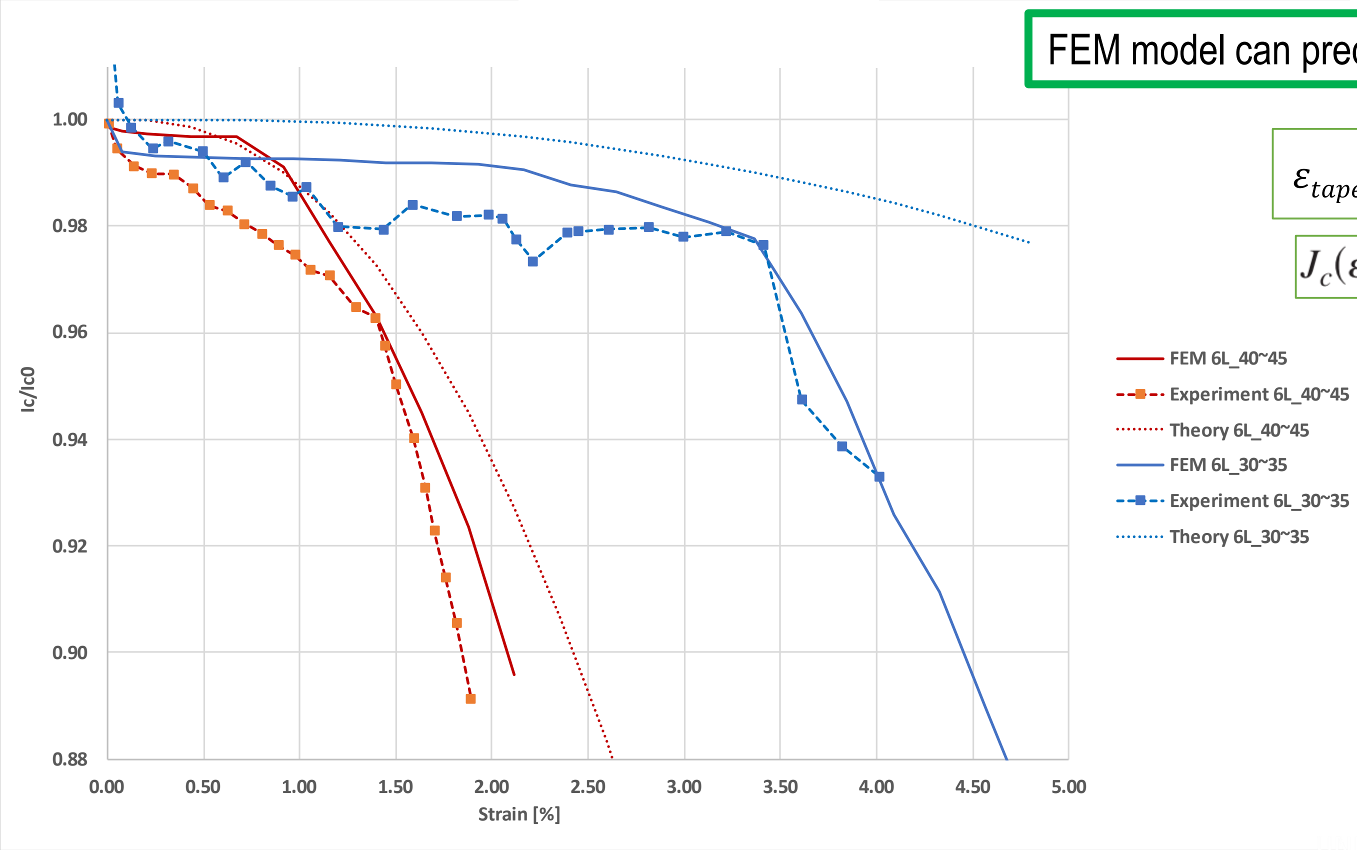
Tape I_c = min I_c along tape length

- 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

Van Der Laan D .C . and J .W . Ekin 2007 Large intrinsic effect of axial strain on the critical current of high-temperature superconductors for electric power applications *Appl. Phys. Lett.* **90** 1–4 [10.1063/1.2435612]

CORC FEM model comparison with experiment

Validation



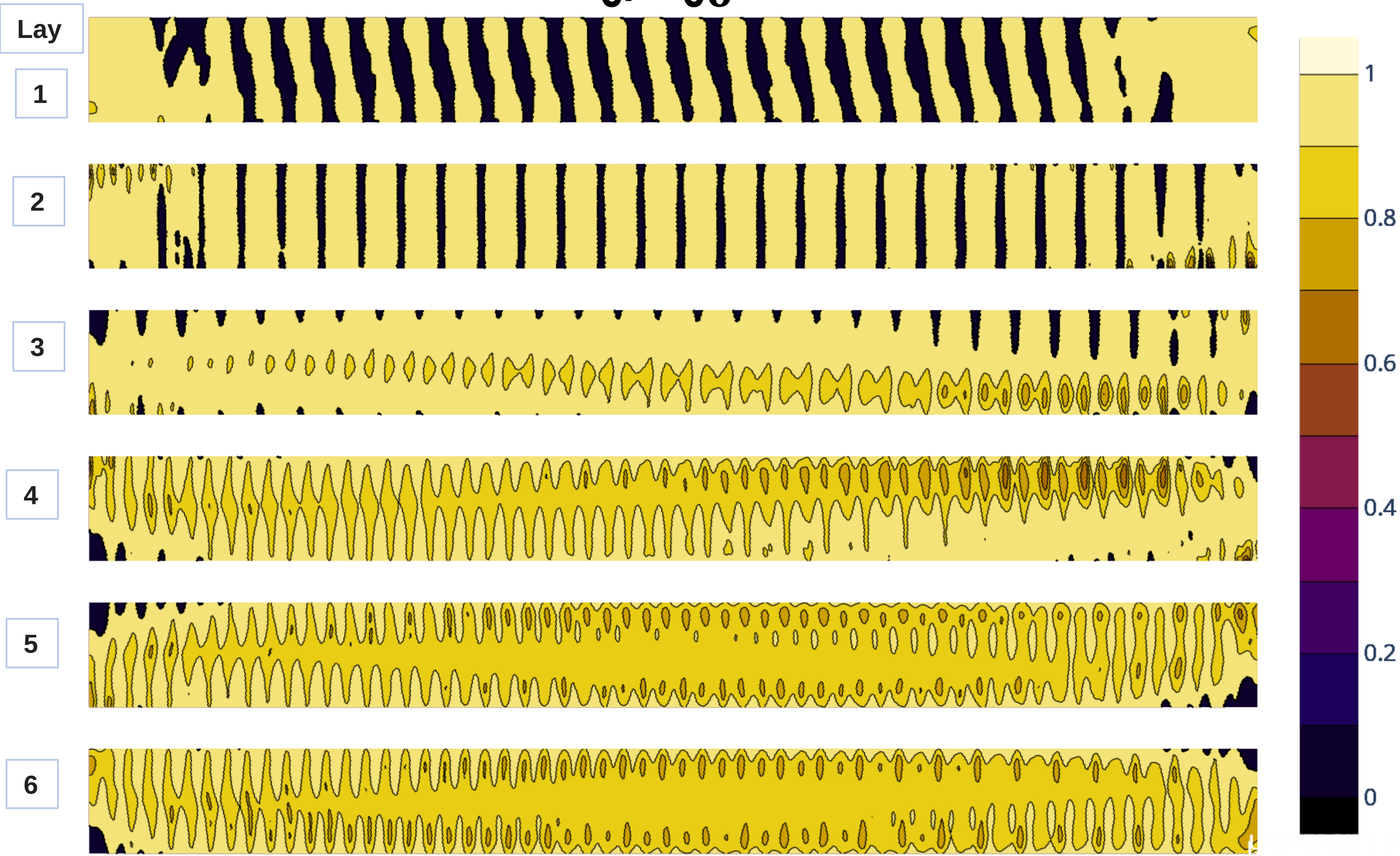
FEM model can predict the cable performance

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

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

CORC FEM model I_c/I_{c0} contour calculation

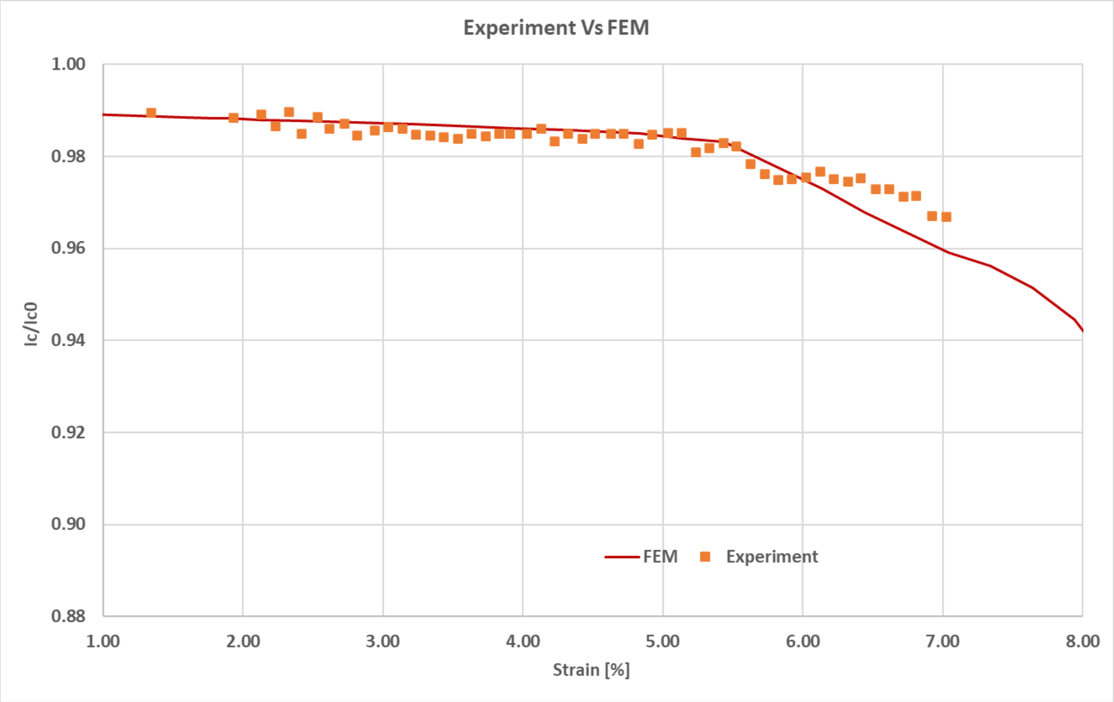
CORC 6L_40~45



ε=3.7%

CORC FEM modeling comparison with experiment

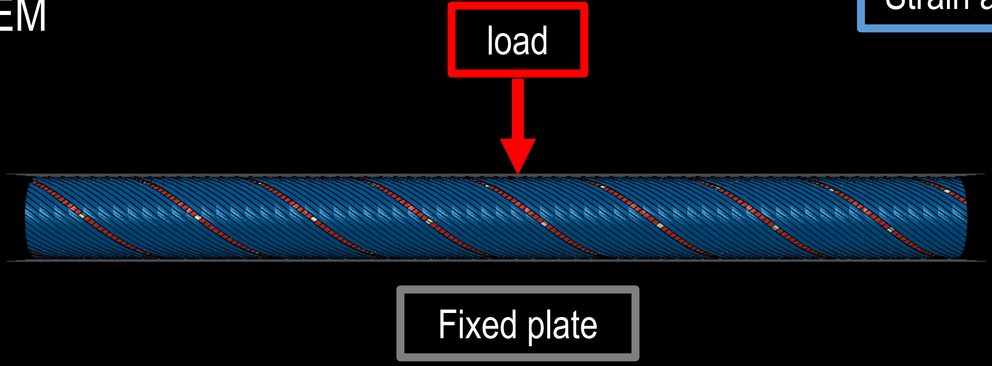
Axial load – Optimized cable



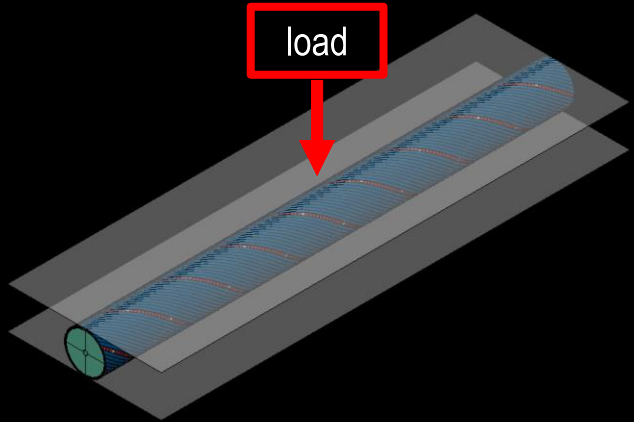
Type	wire
Former size	2.55 mm
Tape number	28
Tape width	2 mm
Gap spacing	0.33 to 0.4 mm
Substrate thickness	30 µm
Copper plating thickness	5 µm
Winding angle	25^0 to 35^0

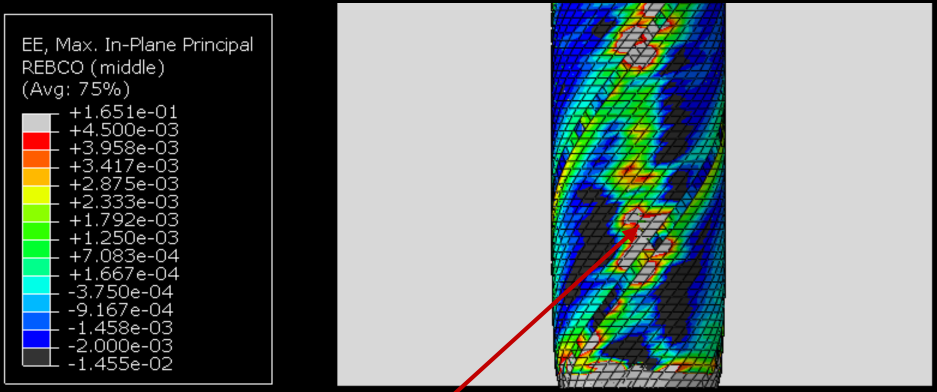
CORC Transverse load

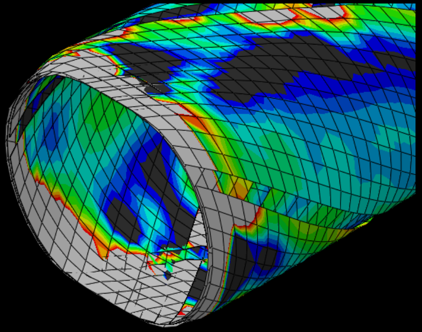
FEM



Strain across tape width and length varied with transverse load



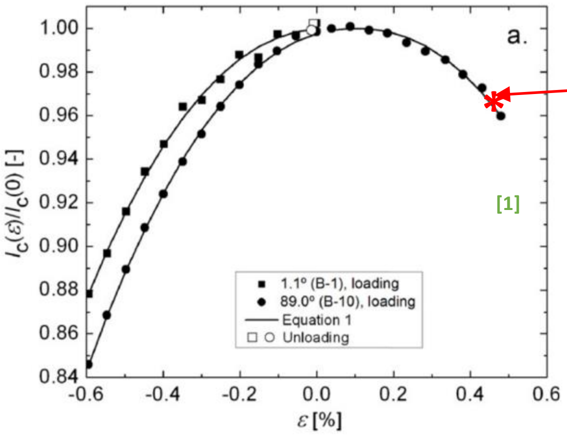




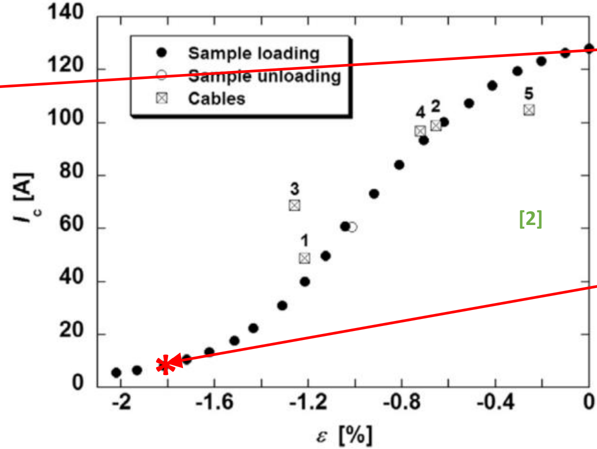
Gray colour indicates strain above critical limit

CORC Transverse load

FEM analysis criteria

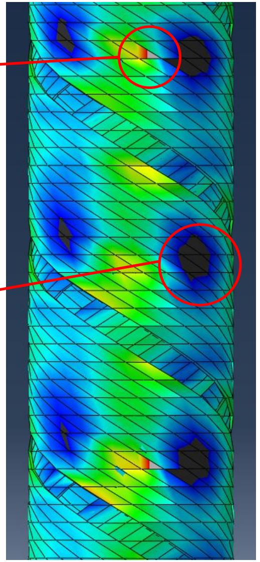


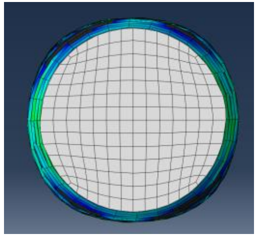
Tensile stain limit = 0.45%



Compressive stain limit = -1.8%

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



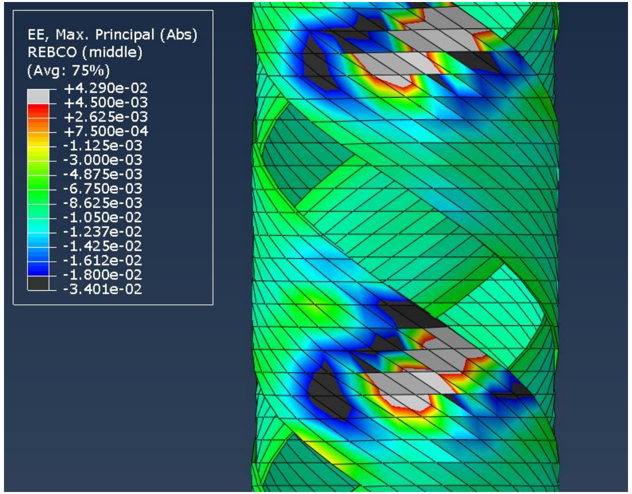


For FEM, an element considered as damaged when maximum in-plane strain is either above 0.45% or below -1.8%

[1] Van Der Laan D .C ., J .W . Ekin, J .F . Douglas, C .C . Clickner, T .C . Stauffer and L .F . Goodrich 2010 Effect of strain, magnetic field and field angle on the critical current density of y Ba2Cu3O7-δcoated conductors *Supercond. Sci. Technol.* **23** 2–9 [10.1088/0953-2048/23/7/072001]
[2] Van Der Laan D .C . 2009 YBa2Cu3O7-?? coated conductor cabling for low ac-loss and high-field magnet applications *Supercond. Sci. Technol.* **22** [10.1088/0953-2048/22/6/065013]

CORC Transverse load

Location of damage



[3]

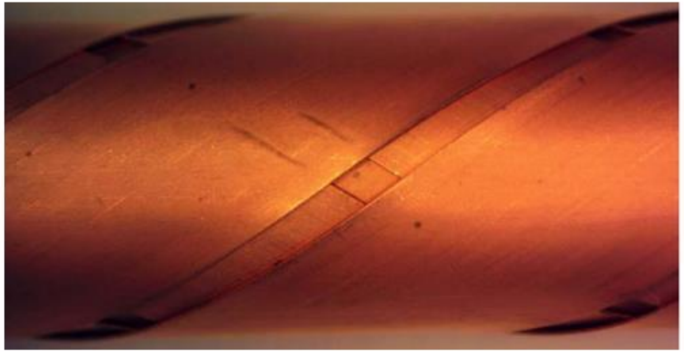


Figure 10. Picture of the outer layer of sample CORC®-11 wound with 1 mm wide gaps between tapes after having degraded due to the application of high transverse compressive load.

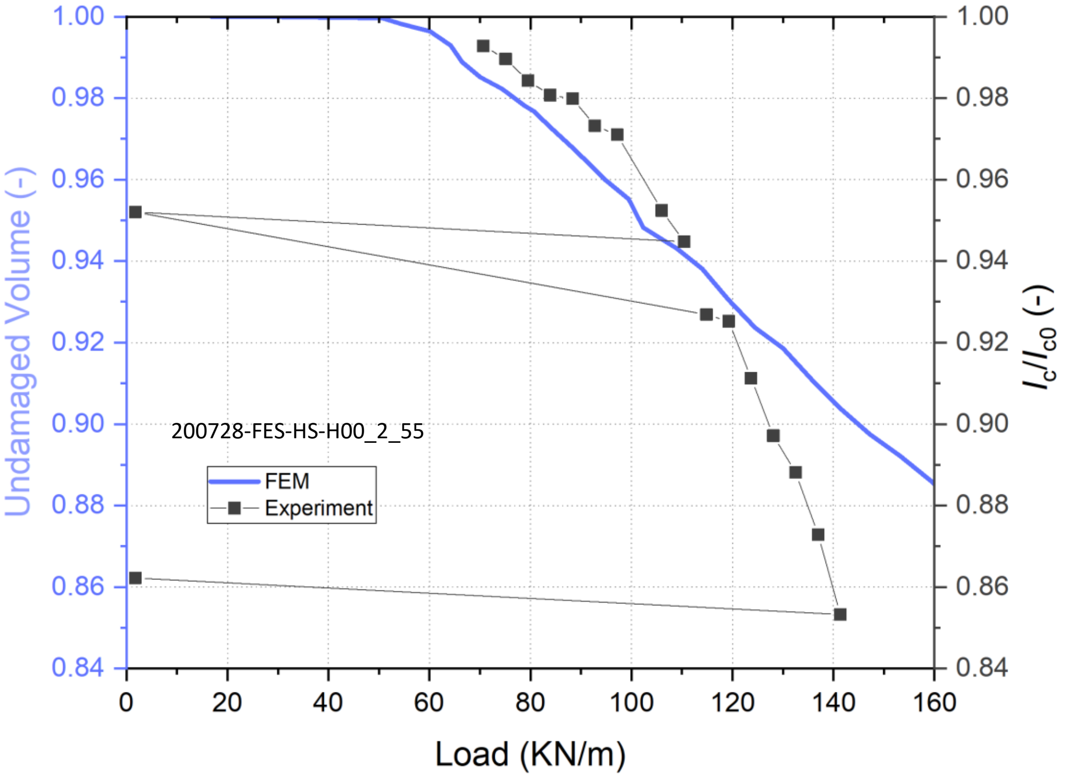
Damage by tensile strain happens in the gap between tapes

[3] Van Der Laan D .C ., J .W . Ekin, J .F . Douglas, C .C . Clickner, T .C . Stauffer and L .F . Goodrich 2010 Effect of strain, magnetic field and field angle on the critical current density of y Ba2Cu3O7-δcoated conductors Supercond. Sci. Technol. 23 2–9 [10.1088/0953-2048/23/7/072001]

CORC Transverse load

Validation

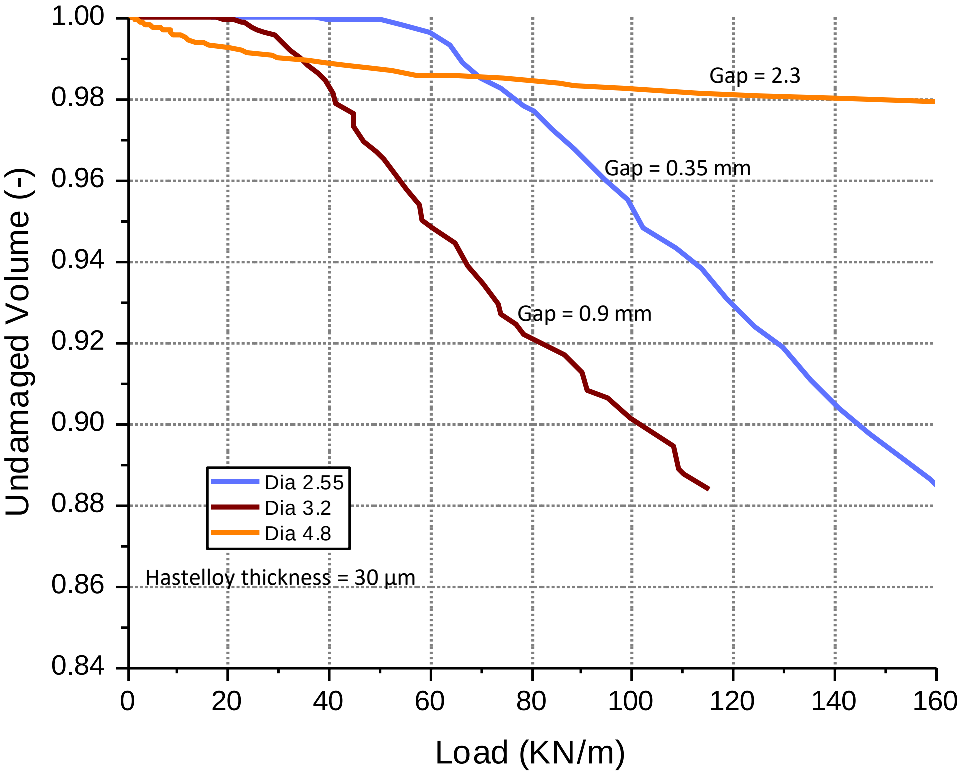
FEM data with selected criteria shows a damage response like Ic degradation



Type	Wire
Former size	2.55 mm
Tape number	12
Tape width	2 mm
Gap spacing	~0.33 mm
Substrate thickness	30 µm
Copper plating thickness	5 µm

CORC Transverse load

Effect of gap spacing between tapes

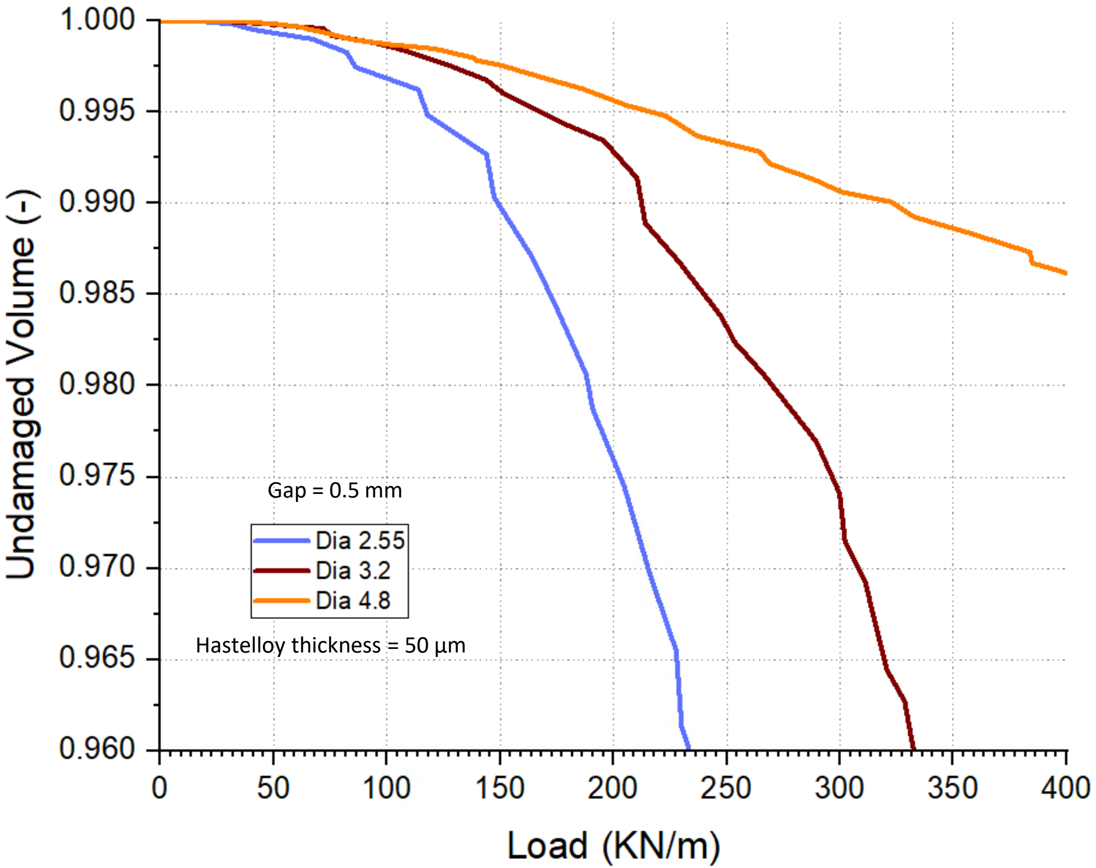


Six-layer cable with different diameter and different gap

- 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.

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.

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Thank you!

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