U.S. MAGNET DEVELOPMENT PROGRAM

Modeling of Stress & Strain-induced Critical Current Degradation in Rutherford Cables

MDP collaboration meeting
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OUTLINE

- THE WHY
- THE HOW – AVAILABLE FACILITIES
- HOMOGENOUS vs. DETAILED MODELS
- PREVIOUS EXPERIENCE IN MODELING Nb-Sn COMPOSITE (PRE-HEAT TREATMENT)
- EXAMPLES OF MODELING Nb_3Sn CABLE STACKS (POST-HEAT TREATMENT)

THE WHY: Why do Nb_3Sn accelerator magnets typically reach at best 90% of SSL (~60% of I_c) ?

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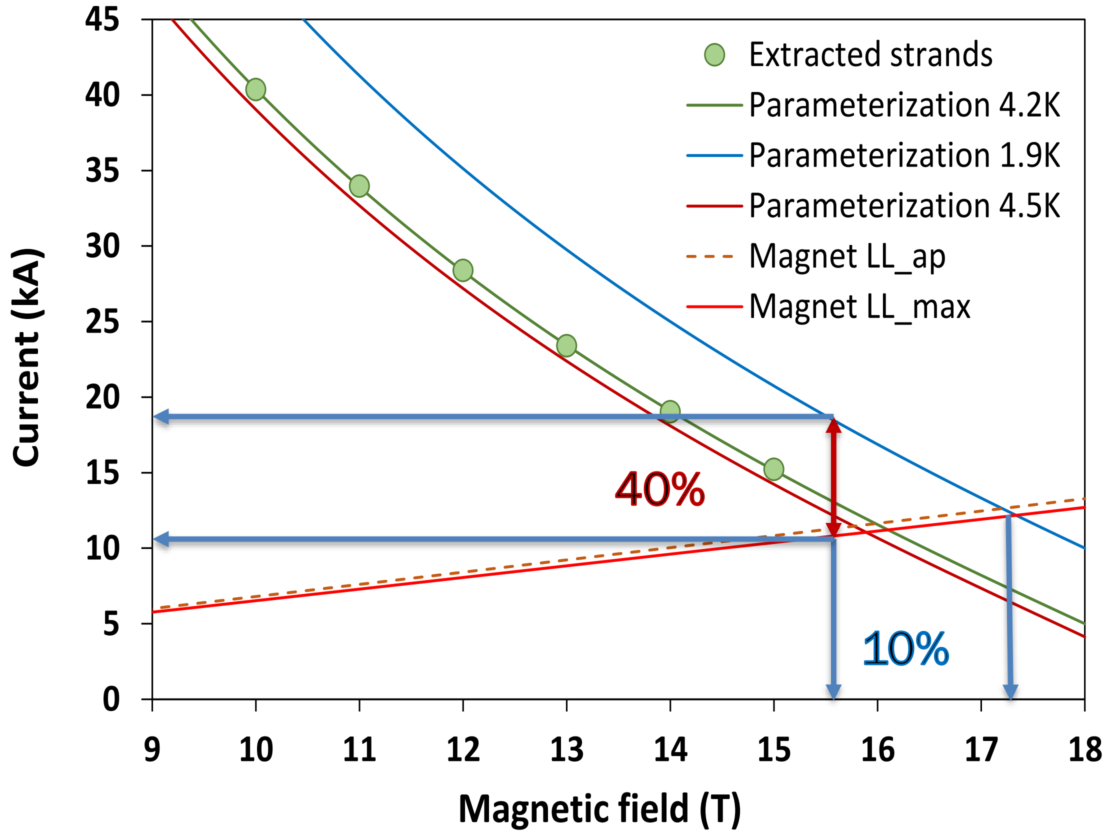
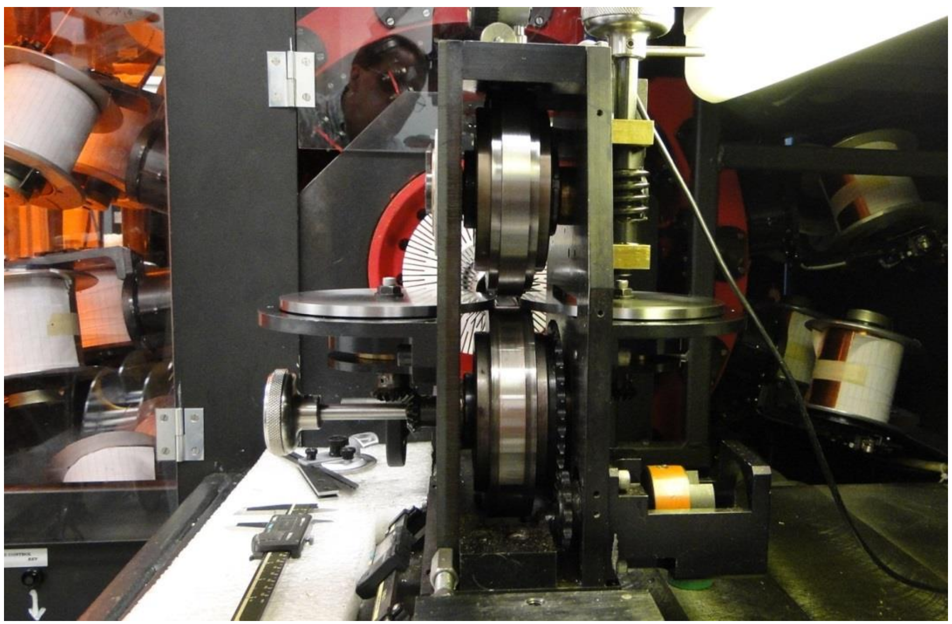
- Magnet short sample limit (SSL) based on extracted strand data.
- Magnet design limit is determined by mechanical constraints.
- The challenge to solve for MDP is to push the design limit of these magnets to their superconducting potential (or SSL).
- To design and build a 16 T Nb_3Sn superconducting dipole, the design limit needs to be at least 17 T.



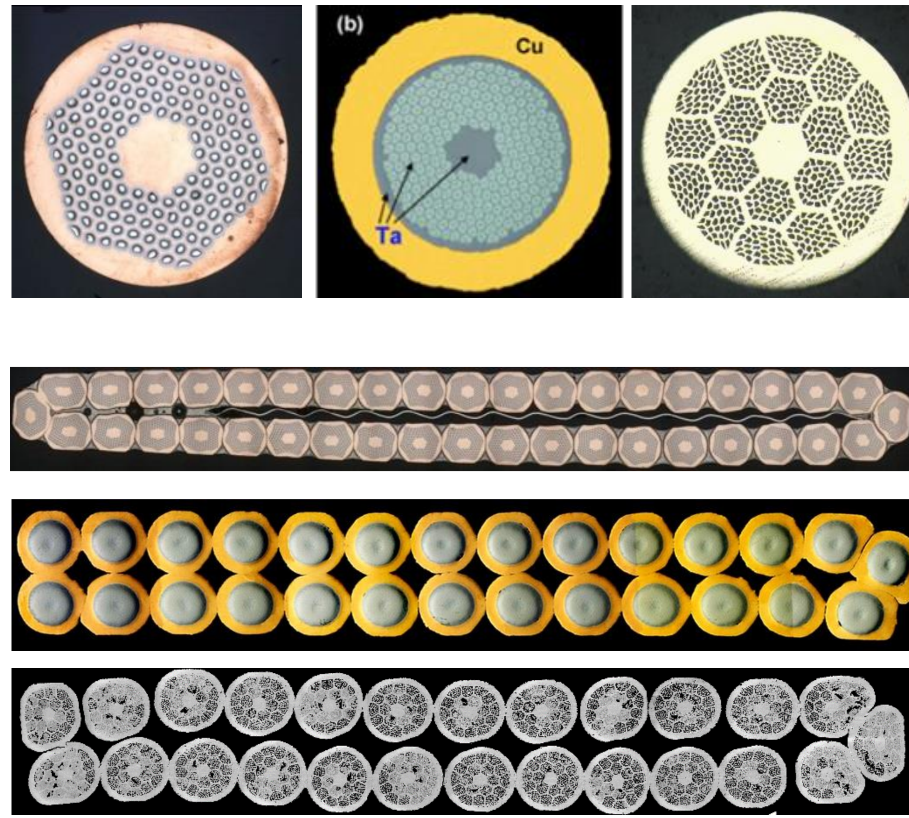
<u>In AUP the ultimate current is set at ~85% short sample limit, i.e. ~ 50% of I_c</u>

THE HOW: With Available Facilities (1)

42-spool R&D Cabling Machine with Keystoned turk-head for Rutherford cable fabrication in 1 step



Nb_3Sn | Nb_3Al | Bi-2212



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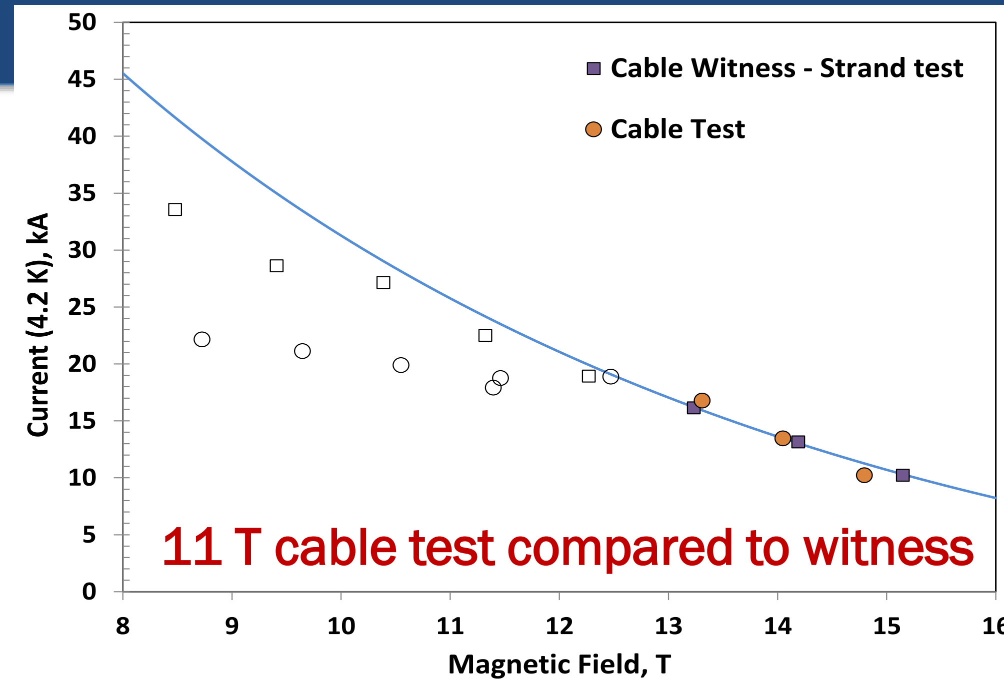
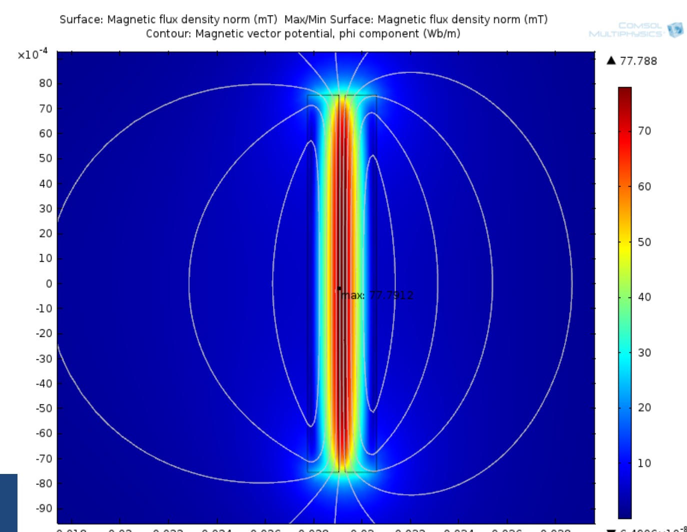
THE HOW: With Available Facilities (2)

2010-2013: SC transformer for cable tests in field up to 15 T and 30 kA

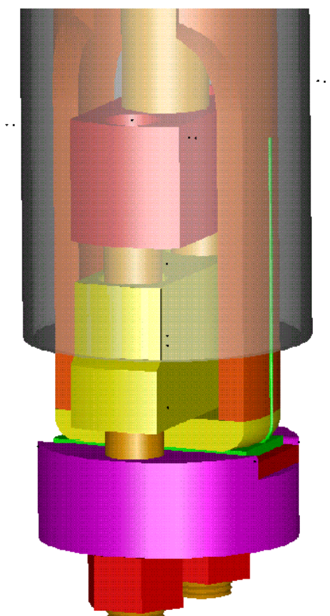


Self-field correction 0.078 T/kA

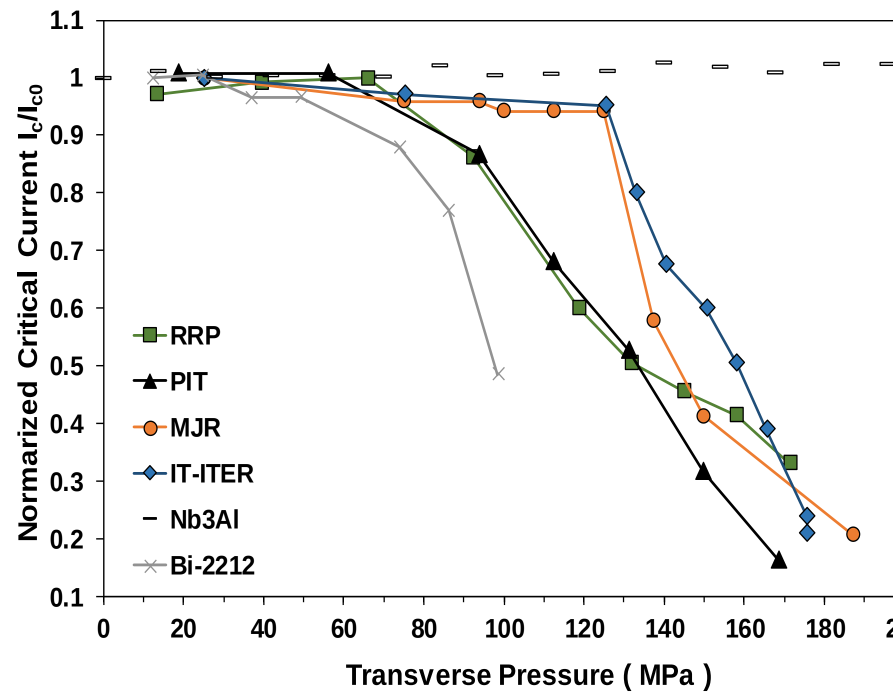


THE HOW: With Available Facilities (3)

2001-2003: Device to test I_c sensitivity to <u>uniaxial</u> cable transverse pressure up to 200 MPa and 14/16 T



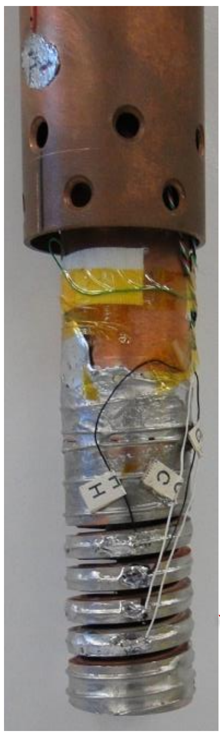
Examples of Data



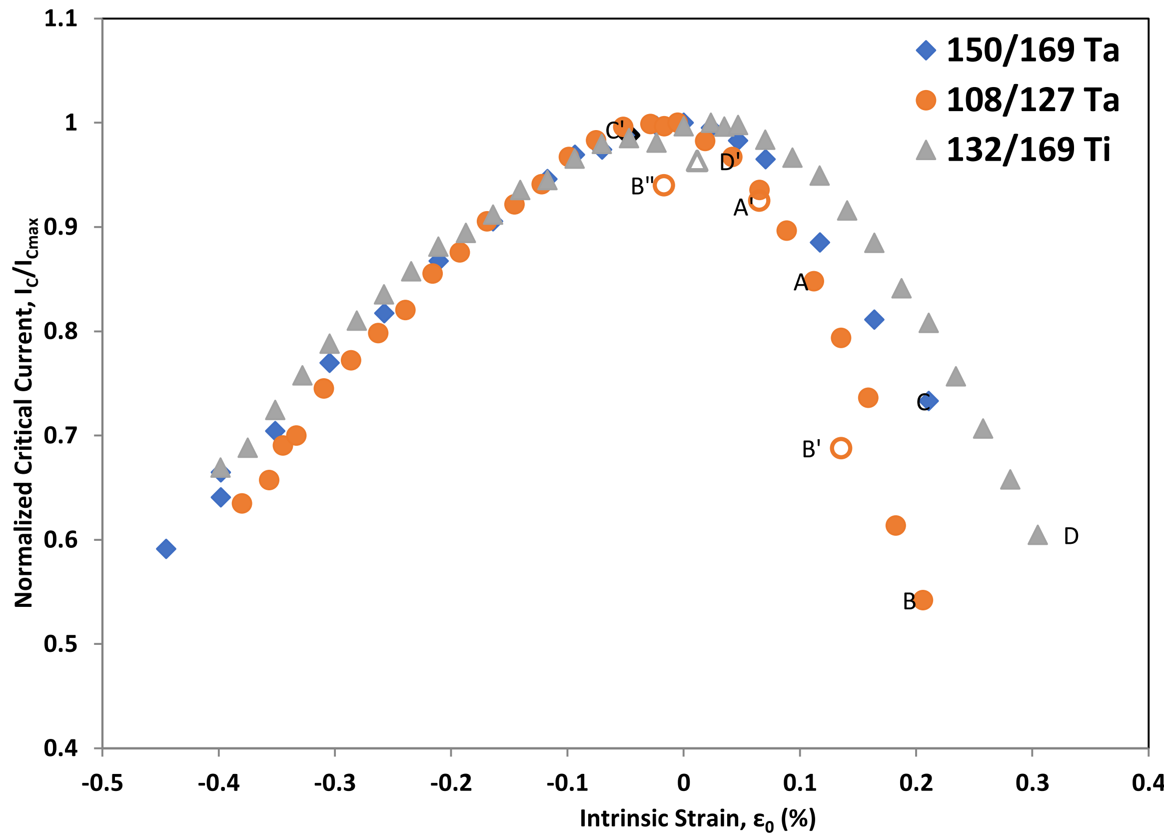
Will also be used by OSU PhD student Chris Kovacs for an experiment to study pre-quench dynamics in impregnated cables.

THE HOW: With Available Facilities (4)

2010: Walters' Spring probe for strain sensitivity studies of I_c in SC wires

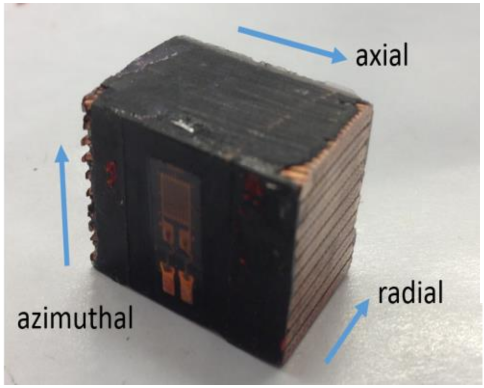


Examples of Data

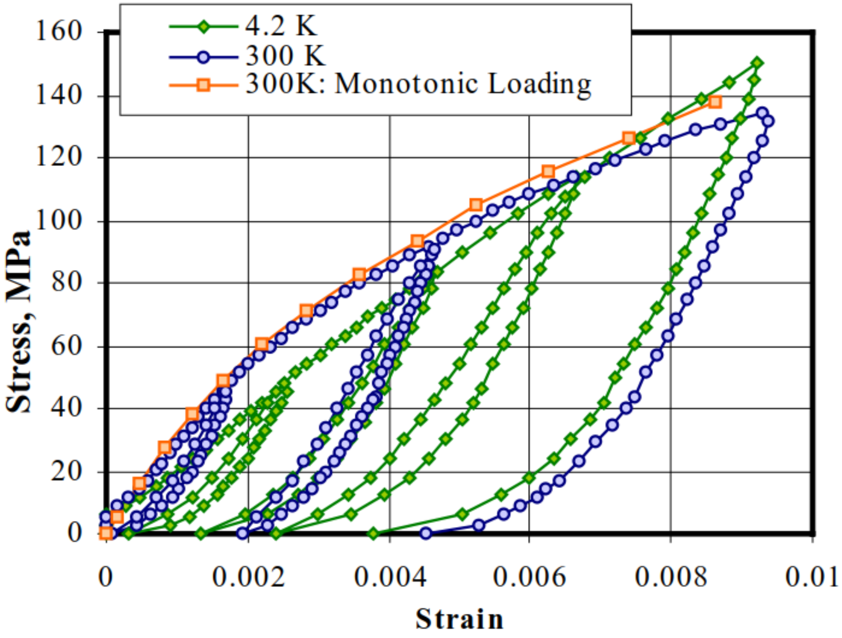


THE HOW: With Available Facilities (5)

2000: Cell loader for compression tests at 300K and 4.2 K



Examples of Data (Impregnated Nb_3Sn)



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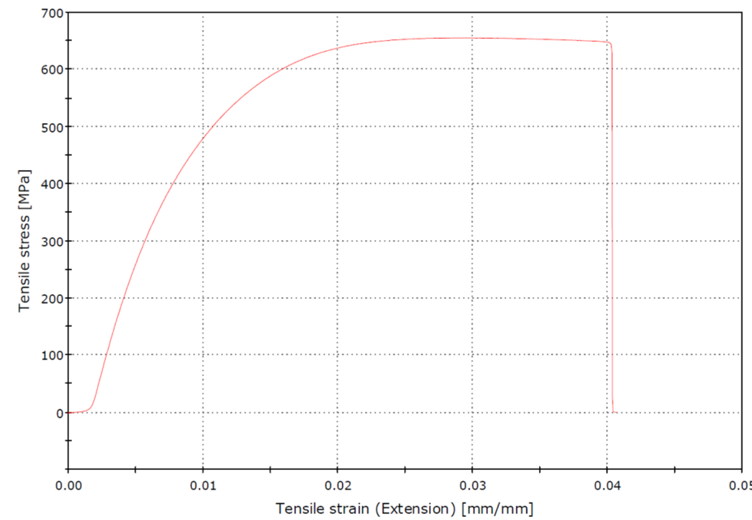
THE HOW: With Available Facilities (6)

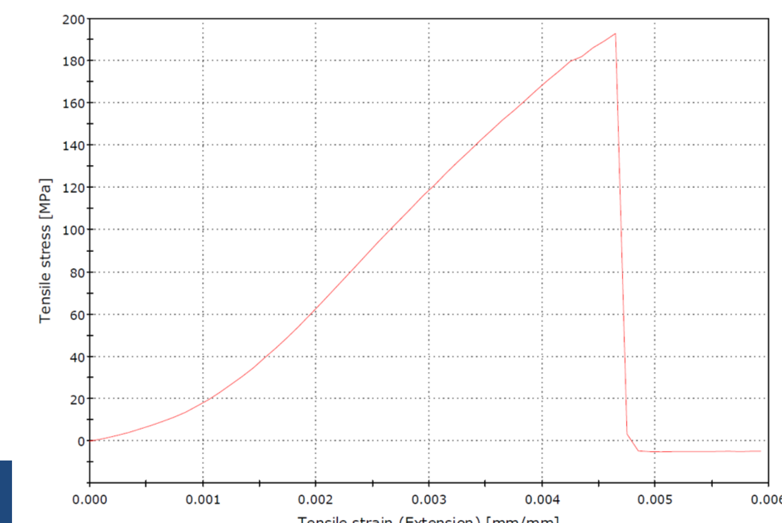
Instron machine, room temperature only

Examples of Data

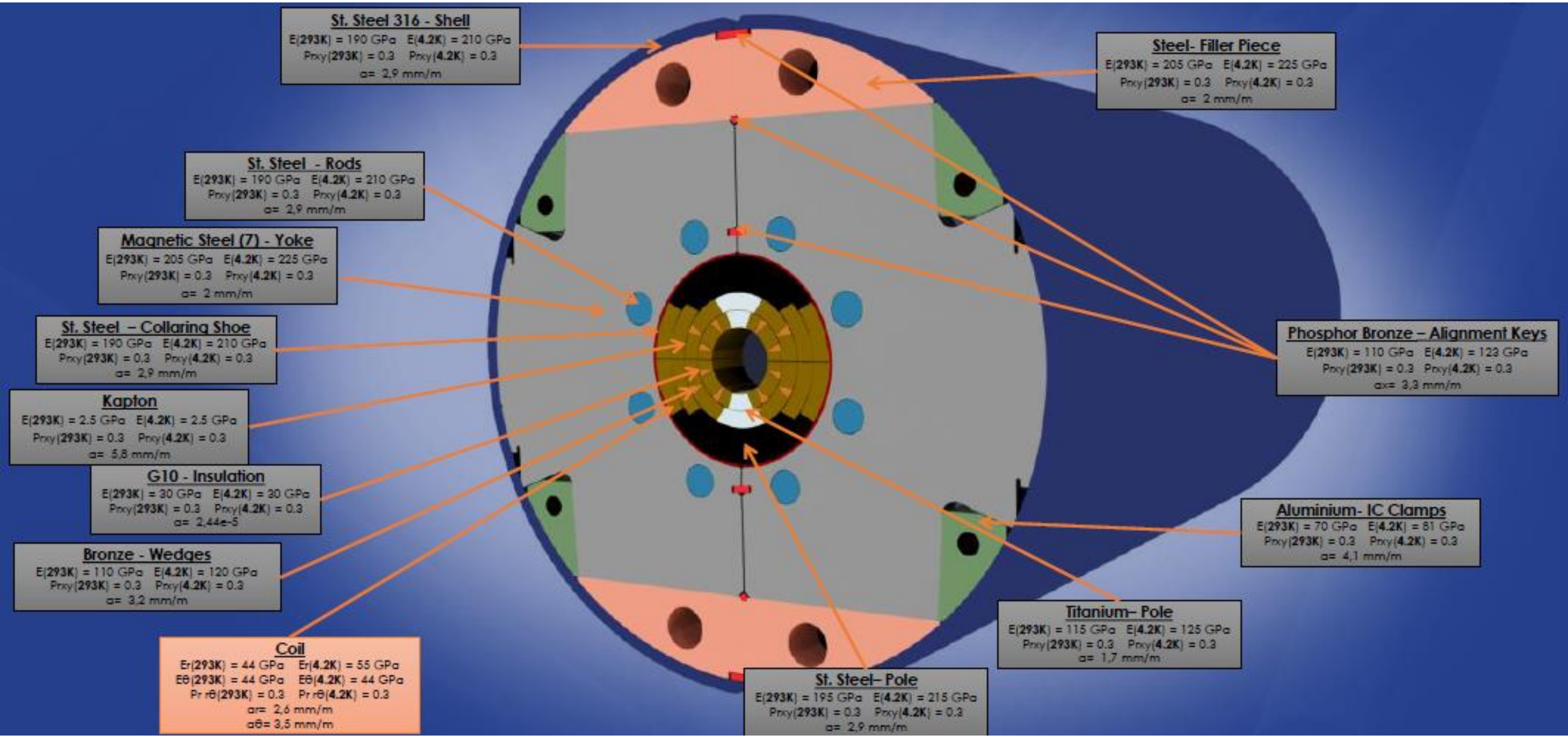
Unreacted Nb_3Sn wire



Reacted Nb_3Sn wire



2D/3D Homogeneous FEM Models (Example below is for 15 T Dipole)

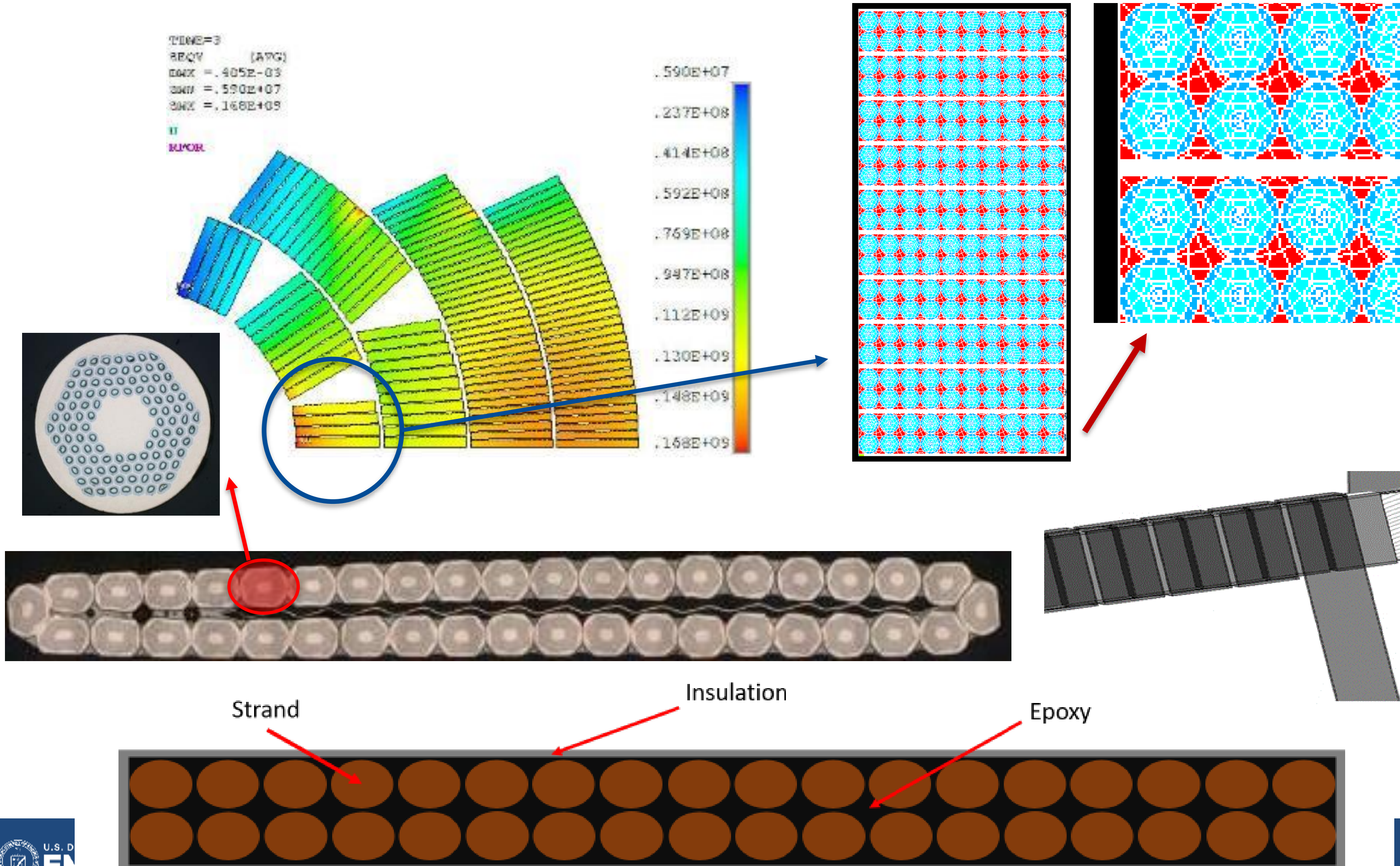


Consistency of Homogeneous Models

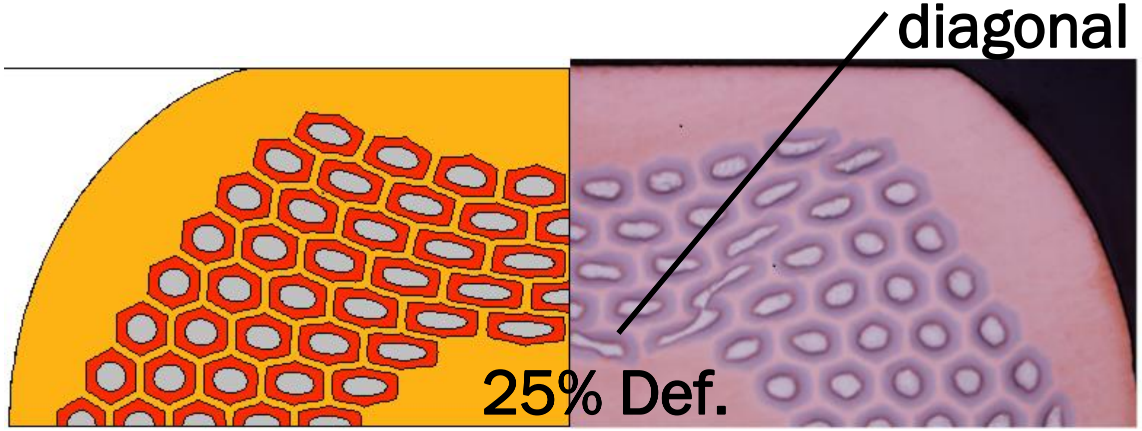
15 T DIPOLE

FEAC						FERMILAB			
		Imported Forces		Mapped Forces					
Bo (T)	I(kA)	Fx(MN)	Fy(MN)	Fx(MN)	Fy(MN)	Fx(MN)	Fy(MN)	Bo (T)	I(kA)
15	10.35	6.35	-3.65	6.35	-3.66	6.79	-4.01	15.01	10.8
16	11.13	7.17	-4.21	7.17	-4.22	7.66	-4.62	16.00	11.6
17	11.92	8.05	-4.82	8.05	-4.83	8.69	-5.35	17.09	12.5

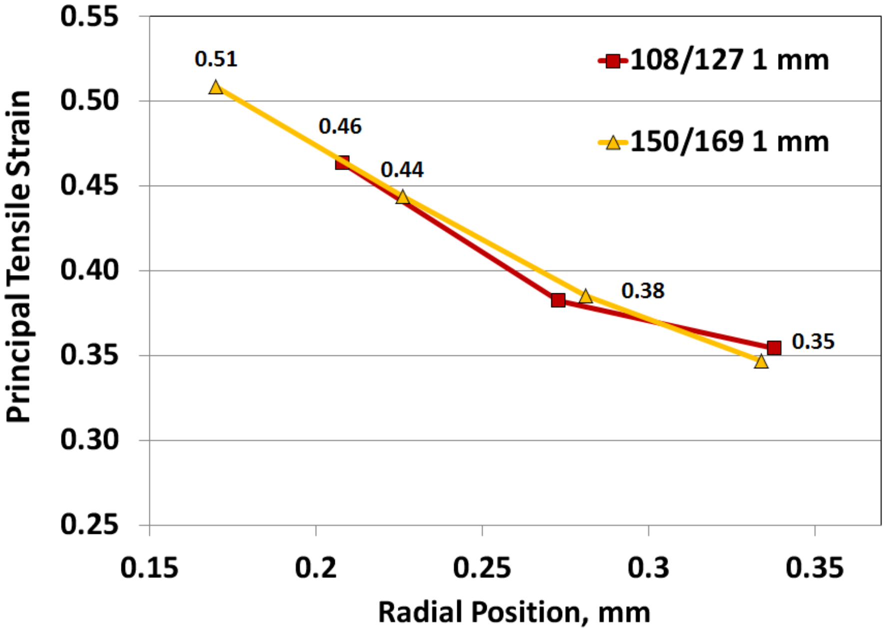
Sub-Modeling at Various Detailing Levels



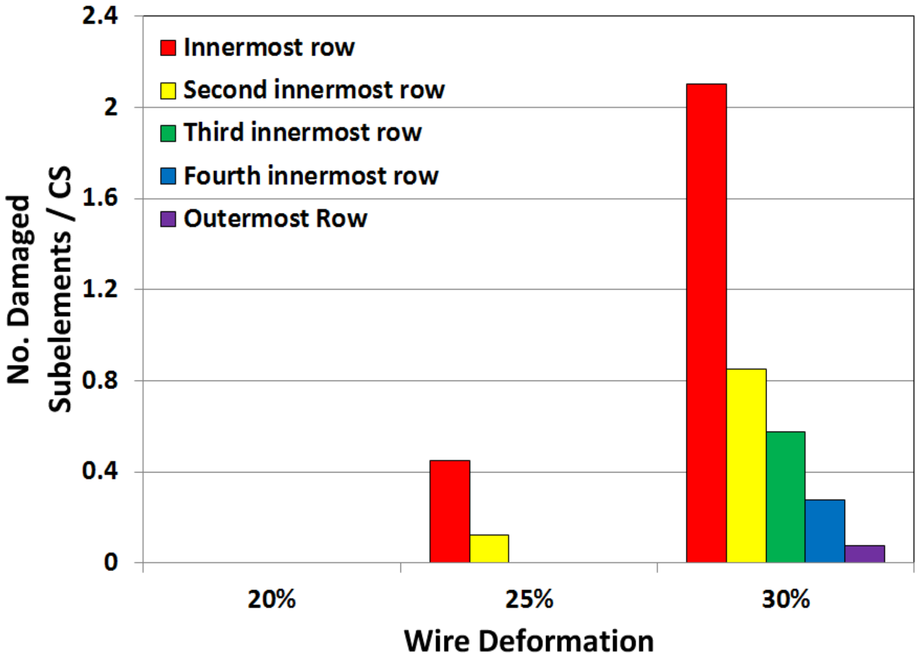
Nb-Sn Strand Modeling vs. DATA



ELASTO-PLASTIC MODEL



DATA – Hundreds of cross sections analyzed



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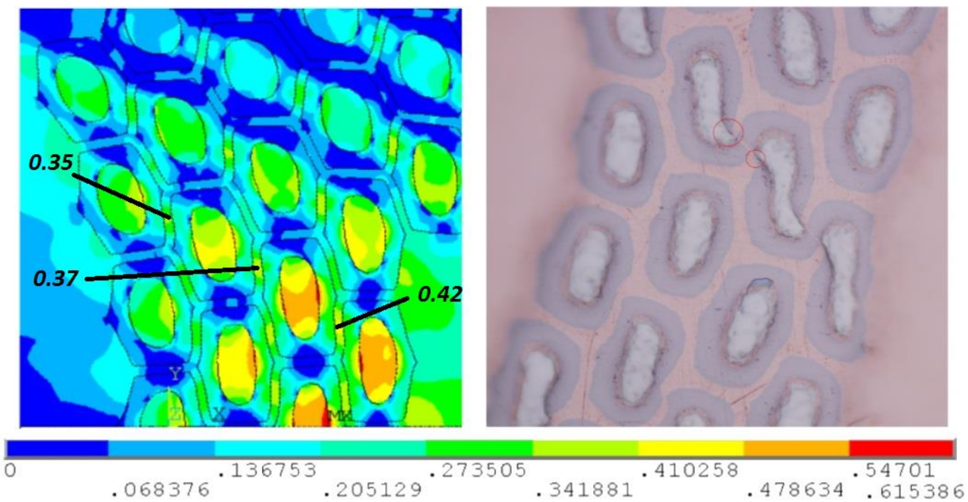
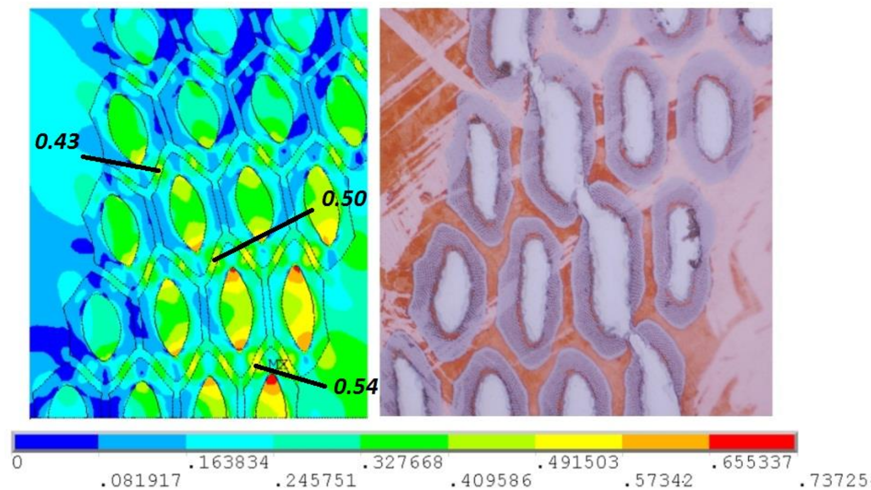
Establishment of a Criterion for Nb_3Sn Pre-Heat Treatment Mechanics

These extensive studies on <u>RRP wires</u> deformed under flat-rolling, which showed that subelement breakage in RRP wires occurs at an <u>equivalent plastic strain</u> in the Cu of 0.48 ± 0.1, allowed to establish a resistance criterion for cable fabrication and, in general, for Nb_3Sn pre-heat treatment mechanics.



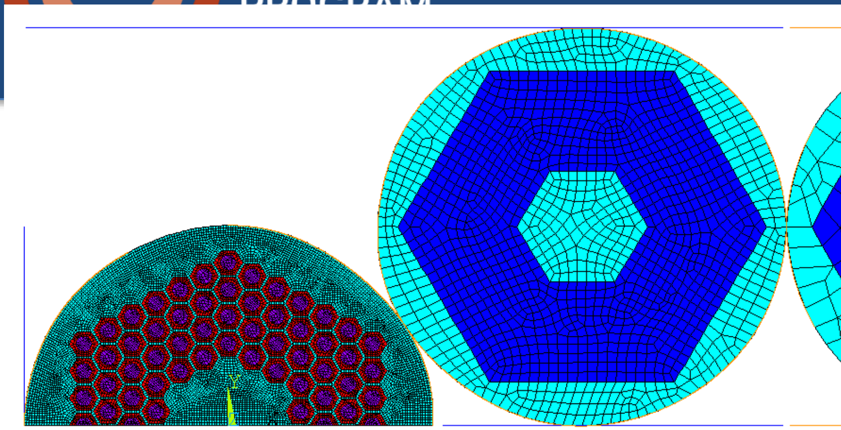
27-strand cable



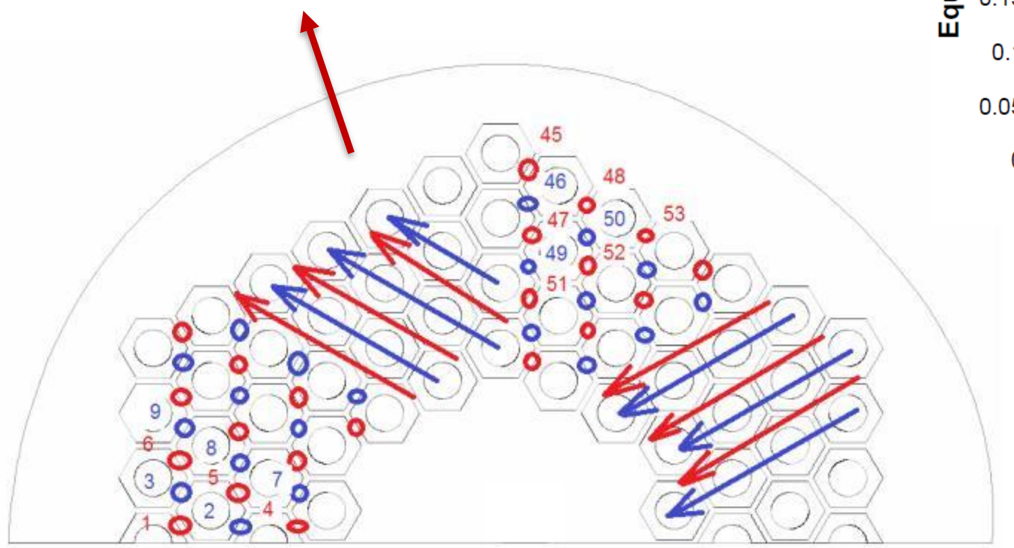
40-strand cable

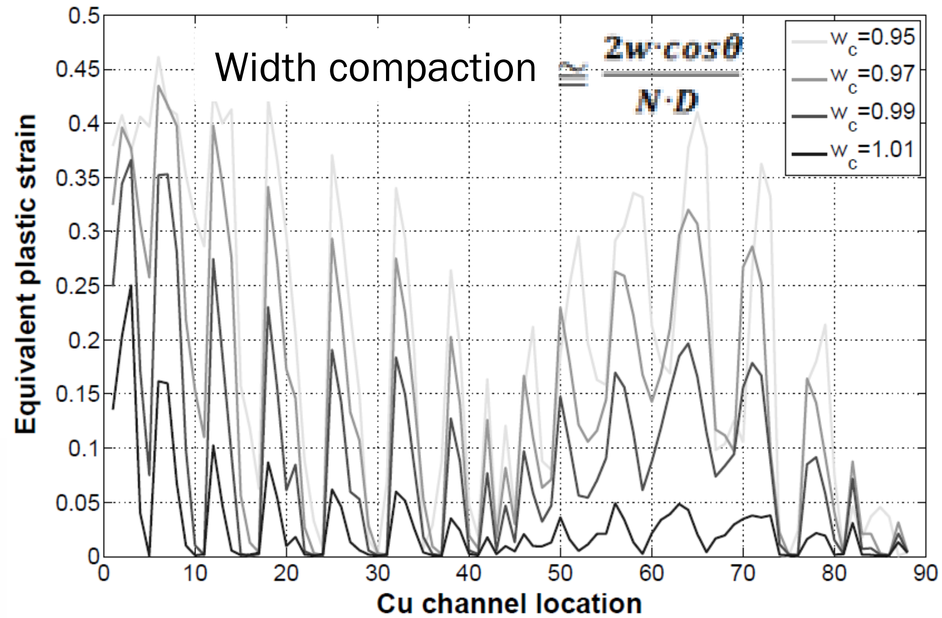
Similar studies performed on <u>RRP cables</u> showed that subelement breakage in the edge strand occurs between 0.35 and 0.54 of <u>equivalent plastic strain</u>, consistently with the 0.48 ± 0.1 criterion previously established.

Strain Distribution in Rutherford Cable



Map identifies <u>Cu channels exhibiting tensile stress, which is where fracture occurs</u>.





Equivalent plastic strain in the Cu channels exhibiting tensile stress as a function of channel location (see map) in edge strand of 40-strand cables with various width compactions (edge compaction of 0.92).

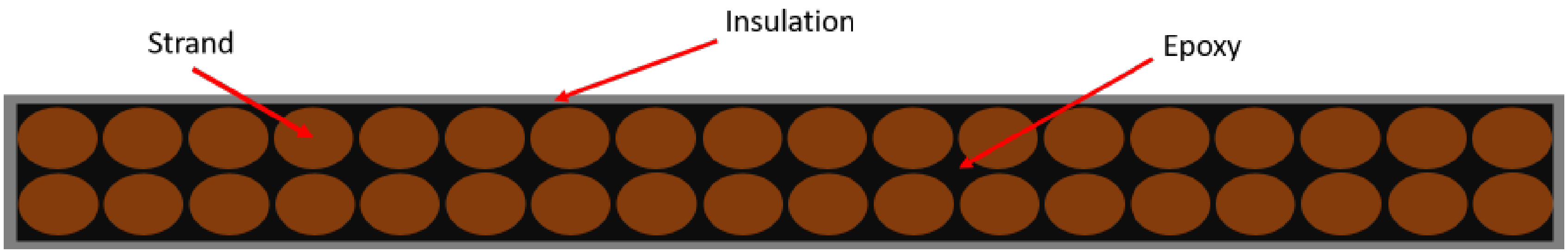
MODELING Nb_3Sn CABLE STACKS (POST-HEAT TREATMENT)

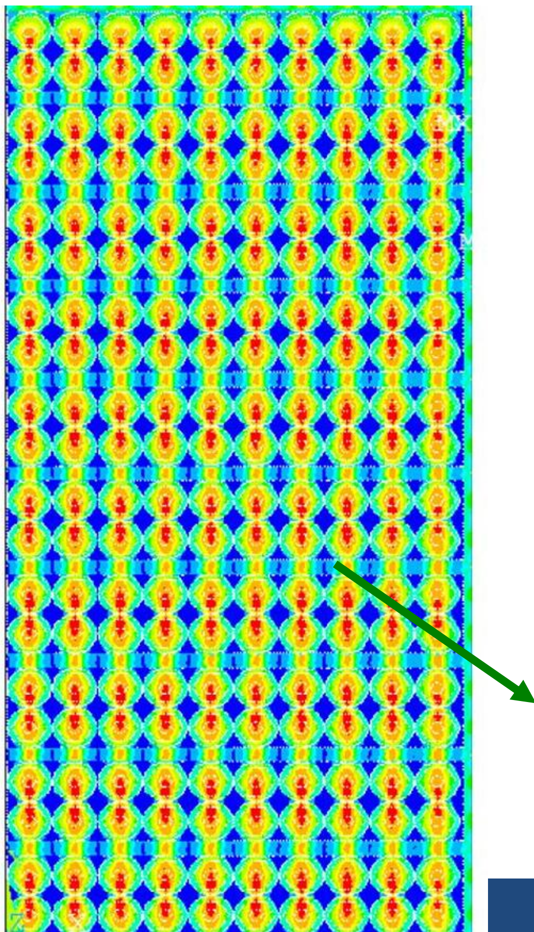
- Simulation of 10-stack test at 300K with sensitivity analysis using homogenous strand.
- Simulation of 10-stack test at 300K and 4.2K with sensitivity analysis using more detailed strand.

- Simulation of strand tensile test at 4.2K with fully detailed strand geometry and pre-stress calculation from heat treatment.

- Simulation of transverse pressure cable test at 4.2K with fully detailed strand geometry and pre-stress calculation from heat-treatment.

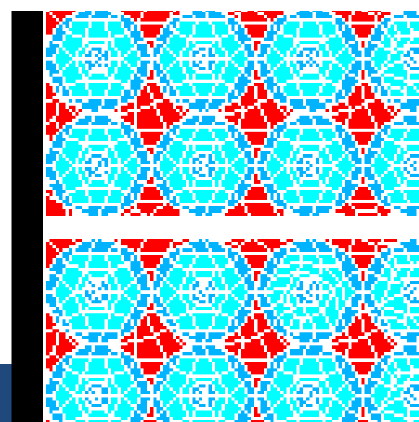
Sub-modeling of 10-stack tests at 300K

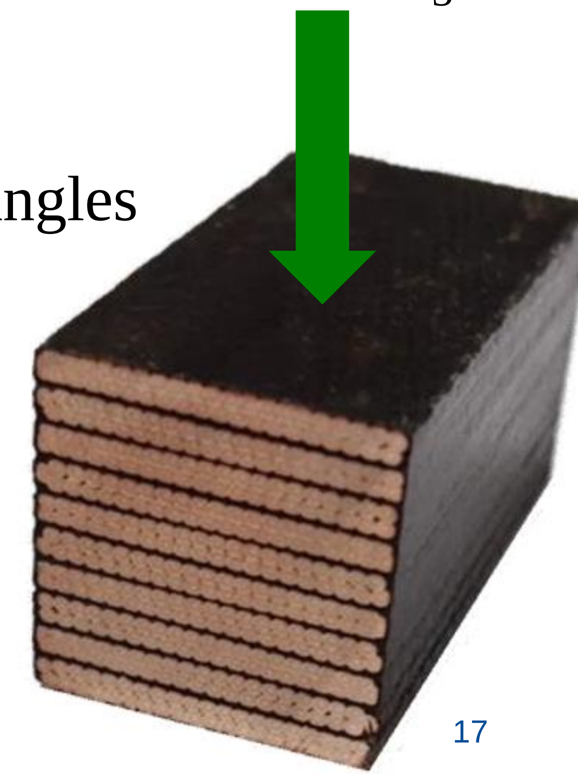




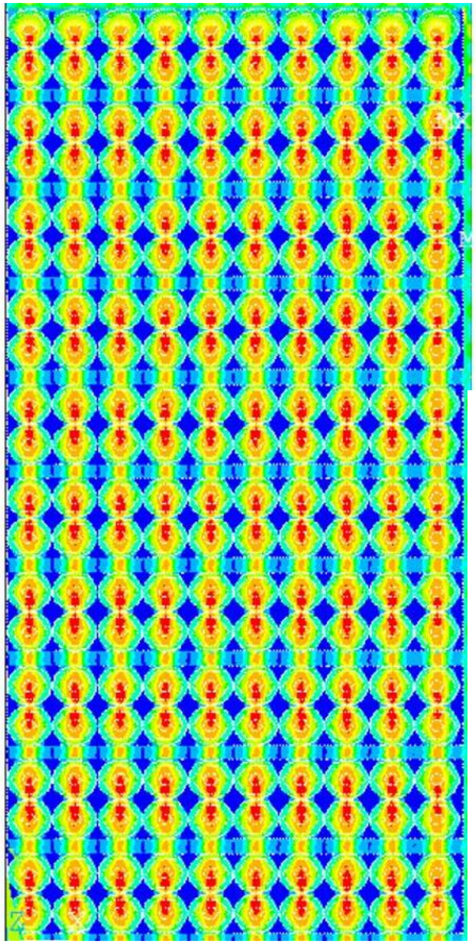
ASSUMPTIONS

- Elastic perfectly plastic, aside from Nb_3Sn (elastic only)
- Isotropic
- No keystone and lay angles
- No pre-stress

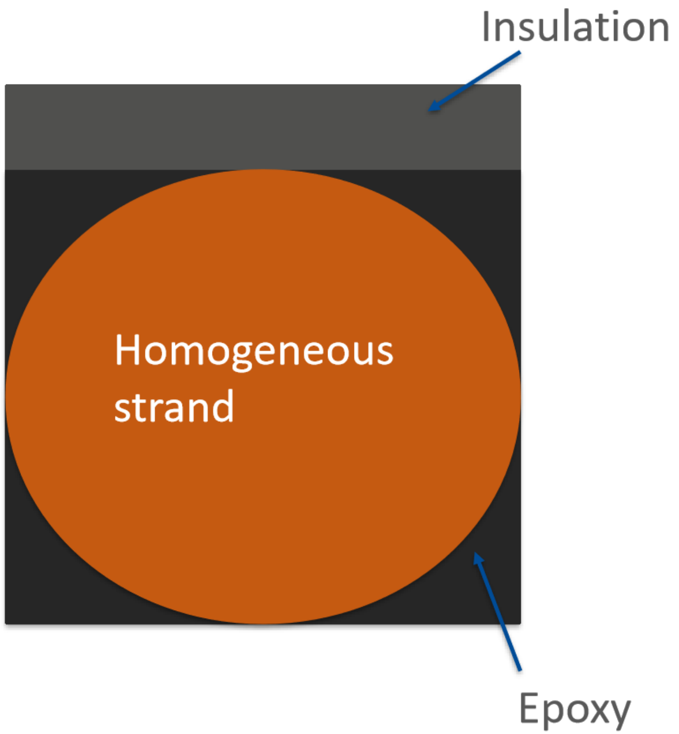


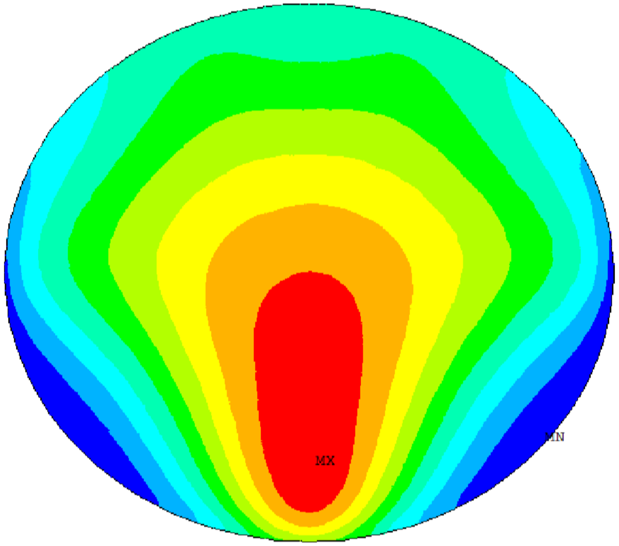


Homogenous Cell Model



Model 5
Maximum at 40 MPa→87 MPa
Maximum at 80 MPa→174 MPa
Maximum at 120 MPa→260 MPa





Max at 40 MPa→ 81.6 MPa
Max at 80 Mpa→163 MPa
Max at 120 Mpa→245 MPa

PARAMETERS FOR COMPARISON ■ Stress and strain (equivalent) behavior ■ Stress and strain maxima ■ Displacement along horizontal direction (U_X) ■ Displacement along vertical direction (U_Y)

Model-obtained Young modulus of composite

Was obtained using an orthotropic transversally isotropic material model:

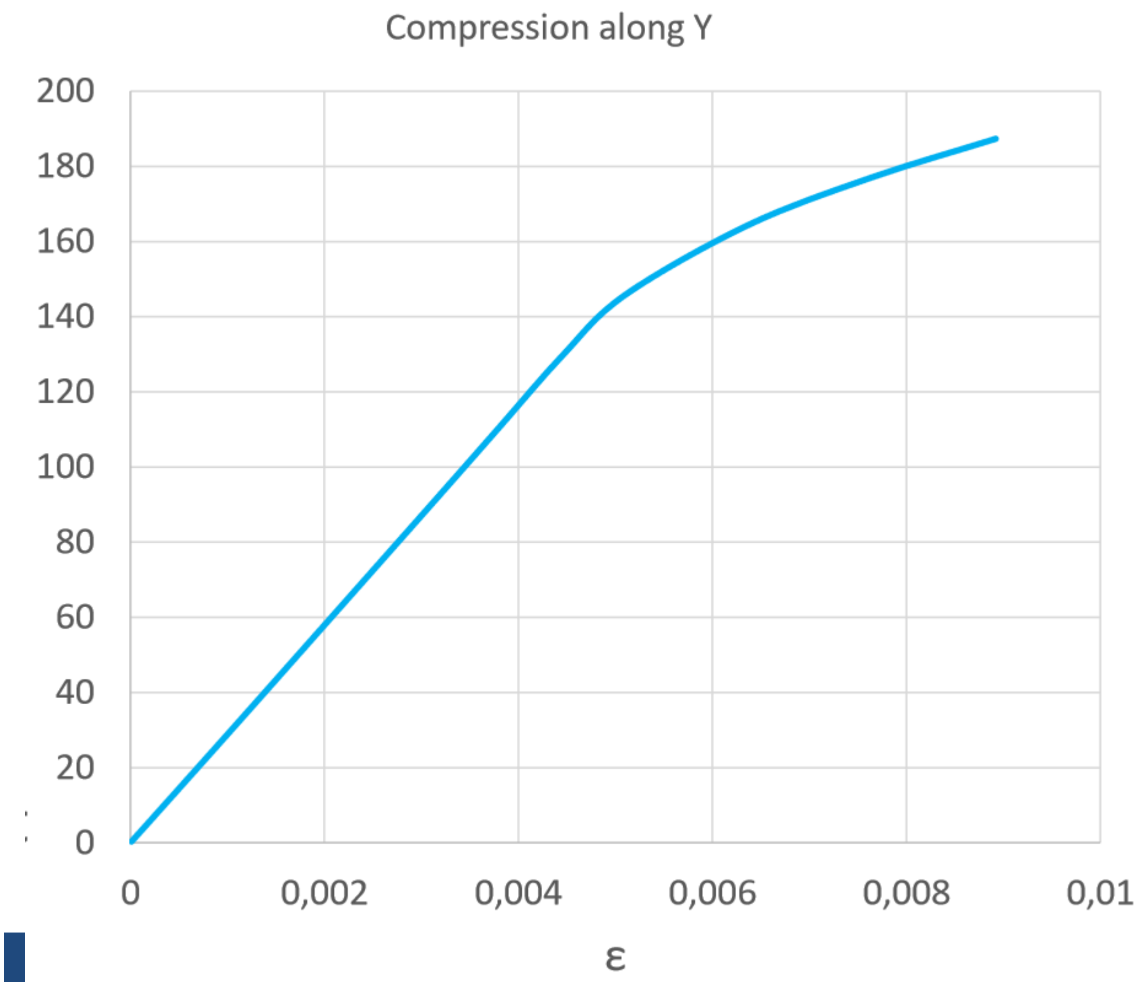
$$E_{\perp} = E_1 = E_2$$

$$\nu_{\perp} = \nu_{12} = \nu_{21}$$

$$E_{||} = E_3$$

$$\nu_{13} = \nu_{23}$$

$$G_{13} = G_{23}$$



Simulation of 10-stack Test

@300K

Homogenous displacement
w/80MPa average pressure
w/sensitivity analysis

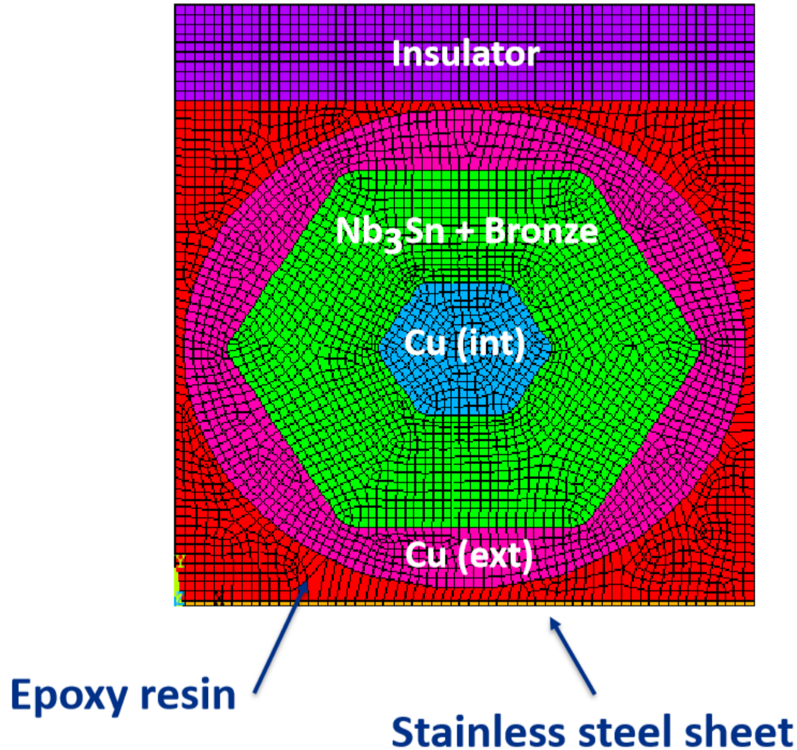
@4.2K, 2 cases:

A. Load first, cool down next
B. Cool down first, load next

Transient analysis
w/sensitivity analysis

APDL of More Detailed Strand Model

- Plane geometry with no keystone angle
- Use of a lighter **single strand** detailed model with symmetry boundary conditions
- Homogeneous Nb_3Sn–bronze region
- **Plane182** elements with generalized plane strain keyoption
- Isotropic materials
- **Bi-linear** materials properties (tests required)



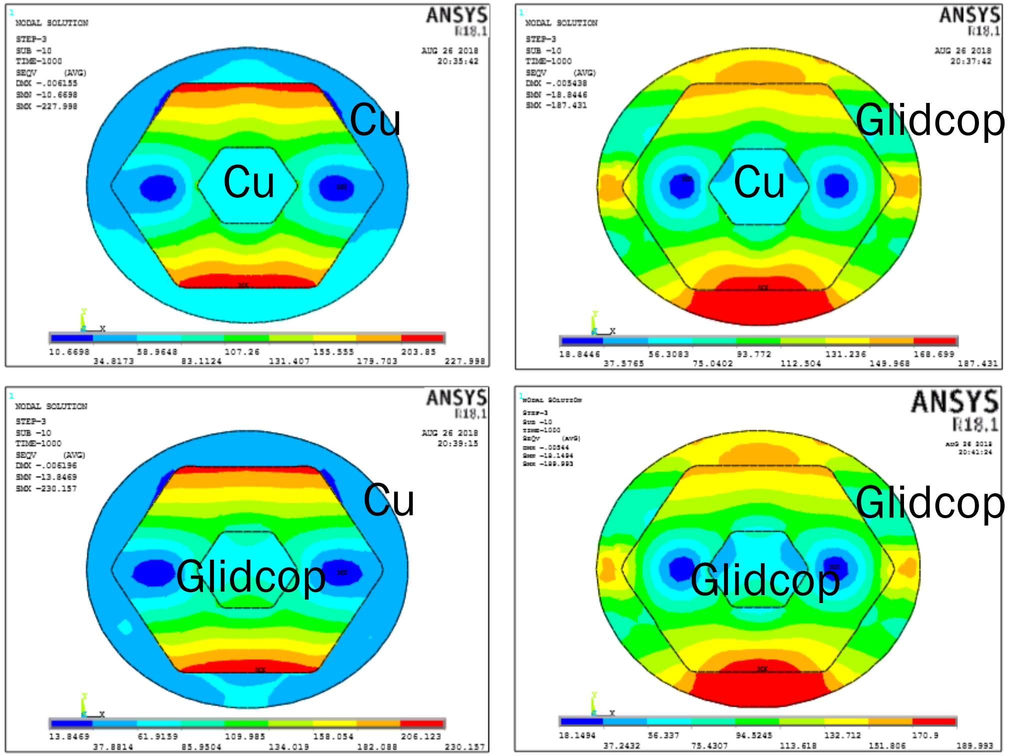
This model was used for instance to study the effect of reinforced Cu, or Glidcop, in the wire itself.

Reinforcing the wire would provide inherent strain management as opposed as reinforcing the cable and/or applying strain management to the mechanicals structure of the coils.

4 Cases were Studied both at 300K and at 4.2 K

$Sy_{int} = 60\ Mpa$
$Sy_{ext} = 60\ Mpa$

$Sy_{int} = 60\ Mpa$
$Sy_{ext} = 180\ Mpa$



$Sy_{int} = 180\ Mpa$
$Sy_{ext} = 60\ Mpa$

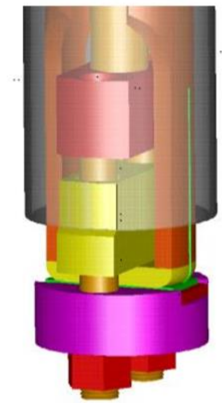
$Sy_{int} = 180\ Mpa$
$Sy_{ext} = 180\ Mpa$

- **It is better to use Glidcop in the outer part of the strand** at 4.2K only
  - **Small difference with inverted loadsteps order**
- **Positive linear correlation between elastic moduli (epoxy, insulator and Nb_3Sn) and maximum stress in Nb_3Sn**

Simulation of Strand Tensile and Cable Transverse Tests

Walters' Spring Device at FNAL

Modeled up to 0.6% axial strain



Modeled up to 200 MPa by uniform displacement

Critical current sensitivity to uniaxial transverse pressure ***at FNAL***

- Structural FEM analysis in Ansys APDL

1. Pre-stress evaluation from heat treatment (950K to 300K)
2. Cool down of sample from 300K to 4.2K + Ramped external load

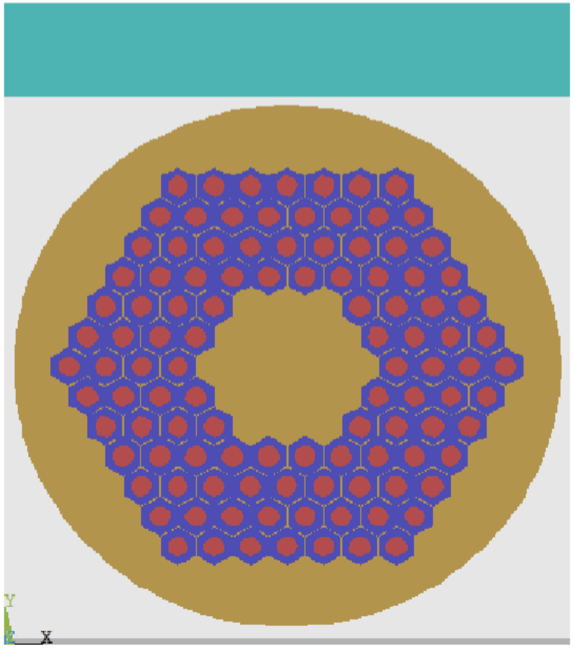
- J_c evaluation for each element using Ekin's law
- Numerical integration on the strand cross section → I_c degradation for the entire strand as a function of external load

Fully Detailed Single Cable Cell – Materials and Geometry

Insulator:
- CTD 101K + S-2 Glass
- 0.125 mm thickness

Epoxy **resin**:
CTD 101K

Stainless **steel** core
- 0.025mm thickness



Strand

OFHC **copper** / Glidcop Al15:
- 0.7 mm strand diameter
- Low yield strenght after annealing (≃ 100MPa)
- Bilinear isotropic hardening

Nb3Sn + **bronze** subelements:
- 108/127
- 50 micron diameter
- Nb3Sn → brittle
- Bronze → porous

Temperature dependent material properties: Elastic modulus and yield strength decrease with temperature (OFHC copper and Glidcop)

Next Steps

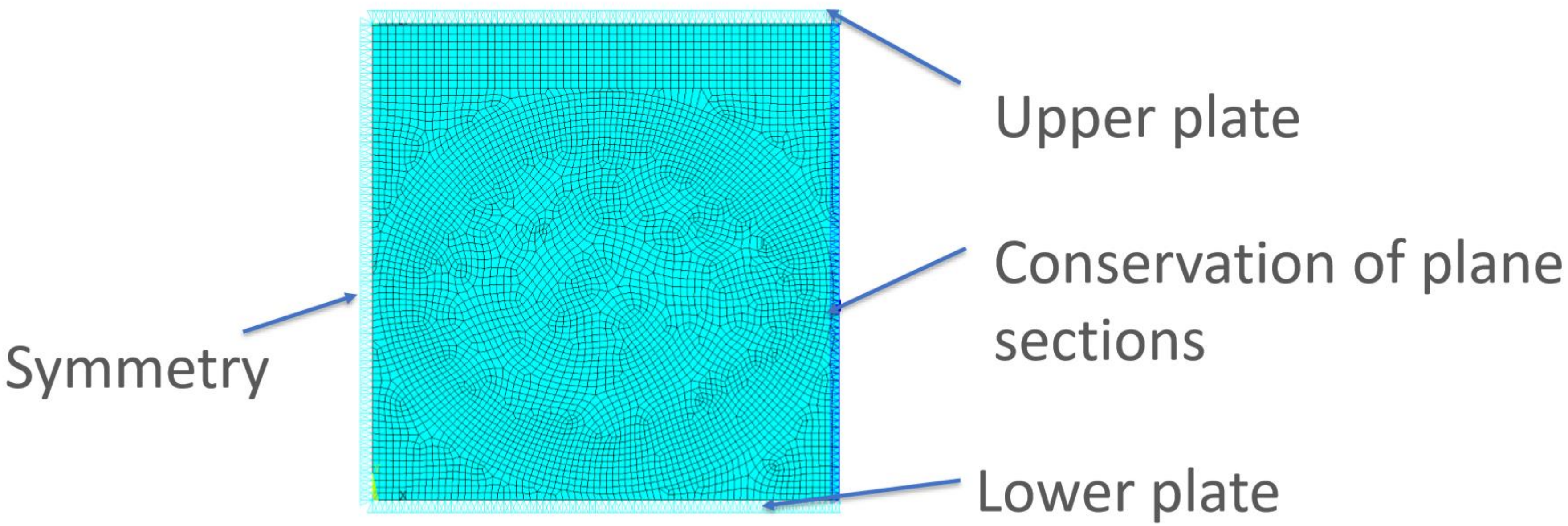
- Measure / obtain accurate values of material properties
- Improve the analysis of the pre-stress state
- Fracture
- Try and obtain the intrinsic strain – critical current law from experimental data
- Keep working on inherent wire reinforcement?

BACK-UP SLIDES

Sensitivity Analysis at Room Temperature

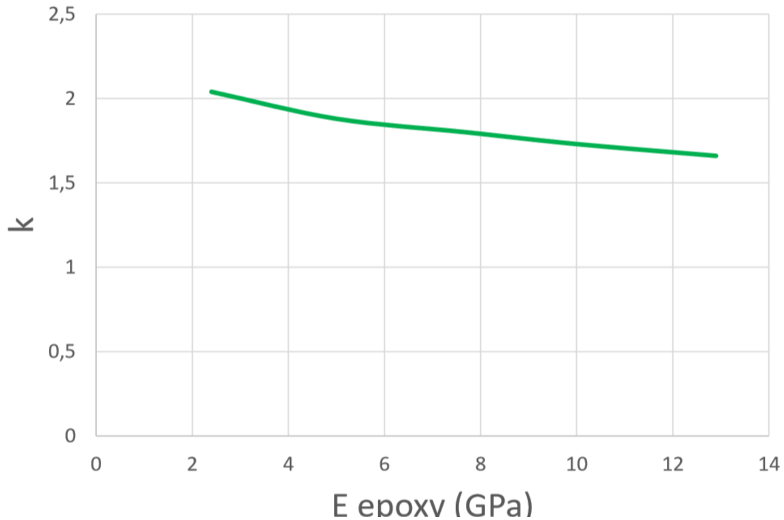
- For this analysis the uniform pressure load was replaced with a uniform displacement.
- The parameters used in the sensitivity analysis included:

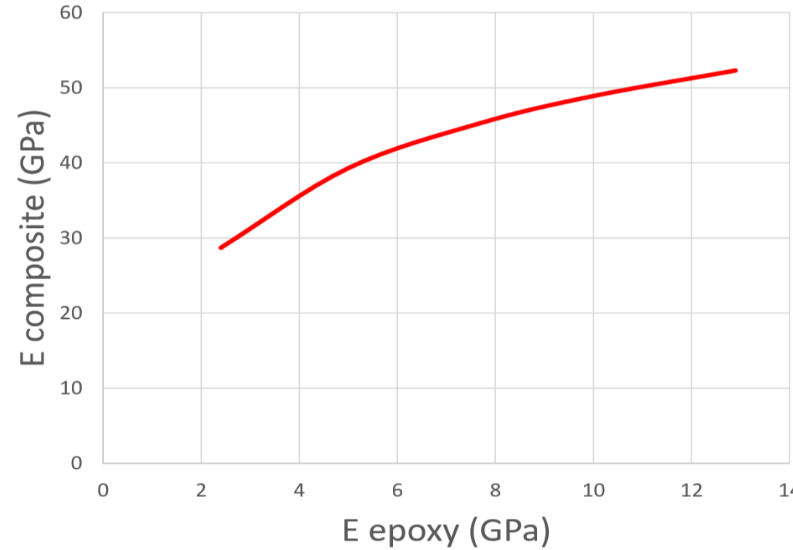
■ E epoxy ■ E insulation ■ E strand ■ Epoxy thickness between two layers ■ Presence or not of stainless steel core.

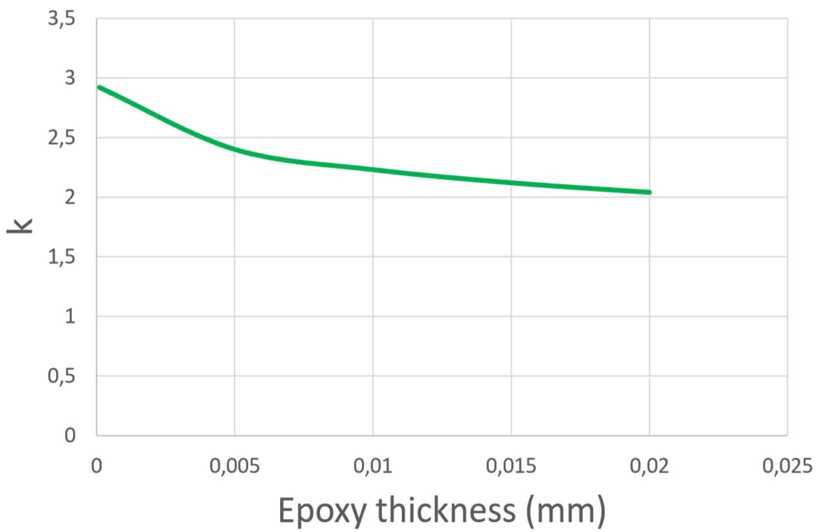


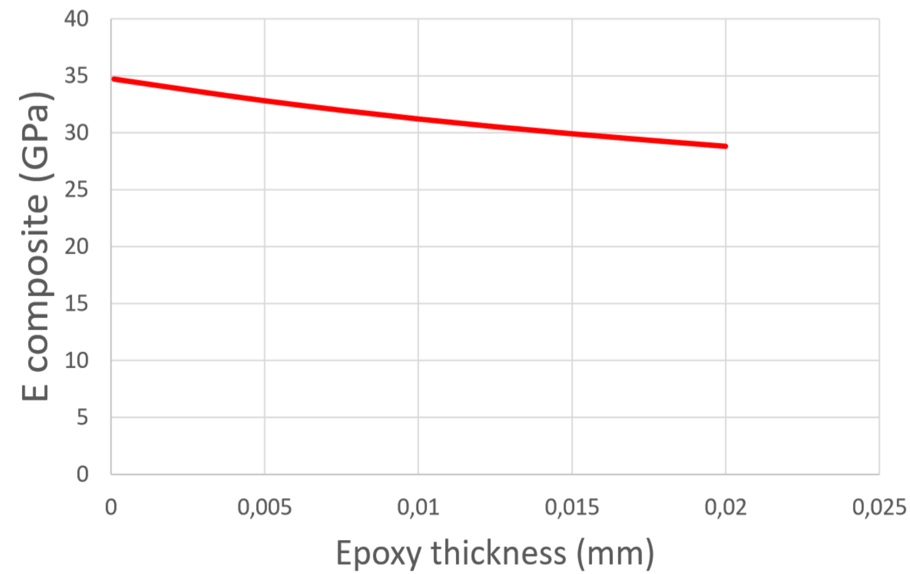
Sensitivity Analysis at Room Temperature

$$k = \frac{\sigma_{int,max}}{\sigma_{ext,av}}$$



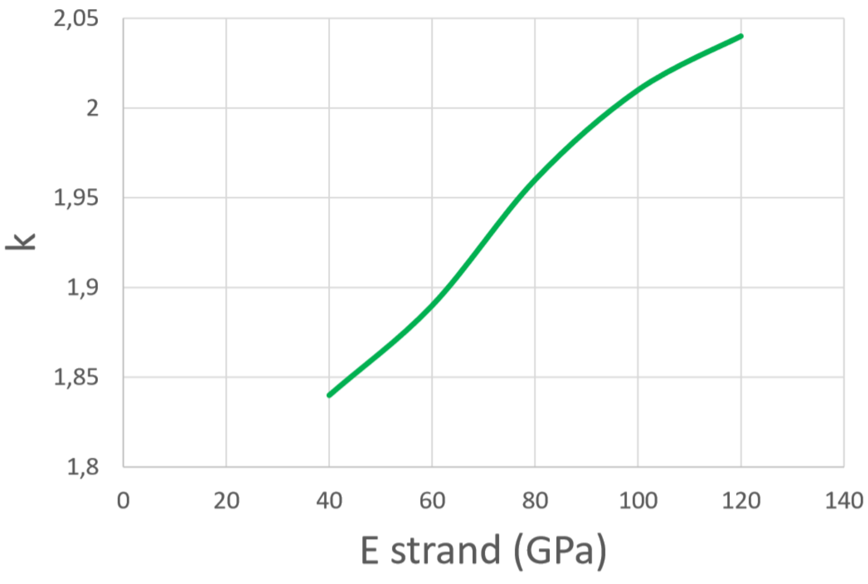


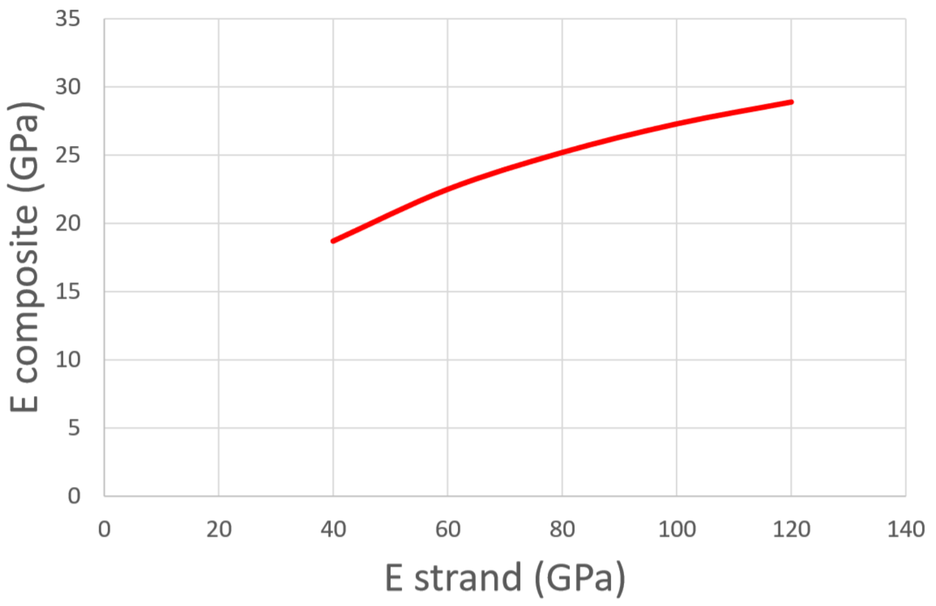




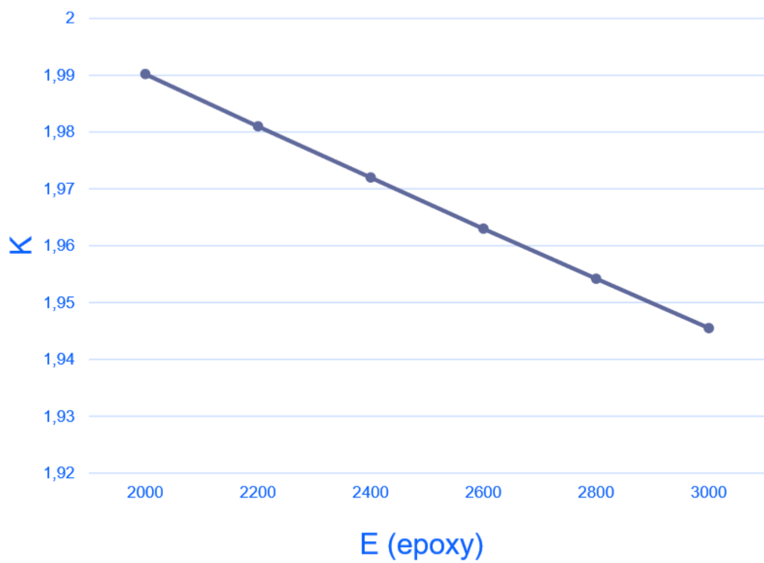
Sensitivity Analysis at Room Temperature

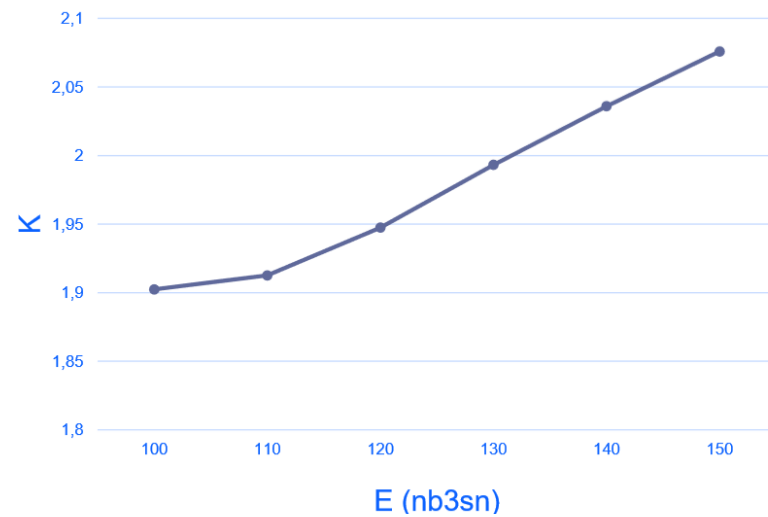
$$k = \frac{\sigma_{int,max}}{\sigma_{ext,av}}$$

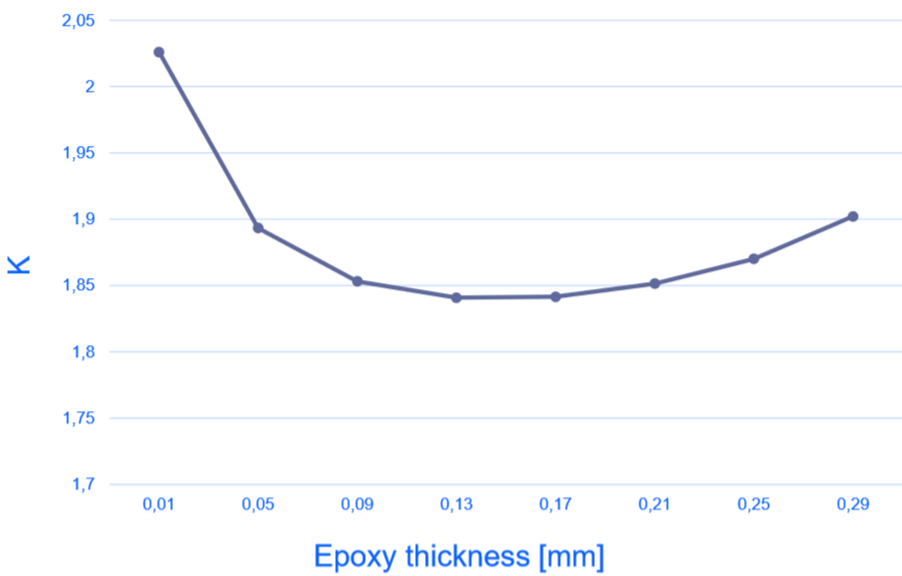




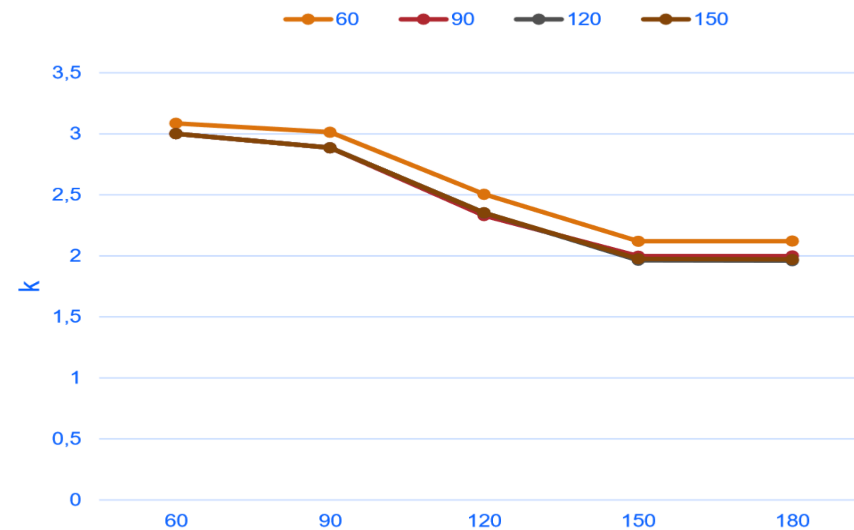
Sensitivity Analysis at Room Temperature





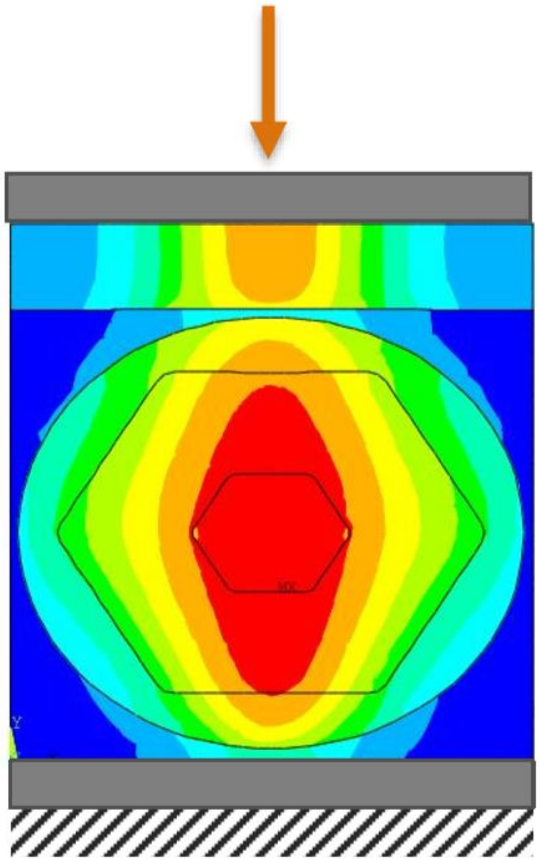


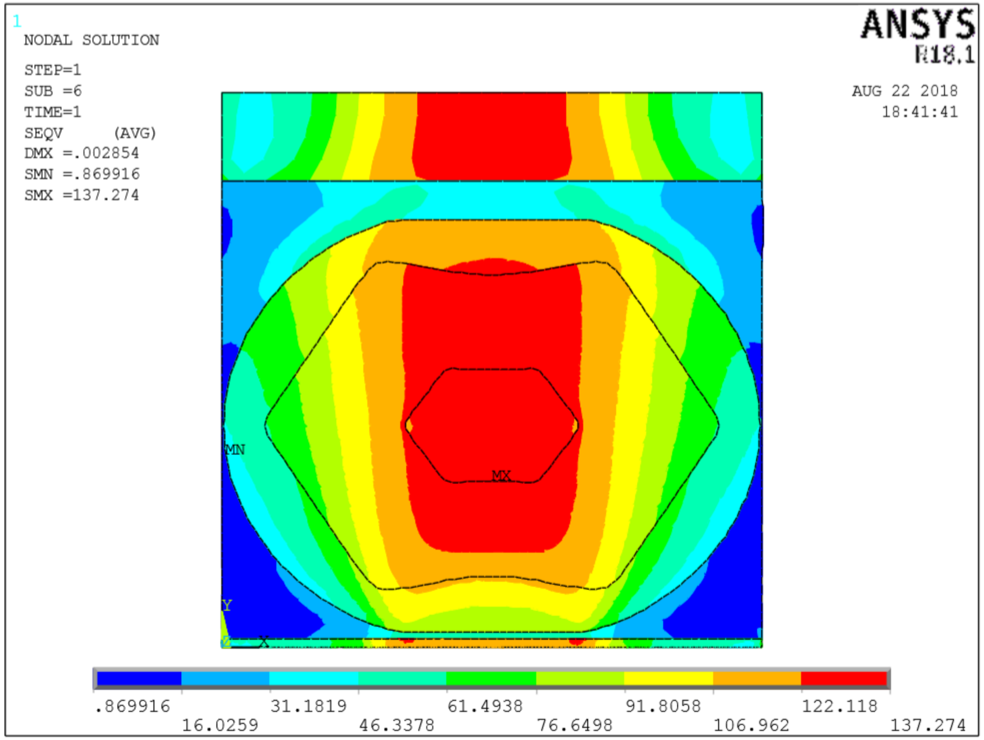
Sy_{ext}



Sy_{int}

Stress Distributions at Room Temperature

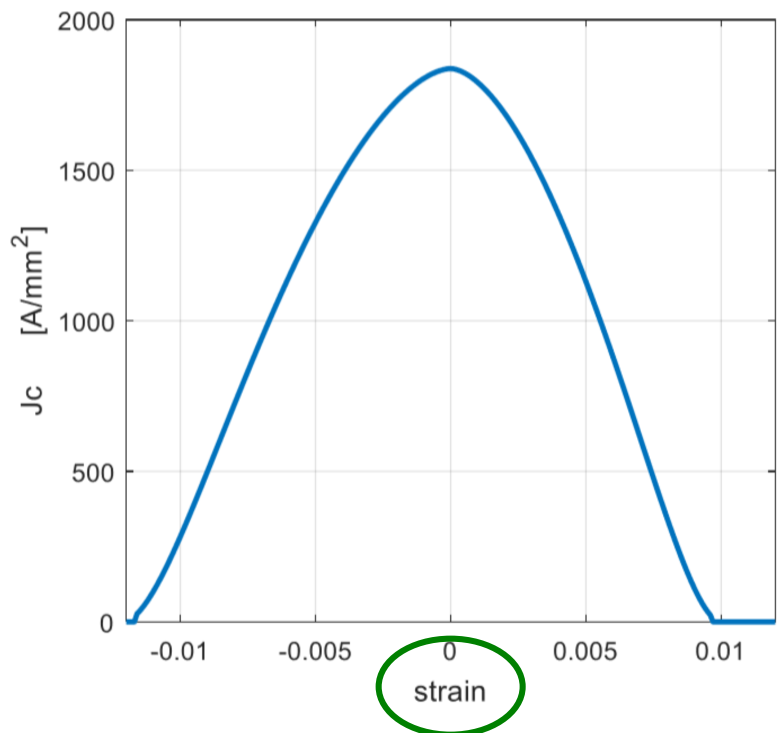




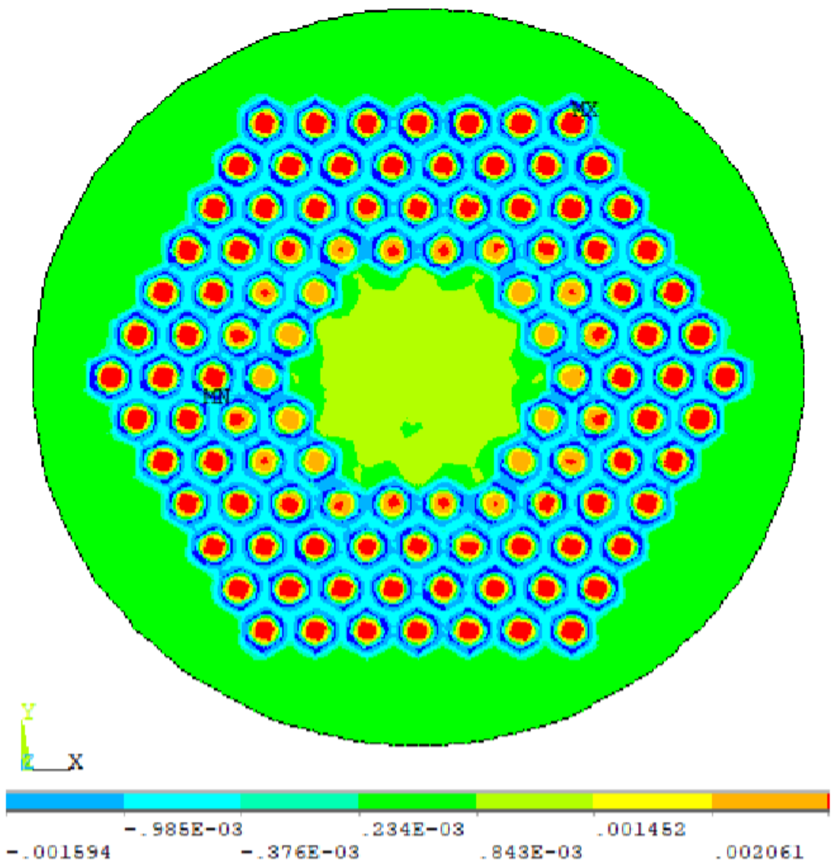
Using a deformed shape for the strand changes only slightly the stress distribution at room temperature

Strand plastic deformation through non-linear 2D contact analysis (coarse mesh) / Re-mesh (refined mesh) / Structural analysis with external pressure

Ekin's law – which strain does it apply to?



Critical current dependence on intrinsic strain (Ekin's law)

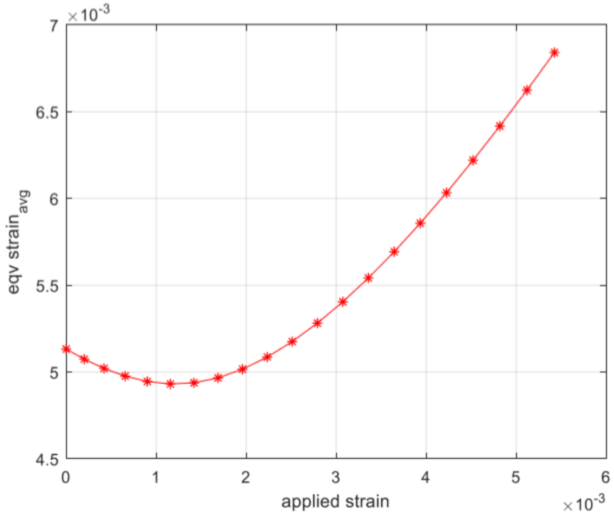


Equivalent strain distribution at 4.2 K with no applied axial strain

Usually applied to axial strain, which is inaccurate. <u>The equivalent strain is physically more appropriate.</u>

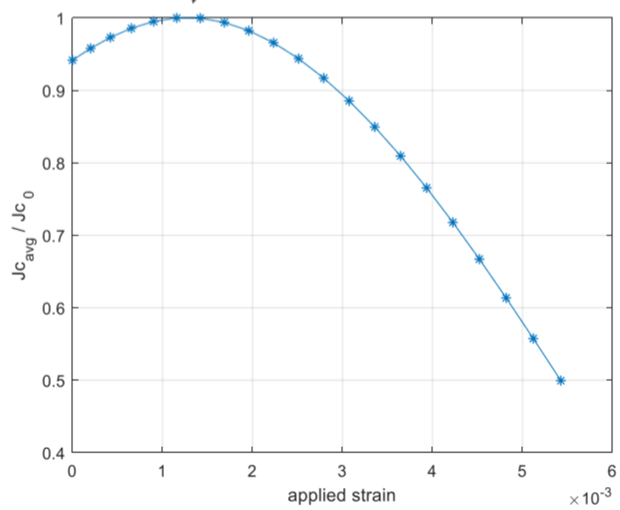
Tensile Test – Critical Current Degradation

Maximum Jc set to 1 (strands only)

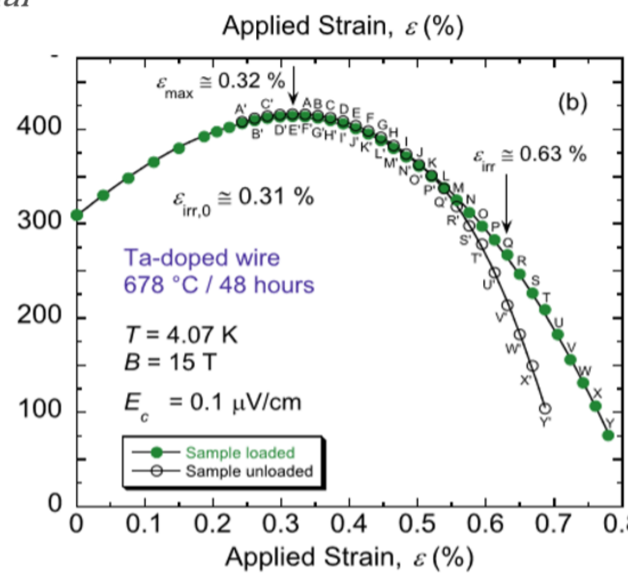


Average equivalent strain in Nb3Sn during loading with axial strain

MODEL

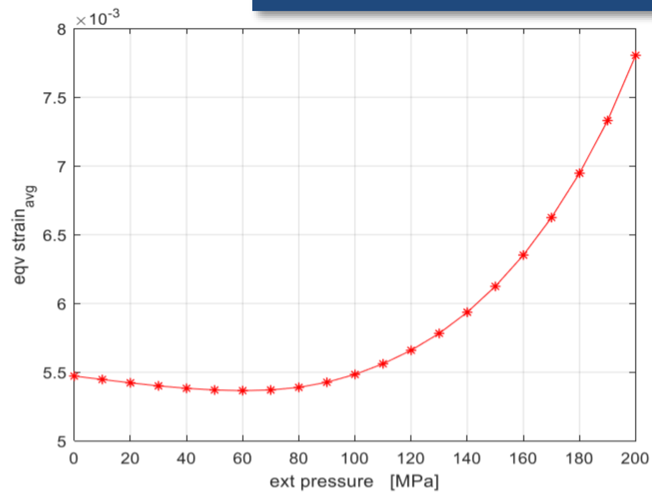


Average critical current density in Nb3Sn during loading at B=15T



DATA (NIST)

Tranverse Pressure Test – Critical Current Degradation



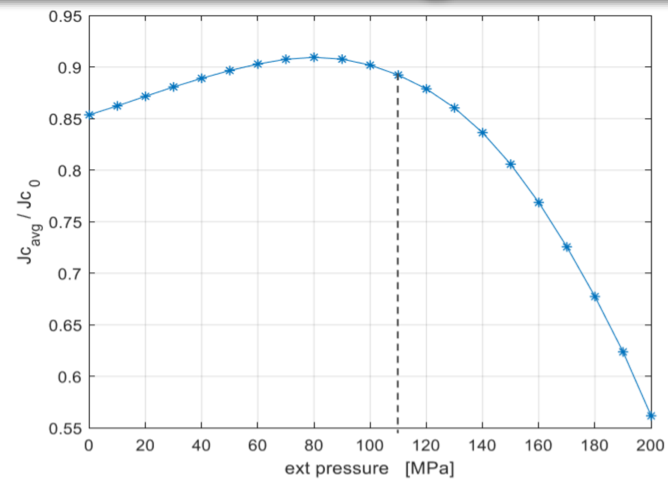
Average equivalent strain in Nb3Sn during loading with external pressure

Resin + insulator thermal contraction

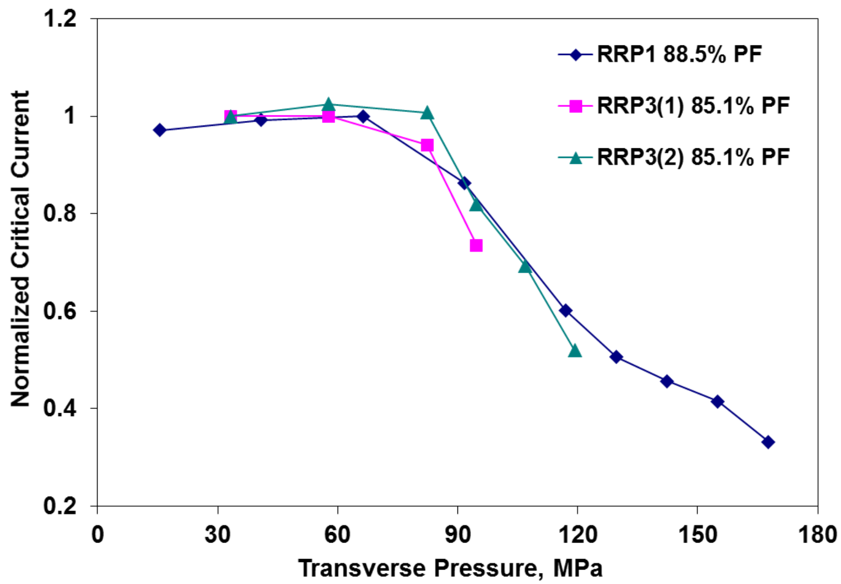
↓

15% loss compared to strand only

MODEL

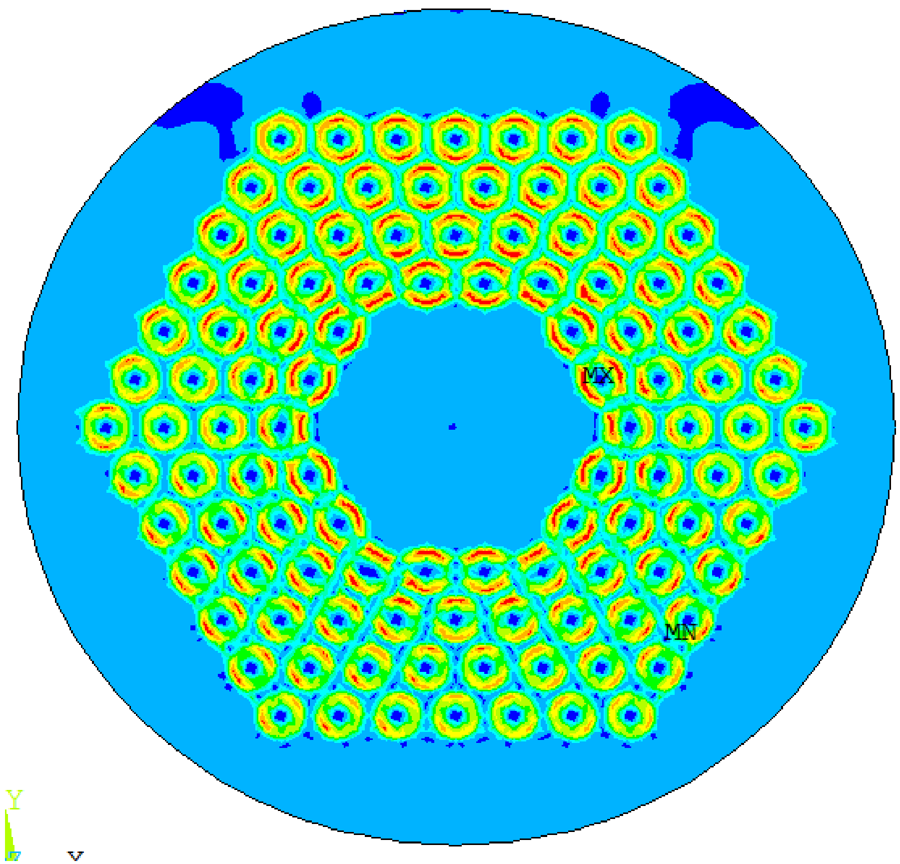


Average critical current density in Nb3Sn during loading at B=15T

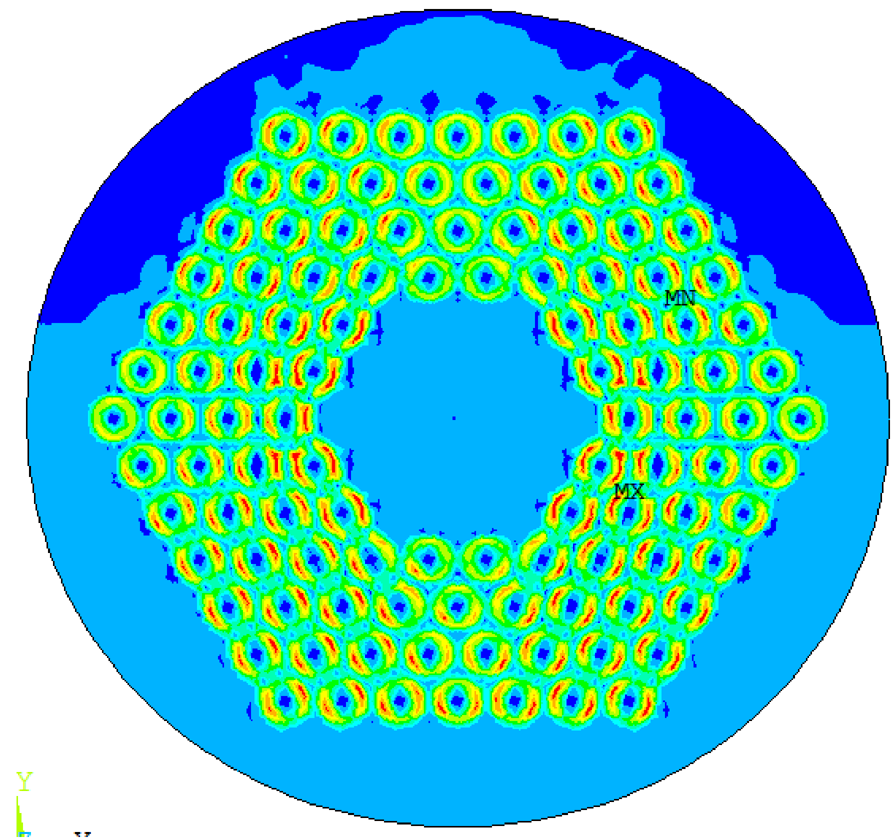


DATA (FNAL)

Stress Distributions at 4.2K

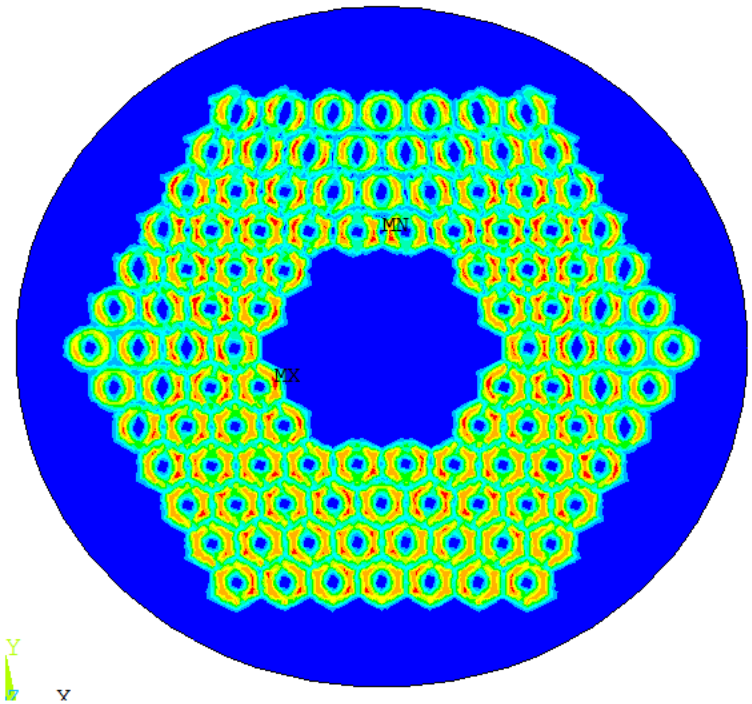


Equivalent stress distribution in transverse pressure test at 0 MPa and 4.2 K

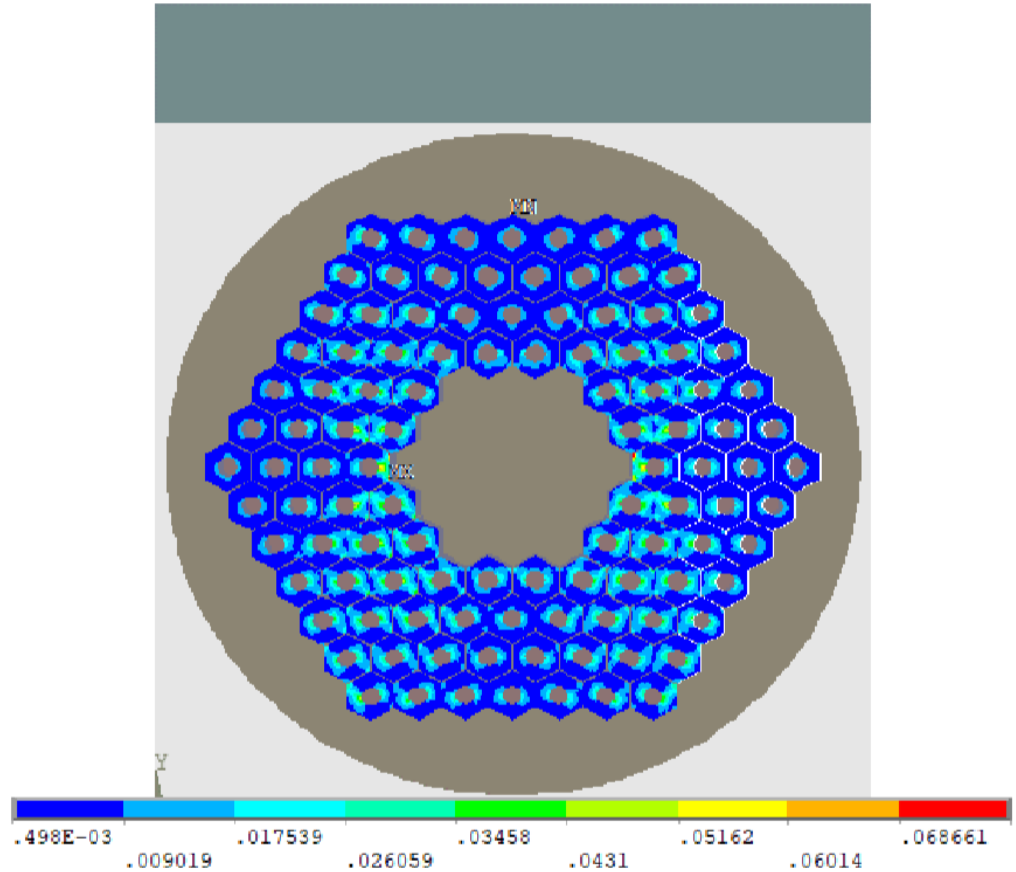


Equivalent stress distribution in transverse pressure test at 100 MPa and 4.2 K

Stress / Strain Distributions



Equivalent stress distribution in transverse pressure test at 200 MPa and 4.2 K



Equivalent strain distribution in transverse pressure test at 200 MPa and 4.2 K