25th International Conference on Magnet

Mechanical–electric Model for Multifilament Composite Superconducting Strands

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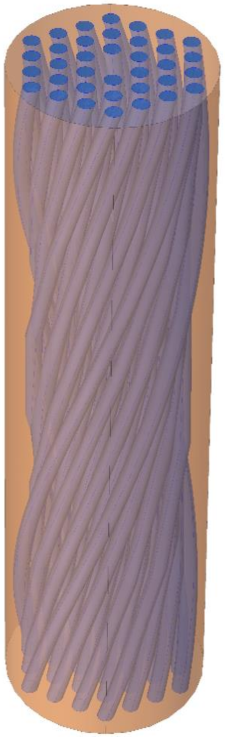
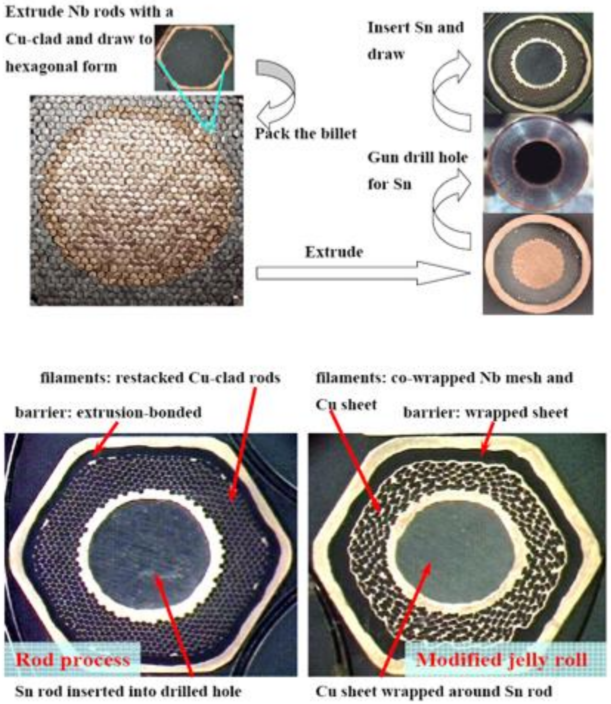
College of Civil Engineering and Mechanics

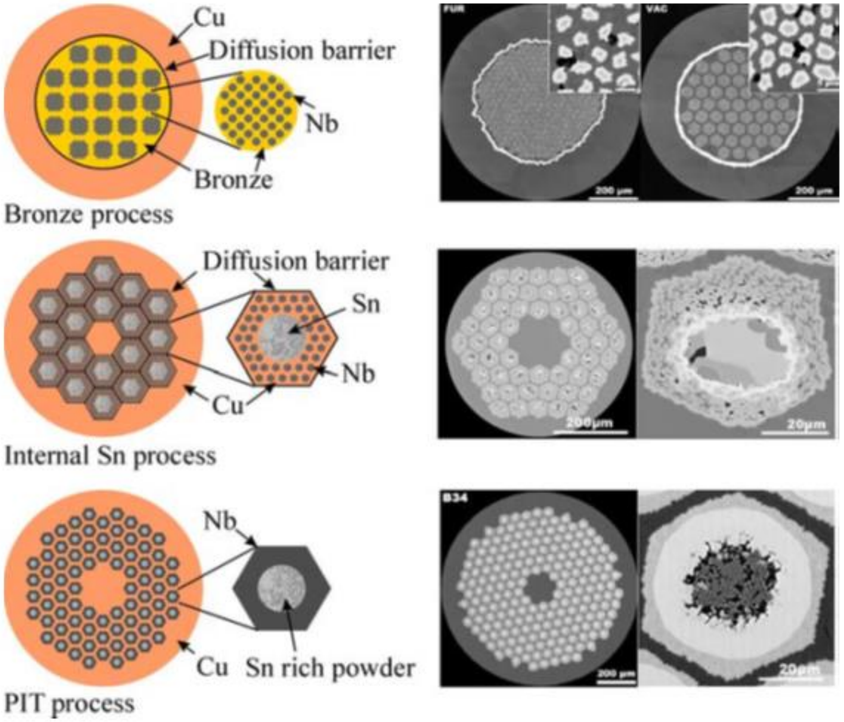
Contents

Introduction—*Superconducting Strand*

The superconducting strand, is the basic cell of cables, is a composite with typical multi-filament twist configuration: Strand, filament bundles, filaments

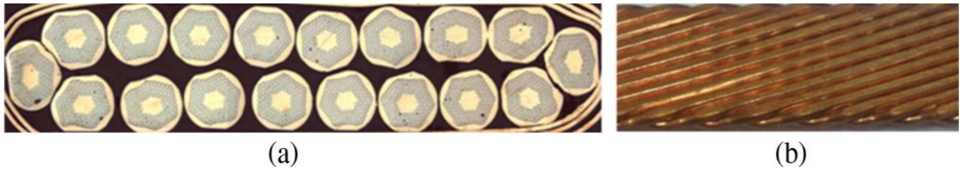




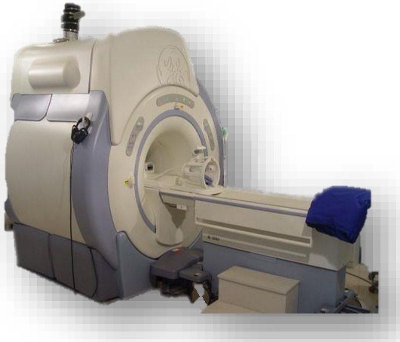


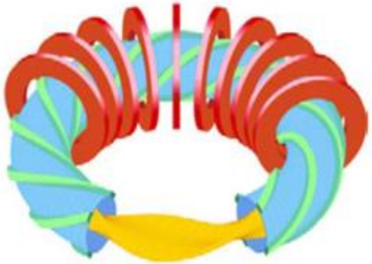
Godeke A. Performance boundaries in Nb3Sn superconductors University of Twente, 2005.

Introduction—*Applications of Strand*

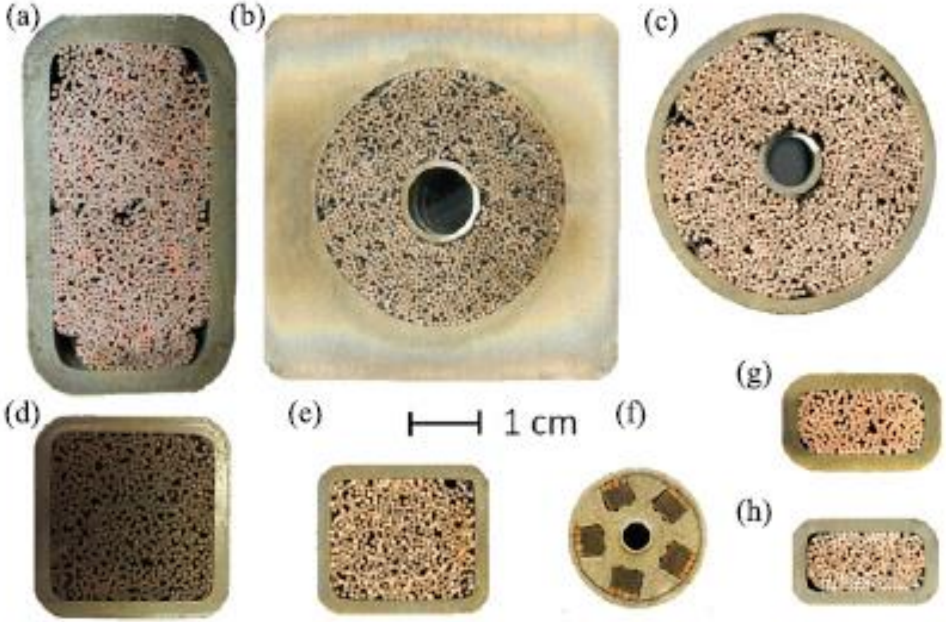


Rutherford cables

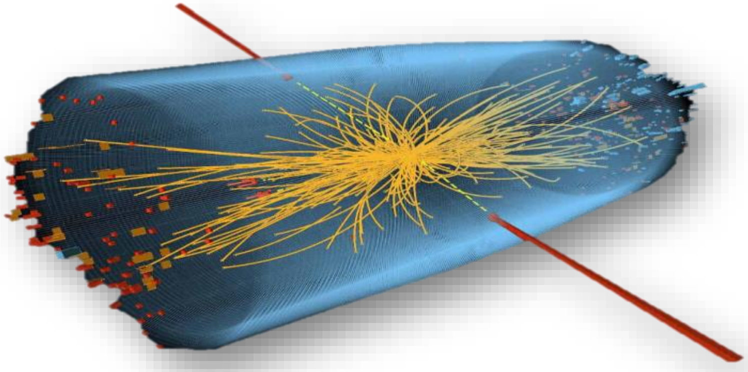




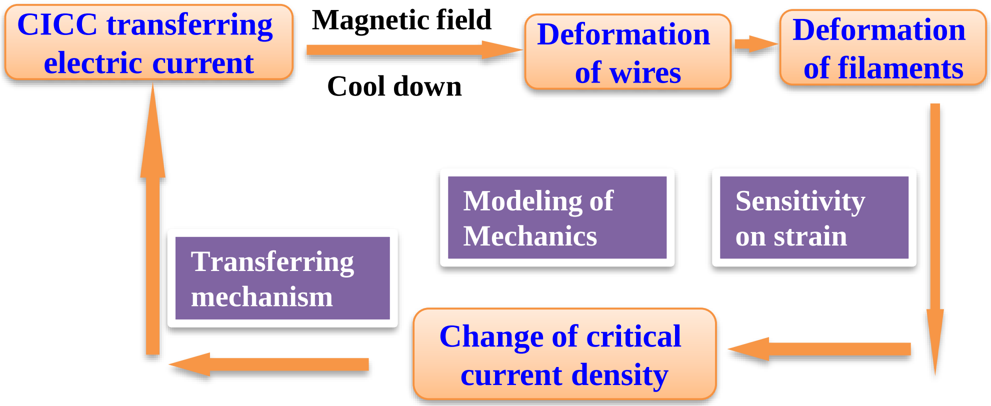
NMR, HEP
FUSIONS



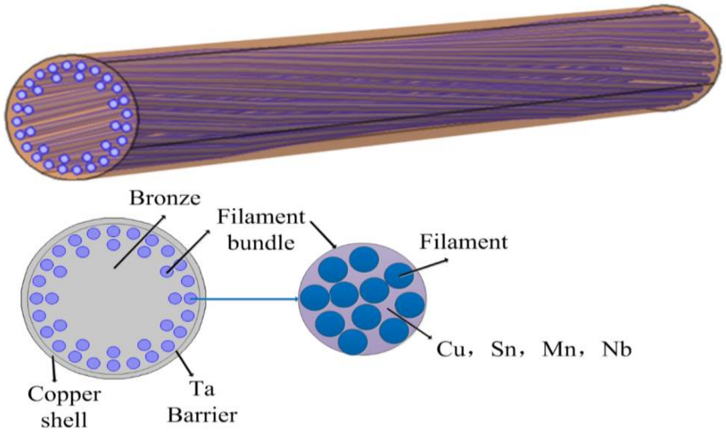
CICC



Introduction—*Problems*


CICC transferring electric current
Magnetic field
Cool down
Deformation of wires
Deformation of filaments
Modeling of Mechanics
Sensitivity on strain
Transferring mechanism
Change of critical current density

Electric current transferring process of CICC

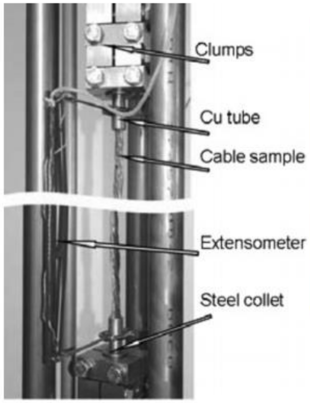


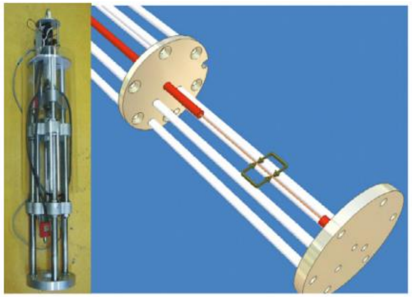
Superconducting strand and its components

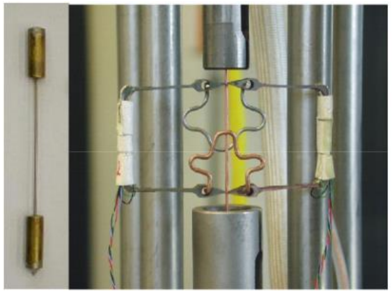
- **Extremely operating conditions**
  - **Very strong magnetic field (>12T)**
  - **Very high carrying current (>60KA)**
  - **Very low temperature (at 4.2K)**
  - **Run times about 30000 time (TF)**

- **Two challenges for Nb_3Sn**
  - ✓ **Brittleness: the damage and its evolution should be considered**
  - ✓ **strain sensitivity: Strain state should be calculated well, because which is used to estimate performance degradation**

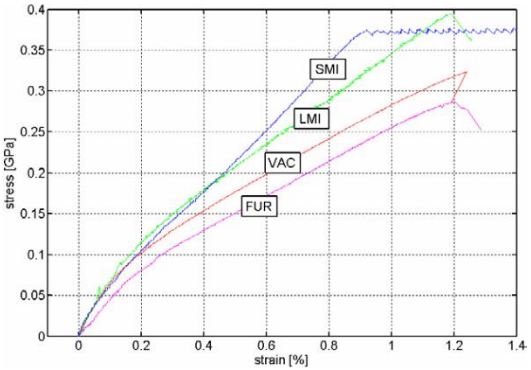
Introduction：Research status on experiments



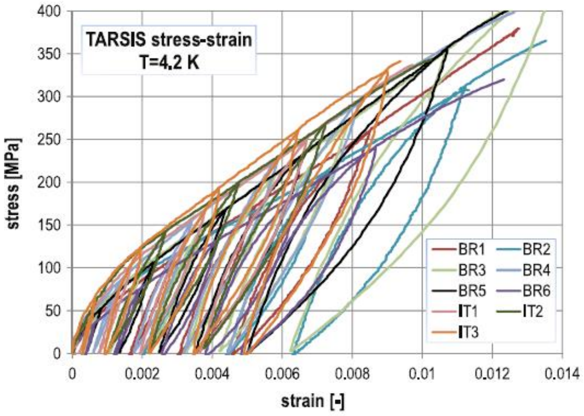




N C Eijnden et al., Supercond. Sci. Technol. 18 (2005)



N C van den Eijnden et al., Supercond. Sci. Technol. 18 (2005)

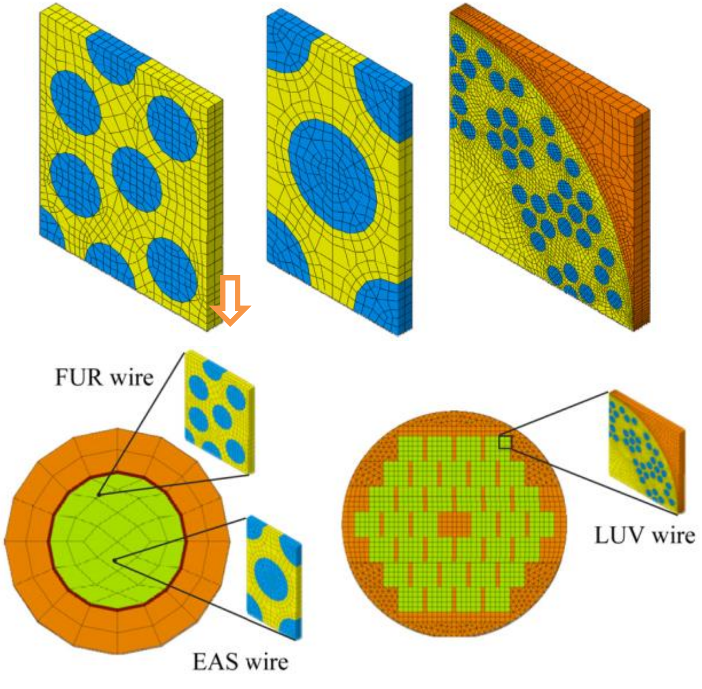


Nijhuis，et al Supercond. Sci. Technol. 26 (2013)

Several experiments have been done，some phenomena are still required more explanations :

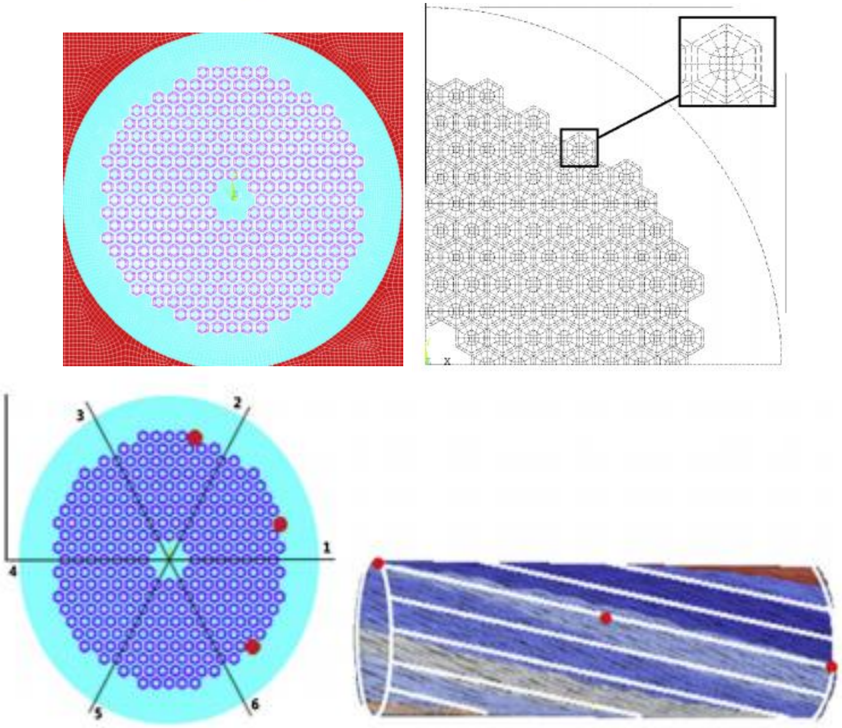
- Why does appear the hysteretic behaviors ?
- Why does appear the plat-form for SMI-PIT strand?
- Which factors are the key affecting these behaviors ？

Introduction： Research status on models



Daniela P Boso, Supercond. Sci. Technol. 26 (2013)

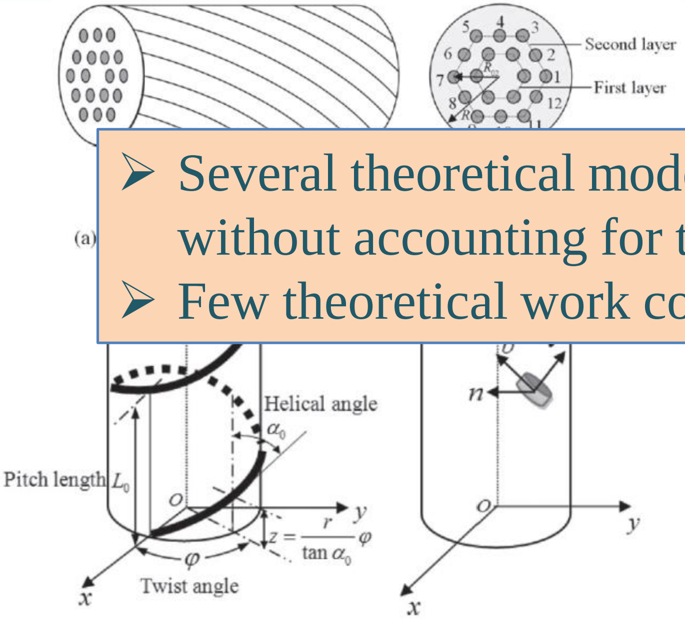
- ✓ RVE model, Axial tension
- ✓ No damage and its evolution

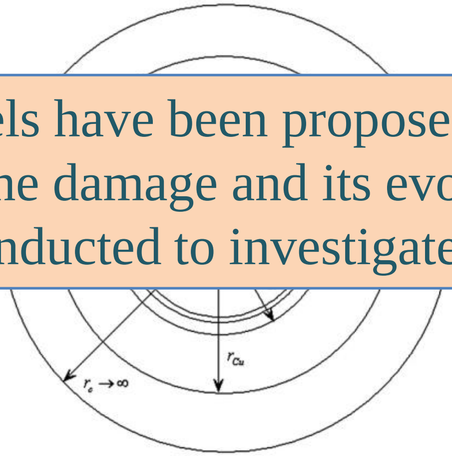


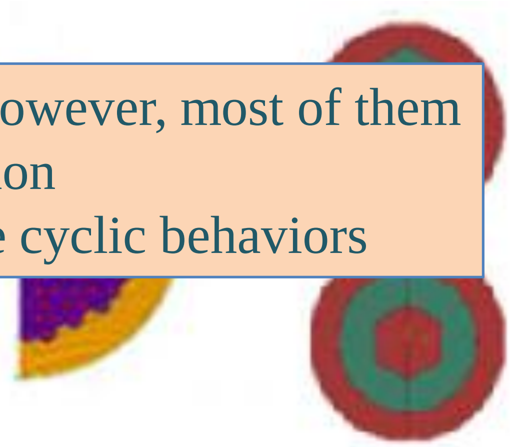
Wang and Chiesa, Cryogenics 63 (2014)

- ✓ Transverse compression, 2D model
- ✓ No damage and its evolution

Introduction : Research status on models







- Several theoretical models have been proposed, however, most of them without accounting for the damage and its evolution
- Few theoretical work conducted to investigate the cyclic behaviors

Multi-layer model

Bimaterial model

Jin Z. et al., IEEE trans. appl. supercond. 23 (2013)

Luo et al., Physic C (2011)

Manil. et al., IEEE T. appl. supercond. (2017)

- ✓ **No damage and its evolution**
- ✓ **No plasticity**

- ✓ **with damage**
- ✓ **No plasticity, no helical shape**

- ✓ **No damage**
- ✓ **No plasticity**

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- **Mechanical Model of Superconducting (SC) Wire**
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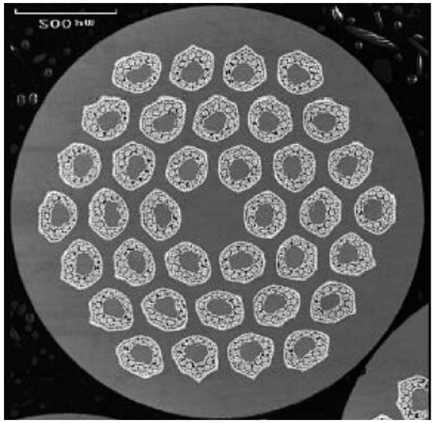
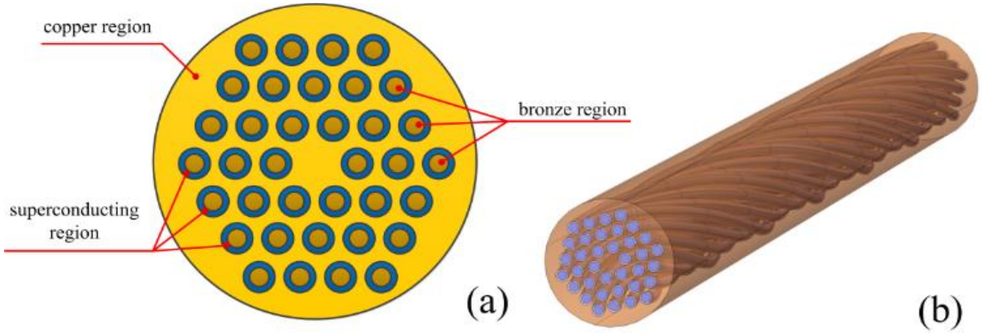
- Conclusions

Model 1—Multi-filament twist model for LMI strand



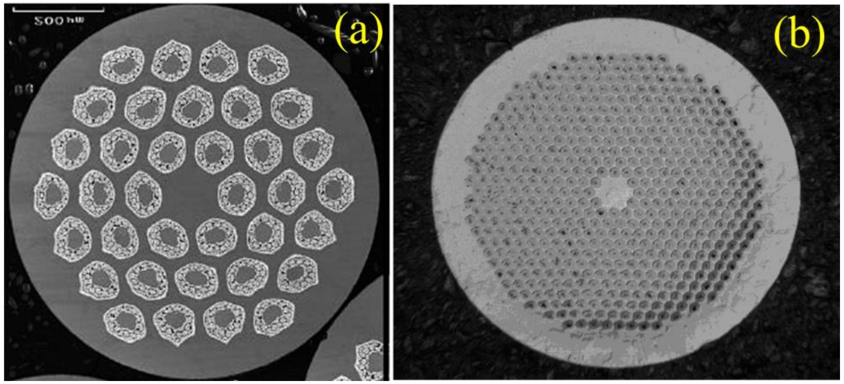


Multi-filament twist model of LMI superconducting wire

Model Building	UG
Model Calculating	ABAQUS
Element Type	Hexahedron elements
Mesh Type	C3D8R: An 8-node linear brick, reduced integration, hourglass control.
Number of elements	278255
Step Type	Dynamic, Explicit

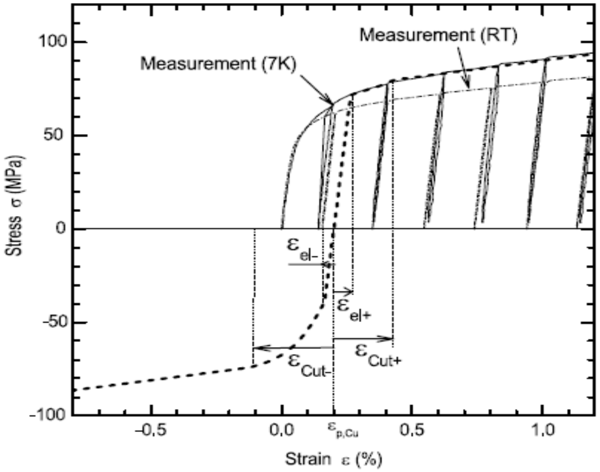
Geometric parameter(mm)	
Diameter of strands	1
Outer diameter of bundle	0.08
Inner diameter of bundle	0.06
Pitch	15

Mechanical model—*Material properties of components*



Component	Volume fraction in LMI（-）	Volume fraction in SMI-PIT（-）	Young's Modulus（×10^{11}Pa）
Nb_3Sn	0.148	0.157	1.35
Copper	0.600	0.415	1.37
Bronze	0.204	-	1.42
Nb	0.080	0.298	1.10
Powder	-	0.130	0.40

Plasticity of matrix materials



- Yielding criterion

$$F=\sqrt{\frac{3}{2}\left(\mathbf{S}-\boldsymbol{\alpha}^{dev}\right):\left(\mathbf{S}-\boldsymbol{\alpha}^{dev}\right)}-\sigma^{0}\le 0$$

- Backstress

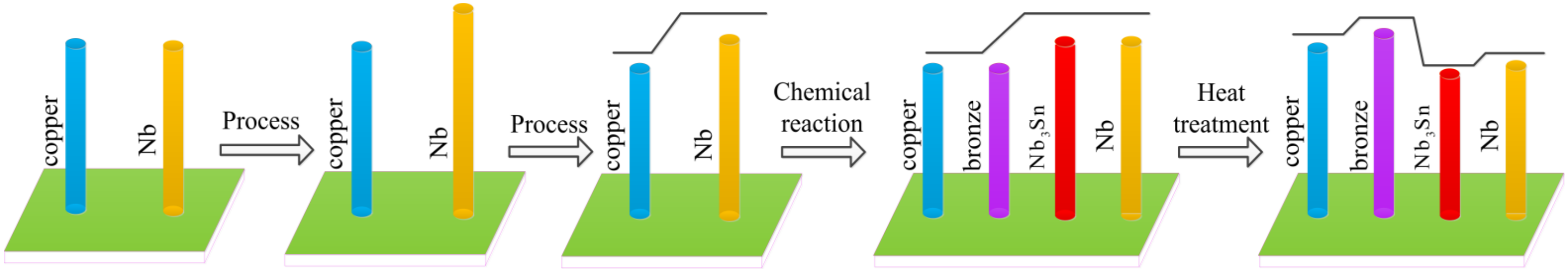
$$\dot{\boldsymbol{\alpha}}=C\frac{1}{\sigma^{0}}\left(\boldsymbol{\sigma}-\boldsymbol{\alpha}\right)\dot{\bar{\varepsilon}}^{pl}-\gamma\boldsymbol{\alpha}\dot{\bar{\varepsilon}}^{pl}$$

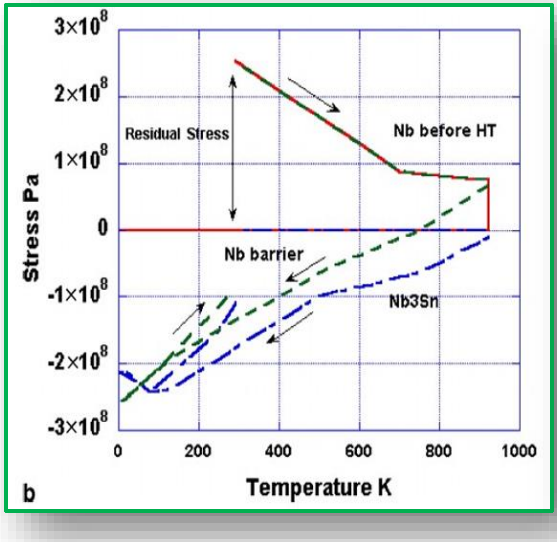
$$\boldsymbol{\alpha}=\sum_{k=1}^{N}\boldsymbol{\alpha}_k$$

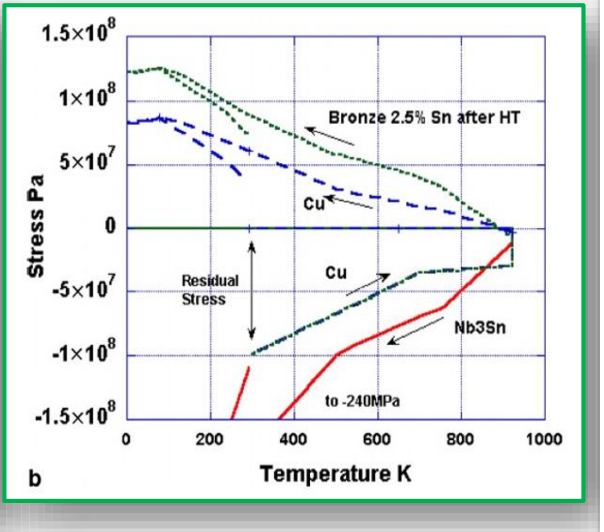
$$\dot{\boldsymbol{\alpha}}_k=C_k\frac{1}{\sigma^{0}}\left(\boldsymbol{\sigma}-\boldsymbol{\alpha}\right)\dot{\bar{\varepsilon}}^{pl}-\gamma_k\boldsymbol{\alpha}_k\dot{\bar{\varepsilon}}^{pl}$$

Kinematic hardening model is used！

Influence factors— *the residual stress in heat treatment*





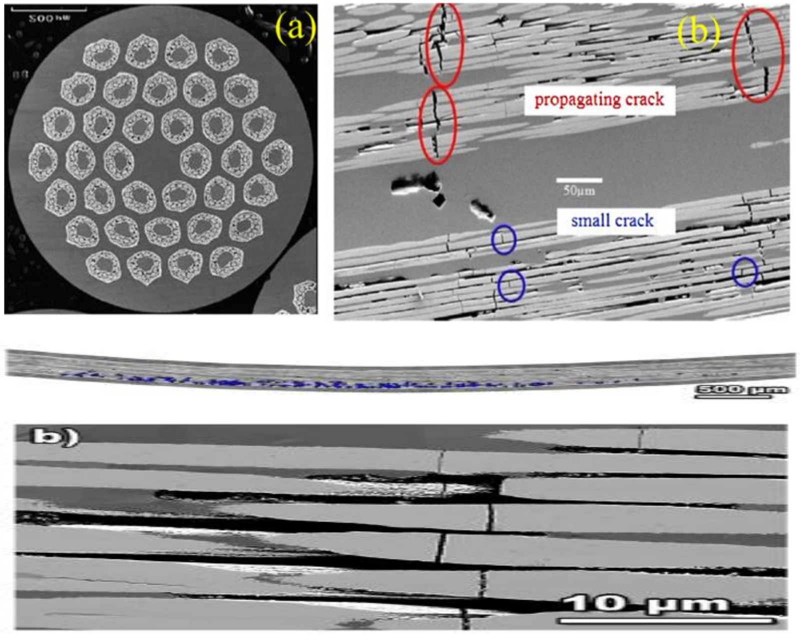


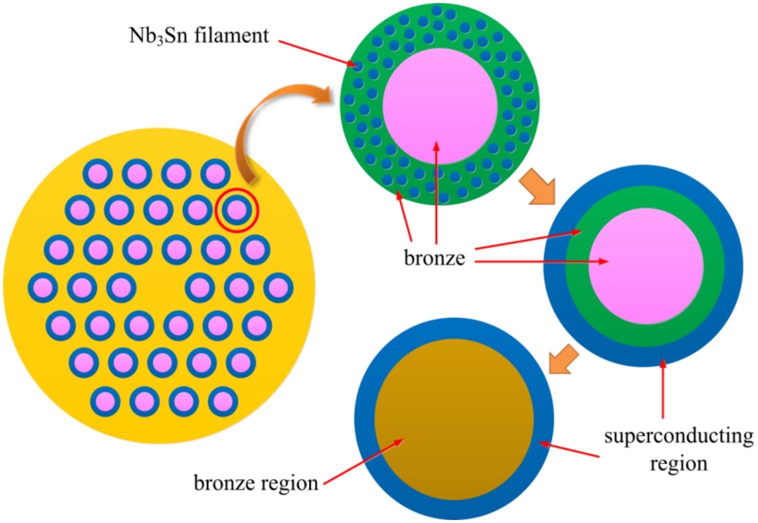
Residual stress of internal tin strand (LMI). N Mitchell, Cryogenics. 45 (2005)

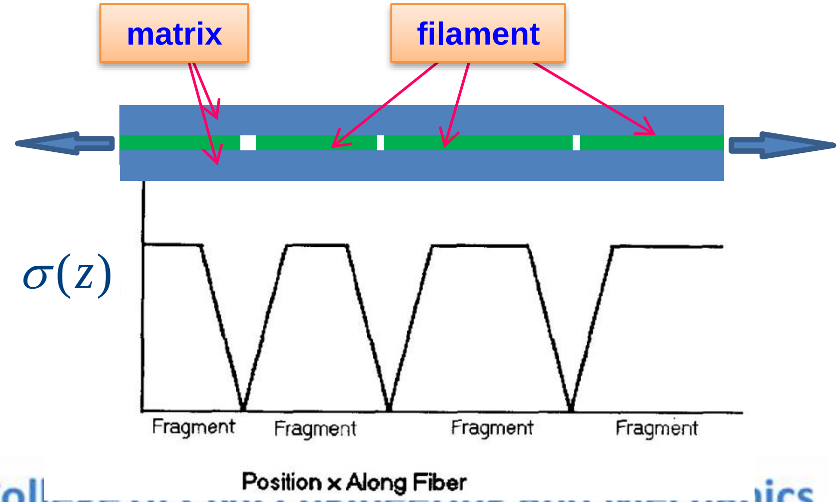
- ✓ Internal tin strand (LMI) without annealing result in the occurrence of residual stress
- ✓ At the operating temperature, the copper and bronze are in tension, while the filaments compression

Influence factors—*Damage of filaments*

Effective properties of filament bundle







- **How does account for the influence of the breaks, especially it's evolution in the effective material parameters**

Influence factors—*Damage of filaments*

Global Load Sharing (GLS) Model

Curtin and Zhou, JMPS,1995

Suppose: a filament with statistically average distribution of breaks; N breaks randomly in a length L

- **The average stress each element**

$$\frac{\sigma}{f}=\frac{1}{L}\int_0^L \mathrm{d}z\sigma(z)+\left(\frac{1-f}{f}\right)\sigma_y$$

- **The average stress of element is rewritten as**

$$\frac{\sigma}{f}=\rho\int_0^\infty dxF(x)\int_0^x dz\sigma(z)+\left(\frac{1-f}{f}\right)\sigma_y$$

- **The distribution of length of fragment**

$$F(x)=\rho\mathrm{e}^{-\rho x}$$

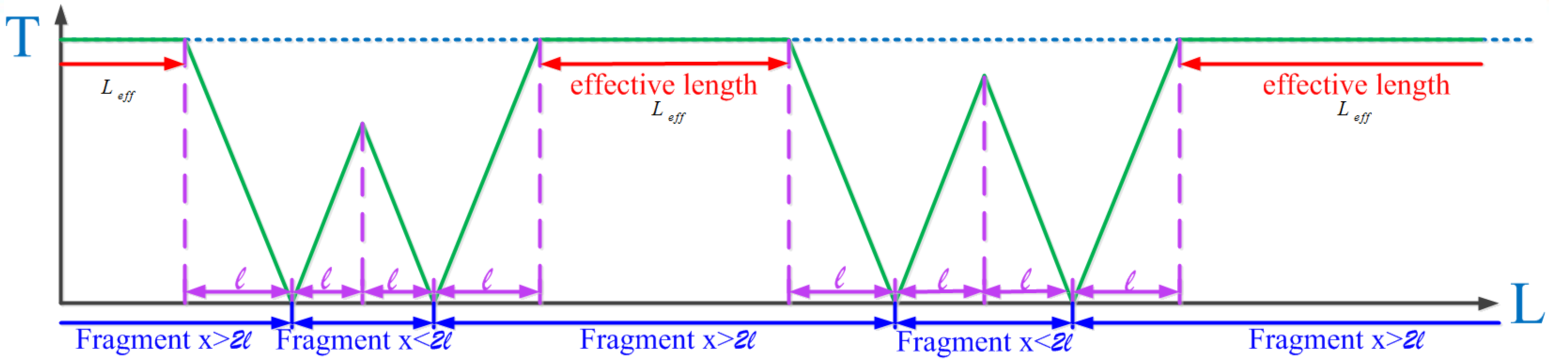
- **Fracture number density**

$$\rho=\frac{N}{L}\qquad N(L,\sigma)=\frac{L}{L_0}\left(\frac{\sigma}{\sigma_0}\right)^m$$

f: Volume fracture $\sigma(z)$: Real stress in filament σ_y: Stress in matrix

m: Weibull modulus σ_0, L_0: Characteristics strength and reference gauge length

Influence factors—*Damage of filaments*



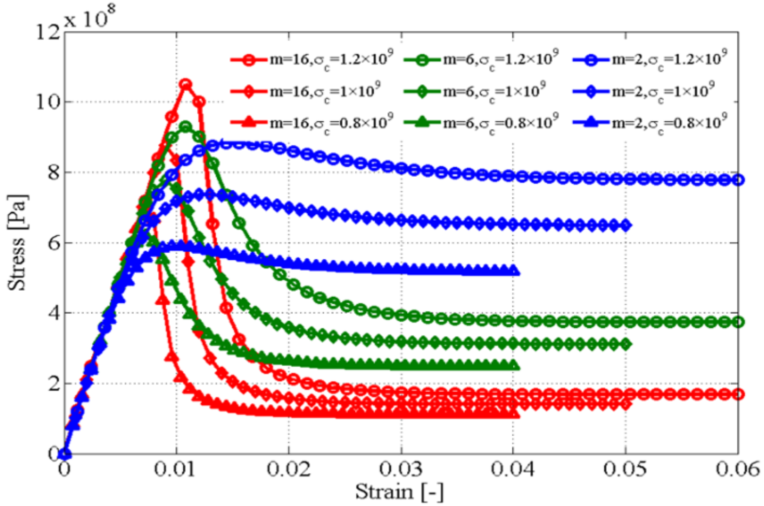
- **Fragment Classification**

$$\int_0^x \mathrm{d}z\sigma(z) = T(x-2l)+\tfrac{1}{2}T(2l) = T(x-l) \quad x \geqslant 2l,$$

$$\int_0^x \mathrm{d}z\sigma(z) = \frac{\tau x^2}{2r} = \frac{x^2}{4l}T \quad x \leqslant 2l.$$

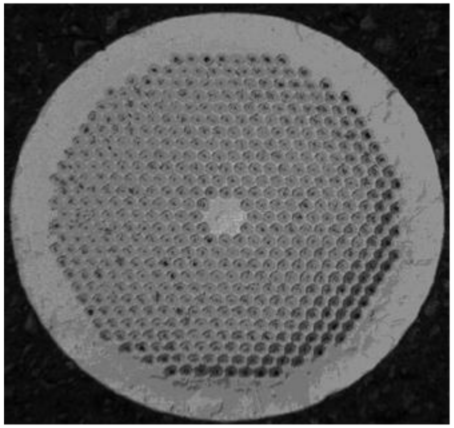
$$\Rightarrow \quad \boxed{\frac{\tilde{\sigma}}{f} = \frac{1}{\tilde{\rho}}\left[1-e^{-\tilde{\rho}\tilde{T}}\right]+\left(\frac{1-f}{f}\right)\frac{\sigma_M}{\sigma_c}}$$

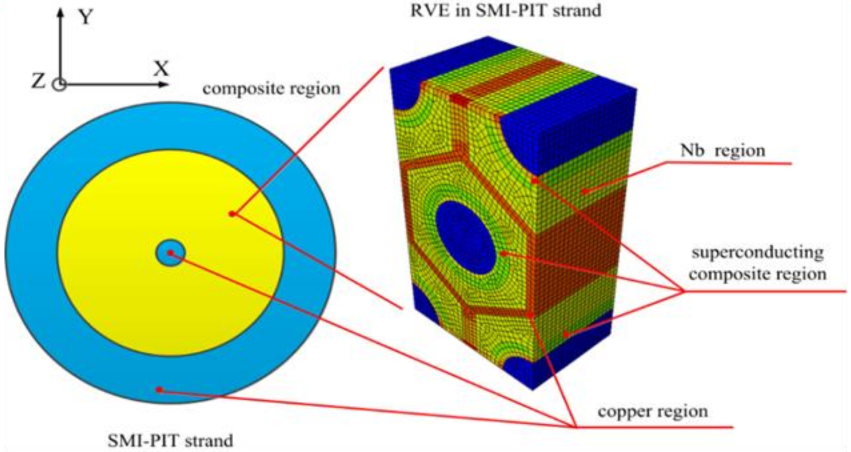
$$d\tilde{\rho} = e^{-\tilde{\rho}\tilde{T}} m\tilde{T}^{m-1} d\tilde{T} \qquad \tilde{T} = \tilde{\varepsilon}E_f$$



Stress-strain curve of filament with damage evolution

Model 2: RVE method for SMI-PIT strand





Represent volume element of SMI-PIT superconducting wire

- RVE method for Superconducting wire is proposed by D P Boso (SUST, 2013, 045006) without accounting for the damage and it’s evolution of filament.

- We considered the influence of damages and its evolution of filament to RVE by using GLS model as discussed previous

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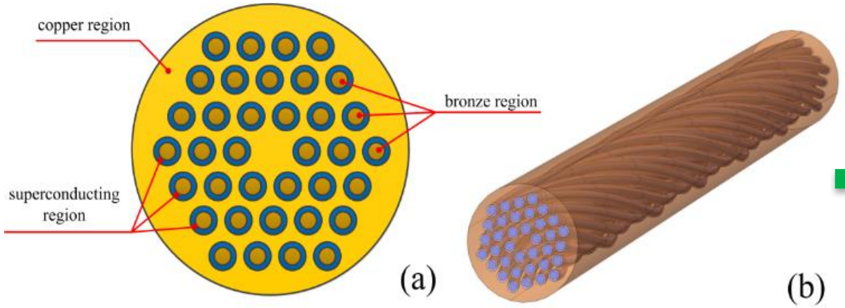
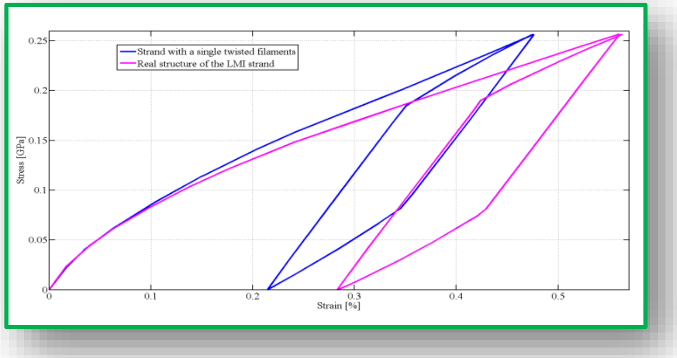
Results discussion—*Reason for hysteresis*

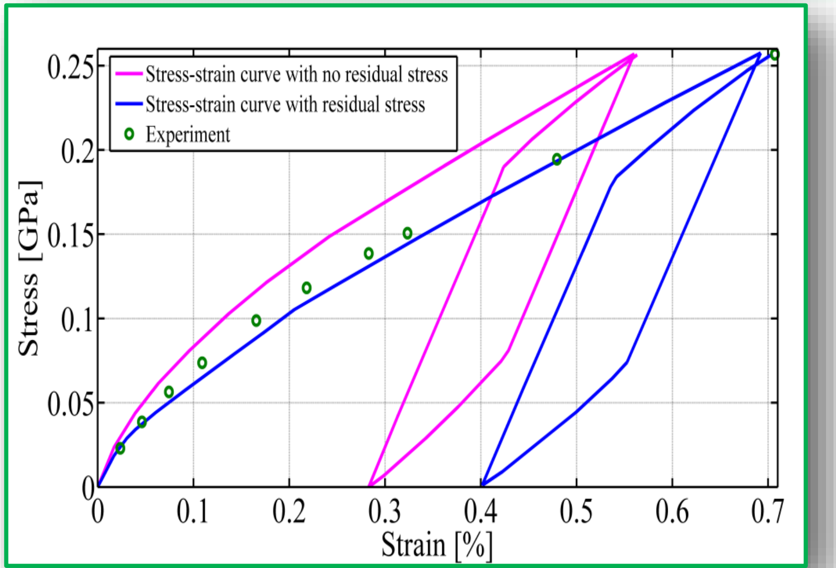




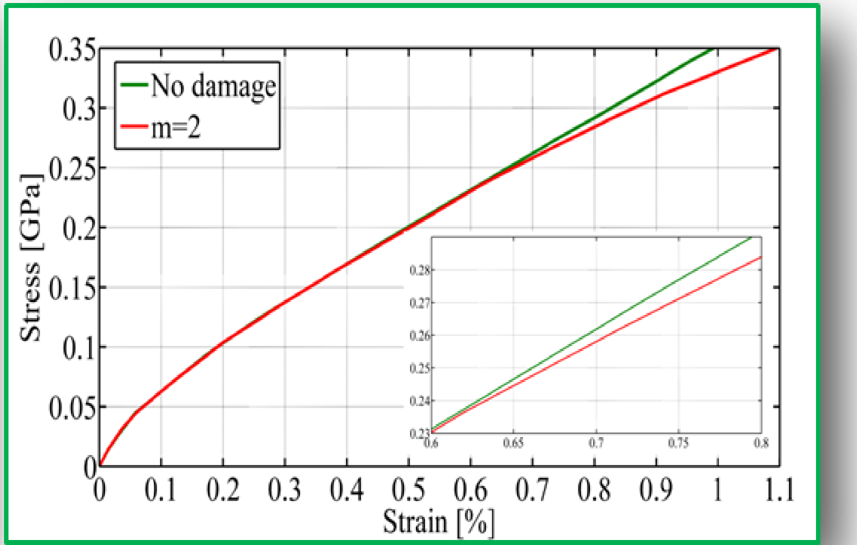
The hysteretic loop is mainly caused by the reverse yielding of the matrix materials in the strand.

- In the unloading process ,copper and bronze will unload completely firstly. At that time, Nb_3Sn is still in tension
- Continuous unloads, copper and bronze will be compressed and then yield in the opposite direction. Upon that, the hysteretic structure occurs.

Results discussion—*initial residual stress and damage*



Effect of the thermal initial residual stress on the tensile and cyclic behavior of the LMI wire



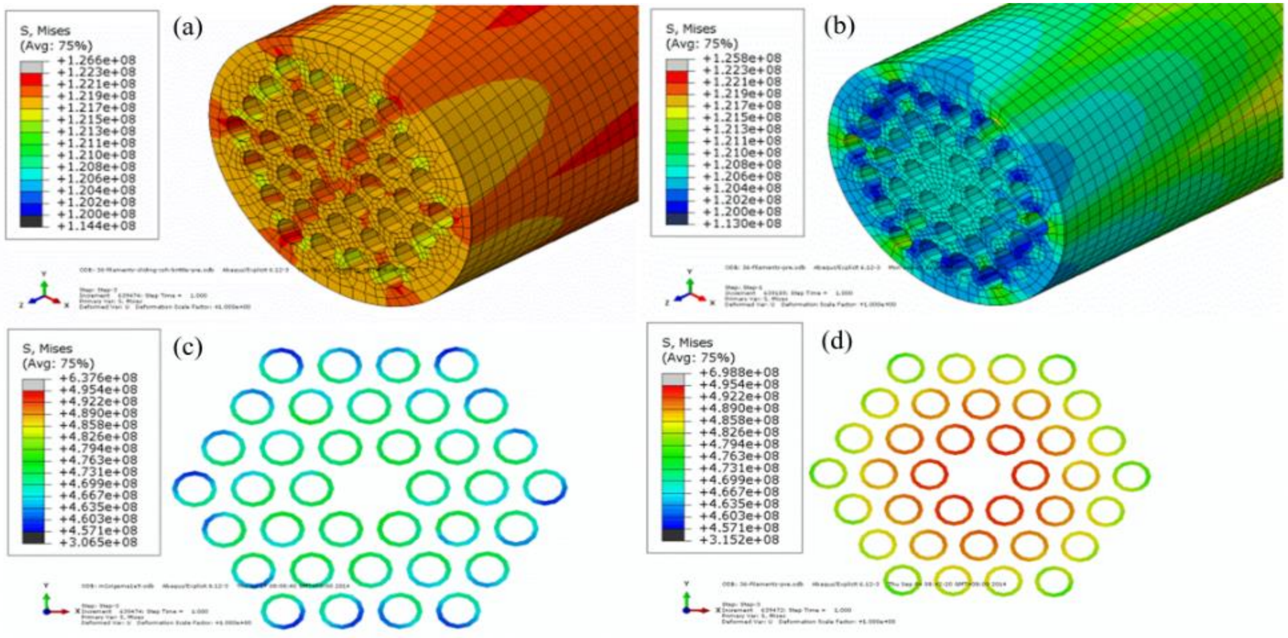
Effect of the damage of the filament in the LMI strand

- **The influence of the initial residual stress on the stress-strain relation of strand is significant.**
- **The influence of the damage of the filaments on the tensile behavior grows obviously with the increasing strain.**

Results discussion—*Damage of the filaments*

matrix

Filament bundle

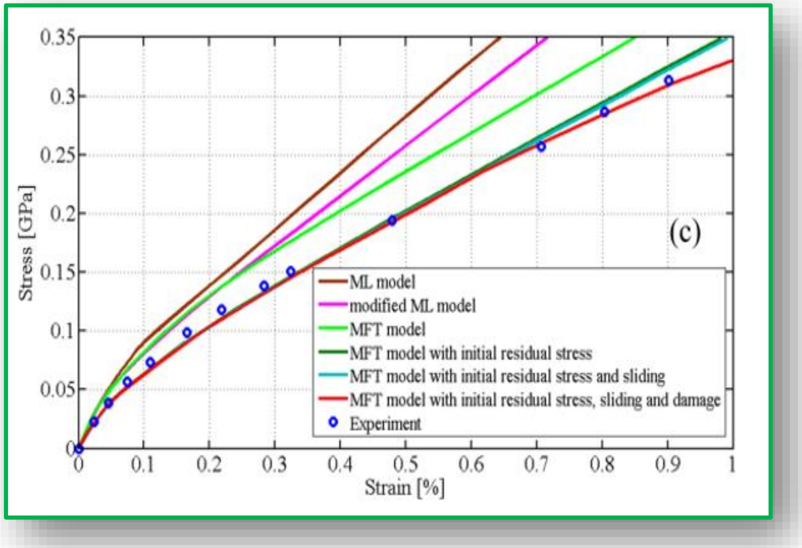


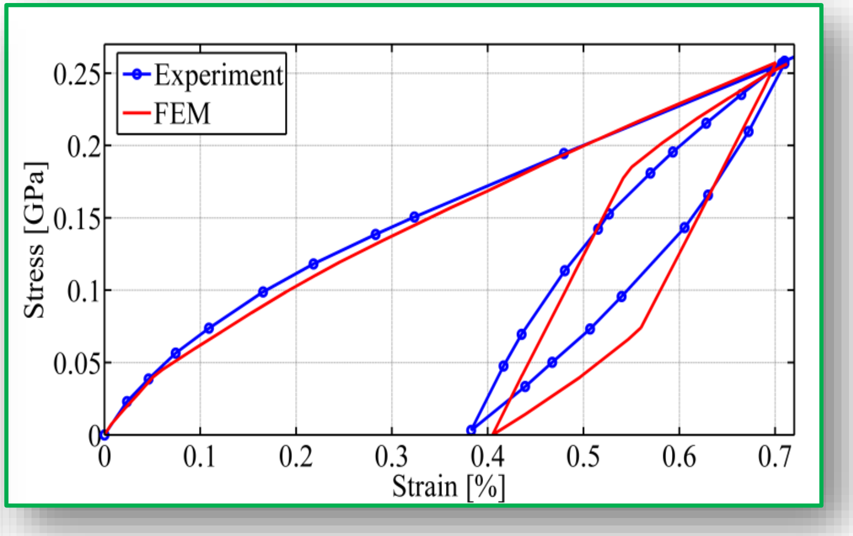
With damage

Without damage

- ✓ Stress of the inner regions larger than that of the outer regions.
- ✓ the average stress of the superconducting regions with the consideration of the damage is obviously smaller than that of the regions without this consideration

Results discussion—*Mechanical experimental verification*



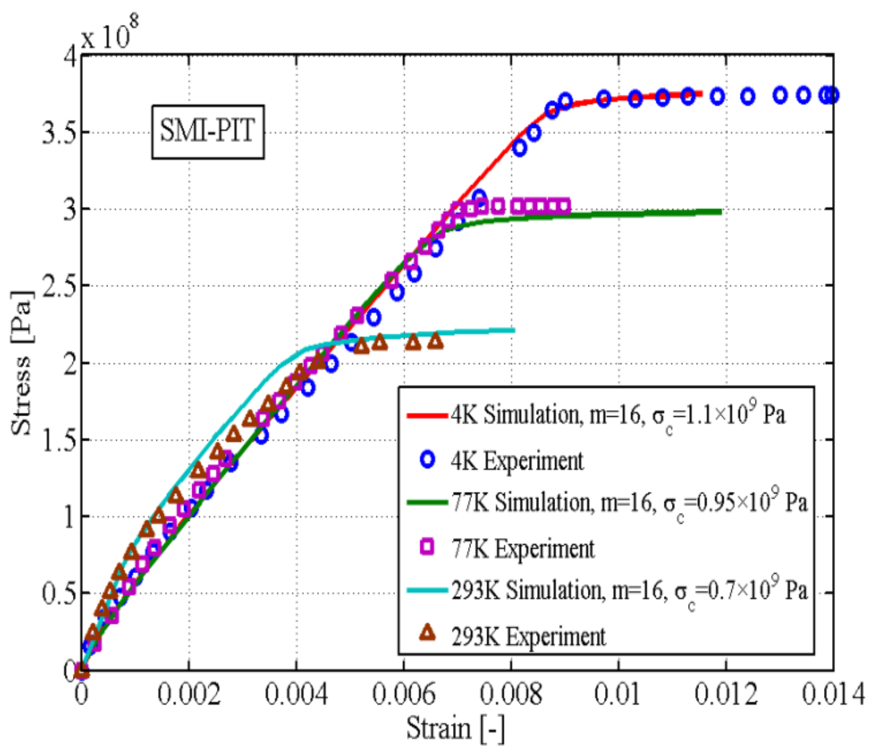


Tension curve of the LMI strand compare to the experiment

Hysteresis loop of the LMI strand compare to the experiment

- **The tension curve of the wire is in good agreement with the experimental result**
- **The unloading modulus and the area of hysteresis loop is close to the experiment value**
- **The residual strain is little large compared to the experiment**

Results discussion—*explanation for platform of SMI-PIT*



Tension curve of the SMI-PIT wire compare between the model and the experiment

- This “platform” is caused by the damage of the filaments in the strand. The damage of the filament results in a “negative stiffness” phase in the stress–strain curve.
- The stress in the SC filament region decreases, while that in the matrix material increases, which leads to a slow change of the average stress of the whole strand.

Results discussion—*Normalized critical current*

Critical current density

$$T_c(\varepsilon) = S_t T_c(0)$$

$$B_{c2}(0,\varepsilon) = S_b B_{c2}(0,0)$$

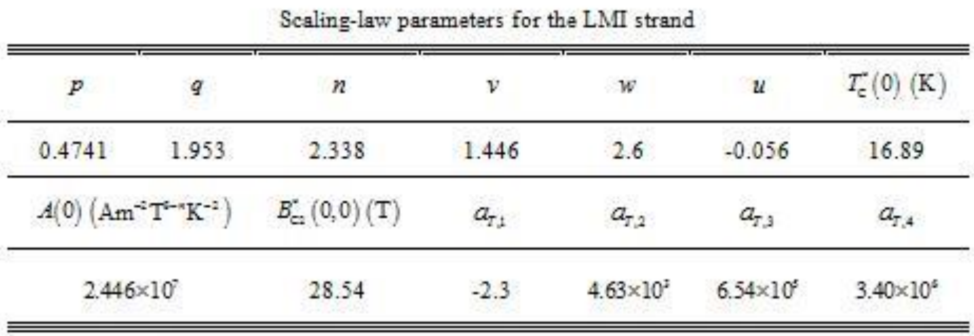
$$J_C(B,T,\varepsilon) = A(\varepsilon)[T_C^*(\varepsilon)(1-t^2)]^2 \times [B_{C2}^*(T,\varepsilon)]^{n-3} b^{p-1}(1-b)^q.$$

Invariant strain functions

$$S_t = \frac{1}{(1+a_{T,1}I_1)} \frac{1}{(1+a_{T,2}J_2+a_{T,3}J_3+a_{T,4}J_2^2)}$$

$$S_b = \frac{1}{(1+a_{B,1}I_1)} \frac{1}{(1+a_{B,2}J_2+a_{B,3}J_3+a_{B,4}J_2^2)}$$

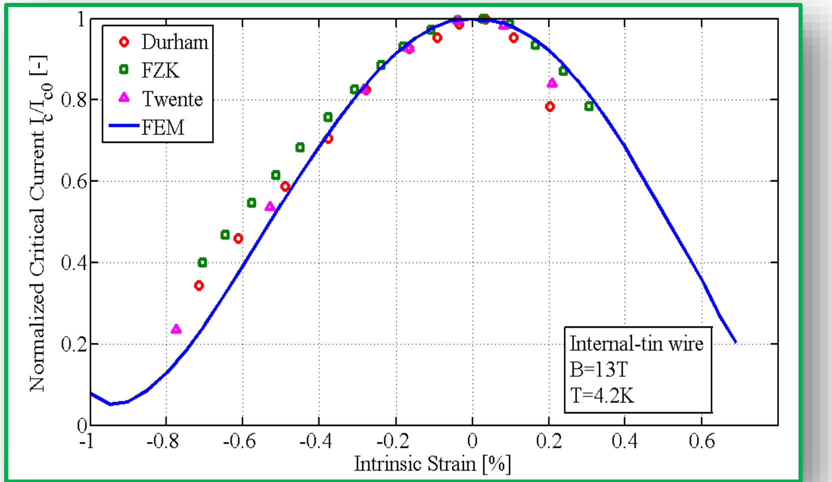
- **The results show acceptable agreement with the experiments.**



Scaling-law parameters for the LMI strand

p	q	n	v	w	u	$T_c^*(0)$ (K)
0.4741	1.953	2.338	1.446	2.6	-0.056	16.89

$A(0)$ ($\mathrm{Am^{-2}T^{3-n}K^{-2}}$)	$B_{c2}^*(0,0)$ (T)	$a_{T,1}$	$a_{T,2}$	$a_{T,3}$	$a_{T,4}$
2.446×10^7	28.54	-2.3	4.63×10^2	6.54×10^5	3.40×10^6



Degradation of critical current of strand

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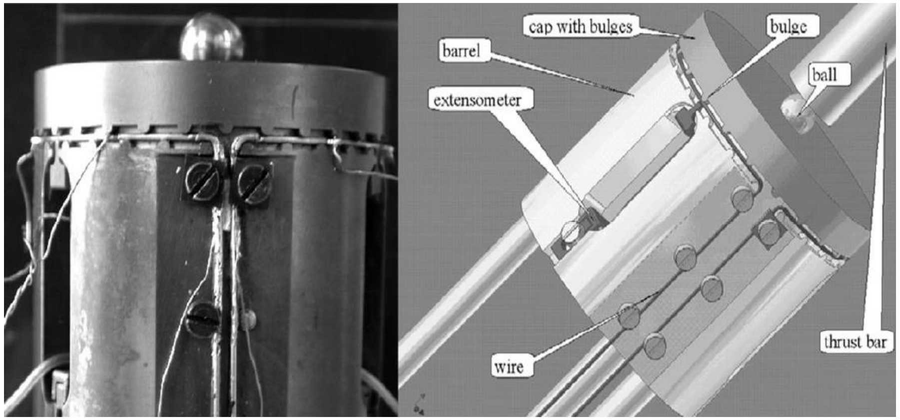
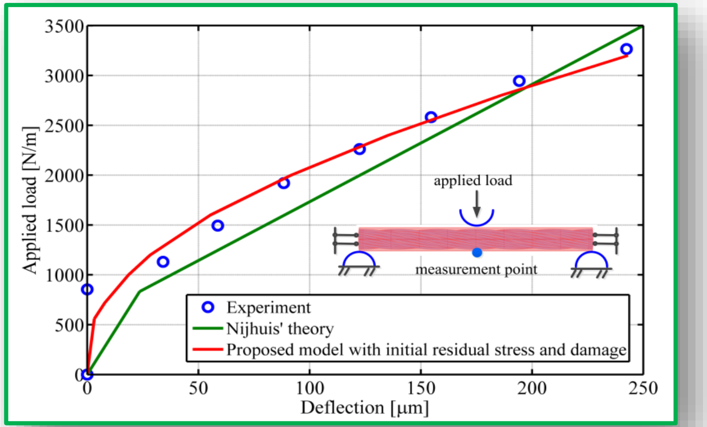
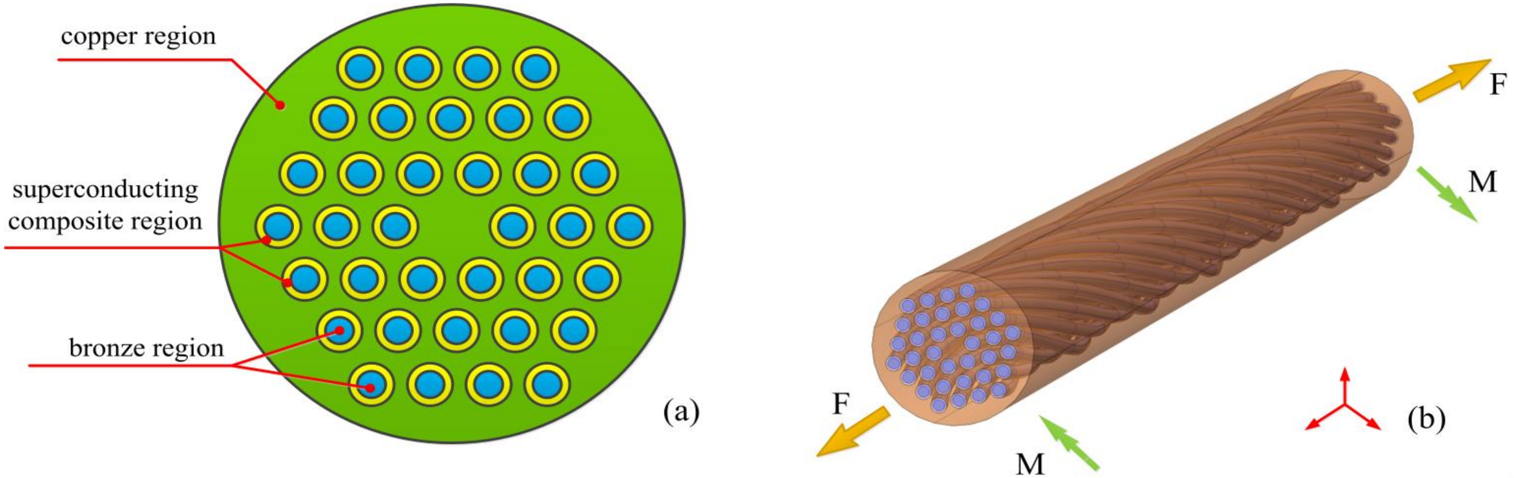
Generalized 1- bending mode



TARSIS devices for bending of Stand

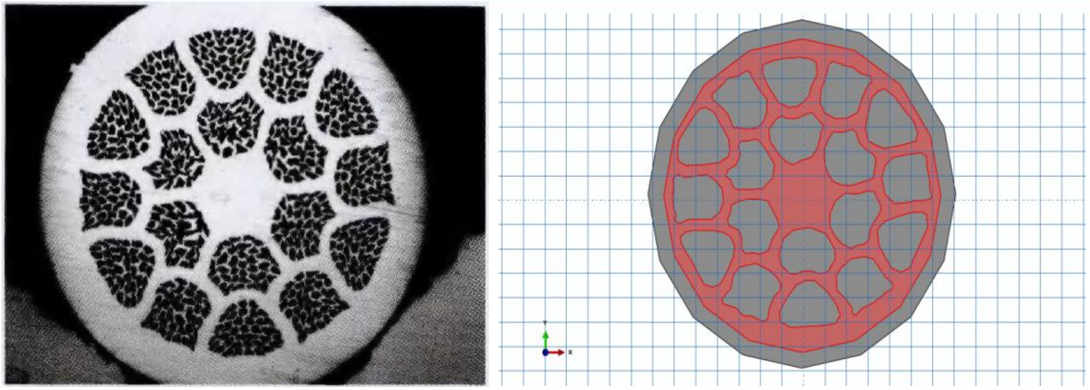


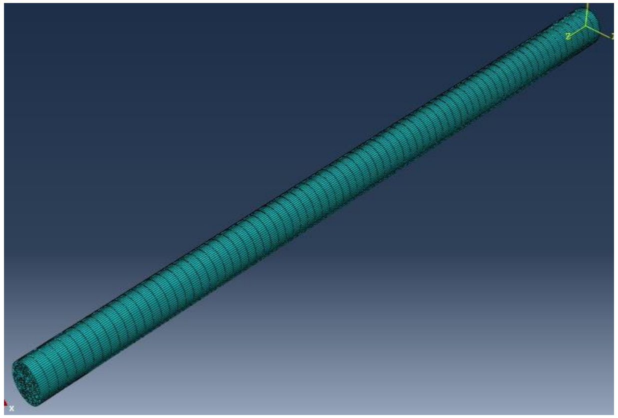
Comparison the results for strand bending



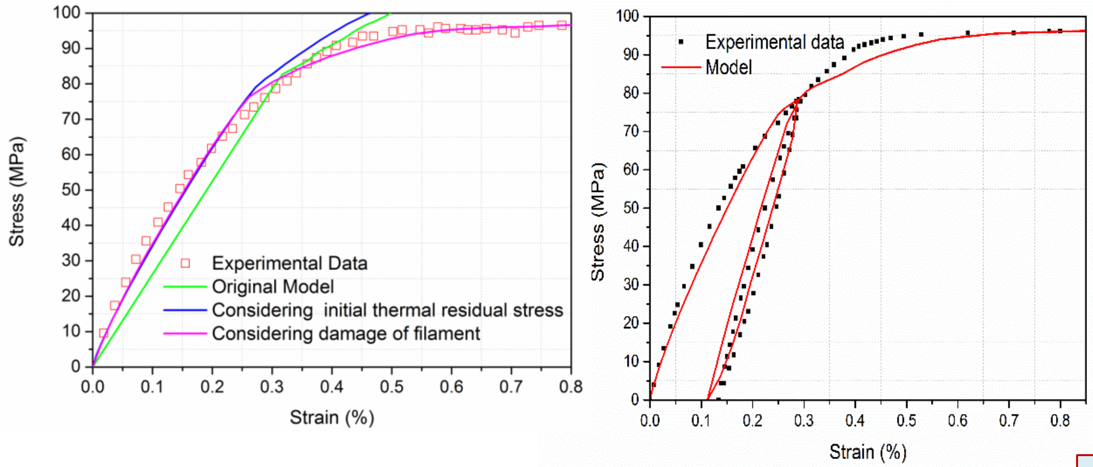
FEM model of LMI strand for bending mode

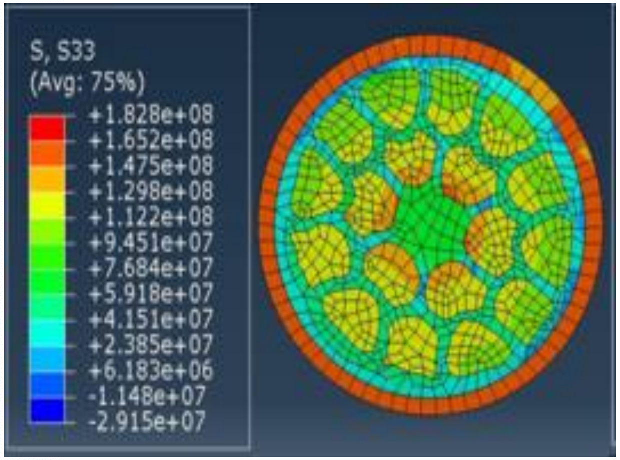
Generalized 2-Bi2212 wires





Cross-section of Bi2212 wire





Stress-strain curve predicted by our model

Stress distribution in cross section

Conclusions

- FEM models are proposed to investigate the mechanical behavior of a multifilament superconducting strands accounting for the influence of residual stress, damage of the filaments.
- Based on the model, the hysteresis loop characteristic for LMI wire and "platform " for SMI-PIT wire of the stress-strain curve are studied in detail.
- The model can be generalized other deformed mode and other multifilament wires.

Thanks for your attention!