The Mechanical Analysis of the Rutherford Cable Subjected to Axial Tension and Cyclic Loading

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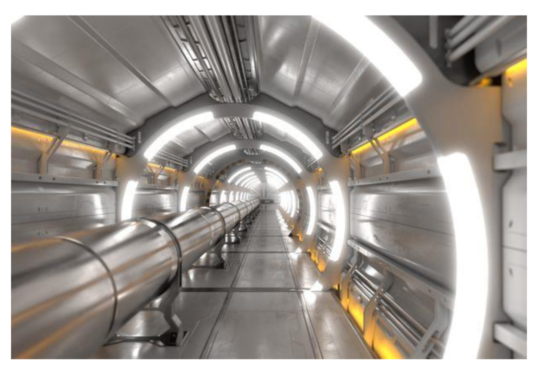
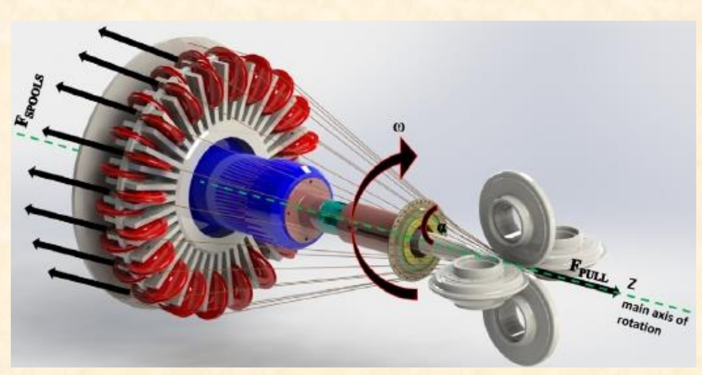
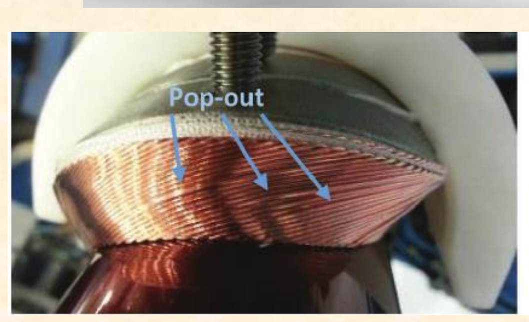
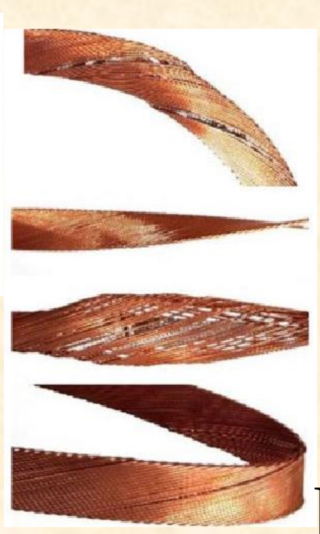
Introduction

- The main high field superconducting magnets of all existing large particle accelerators are based on Rutherford cables.
- Future Circular Collider(FCC) and High Luminosity upgrade of Large Hadron Collider (HL-LHC) are proposing new requirements of 16T.
- Nb_3Sn Rutherford cables are designed to cater to the meet in the higher field for their advantage:
  - ✓ large filament dimensions
  - ✓ lower thermal and electrical properties of copper
  - ✓ the wind-and-react technique



Problem




✓ cable winding process:

- Mechanical Loads: tension, compression, bending, torsion
- Mechanical Instability: "pop-out", "protrusion"
- Large Temperature Change: thermal residual stress

✓ Magnets Running: the influence of electric field, magnetic field, and temperature field

Requiring a method to build up the Rutherford cable finite element model efficiently and simulate the mechanical behaviors during the whole process.

Model

Geometrical modeling

✓ strands number (n) ✓ lay angle (α) ✓ chirality (c) ✓ strand diameter (d) ✓ clearance (δ)

D=d+δ, R=D/2, α∈(0,π/2), t∈(0,1), θ=t*180-90, p=D/cosα, k=tanα, $h_p=\frac{n-2}{2}Dk+\frac{p}{2}$, $h_\Delta=\frac{2h_p}{n}$

The straight wires

$$x_1=\frac{n-2}{2}Dt-\frac{n-2}{4}D$$
$$y_1=-R$$
$$z_1=kx\cos\kappa+\frac{n-4}{4}Dk$$

The helical wires

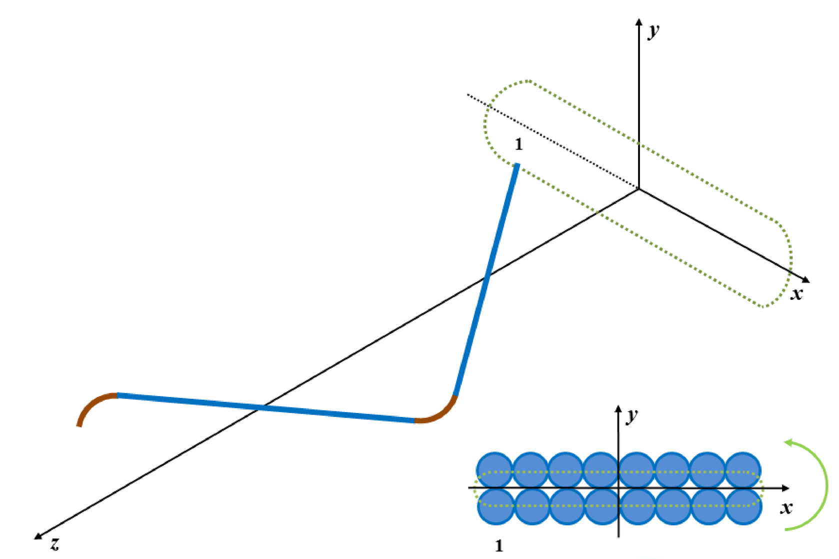
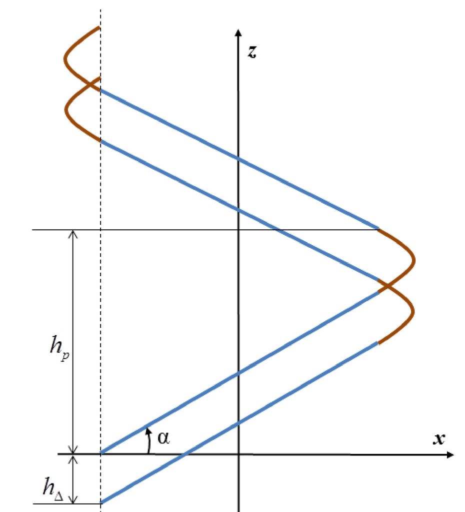
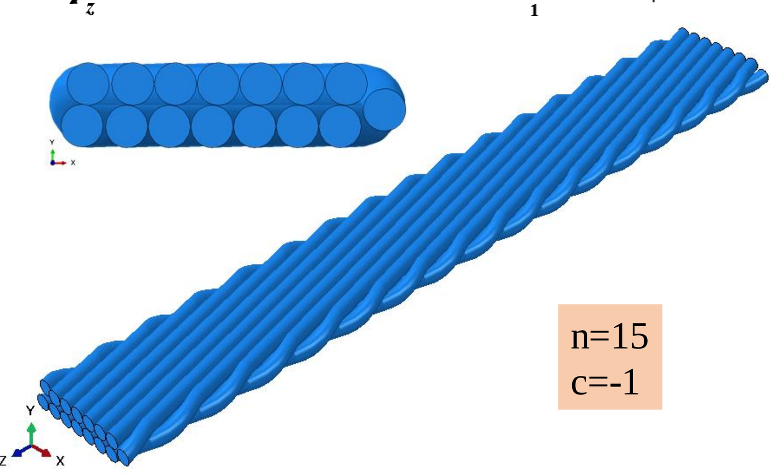
$$x_2=(R\cos\theta-\frac{n-2}{4}D)\cos\kappa$$
$$y_2=R\sin\theta$$
$$z_2=\frac{p}{2}t+\frac{n-2}{2}Dk$$

Parametric equation of wire i

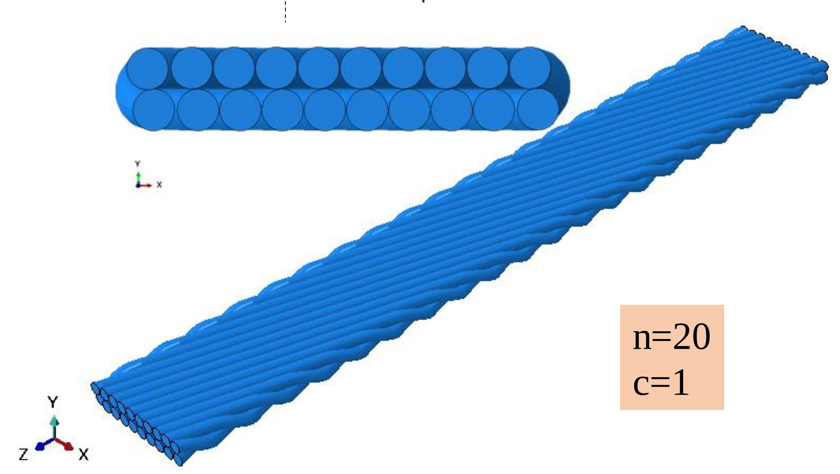
$$x=x_m$$
$$y=cy_m\cos\kappa$$
$$z=z_m+jh_p-(i-1)h_\Delta$$

κ=jπ (j=0,1,2,…)

m=1, straight lines; m=2, helical lines.
c=1,right-hand twisting; c=-1,left-hand twisting

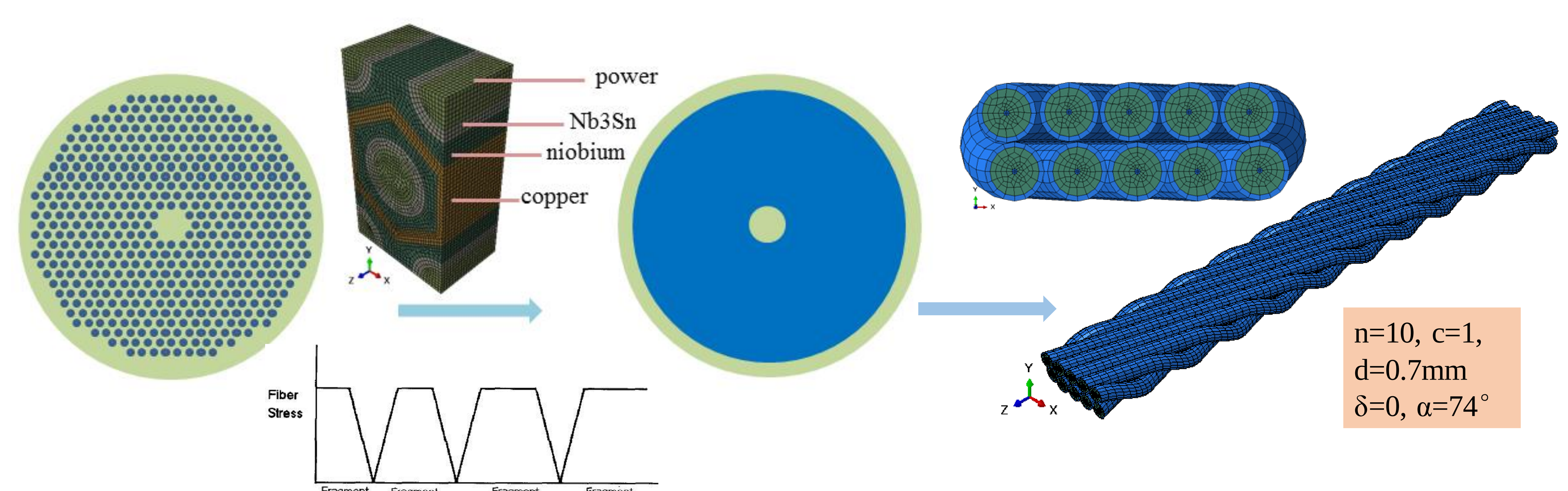
n=15
c=-1



n=20
c=1

Mechanical modeling

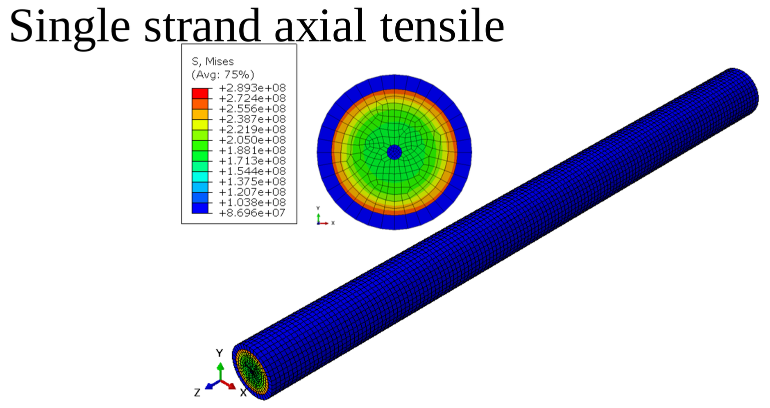
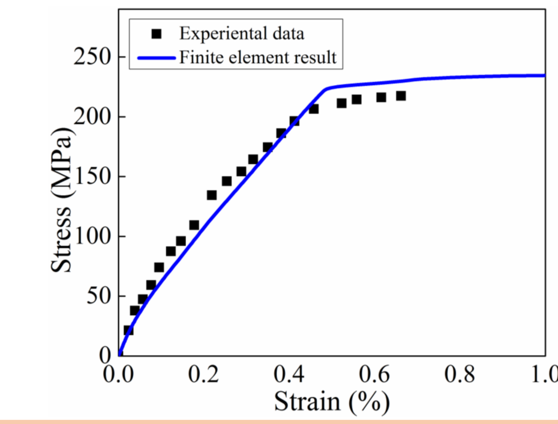
✓ Representative volume element (RVE) ✓ Damage of filaments



n=10, c=1,
d=0.7mm
δ=0, α=74°

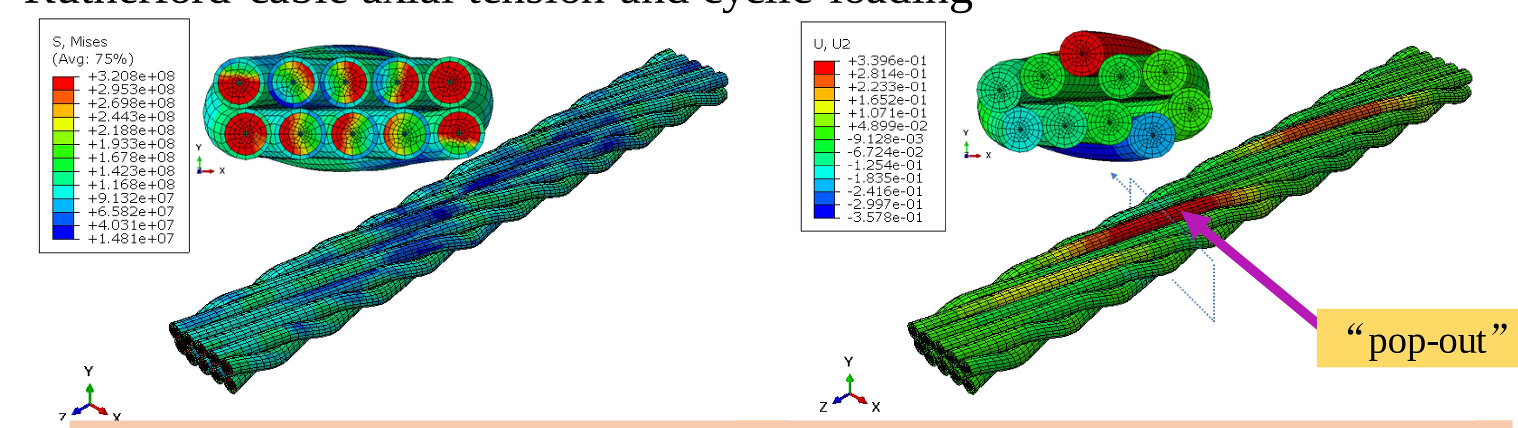
Results and discussion

- Single strand axial tensile

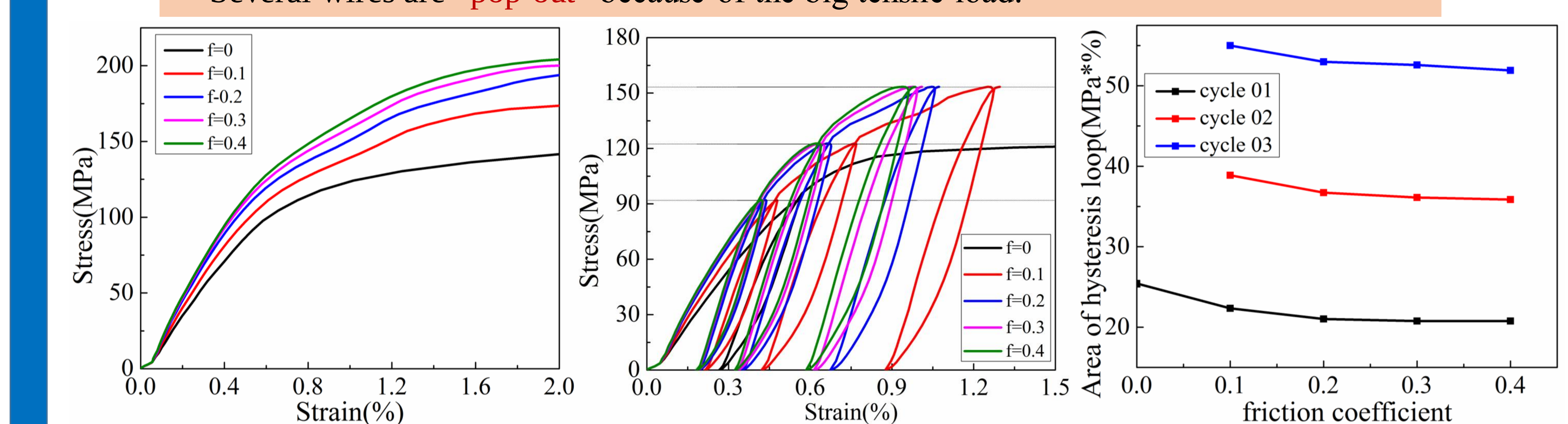



✓ The strain-stress curve of the single strand is in good agreement with the experimental data.

- Rutherford cable axial tension and cyclic loading



✓ The superconducting region bears larger stress than the copper regions.
✓ The stress distribution is antisymmetry at the end cross-section.
✓ Stress concentration at the cable edge in X direction and the contact area between wires.
✓ Several wires are "pop-out" because of the big tensile load.



✓ When the strain is the same, the bigger friction coefficient, the bigger stress.
✓ There are hysteresis loops when the model is bearing cyclic tensile loading.
✓ The occurrence of hysteresis loops is not the result of the friction.
✓ The hysteresis loop's area increases as the cycle number increases at first.

Conclusions

◆Develop a method to build up Rutherford cable's geometry efficiently, considering strand numbers, lay angle, chirality and so on.

◆Analyze the finite element model of Rutherford cable under axial tension and cyclic loading, while taking the friction and filaments damage into consideration.

◆The axial tensile load during manufacture process may contribute to the "pop-out".

◆The friction has an obviously effect on Rutherford cable's mechanical behavior when applied to tensile load.

◆Rutherford cable's structure and the strands' hysteresis characteristics contribute to the hysteresis loops in the cyclic tensile loading.

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