Structural Modeling of REBCO VIPER Cable for High-Field Magnet Applications

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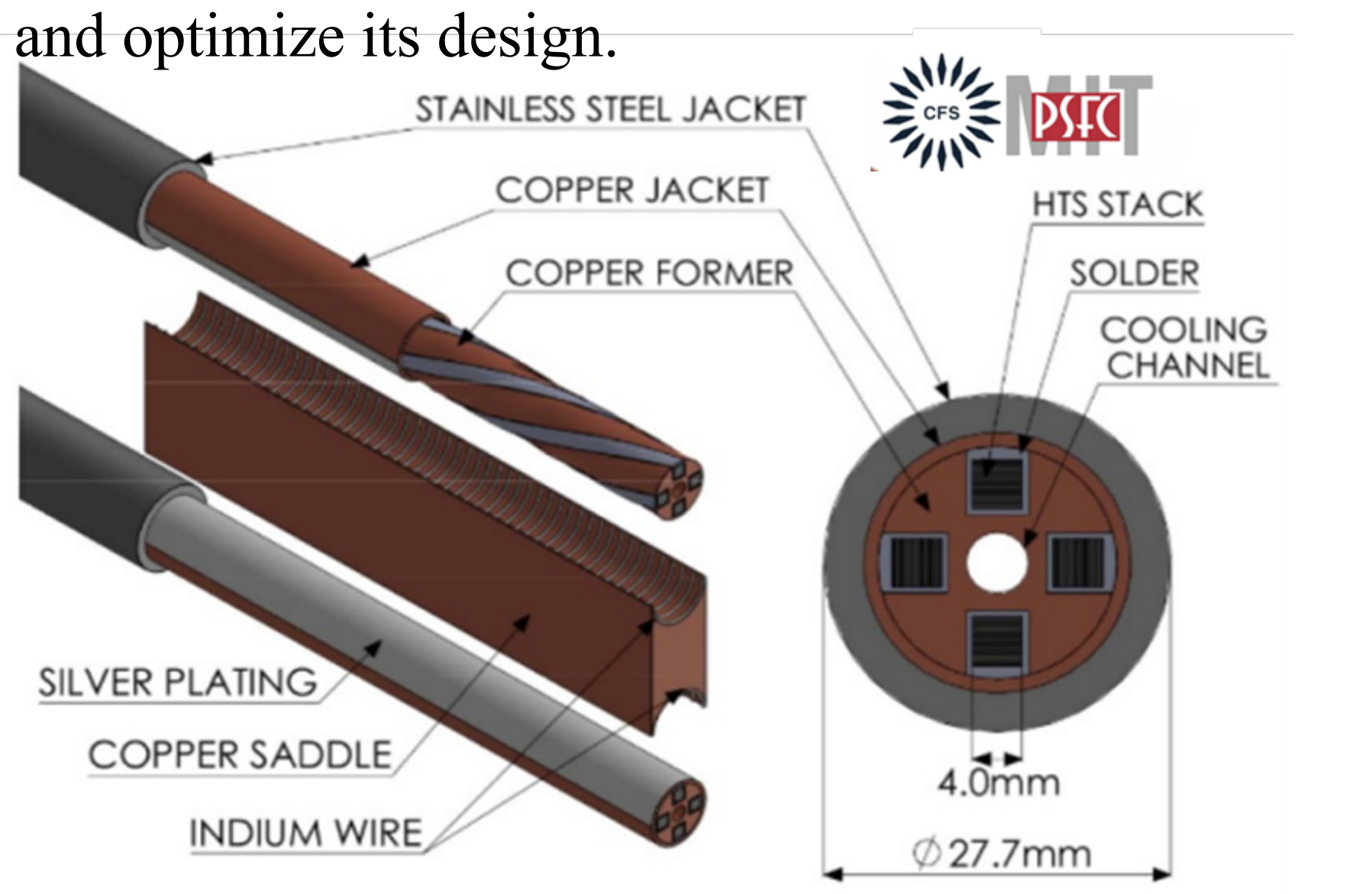
Introduction

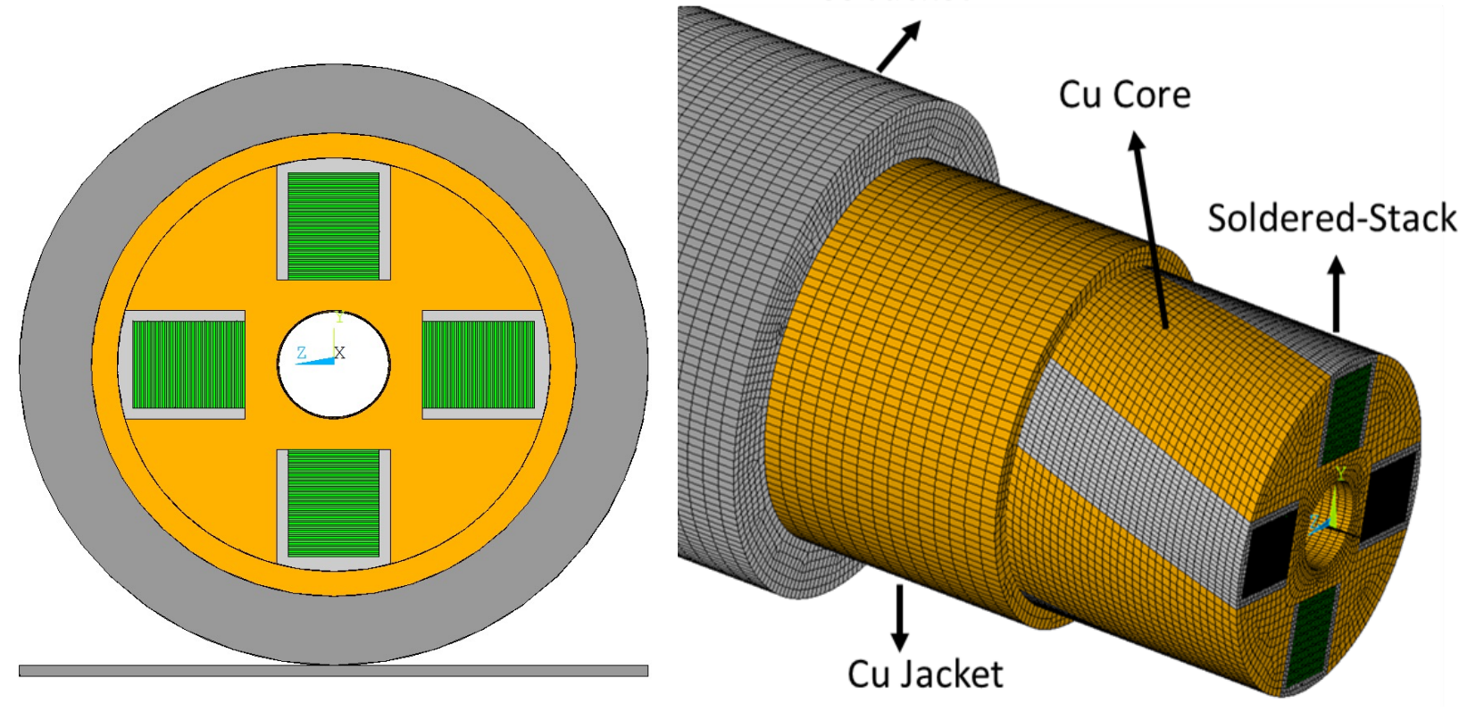
The **VIPER cable** [1] is based on the **Twisted Stacked-Tape Cable (TSTC)** design. During the fabrication and the operation of a magnet, the cable will experience loads including **bending** to the shape of the coil, **thermal cool down**, and **cyclic transverse electromagnetic load**. Understanding the stresses generated in the HTS tape-stacks during these conditions is crucial to characterize the cable's performance and optimize its design.

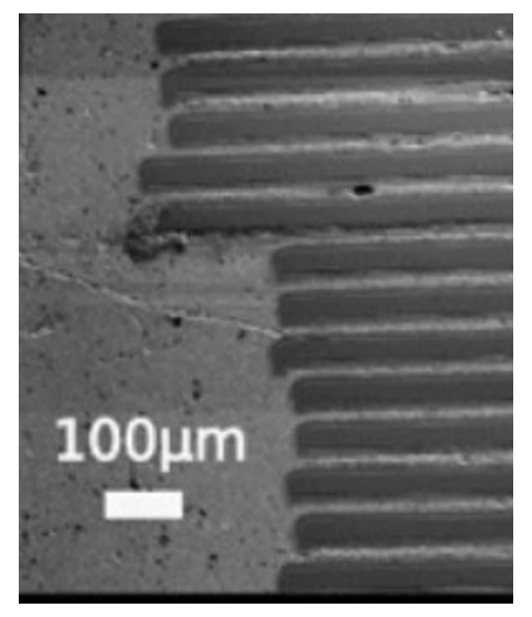


Structural **Finite Element Analysis (FEA)** is used to simulate the stresses of the tape stacks for:
(1) Bending to 1 m diameter
(2) Cooldown to cryogenic temperature (77 K)
(3) Cyclic transverse Lorentz load during operation
The simulations are used to investigate the mechanical effects of **solder impregnation** (filling the channel that contains the tape-stack) onto the overall response of the tape-stacks. The results obtained shed light on the early-stage critical current degradation observed experimentally in the VIPER cable during cyclic Lorentz loading (400 kN/m) [1].

Finite Element Analysis

Structural FEA using ANSYS® was done to investigate the mechanical behavior of a VIPER cable.
Solder is filled into the space between tape-stacks and core and between the individual tapes through Vacuum Pressure Impregnation (VPI), and it is crucial to understand how the solder affects the the tape-stacks mechanically under various loads.





Solder VPI and Tape-Stack

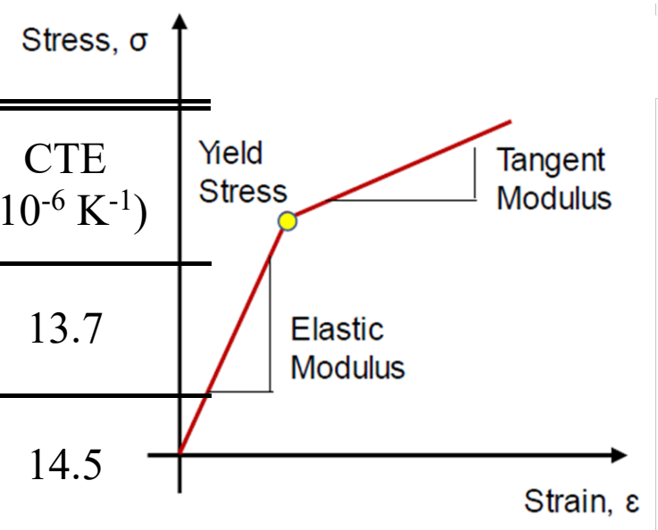
Tape stacks are modeled with SOLSH190 structural **solid-shell** elements. Surface-to-Surface contact pairs were used for the interactions between adjacent parts. The interaction between tape stack and the solder VPI is modeled through different friction coefficients (μ).

- μ = 0.02: perfect slip condition;
- μ = 0.2: standard metal-to-metal contact;
- μ = 1.0: no slip condition.

Neighboring Components		Contact Interaction	
Component 1	Component 2	Sliding	Separation
REBCO tape	REBCO tape	Allowed	Not Allowed
Tape-stack	Solder	Allowed	Not Allowed
Tape-stack	Cu Core	Allowed	Not Allowed
Solder	Cu Core	Allowed	Not Allowed
Solder	Cu Jacket	Allowed	Not Allowed
Cu Core	Cu Jacket	Allowed	Allowed
SS Jacket	Cu Jacket	Allowed	Allowed

Material Properties and Loading Conditions

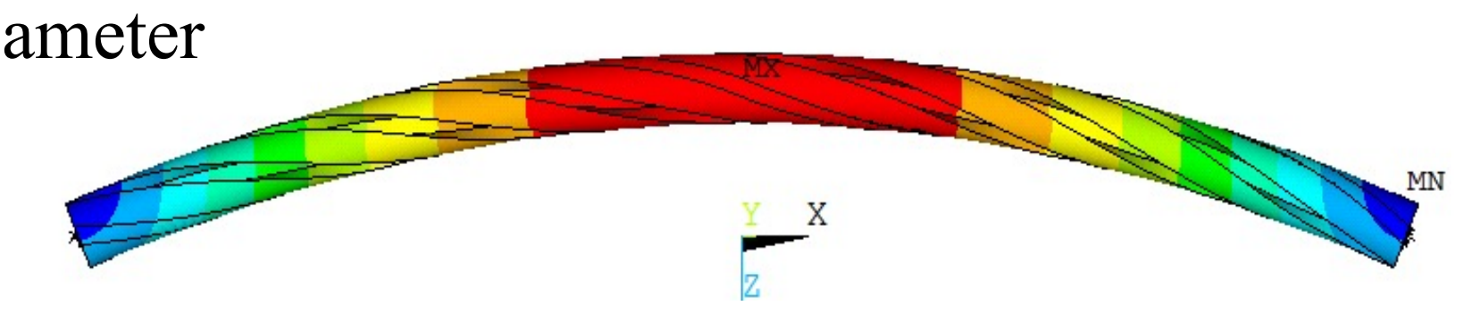
Bilinear isotropic material properties are adopted to capture the **elastic-plastic deformation** of the VIPER cable.



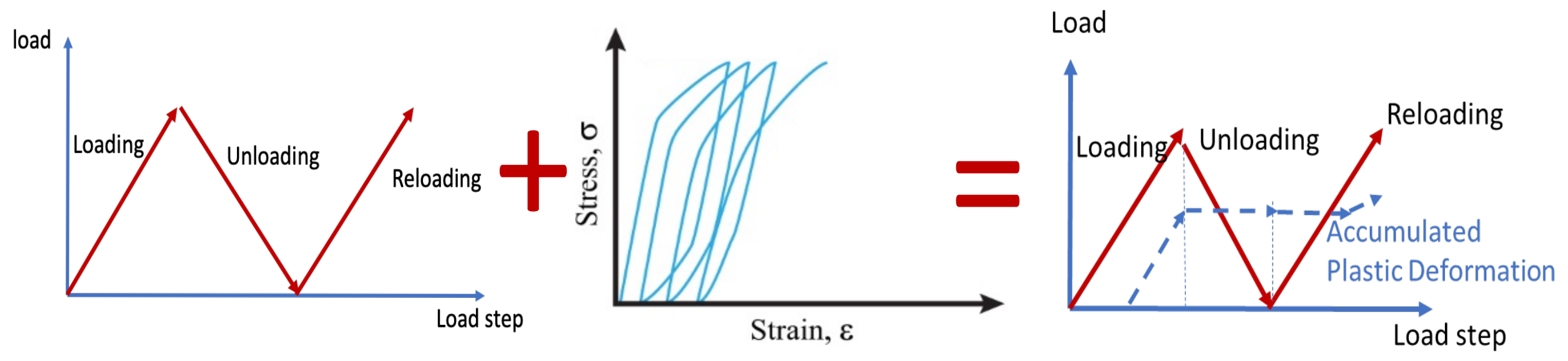
Material	Temp (K)	Elastic Modulus (GPa)	Yield Stress (MPa)	Tangent Modulus (GPa)	CTE (10^{-6} K^{-1})
REBCO Tape	77	145	860	13	13.7
	295	135	640	8	
OFHC Copper	77	119	200	4.5	14.5
	295	110	200	4.5	
Solder (Sn60/Pb40)	77	20	100	1	24
	295	30	40	1	
Stainless Steel	77	180	950	10	12.8
	295	----	750	10	

Loading conditions:

- Bending:
  - A VIPER cable, two full twists in length, was modeled
  - Jackets were neglected
  - 1 m bending diameter



- Cooled down to 77 K + cyclic transverse Lorentz load of 1600 kN/m
  - 1/4 of a full twist length (periodic boundary condition)
  - Cyclic Lorentz load is applied to study the effect of accumulated deformation of supporting structures [2].



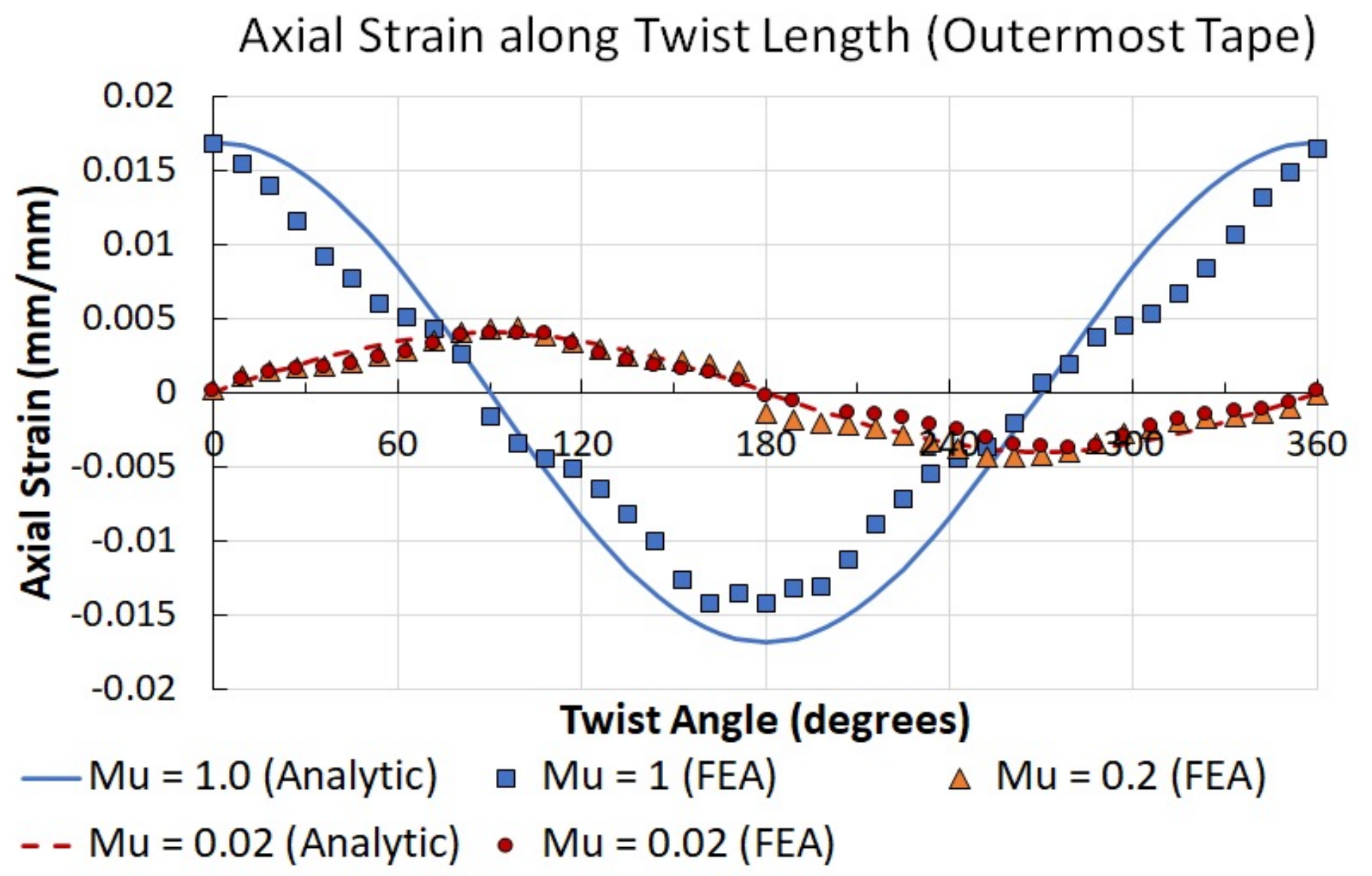
Bending to 1 m Diameter

The strain of the tape-stack from bending is mainly in the axial direction. Analytical expressions for axial strain from bending [3]:

$$\textbf{No-Slip Condition:} \quad \epsilon_b = \frac{x \sin\theta + (0.093n+3.822)\cos\theta\cos\alpha}{\frac{1}{2}D}$$

$$\textbf{Perfect-Slip Condition:} \quad \epsilon_b = \frac{x \sin\theta}{\frac{1}{2}D}$$

- x is the position along the width of the tape in millimeters;
- θ is the orientation of the tape (twist angle);
- n is the individual tape number from 1 to 53;
- α characterizes how twisted the tape is（depends on twist pitch and tape number);
- D is the bending diameter in millimeters

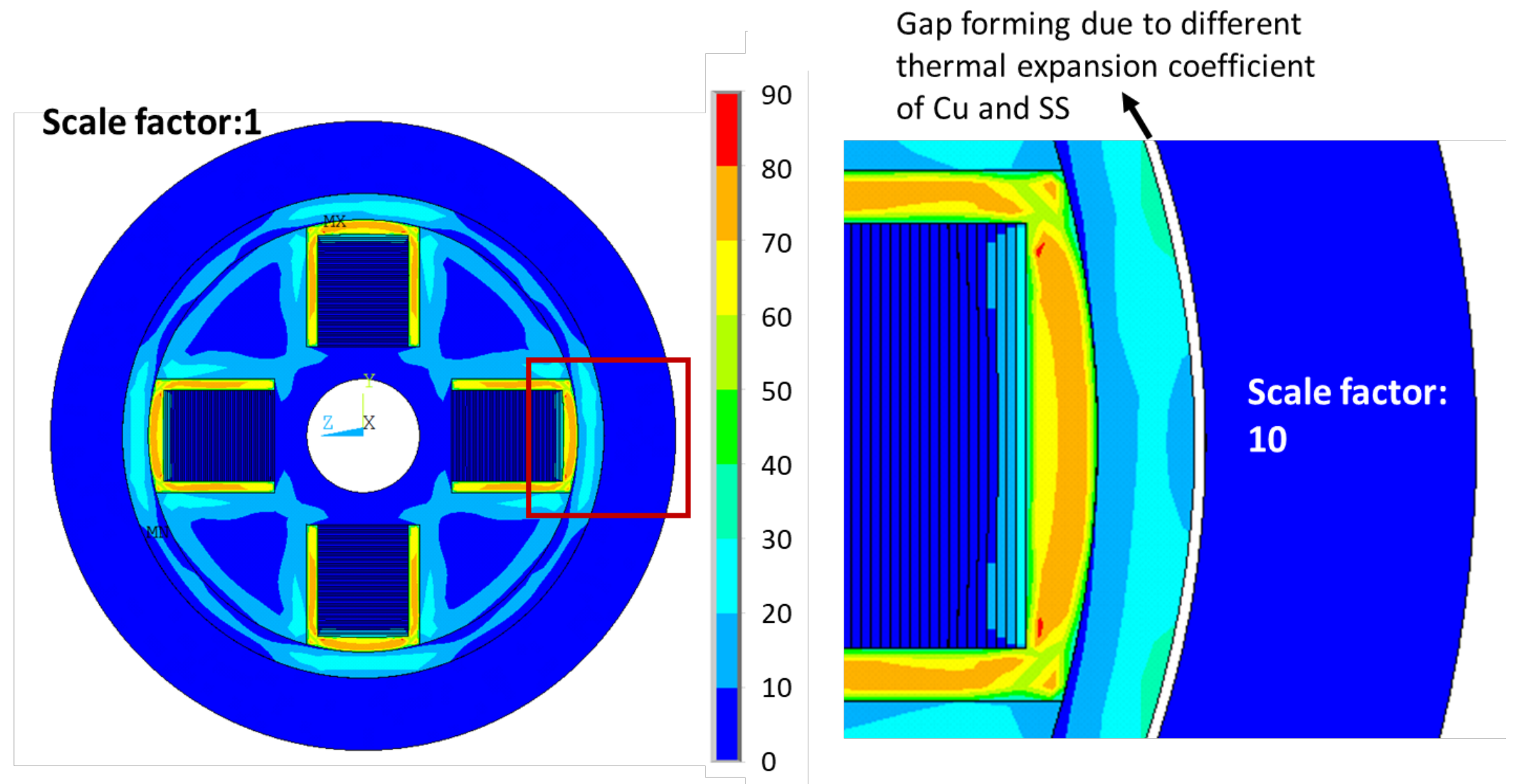


- Axial strain data from FEA simulation shows good agreement with the analytical model for all tapes (shown above for outermost tape)
- The outermost tape in the stack has the highest strain
- μ = 1 (No-Slip) produces axial strain of 1.5% due to bending, which may result in I_c degradation.
- μ = 0.02（Perfect-Slip) produces axial strain of less than 0.5%.

Cooldown + Cyclic Lorentz Load

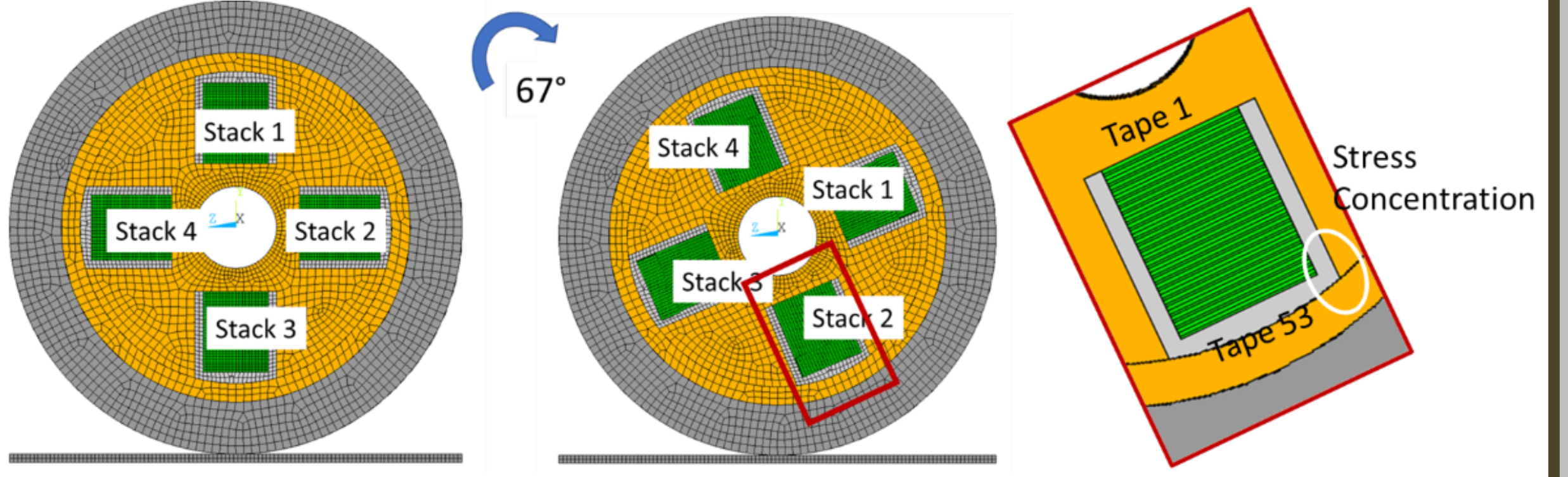
Cooldown to 77 K:

- A gap forms between SS and Cu jackets (different coefficient of thermal expansion)
- The gap might bring mechanical instability
- The thermal stress in the tape-stack is negligible (under 30 MPa)



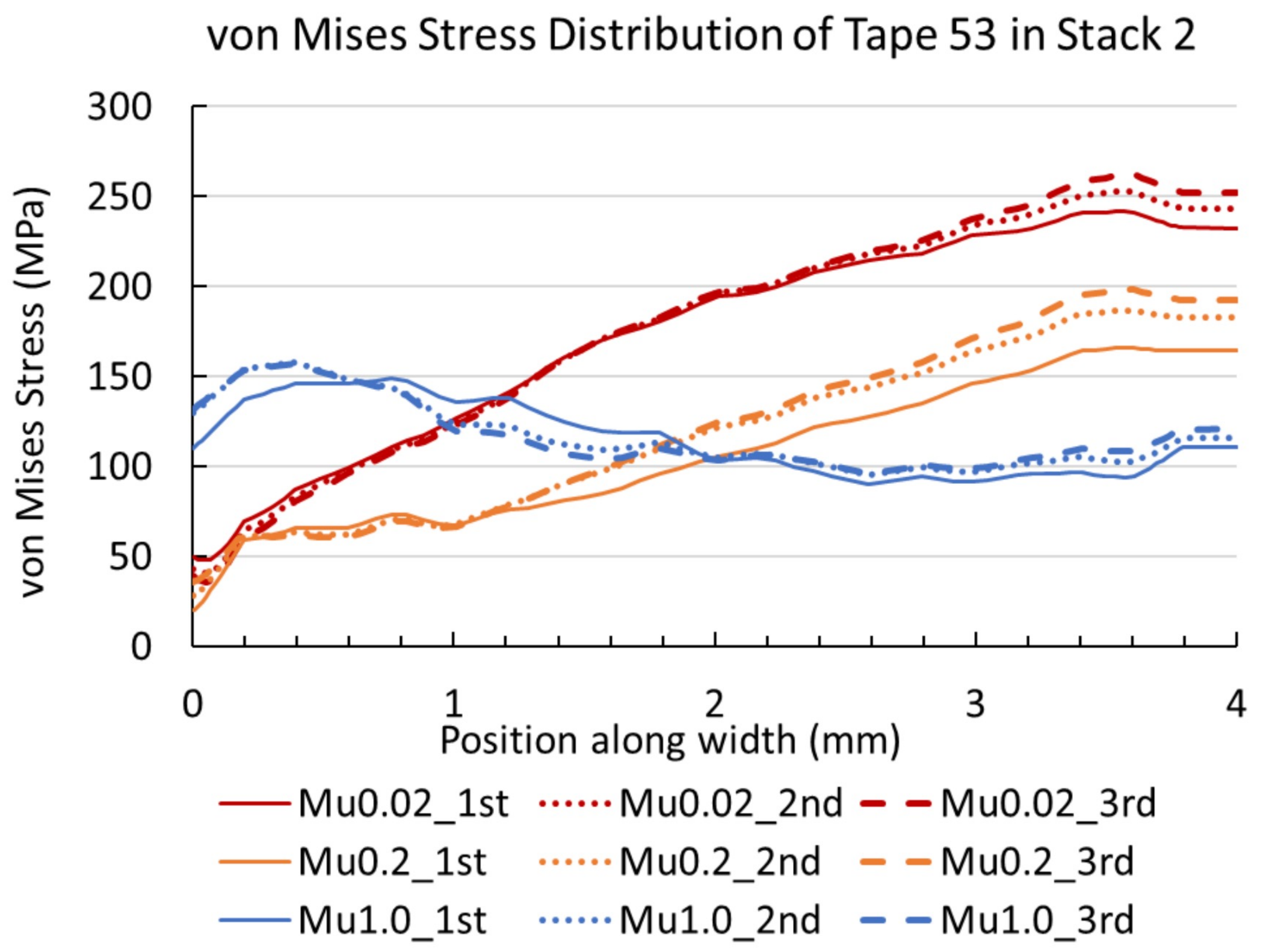
Cyclic Lorentz Load:

- Cyclic Lorentz load is applied after the cooldown
- The stress distribution was studied along the twist pitch



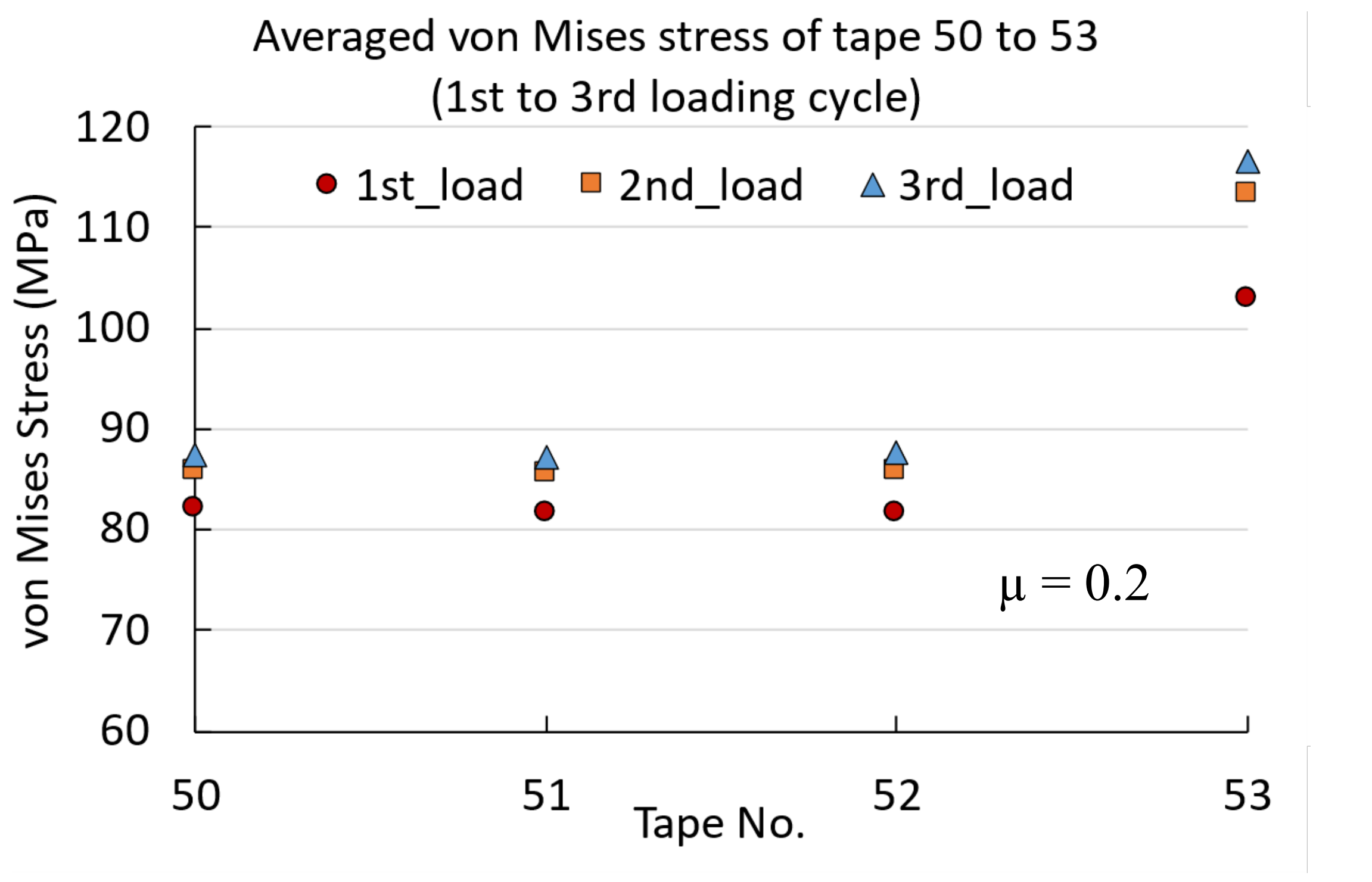
- Worst-case orientation under Lorentz load show above [4]:
- The **stress concentration** is caused by electromagnetic load on the stack pressing against the support structure of the jackets
- **Sliding between the tapes** contributes to the stress concentration in the bottom-right corner of the stack, indicating that the friction coefficient between tapes is an important parameter in the model

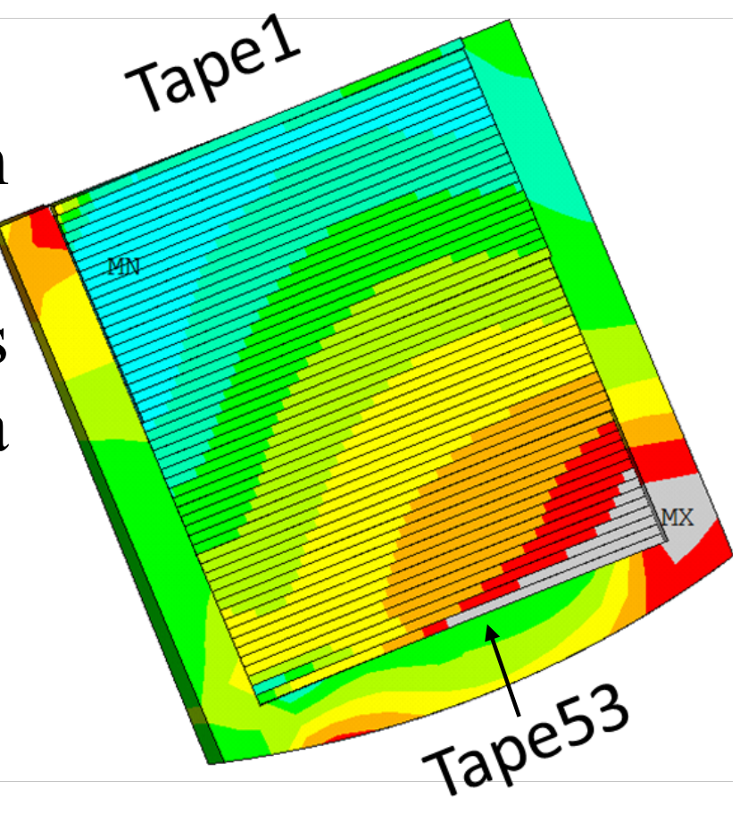
Von Mises stress distribution of the worst-case-scenario under three cycles of Lorentz loading (1600 kN/m), with μ of 0.02, 0.2 and 1 is shown below.



For the first loading cycle (solid lines):

- High friction (μ = 1, No Slip condition) results in a more uniform stress distribution with a peak stress of 150 MPa
- Low friction coefficient (μ = 0.02, Perfect Slip condition) results in a much higher peak stress of 240 MPa.
- Higher friction coefficient (μ = 1) reduces the deformation by restricting the relative motion of the adjacent tapes, and therefore reduces stress **(opposite behavior from bending)**





Effect of cyclic loading:

- Accumulated plastic deformation in each slot occurs within the solder filler
- The average stress increases in all four tapes with each successive loading cycle, with a 10% increase in tape 53 after one cycle
- Repeated loading worsens the stress state in the stack due to plastic deformation in the solder from previous cycles

Conclusion

The mechanical behavior of the VIPER cable under **bending, thermal cooldown and cyclic Lorentz load** was investigated. The effect of the solder impregnation onto the stress state of the tapes was studied via a set of friction coefficients of 0.02 (perfect-slip), 0.2, and 1 (no-slip).
For **bending**, high friction between tape-stack and solder results in high axial strain in the tape stack and may lead to I_c degradation. The comparison with an analytic model suggests that friction coefficients 0.02 and 1 can represent perfect-slip and no-slip conditions respectively.
During **thermal cooldown**, the stress on the tape stack is negligible. However, a small gap between the copper and stainless-steel jackets may cause mechanical instability.
Under **Lorentz load,** a higher friction coefficient reduces the deformation of the cable by restricting the relative sliding between the neighboring tapes, which results in a more uniform stress distribution and a lower peak stress. A lower friction coefficient allows more sliding between tapes and results in a higher peak stress in the stack.
Under **cyclic loading**, due to the accumulated plastic deformation and stress concentration in the solder, both the averaged von Mises stress and the peak stress of the outermost four tapes increase after the first three cycles. These results may explain the early-stage degradation observed in the experiments conducted on VIPER cables [1].
Considering the mechanical effect of solder impregnation of the tape-stacks in the cable, if the solder is easy to deform under bending (low friction), it will not cause high strain in the tape-stack. Alternatively, for solder that is hard to deform (high friction), one possible way is to bend the cable into desired shape (wind the magnet first), and then impregnate the channel with solder.

References

[1] Hartwig, Zachary S., et al. "VIPER: an industrially scalable high-current high-temperature superconductor cable." *Superconductor Science and Technology* 33.11 (2020): 11LT01.
[2] Zhao, Zijia, Peter Moore, Jillian Stern, Bjorn Isaacson, Luisa Chiesa, and Makoto Takayasu. "Structural Finite Element Evaluation of Twisted Stacked-Tape Cable Under Cyclic Lorentz Loads." *IEEE Transactions on Applied Superconductivity* 31, no. 5 (2021): 1-5.
[3] Takayasu, Makoto, and Luisa Chiesa. "Analytical investigation in bending characteristic of twisted stacked-tape cable conductor." *IOP Conference Series: Materials Science and Engineering*. Vol. 102. No. 1. IOP Publishing, 2015.
[4] Zhao, Zijia. "Structural Analysis of High Temperature Superconductors for High Field Superconducting Magnets." PhD diss., Tufts University, 2021.