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Structural Modeling of HTS Tapes and Cables

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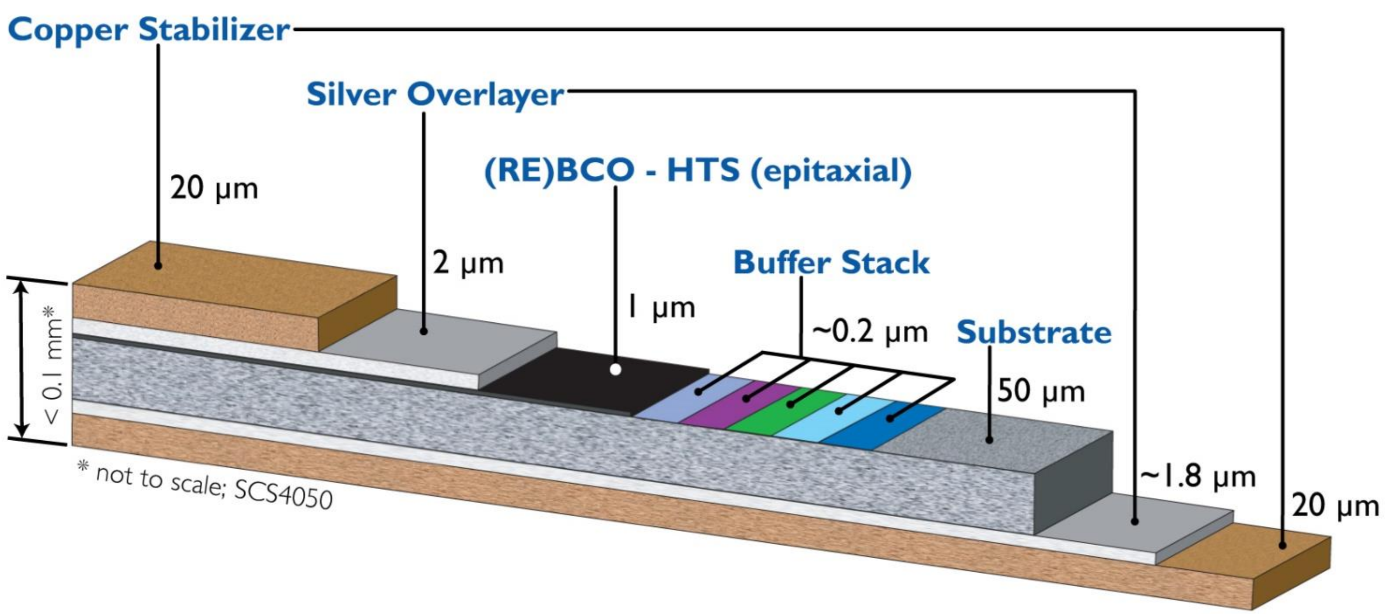
2G HTS Tapes

Recent developments in **2G HTS** make them of interest in many superconducting applications like large magnets for **fusion** and **high-energy physics**

SuperPower
(SCS 4050)



SuNAM (SCN 04150) and **AMSC** (344C) were also used in electromechanical experiments and simulations

HTS Cabling Techniques

The various large magnet applications require **cables capable** of **carrying high currents** often in the presence of **high magnetic fields**

CORC - conductor on round core
RACC - Roebel assembled coated conductor

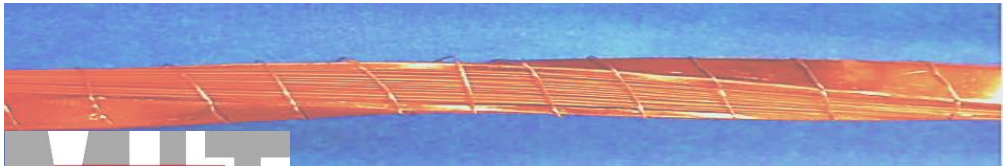
HTS stacked-tape cables

TSTC – twisted stacked-tape cable

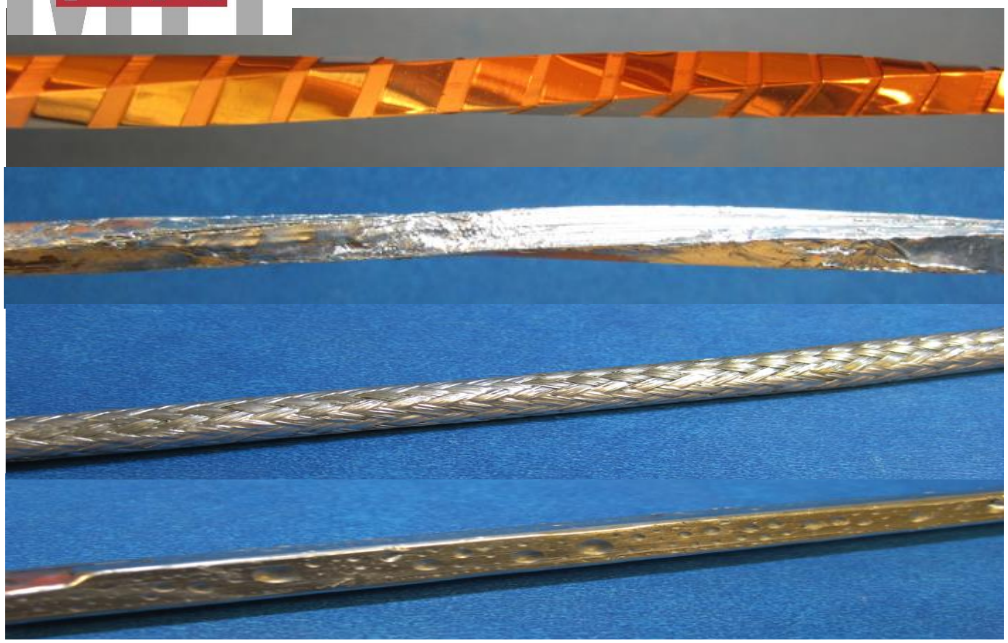
ENEA CICC – slotted core stacked tape cable in conduit conductor

RSCCCT – round strands composed of coated conductor tapes

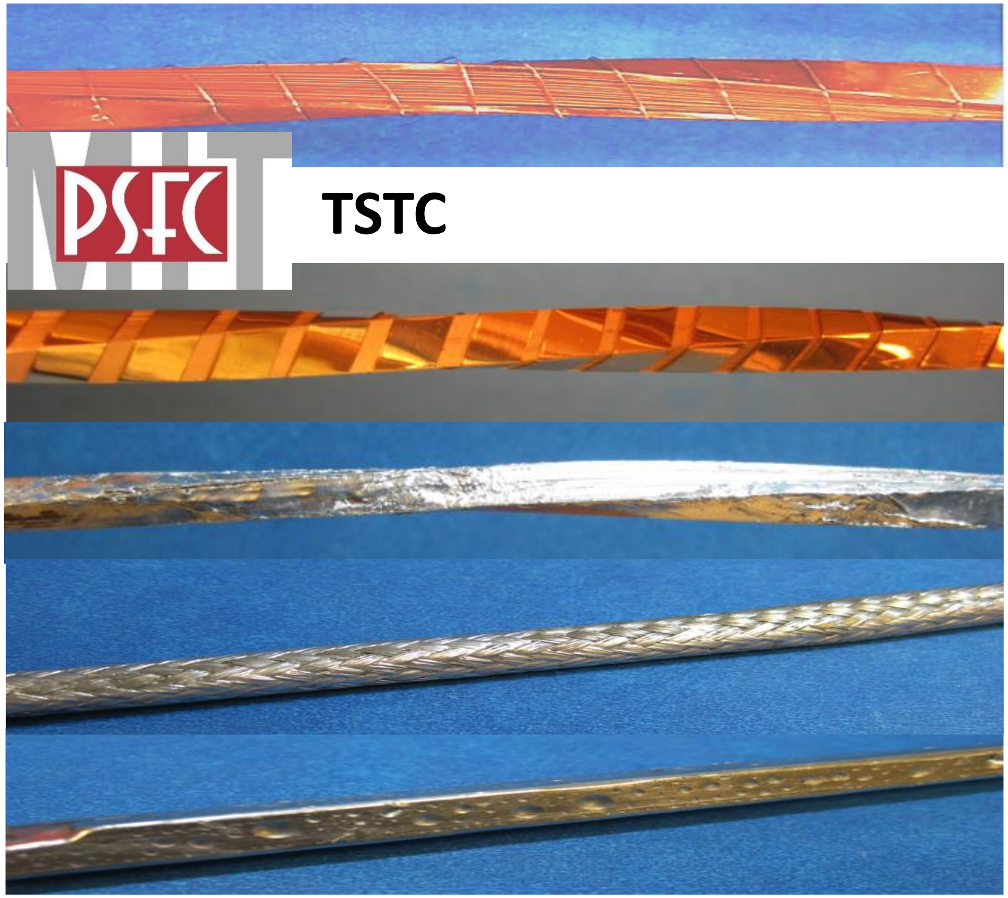
HTS Stacked-Tape Cables



TSTC

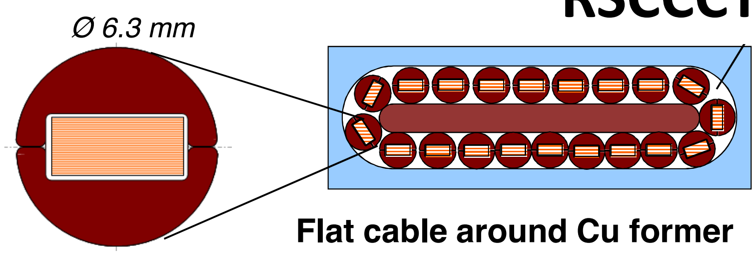


HTS Stacked-Tape Cables

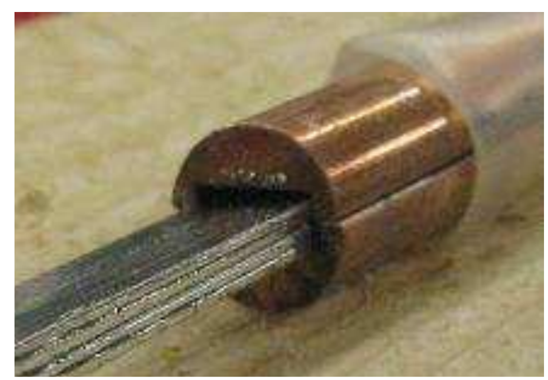


TSTC

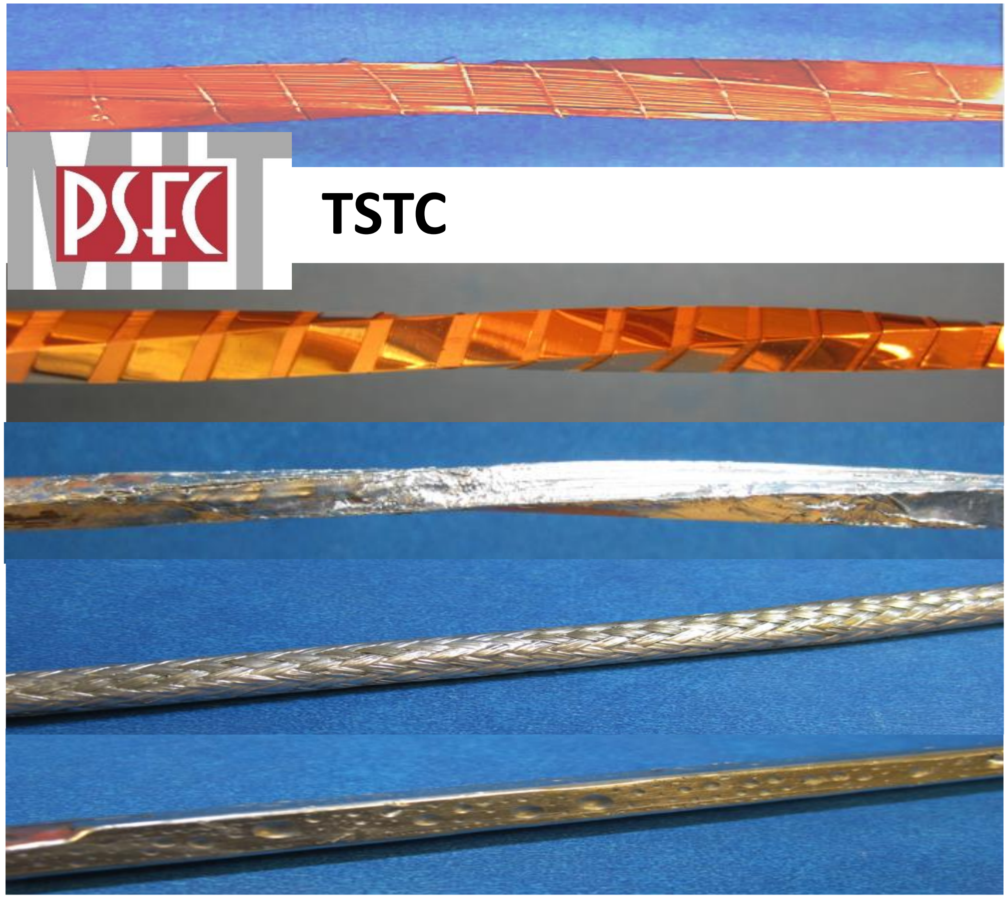
RSCCCT



Flat cable around Cu former



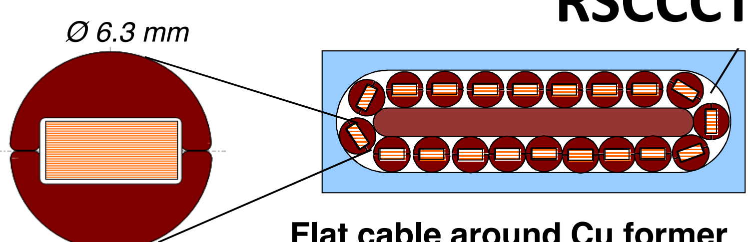
HTS Stacked-Tape Cables



TSTC

ENEA CICC

RSCCCT

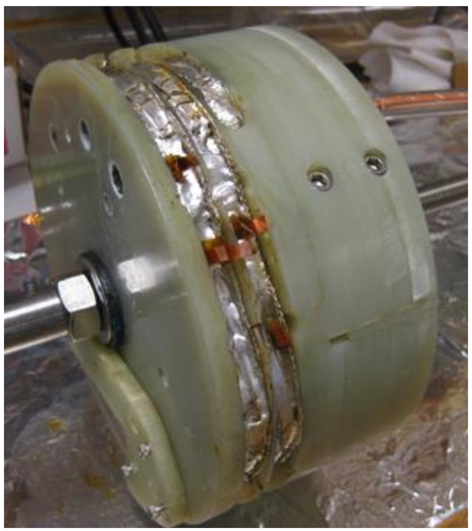


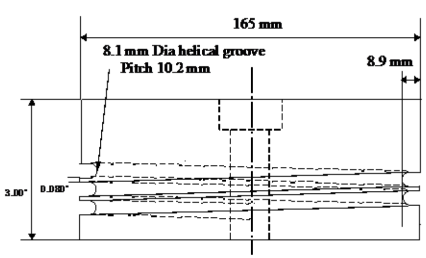
Flat cable around Cu former

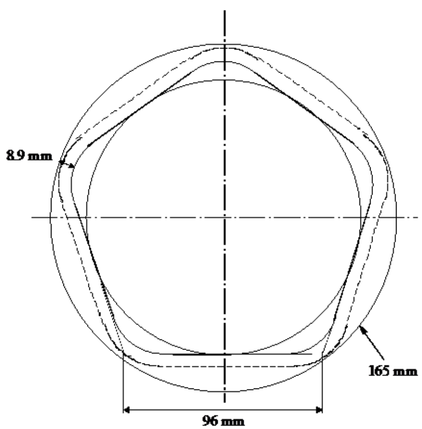
High Field – High Current Tests

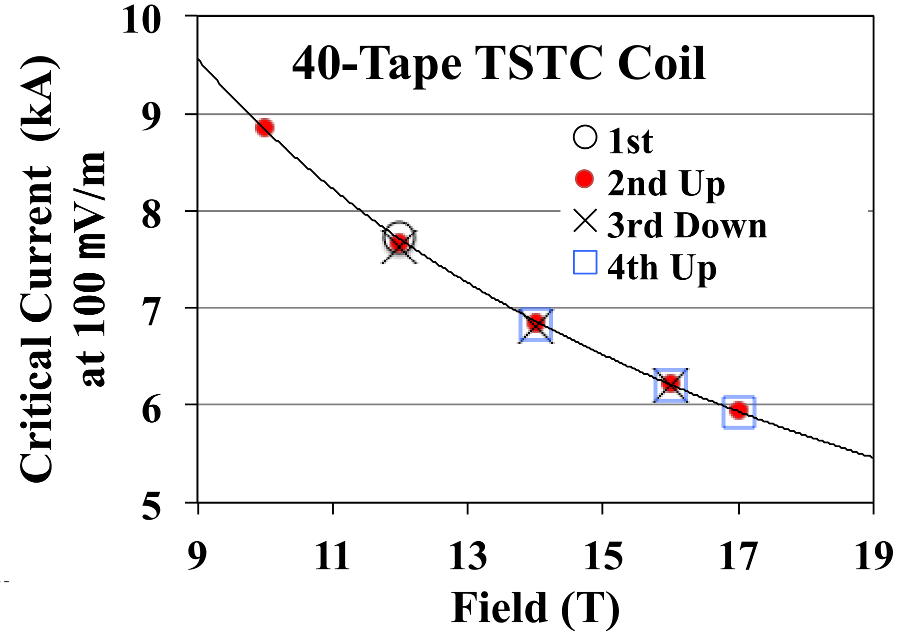
40-Tape soldered TSTC (SuperPower 4mm) 2.6 m long wound with 200 mm twist pitch in pentagon shaped coil

Tested at **NHMFL** using 20 T, 195 mm warm-bore Bitter magnet (4.2 K)









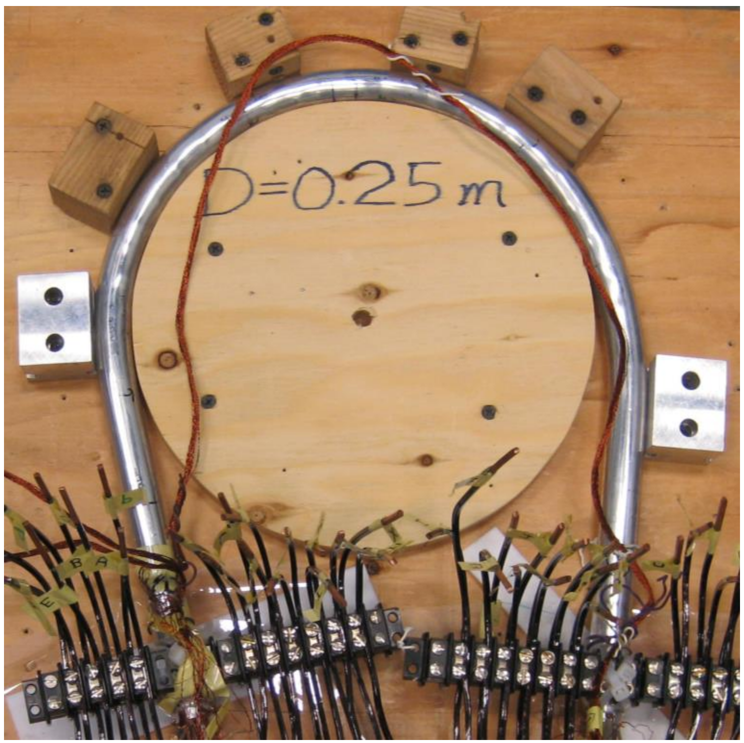
No cyclic load or Lorentz load effects

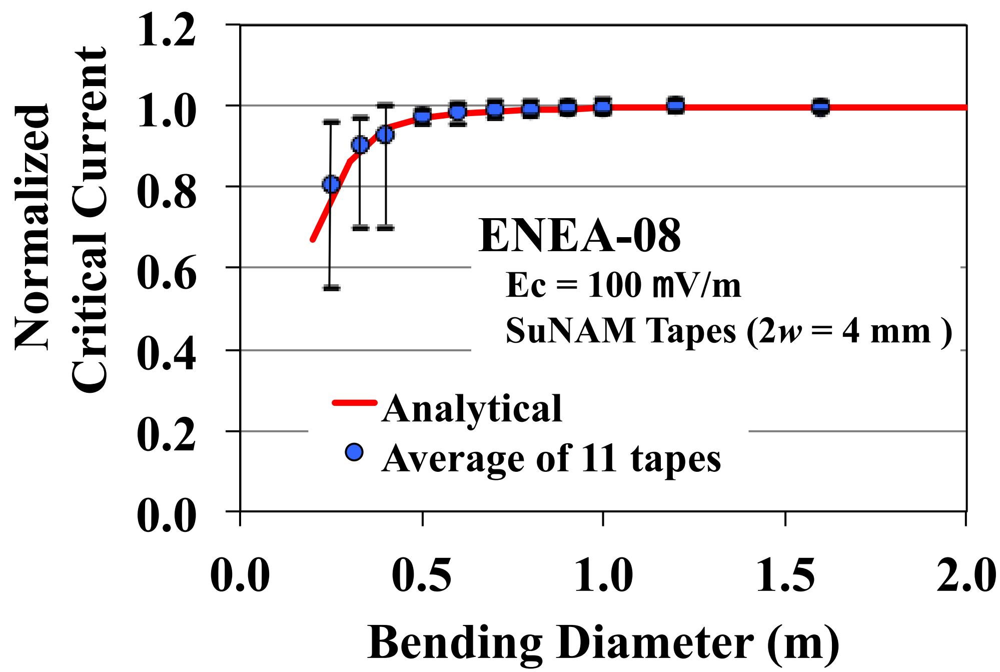
16% lower Ic than single tape estimation

Bending Characterization

ENEA slotted core CICC 850 mm long with 500 mm twist pitch
(5 slot design with 20 SuNAM REBCO tapes – 4 per slot)

Tested under pure bending at **Tufts**/**MIT** in self-field at 77 K



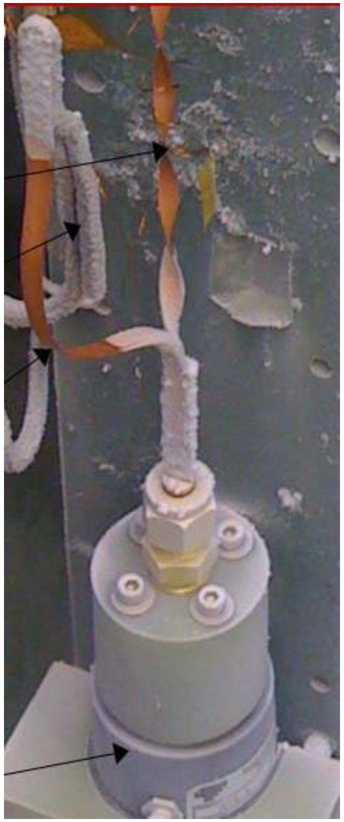


analytical = perfect-slip model

Single Tape Tests

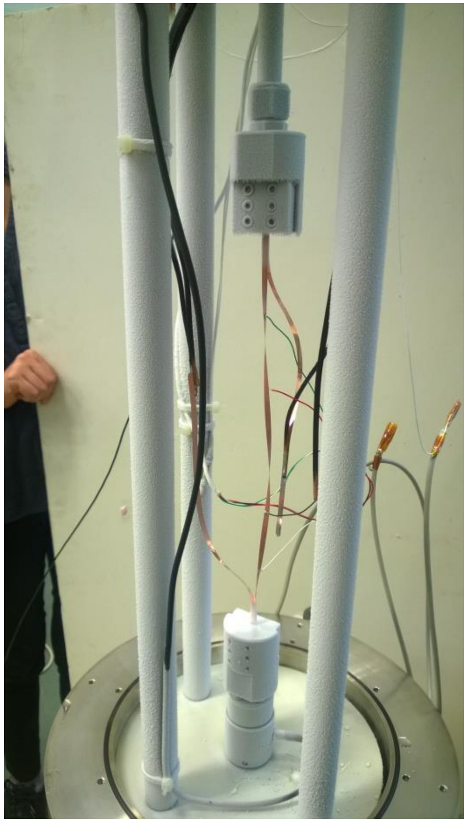
Electromechanical investigation of HTS tapes
(performance of single tapes under mechanical loads)

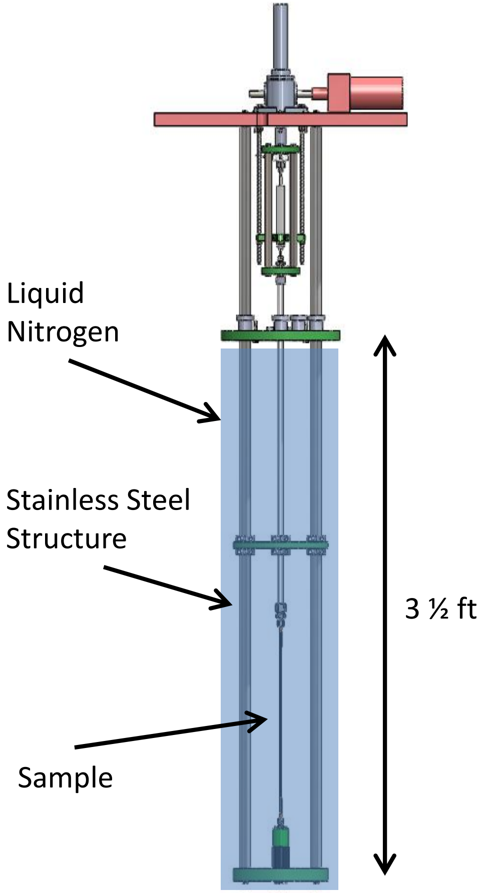
Torsion



Tension

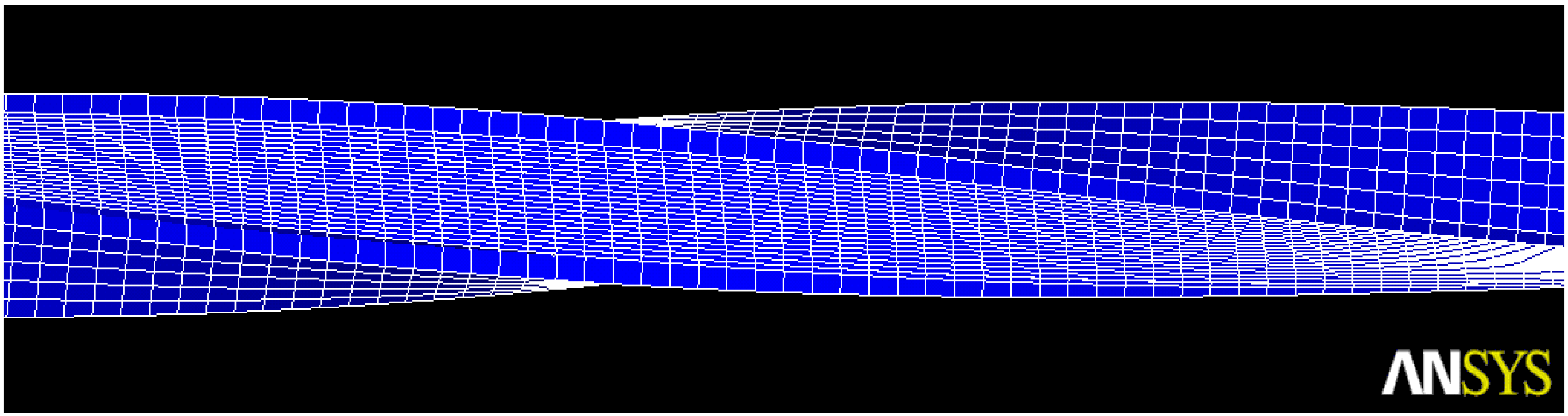
Torsion-Tension





FEA Roadmap

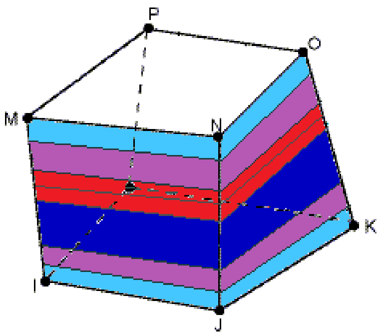
Investigation of electromechanical behavior of HTS tapes and cables using structural finite element analysis (FEA)

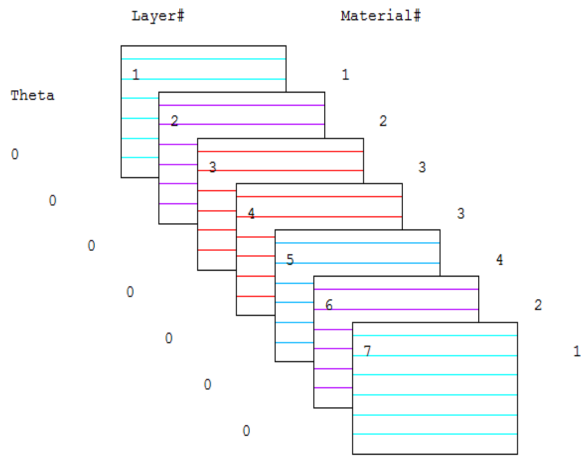


- **Tension, torsion** and combined **tension-torsion** of single tapes
- **Bending of stacked-tape cables** (PSM vs NSM)
- **Model of ENEA slotted core CICC under bending** (optimization)

FEA Methodology

SOLSH190 – 3D 8-node structural **solid-shell element** with layered capabilities





ANSYS Documentation

FEA Methodology

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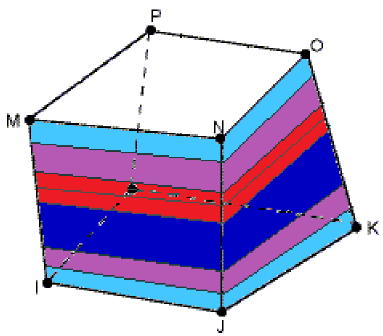
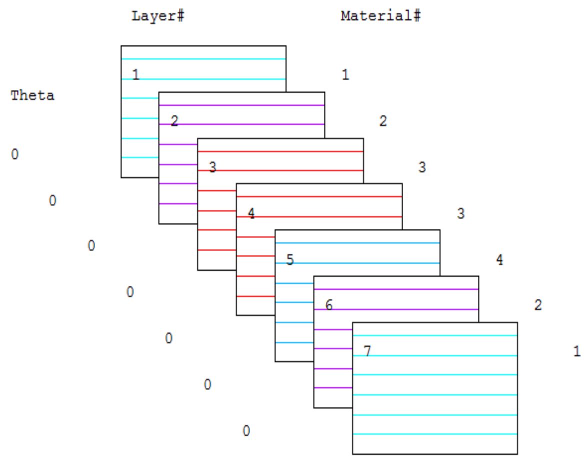
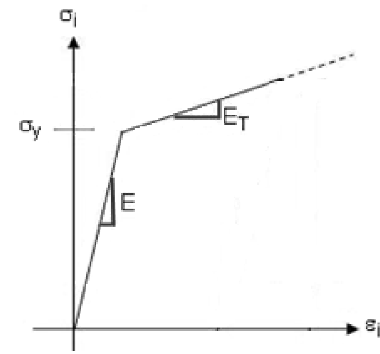




Bi-linear material properties



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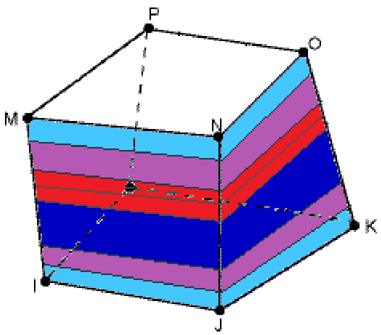

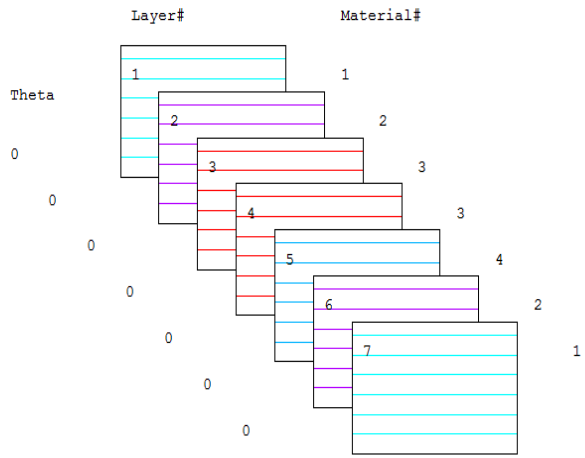

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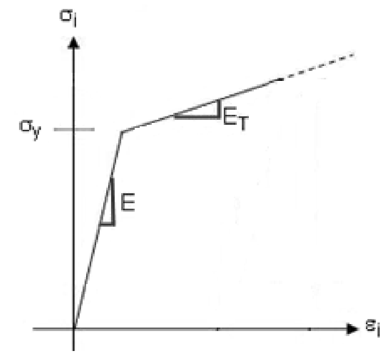
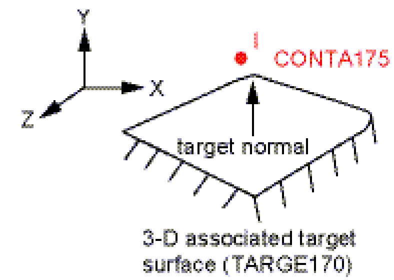


Multipoint constraint (MPC) for rotation and bending



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FEA Methodology

Tufts UNIVERSITY

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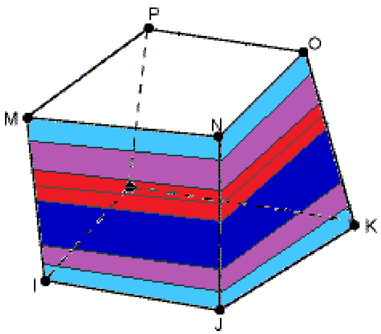

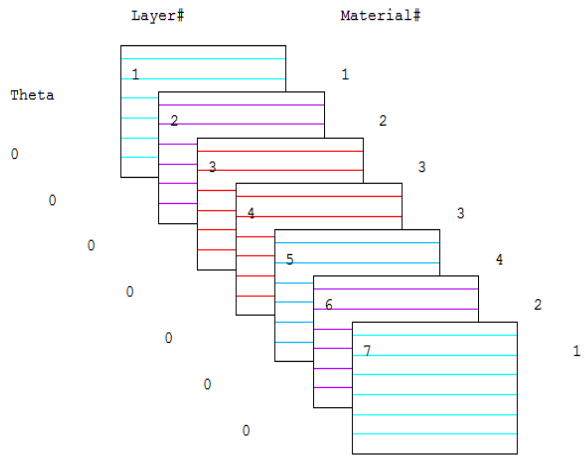

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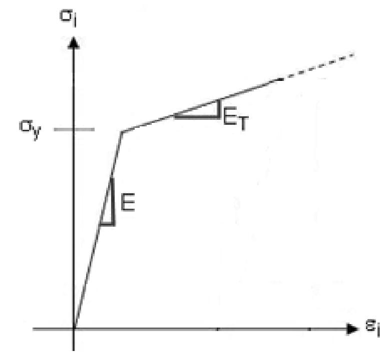
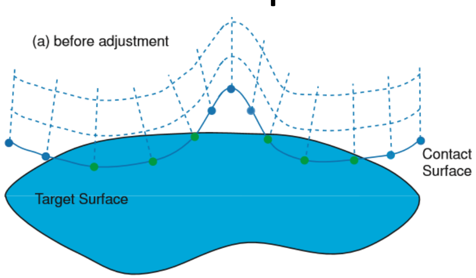


Surface-to-surface contact pair



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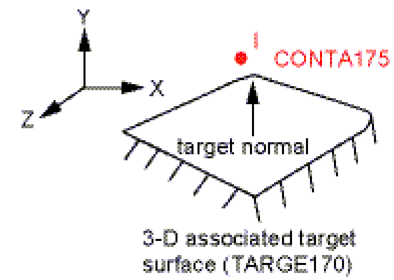

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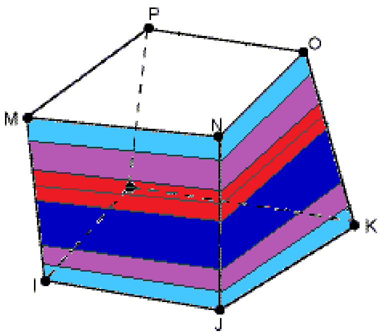

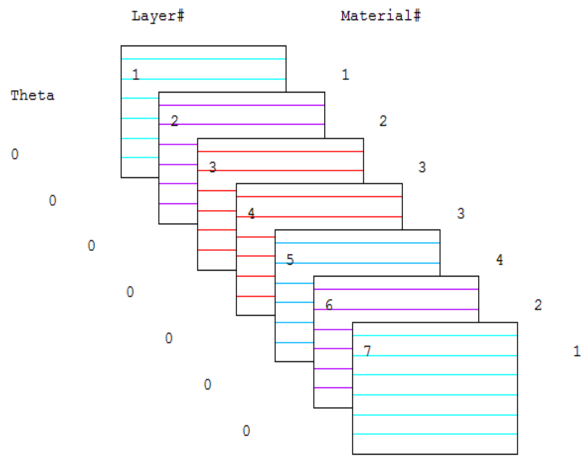

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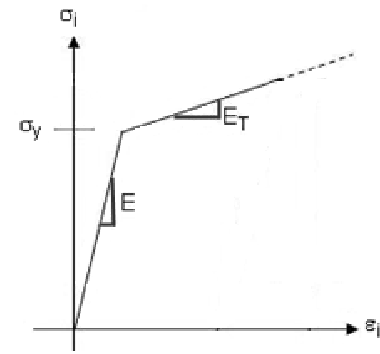

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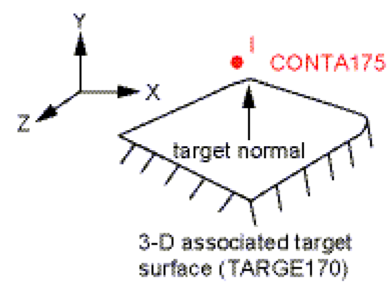

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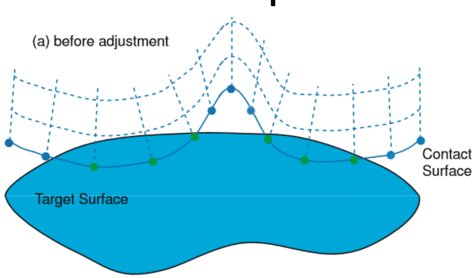
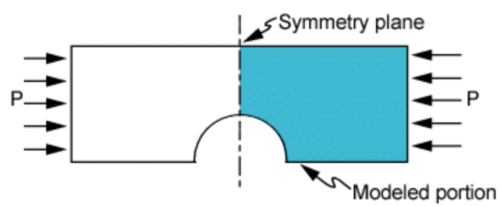


Symmetry end condition



ANSYS Documentation

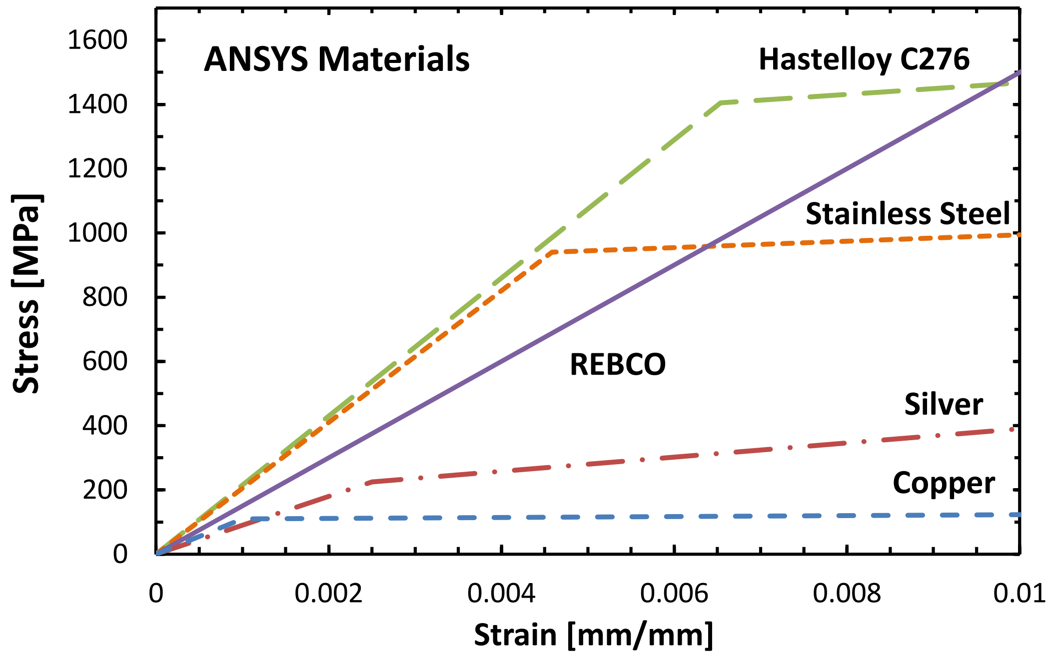
Static non-linear analysis with large displacement option

HTS Tapes and Material Properties

	SuperPower	SuNAM
Type	SCS4050-AP	SCN04150
Processing	IBAD-MOCVD	IBAD
Width	4.027 ± 0.057 mm	4.062 ± 0.008 mm
Thickness	0.092 ± 0.001 mm	0.144 ± 0.001 mm
Substrate	Hastelloy C-276 *(50 μm)*	Stainless Steel *(100 μm)*
Cu Stabilizer	Electroplating *(40 μm)*	Electroplating *(40 μm)*
Critical Current 77 K & self-field	112 ± 3 A	229 ± 6 A

Isotropic bilinear material properties

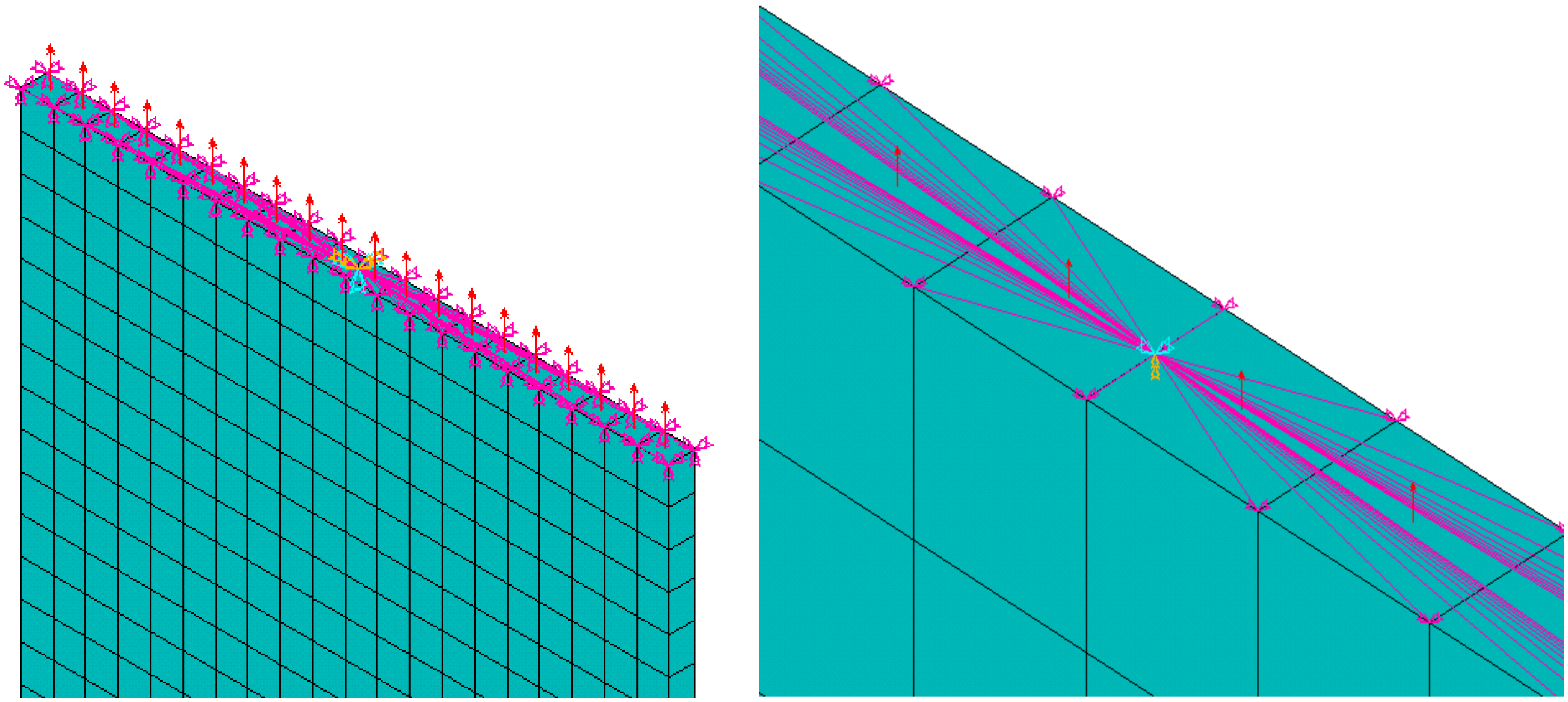
- modulus of elasticity (E)
- yield strength (Y)
- tangent modulus (T)



Single Tape Model

To apply both displacements and rotations directly to the tape ends, a **pilot node multipoint constraint** contact pair was used

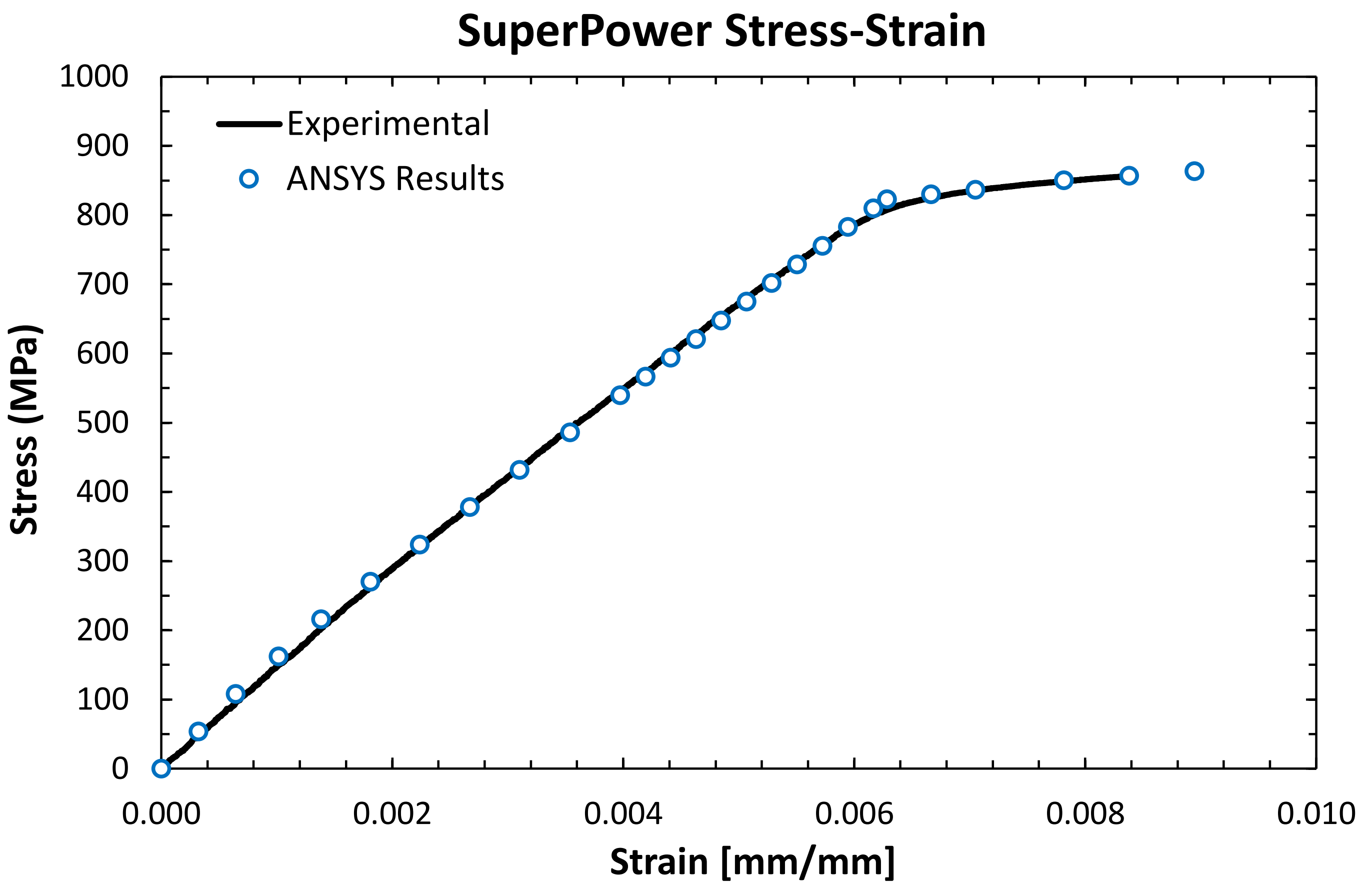
The axial load was applied to the top end using a **surface pressure load** which uniformly distributes the load over the entire area



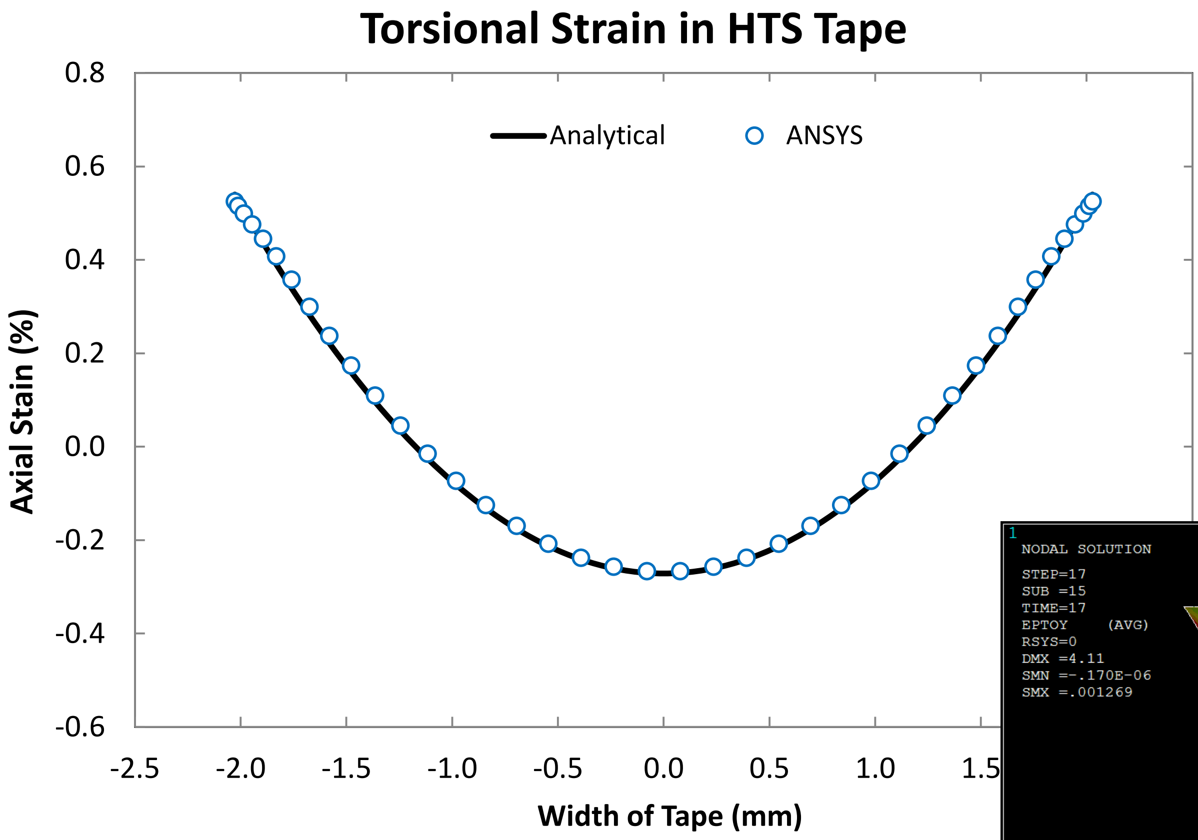
Tension Simulations

Stress-strain curves at 77 K (experimental data measured at **Tufts**)

Material properties for each layer were modified to best fit the experimental data



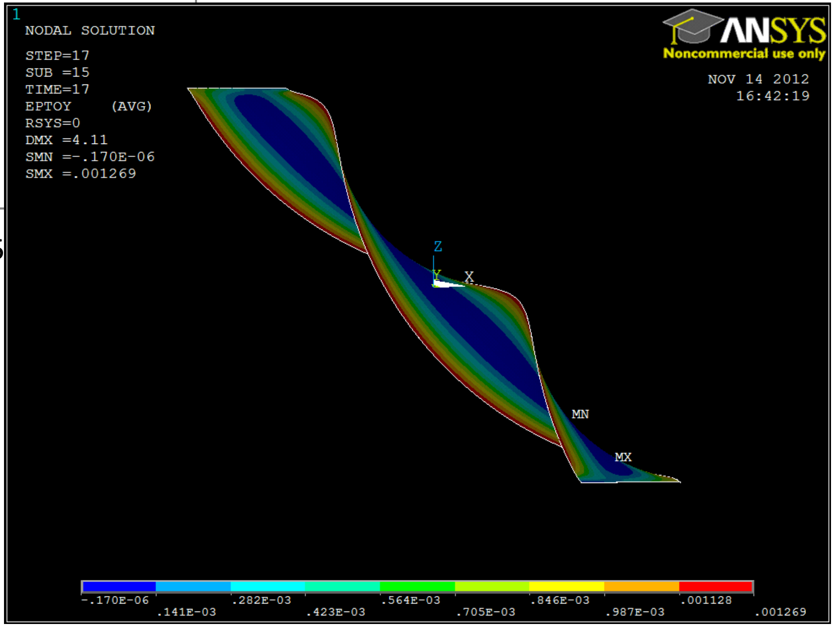
Torsion Simulations



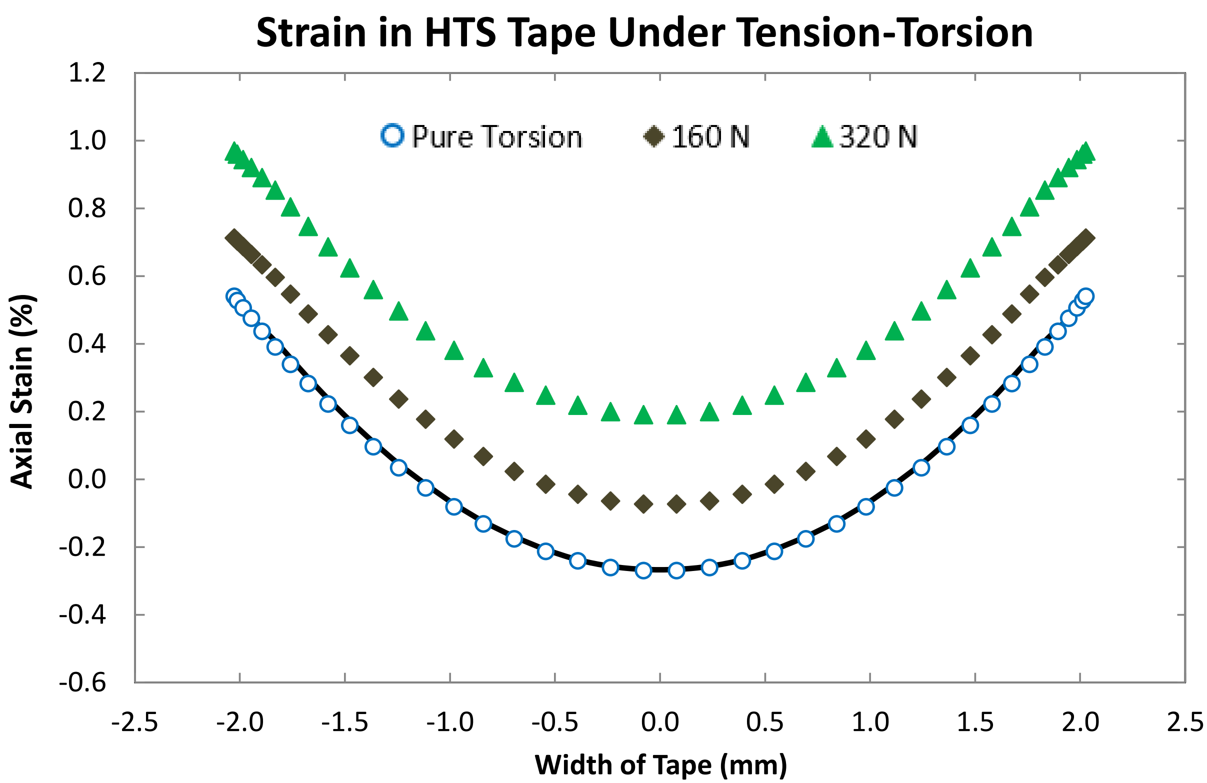
Analytical Relationship

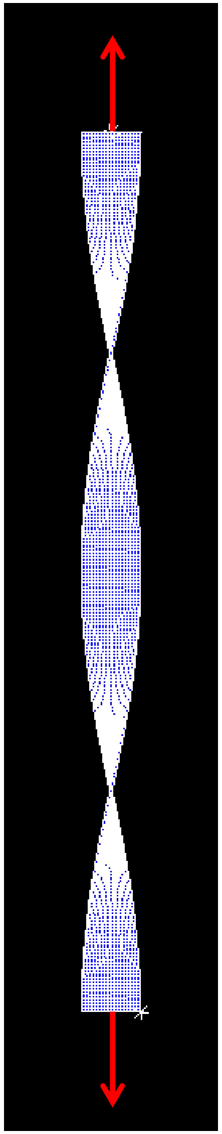
(Takayasu)

$$\varepsilon_x = \varepsilon_t + \varepsilon_o = \frac{\theta^2}{2}\left(x^2 - \frac{w^2}{3}\right)$$



Combined Tension-Torsion

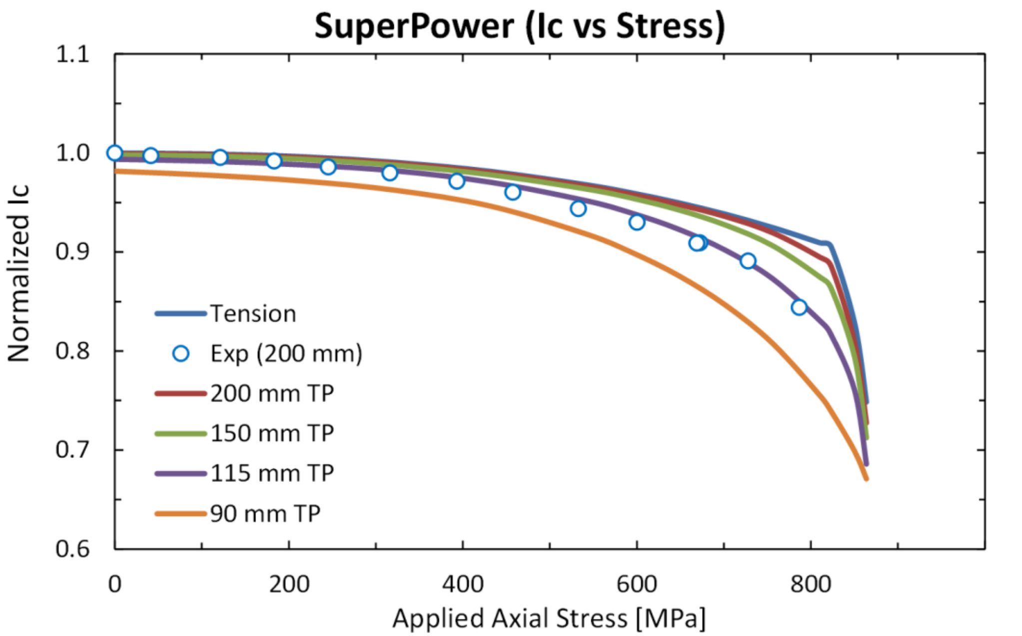




$$I_{c\theta} = \frac{1}{2w}\int_{-w}^{w} I_c\,(\varepsilon_{b\theta},\ x)\ dx$$

Ic is represented by a polynomial function based on experimental tension/compression data

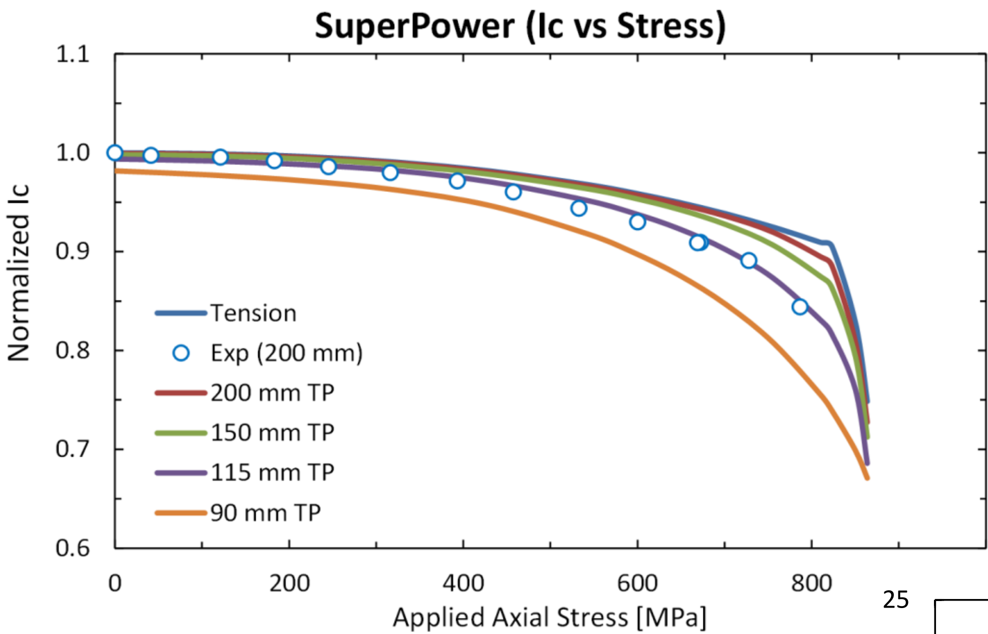
Tension-Torsion Simulations



Sharp degradation in Ic correlates to the yield strength of the tape

Tension-Torsion Simulations

Tufts UNIVERSITY



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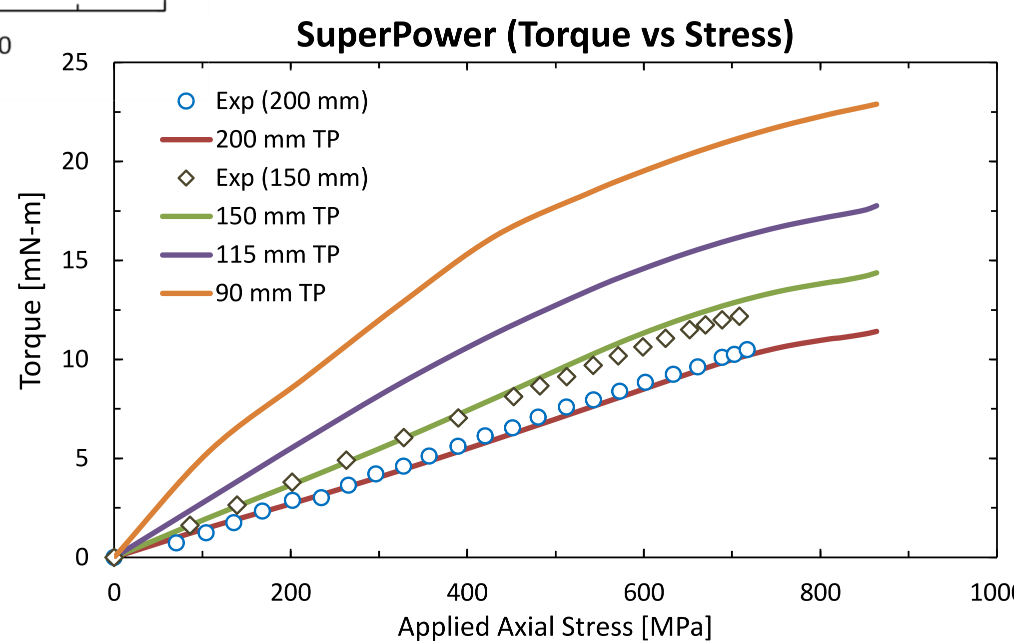
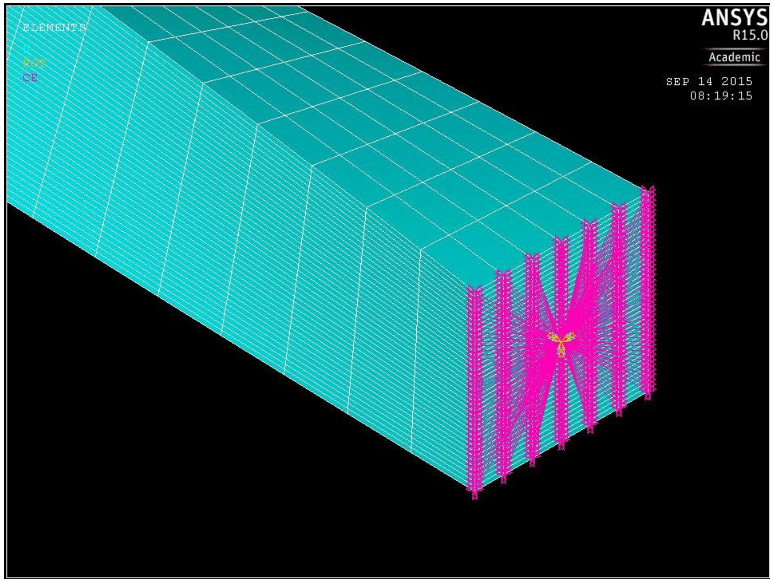


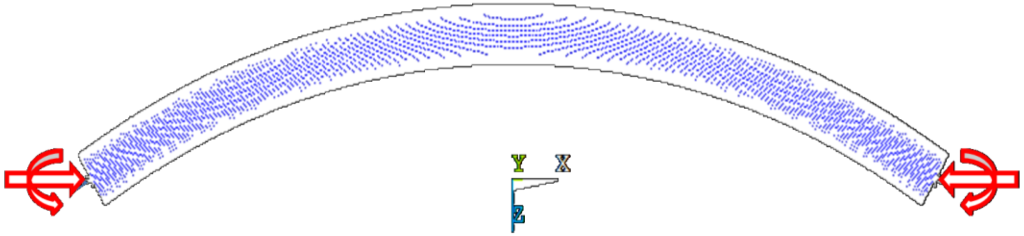
Shorter twist pitches correlate to a greater increase of torque under applied tension

Stacked-Tape Models

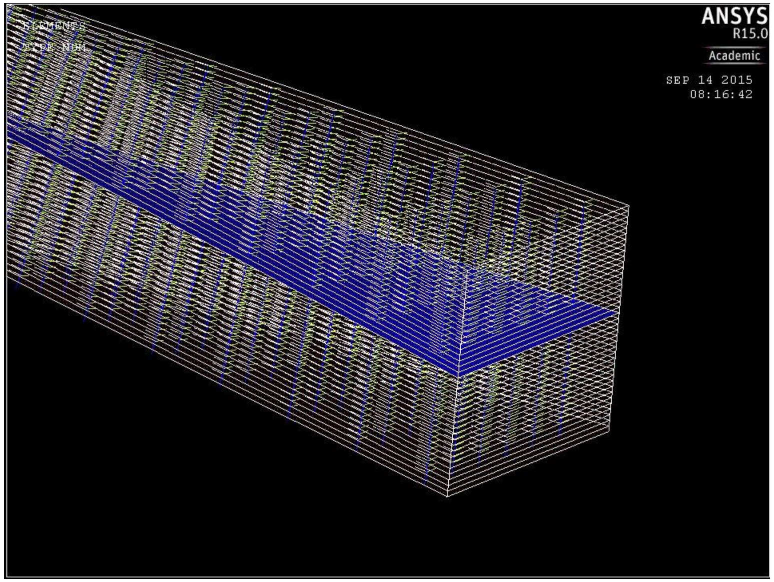
Multipoint constraint
(bending & rotation)

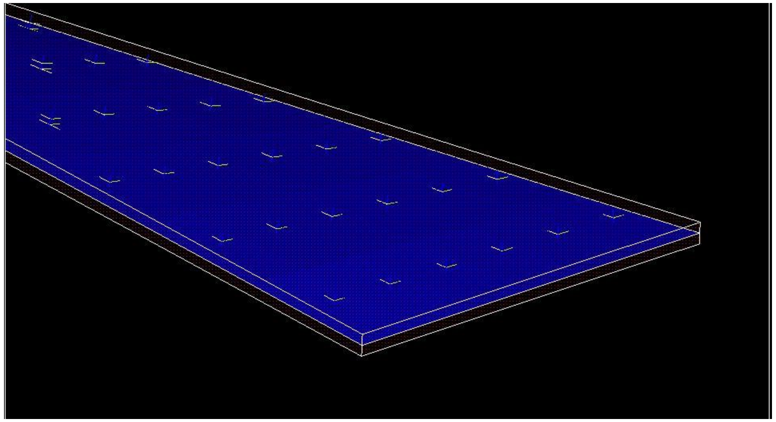


Bending Application

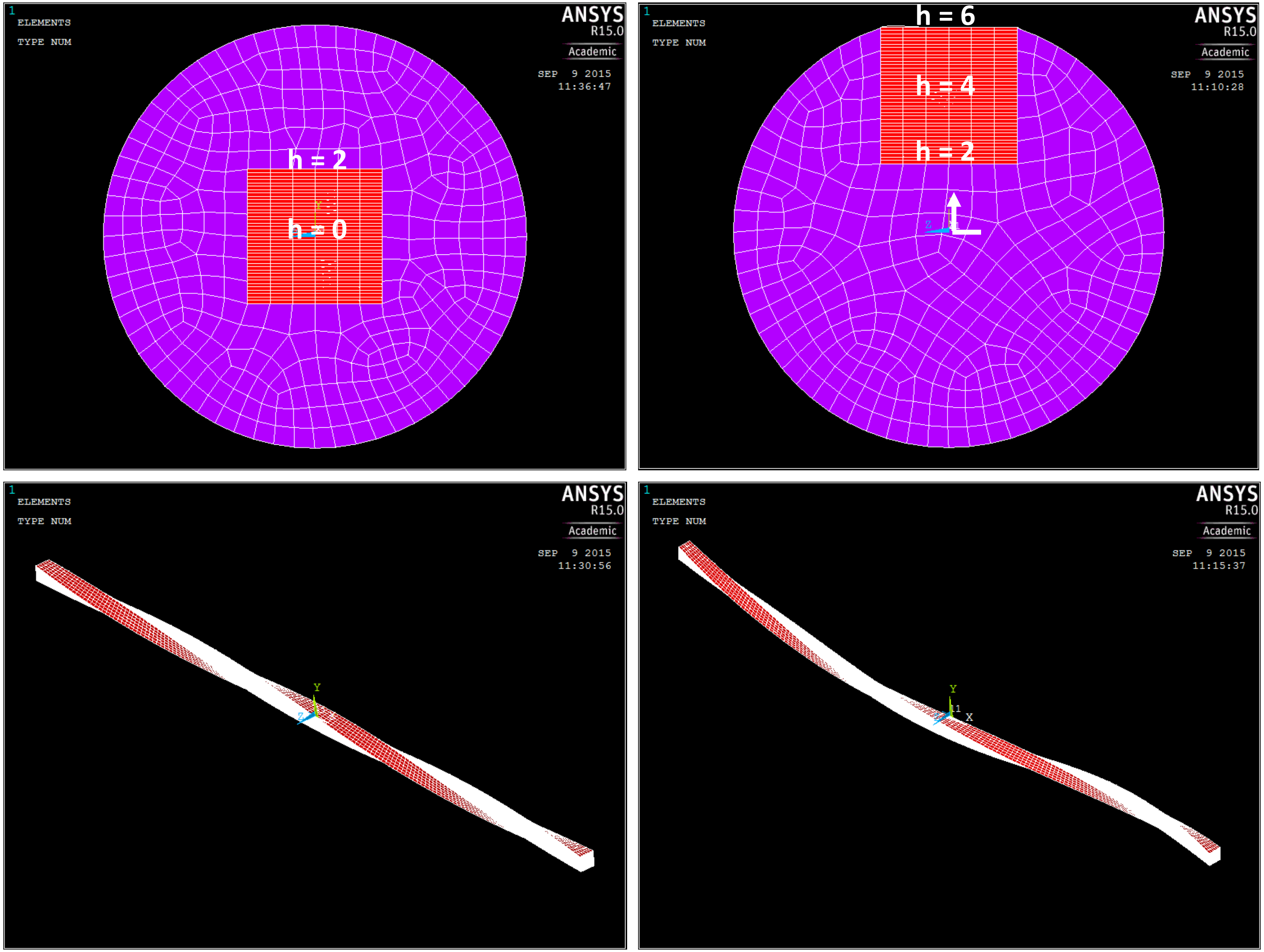


Surface-to-surface contact



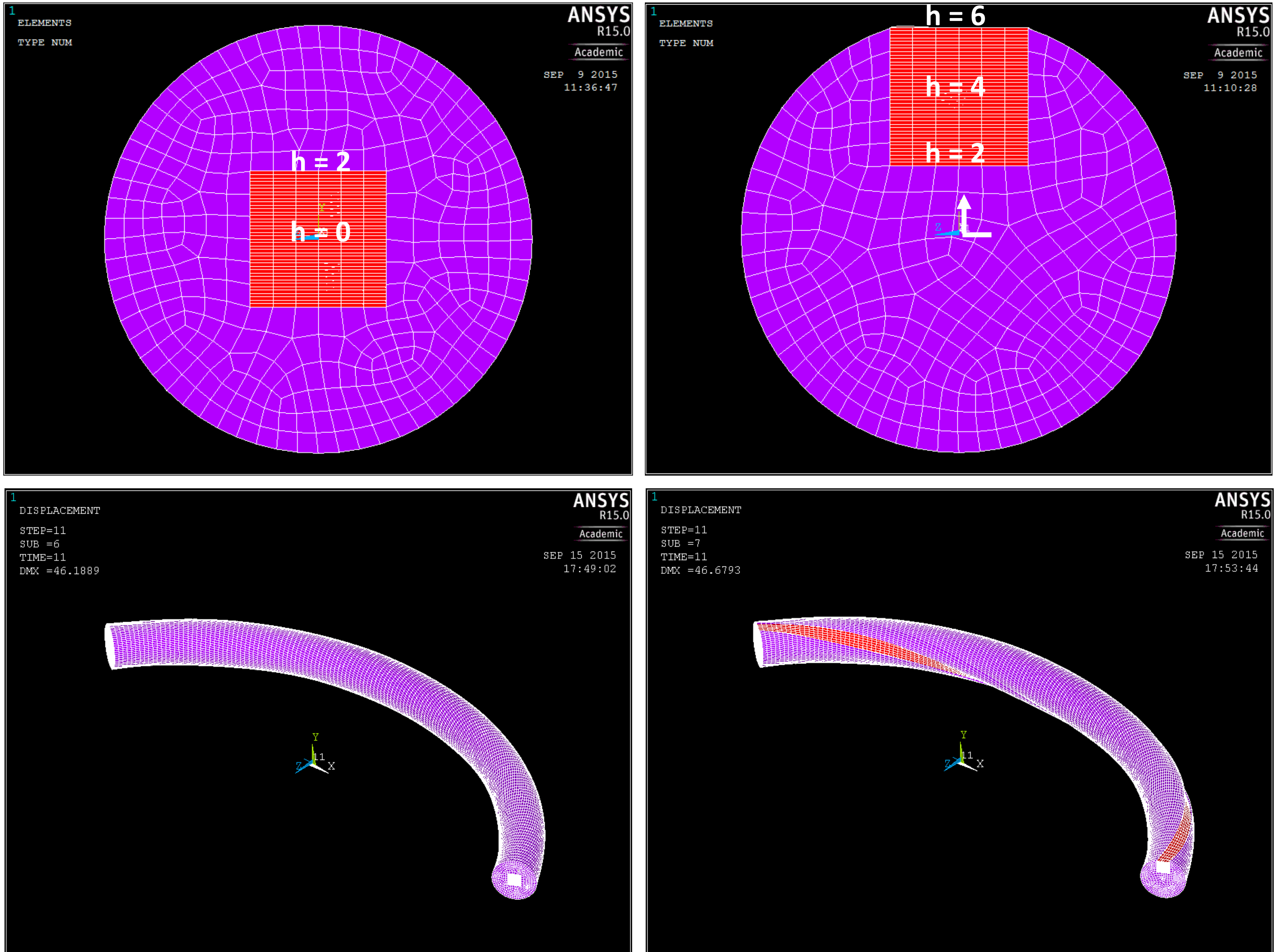


Cable Bending Simulations



Off-center distance (h)

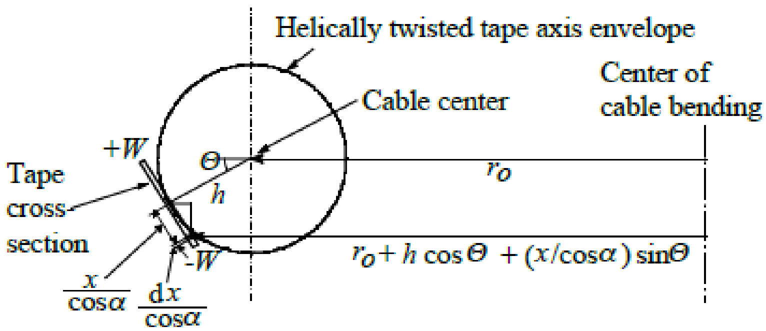
Cable Bending Simulations



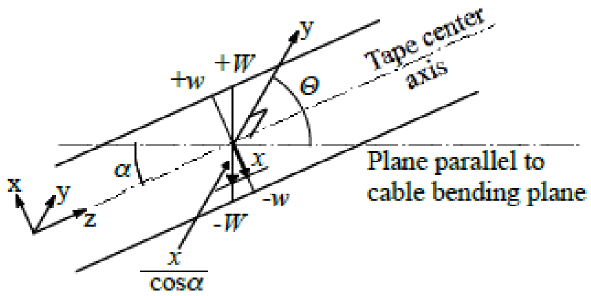
Off-center distance (h)

Cable Bending Simulations

Analytical model for stacked-tape cables under bending *(Takayasu)*

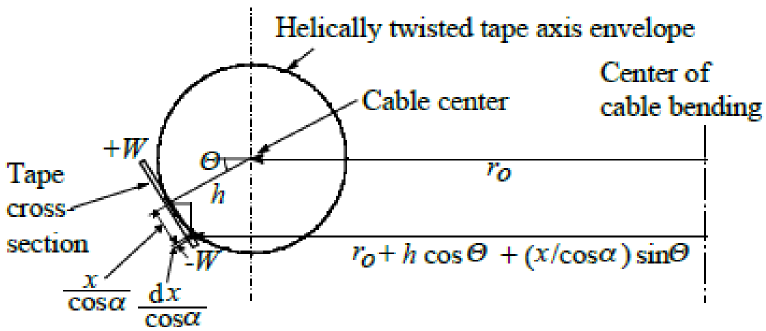


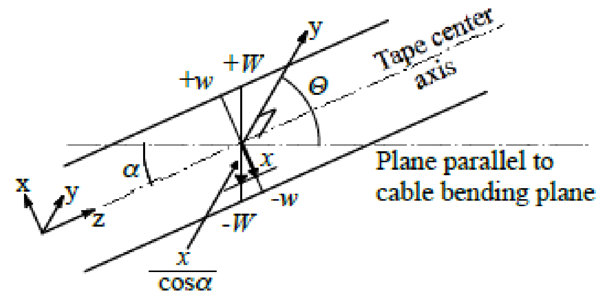
Perfect-Slip Model (PSM)



No-Slip Model (NSM)

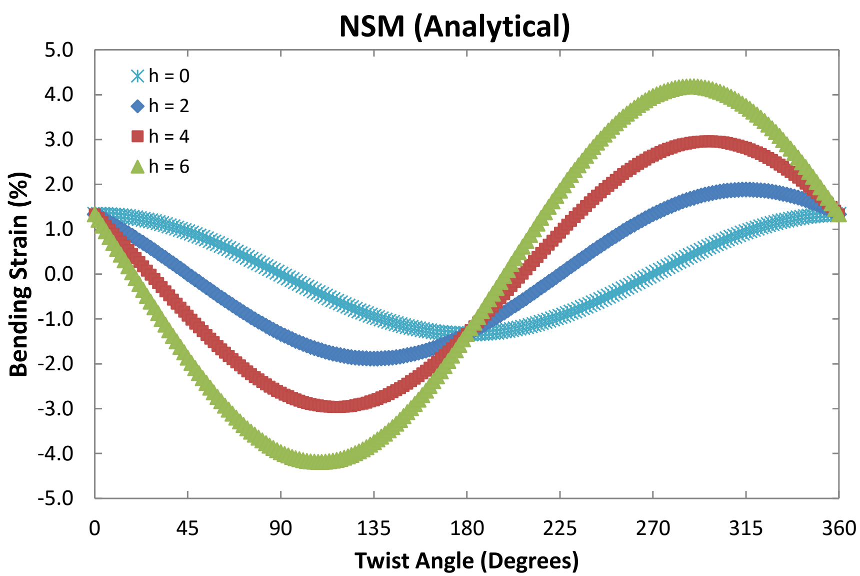
Analytical model for stacked-tape cables under bending *(Takayasu)*





Perfect-Slip Model (PSM)

No-Slip Model (NSM)



Cable Bending Simulations

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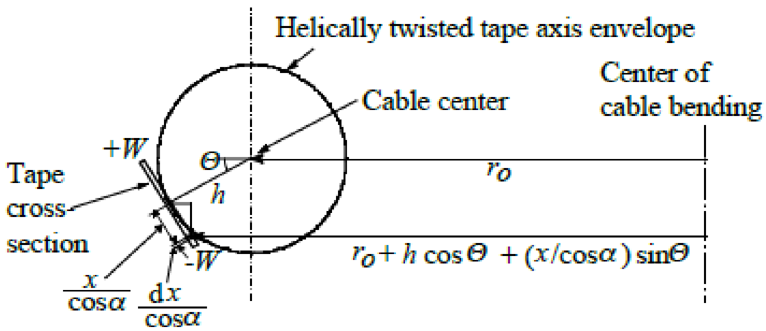

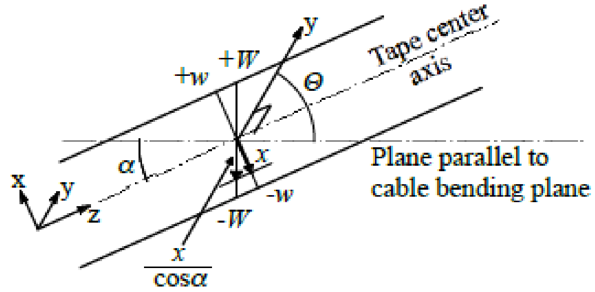

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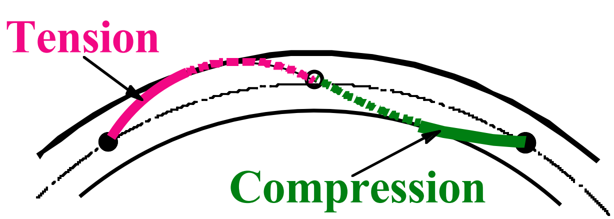
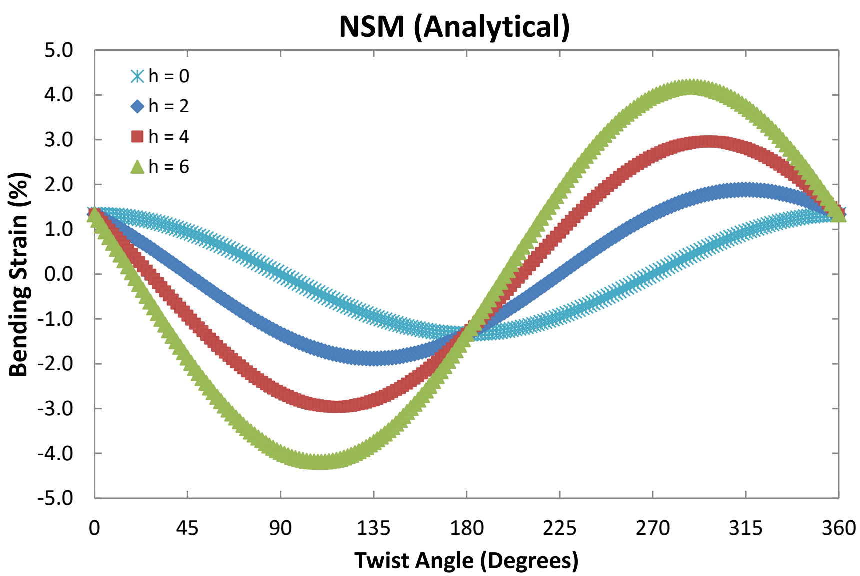


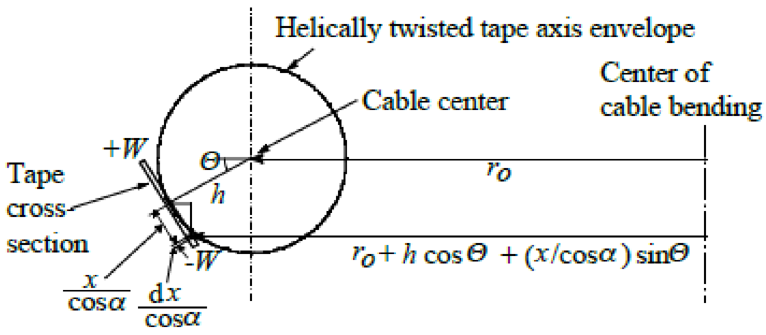
All stacked tapes have the same bending strain

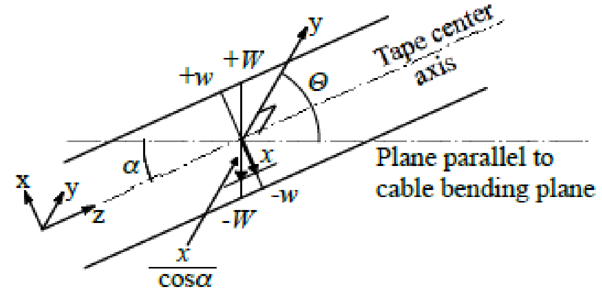
No-Slip Model (NSM)



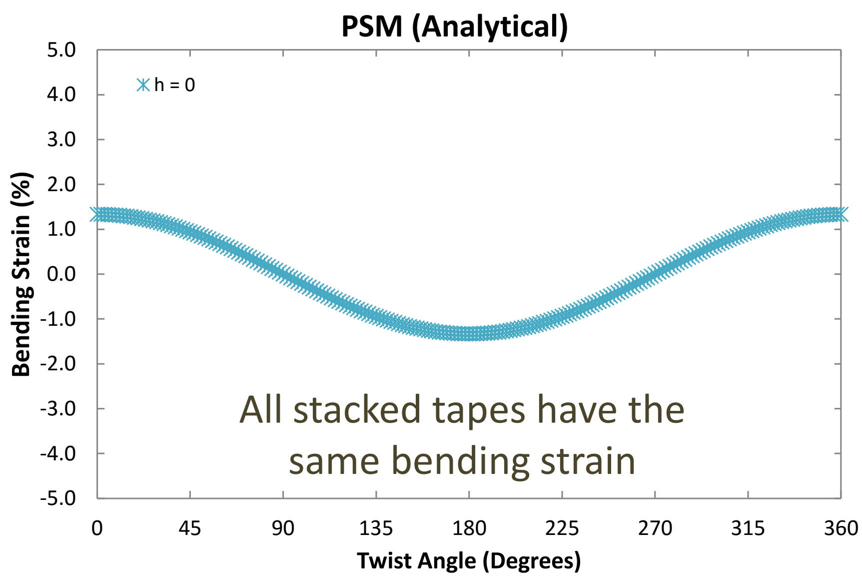
Cable Bending Simulations

Analytical model for stacked-tape cables under bending *(Takayasu)*

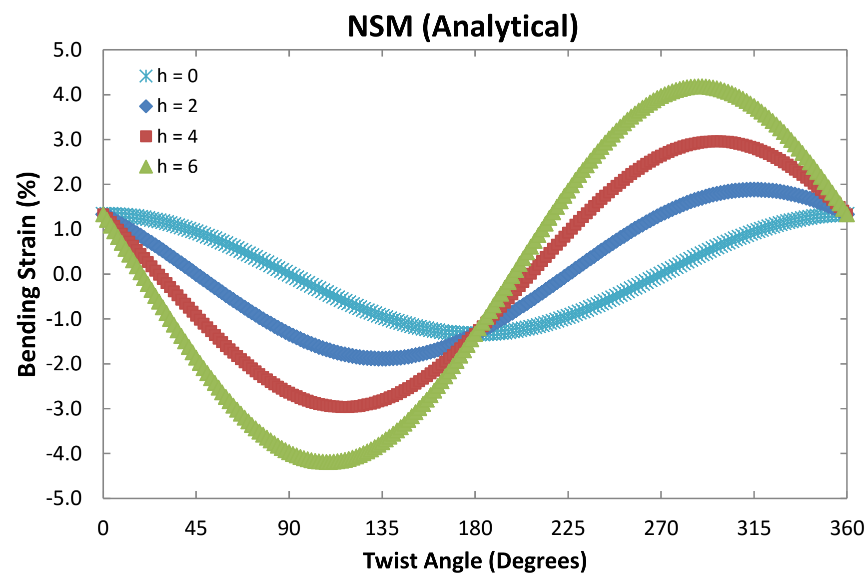




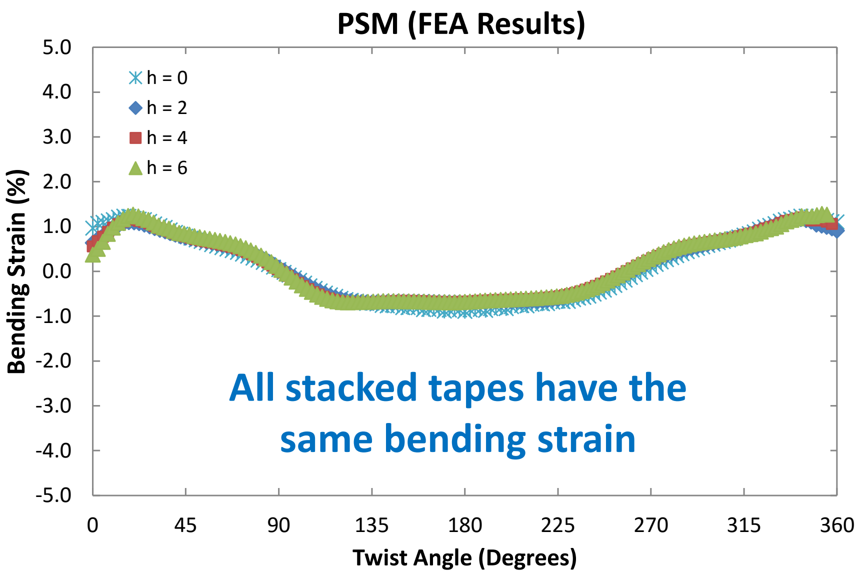
Perfect-Slip Model (PSM)

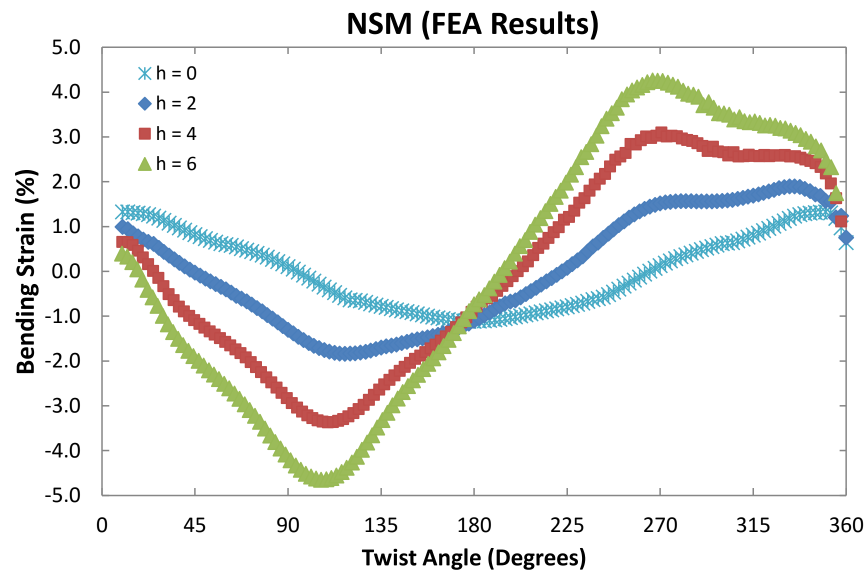


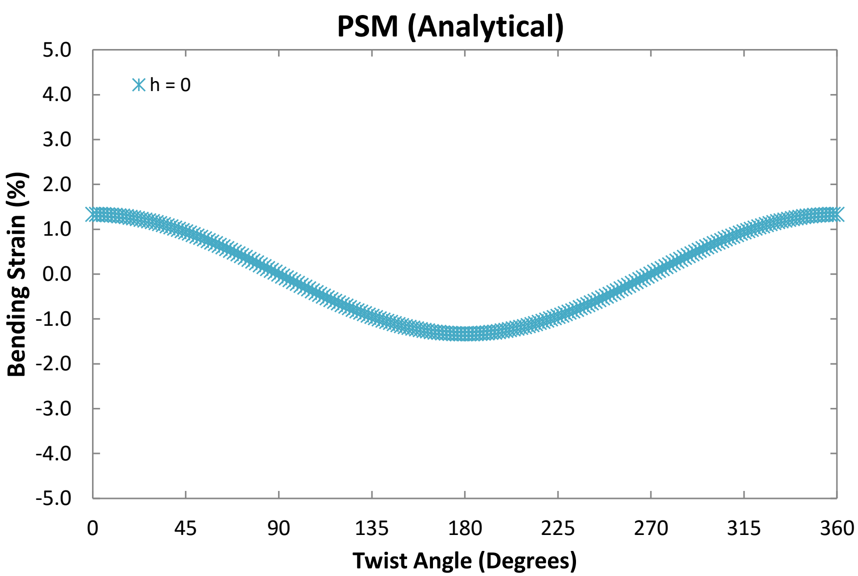
No-Slip Model (NSM)

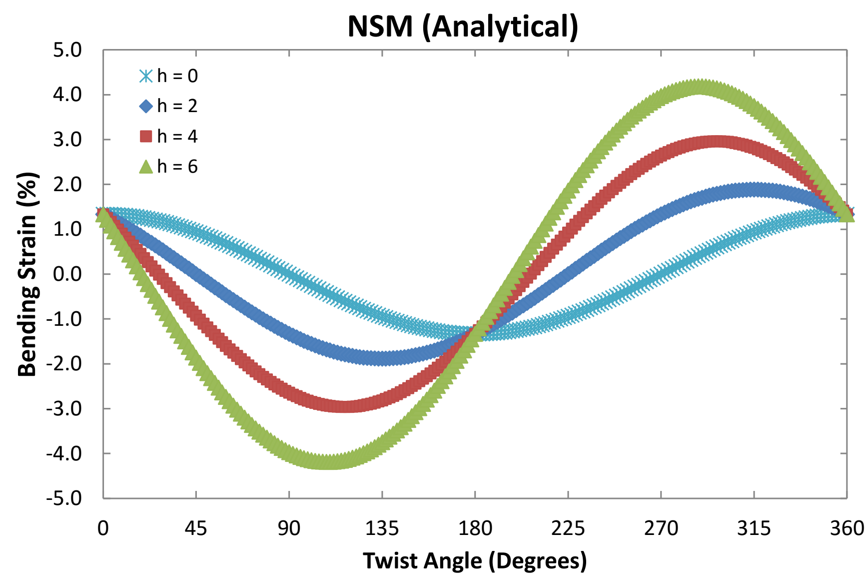


Cable Bending Simulations

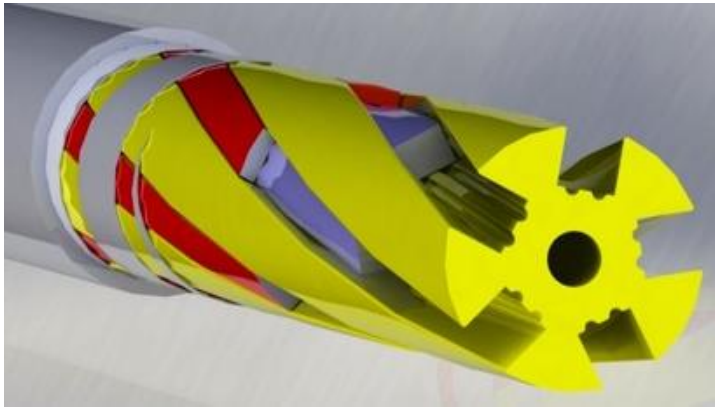


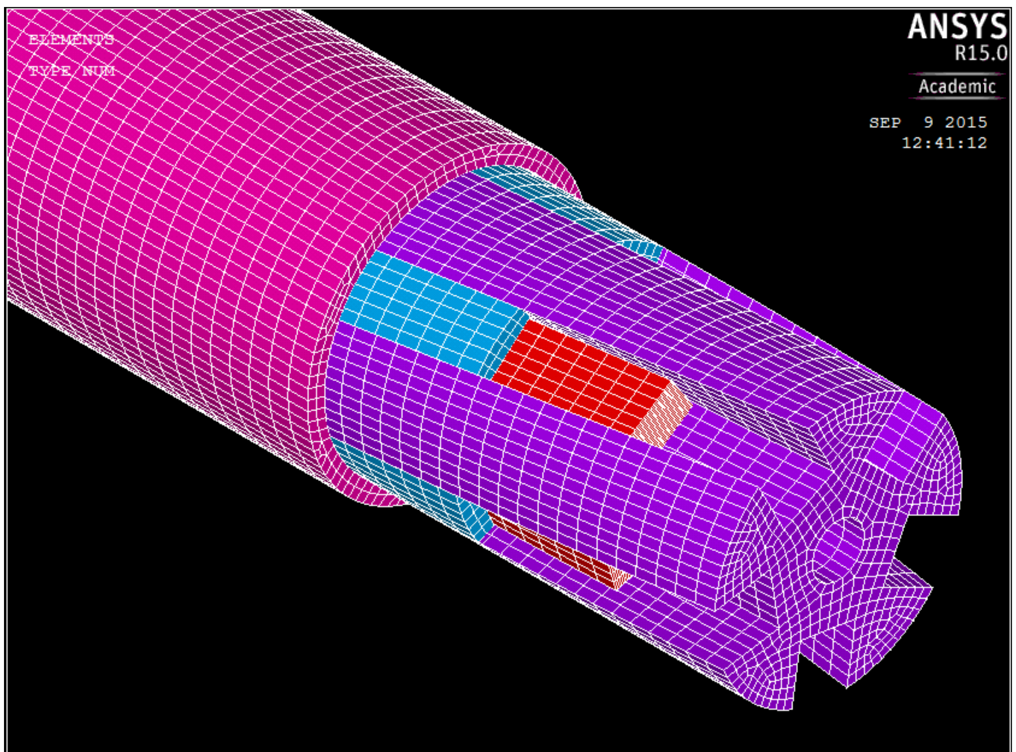




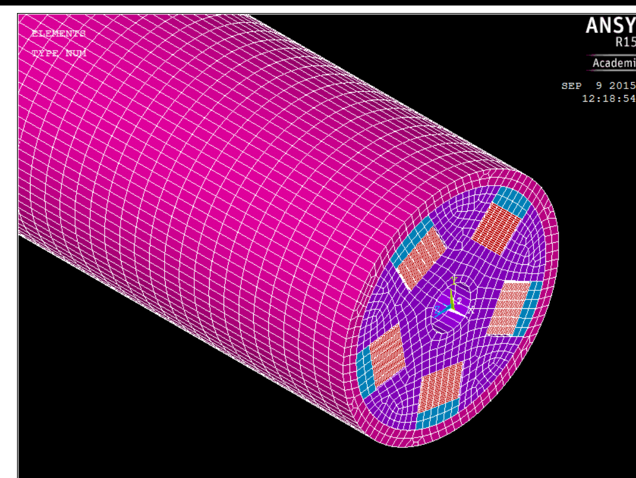


ENEA CICC Bending Model

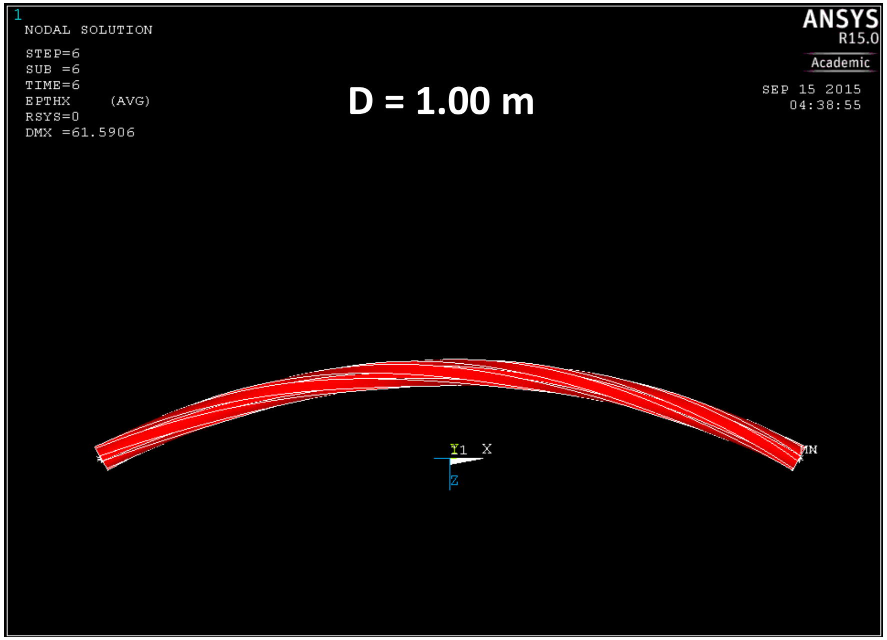




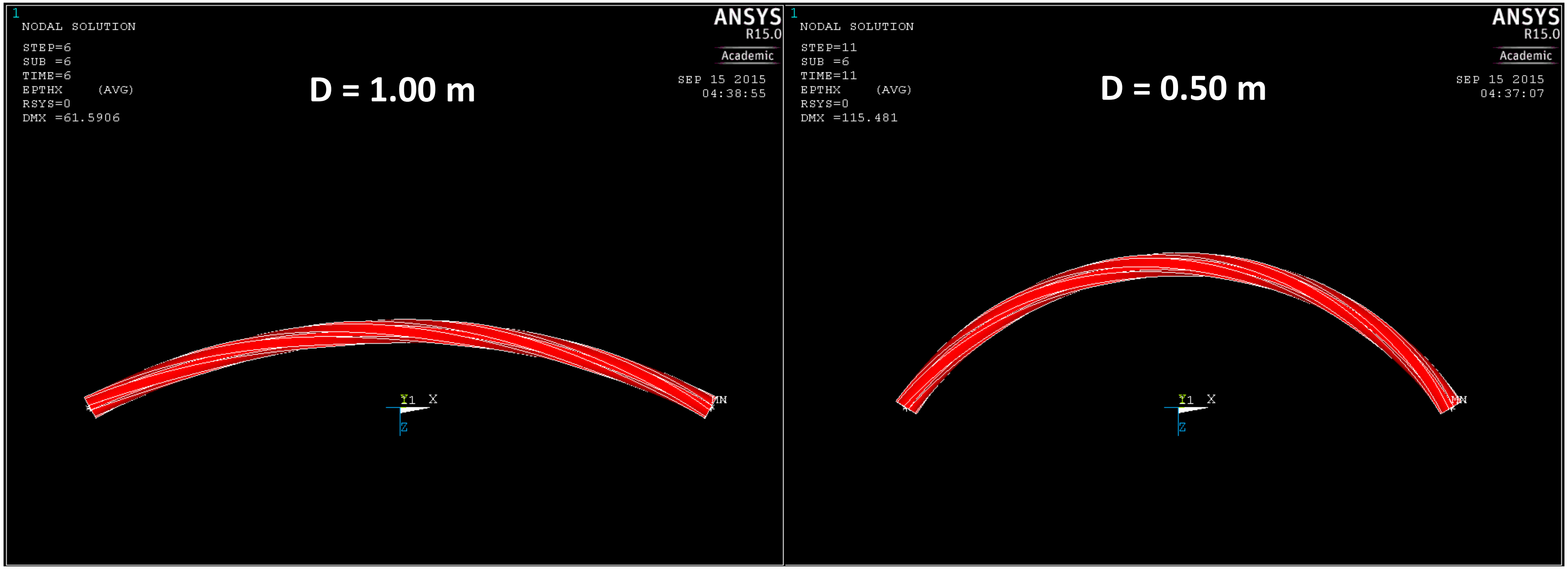

```
!!!!!!!!!! Define Cable Parameters !!!!!!!!!!
Rj = 10.81 ! radius of jacket
Ro = 9.5   ! radius of core
Ri = 2.0   ! radius of cooling channel
Rc = 4.95  ! radius of channel base
Rs = 0.54  ! radius of copper spacer wire
Wc = 4.3   ! width of channel
W  = 4.0   ! width of tape
H  = 0.15  ! thickness of tape
Nt = 20    ! number of tapes per stack
Tp = 500   ! twist pitch
Lm = 100   ! length of model
LL = Tp/Lm ! fraction of model length
Ns = 5     ! number of slots (max=6 & min=2)
Es = 0.75  ! element edge length
```



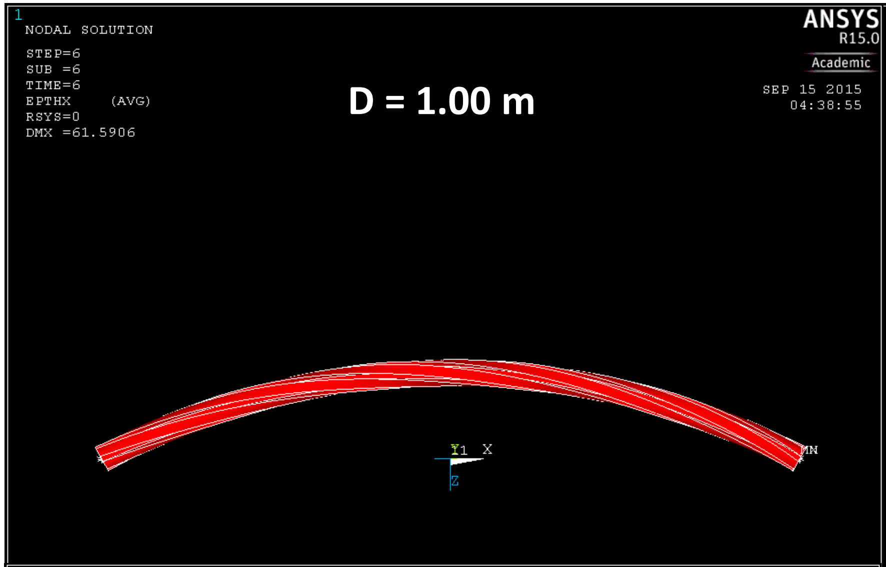
ENEA CICC Bending Model

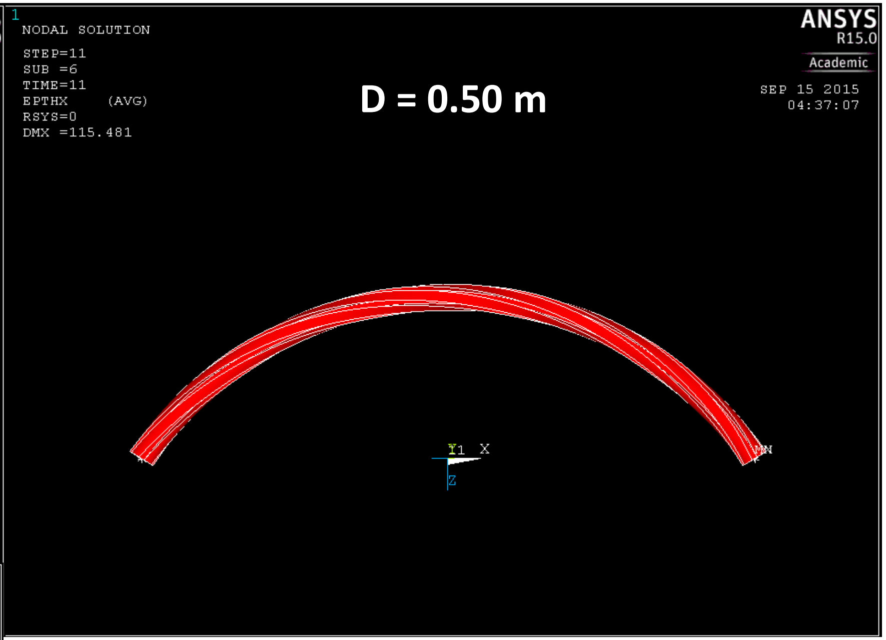


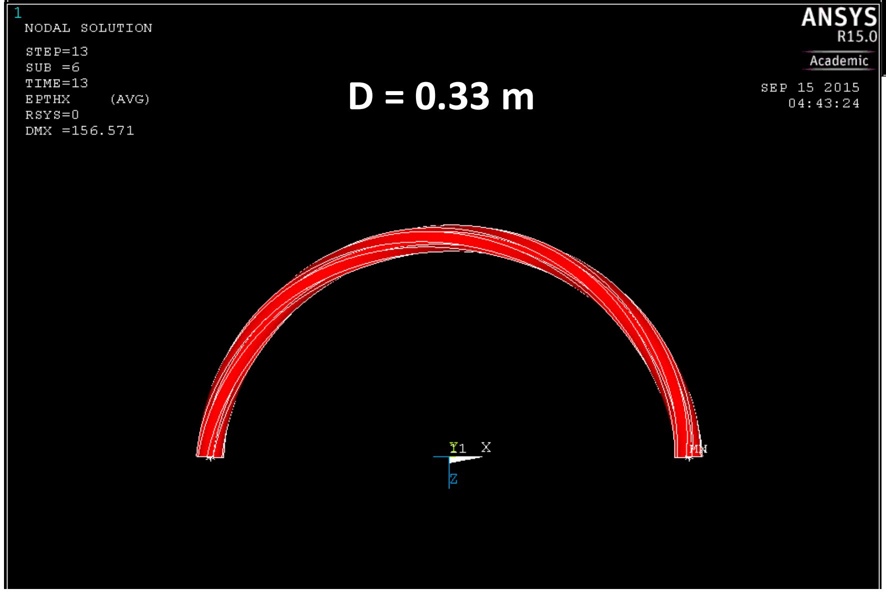
ENEA CICC Bending Model



ENEA CICC Bending Model

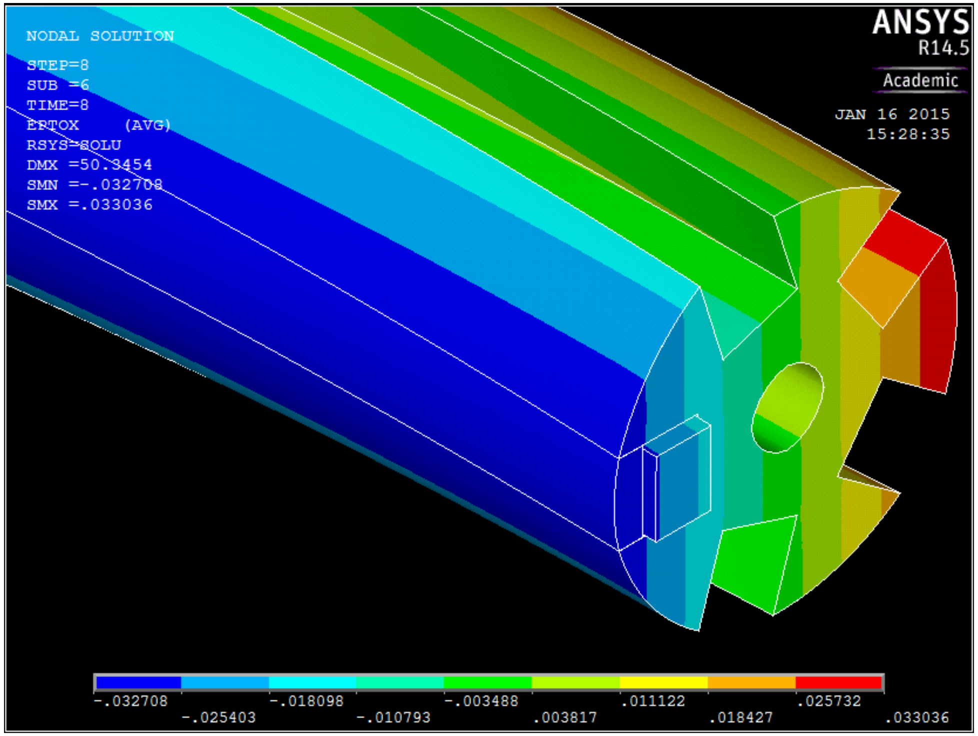


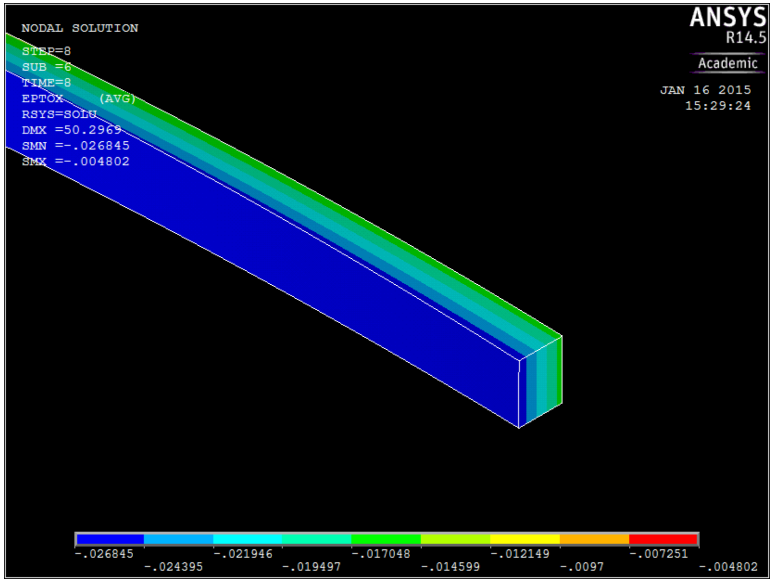


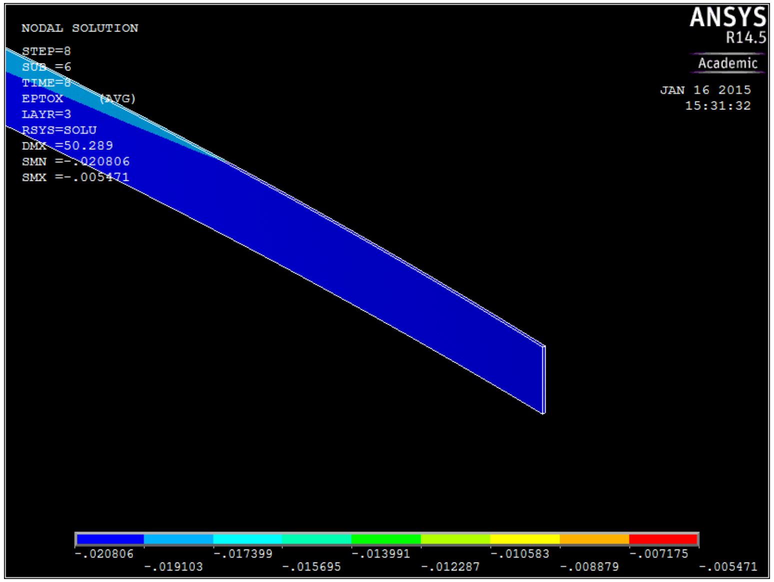


ENEA CICC Bending Model

ENEA CICC Bending Model







Strain results for tapes in the ENEA CICC under bending is a **work-in-progress** and will be presented at MT24

Conclusion

Successfully developed method to numerically model layered 2G HTS tapes and validated model under various mechanical loads *(tension, torsion and combined loading of single tapes)*

Created technique to model behavior of stacked-tape cables and validated model under bending with analytical models (PSM & NSM)

Developed a detailed cable model of the ENEA slotted core CICC under bending which will be used to compare predicted Ic behavior with experimental results *(optimization is being conducted at ENEA)*

Stacked-tape cable modeling technique can be applied to large scale conductor design, conductor fabrication and electromagnet operation

Bologna, Italy | September 14-16, 2015

Thank you for your attention

Questions?

Mechanical Engineering Department