Mechanical Properties of the NCSX Modular Coil Conductor

14 January 2004

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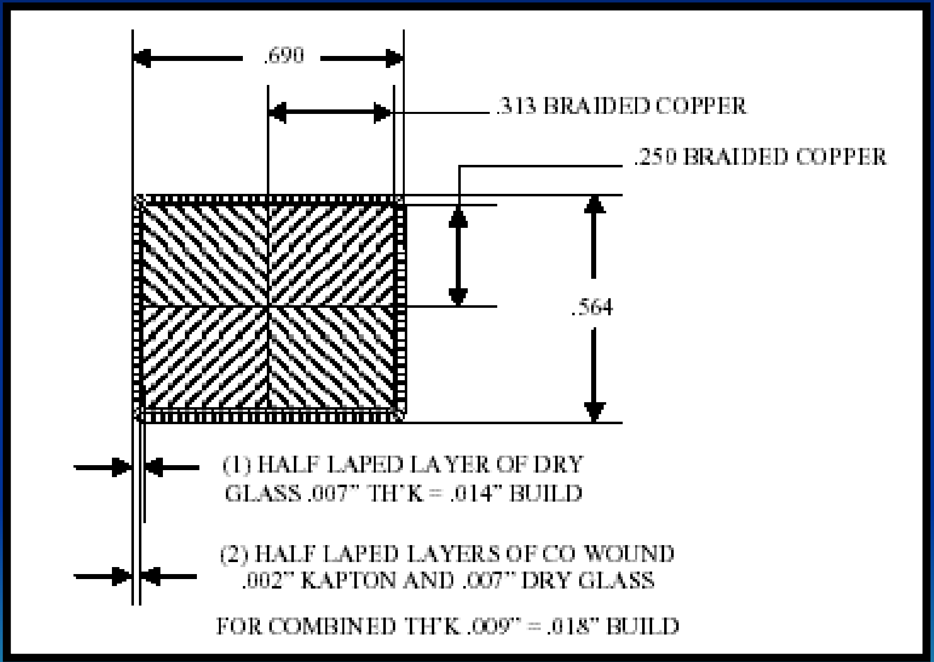
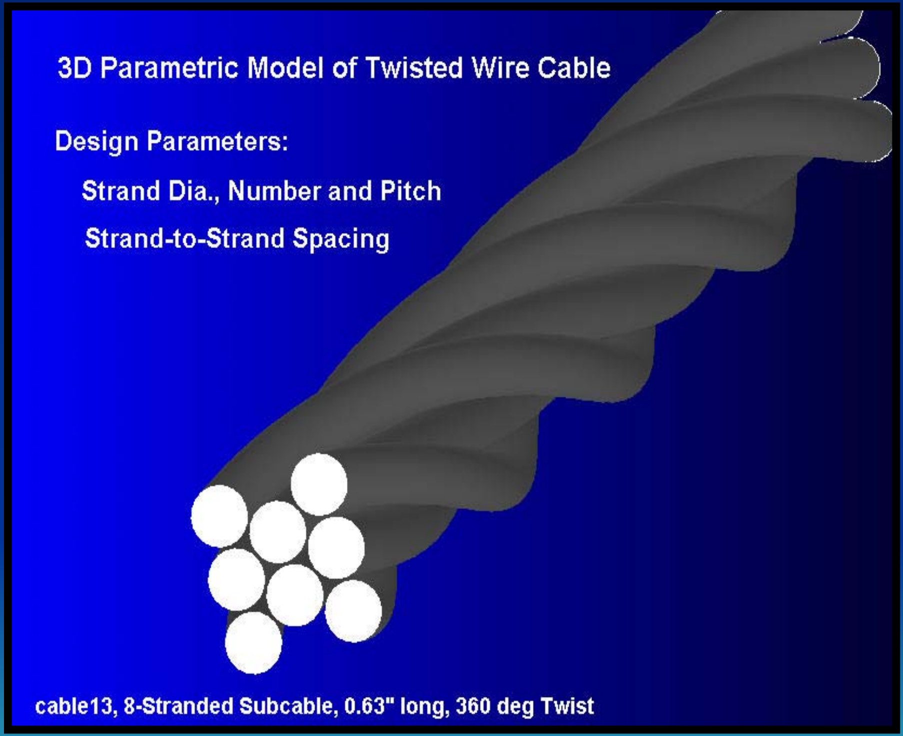
Q: What is the Modular Coil Conductor Elastic Modulus?

CTD Mechanical Tests of Insulated Single Modular Coil (ISMC)



ANSYS Twisted Cable Model (Glass Wrap and Impregnating Epoxy not shown)



A: Detailed in the memos…

- "Princeton Plasma Physics Laboratory Test Program to Determine the Mechanical and Thermal Properties of the Epoxy/Insulation System for the NCSX Modular Coils," Composite Technology Development, Inc., Lafayette, CO, 11/21/03.
- Leonard Myatt, "Mechanical Properties of the Modular Coil Conductor, Test Data & Modeling," January 6, 2004.
- Or…see the highlights that follow.

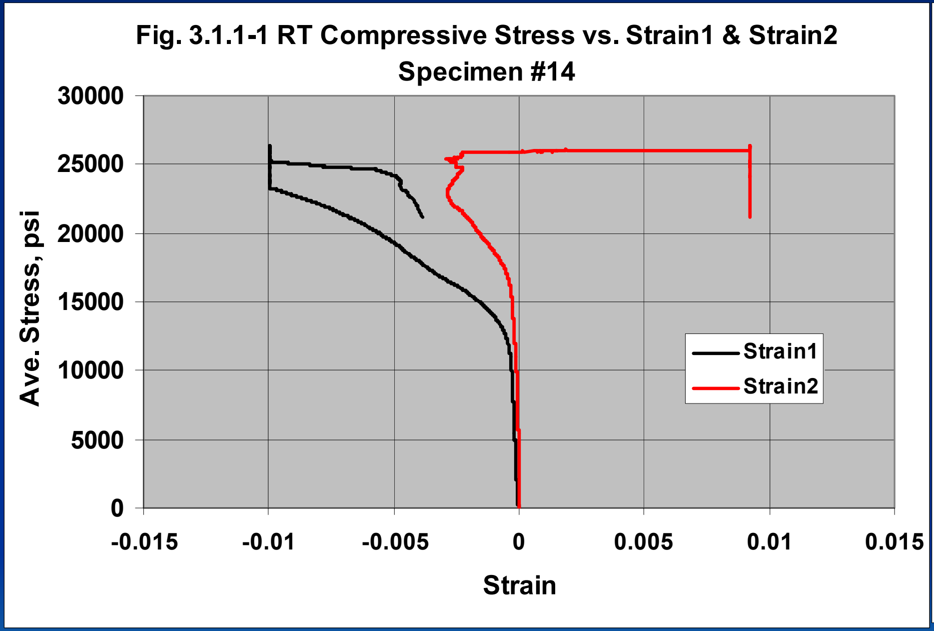
Compression Test Data by CTD

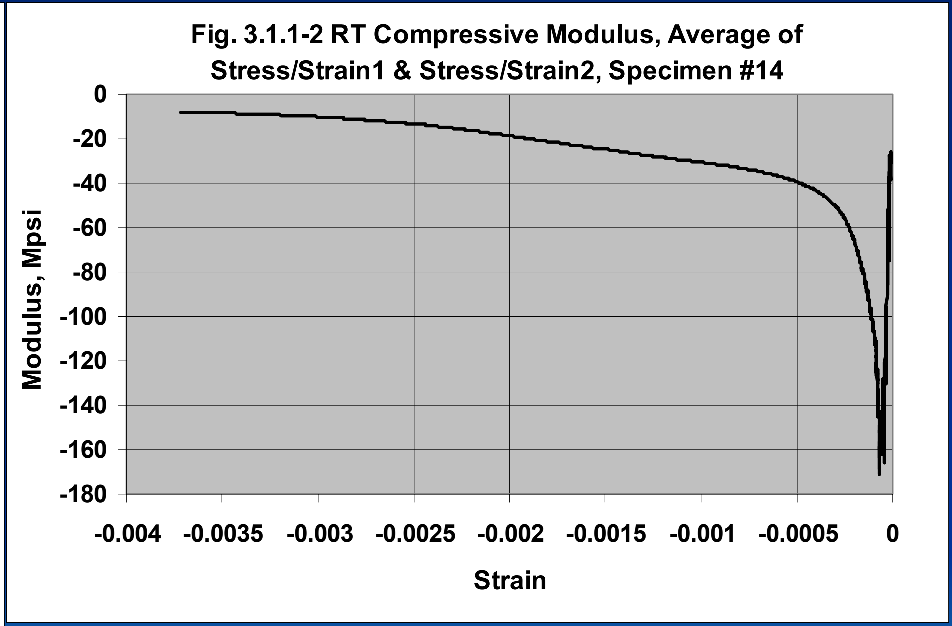
- Lots of test data provided on a CD.
  - Forces from MTS machine.
  - Strains from strain gages.
  - Deflections from LVDT (used to calc strain).
- Average Room Temp (RT) moduli:
  - 37 Mpsi from strain gage data
  - 2.9 Mpsi from LVDT

Compression Specimen #14 Strain Gage Data and RT Modulus

Strange looking data…
…not unique to Specimen #14.

Average the strains and take a derivative.



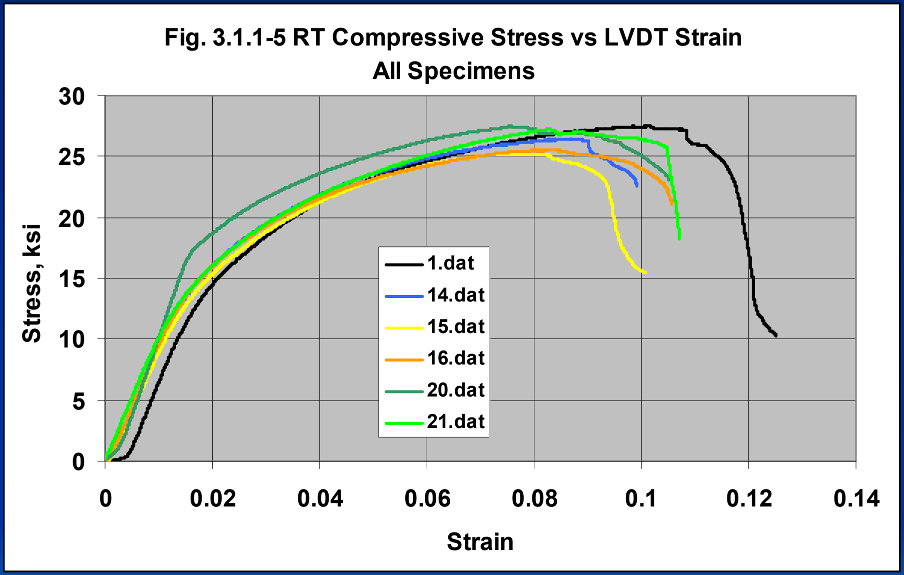


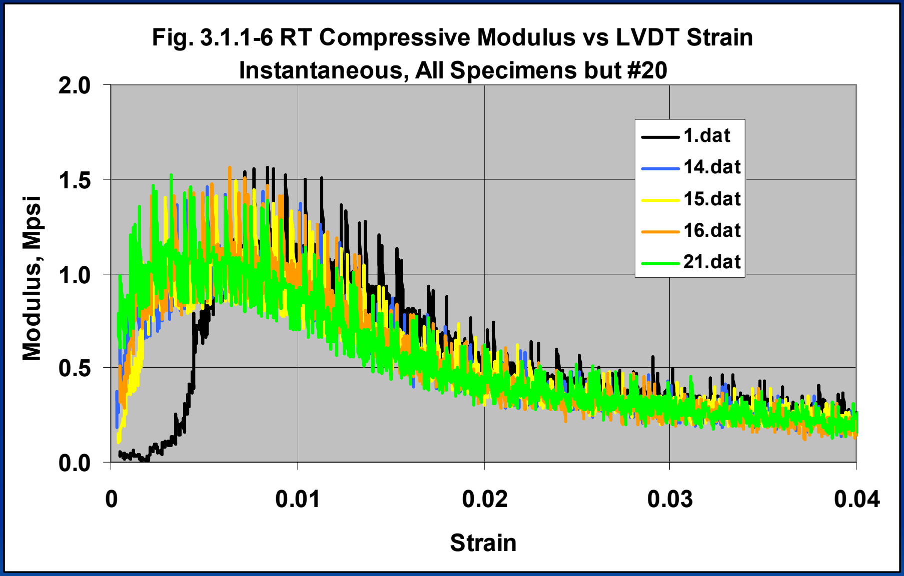
CTD report lists a modulus of 62.6 Mpsi

RT LVDT Strain and Modulus (Many Compression Specimens)

Stress vs. LVDT Strain looks OK

Modulus vs. LVDT Strain looks OK
With Max. values at ~1.1 Mpsi





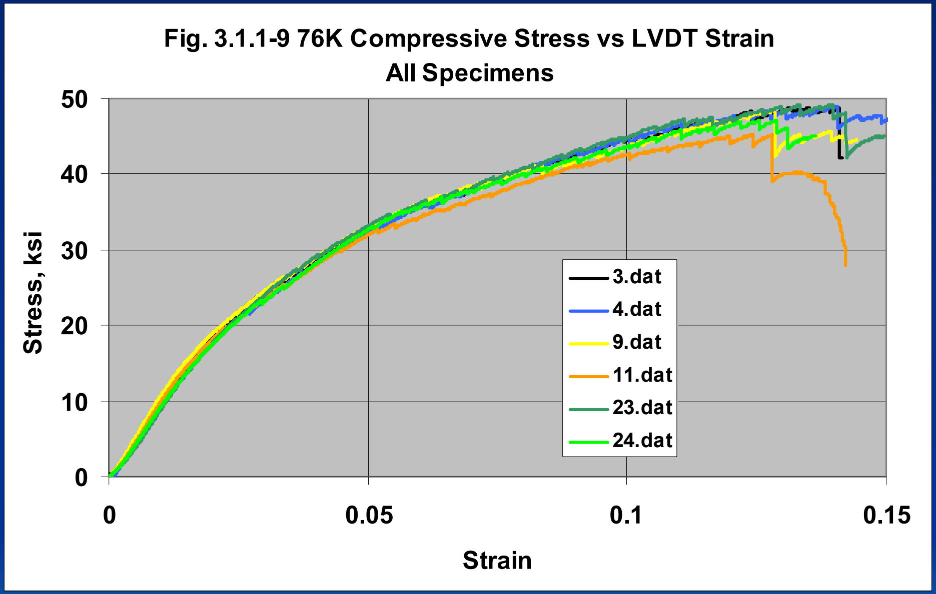
Ultimate Stress: ~26 ksi
Onset of yield: ~10 ksi

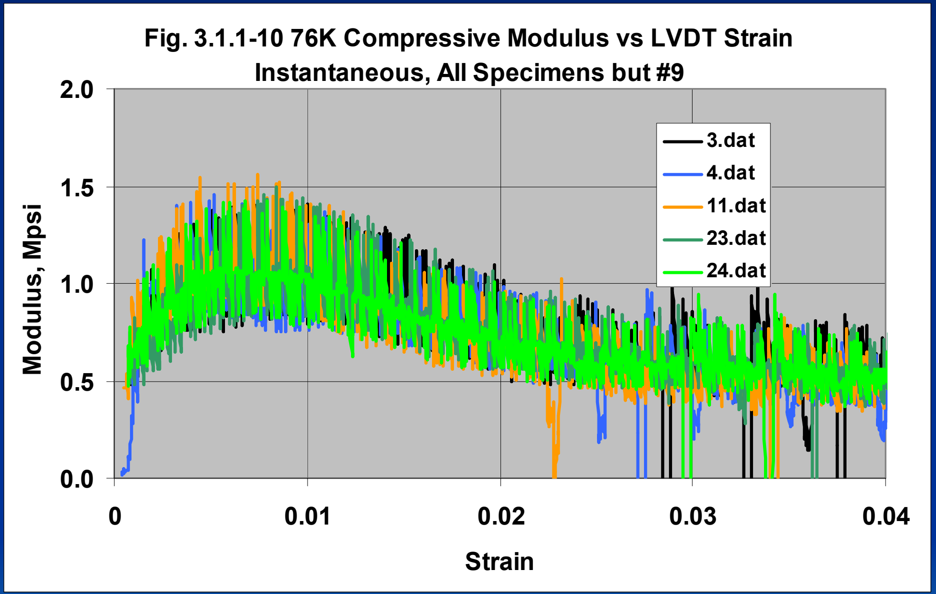
Numerical derivative of data typically noisy.

76K LVDT Strain and Modulus (Many Compression Specimens)

Curves look reasonable.
Cold specimens fail at higher stress.

Modulus vs. LVDT Strain looks OK
…but little change from RT values.





Ultimate Stress: ~45 ksi
Onset of yield: ~15 ksi

Misc. Observations

- Rule of Mixtures Modulus: 85 GPa (12 Mpsi)
- LVDT Compression Modulus: ~8 GPa (1.1 Mpsi)
- Compression Yield/Ultimate: ~0.40
- Q: At what stress level is the current-carrying capacity of the conductor affected?
- Q: What are the effects of cyclic loading?

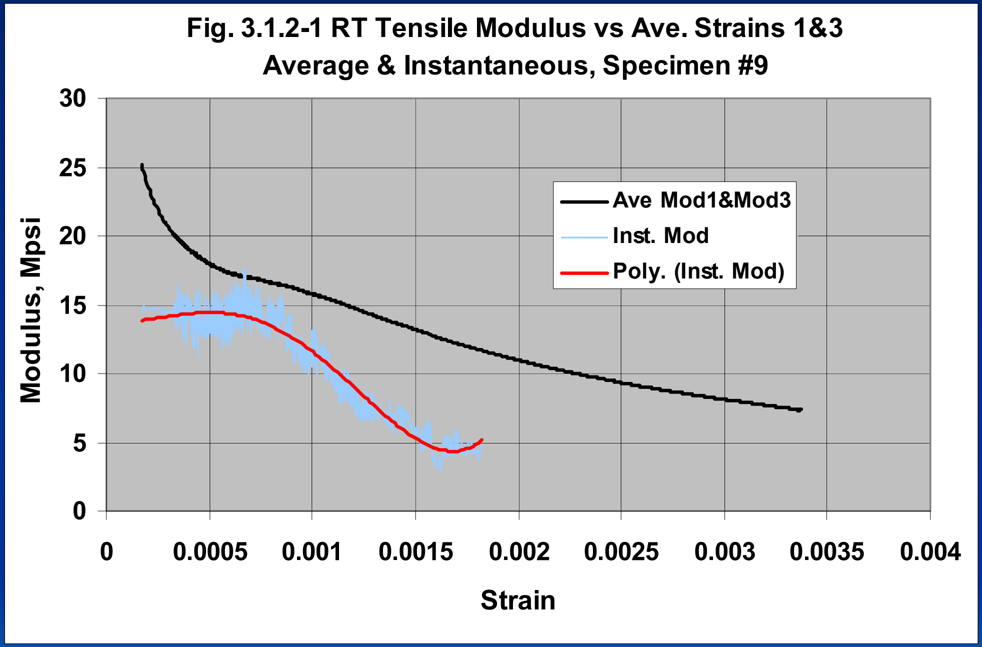
- OK…let's look at some tension test data.

Tension Test Data by CTD

- Lots of test data provided on a CD.
  - Forces from MTS machine.
  - Strains from strain gages.
  - Deflections from LVDT (used to calc strain).
- Average RT moduli:
  - 13.2 Mpsi from strain gage data *(sounds high)*
  - LVDT modulus not reported

Tension Specimen #9 Strain Gage Data and RT Modulus

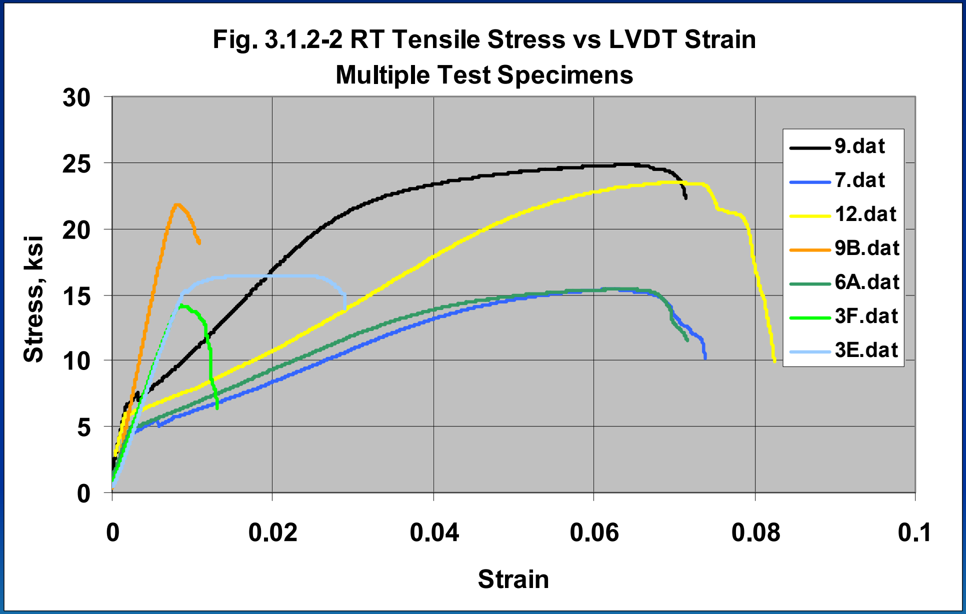
- CTD memo reports a modulus of 13.9 Mpsi.
- Derivative of Stress vs. Strain gage data curve indicates similar result.

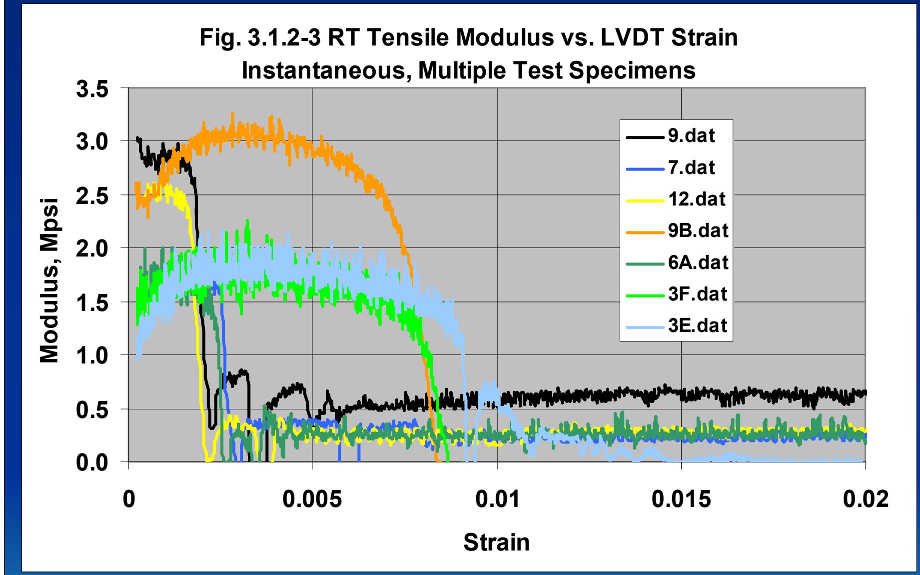


RT LVDT Strain and Modulus (Many Tension Specimens)

All specimens have "steep" initial slope.
Some stay "stiff" and failure at low strains.
Some soften at 4-7 ksi and fail at high strains.

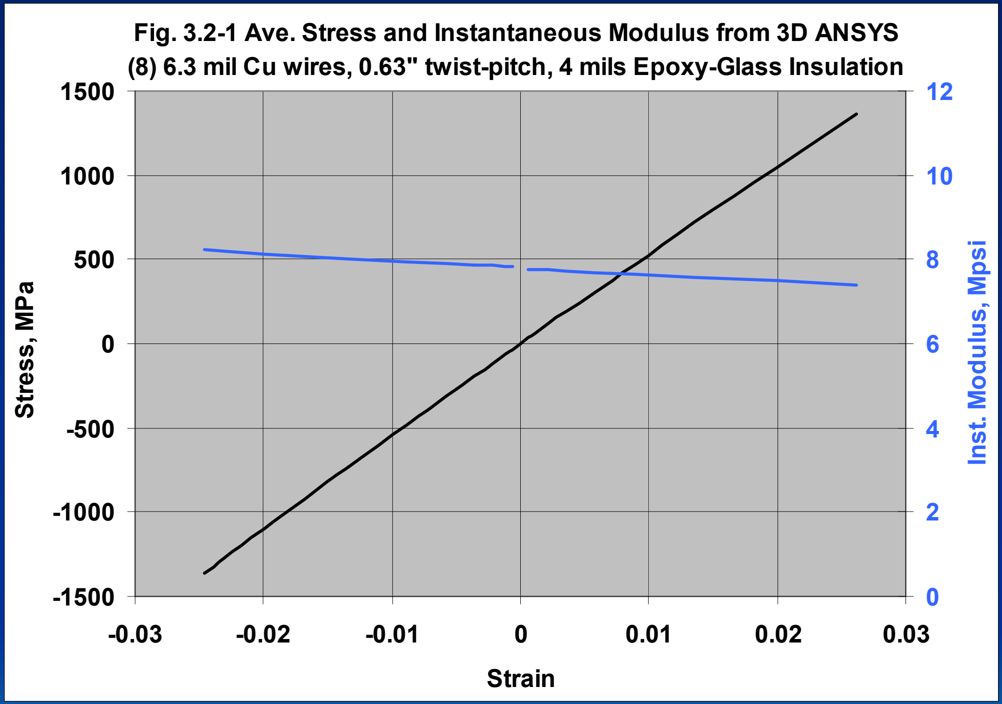
Modulus vs. LVDT Strain shows these two different characteristics.





What would a 3D ANSYS Model of a Strand Cable Predict?

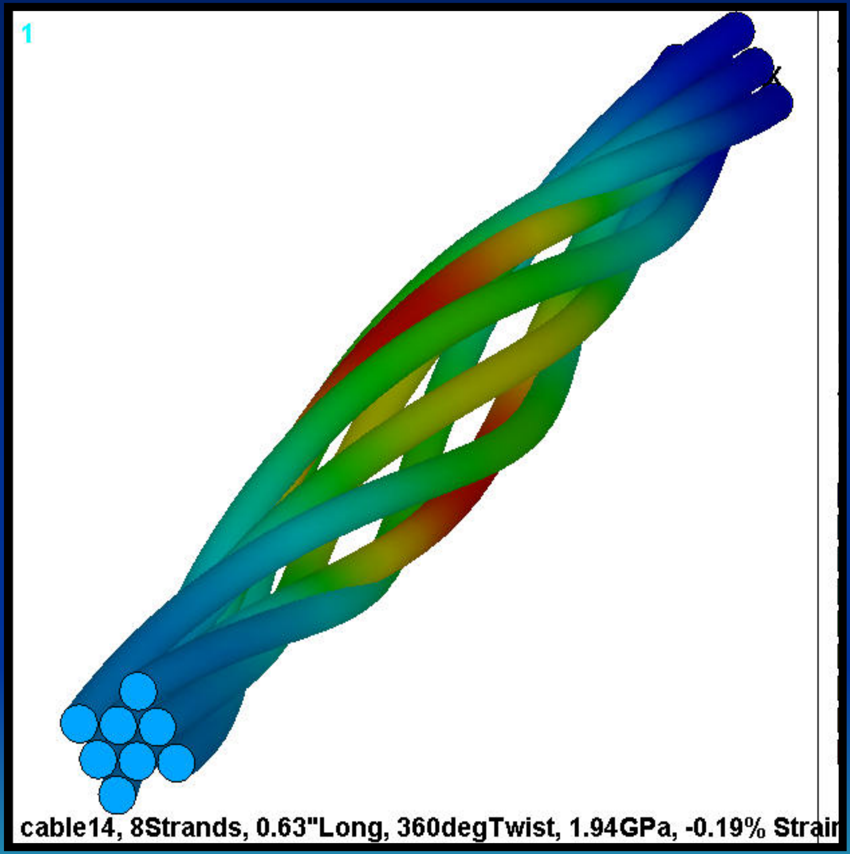
- Modeling the entire 44x5x9 Cu stranded cable would be *crazy* (computer resource issue).
- Modeling an 8-strand cable is relatively easy.
- With linear materials and Large-Deflection theory, the modulus is only a weak function of axial load direction & magnitude.
- ~8 Mpsi which matches Rule of Mixtures.



Stress-Strain curve (black)
Local derivative indicates modulus (blue)

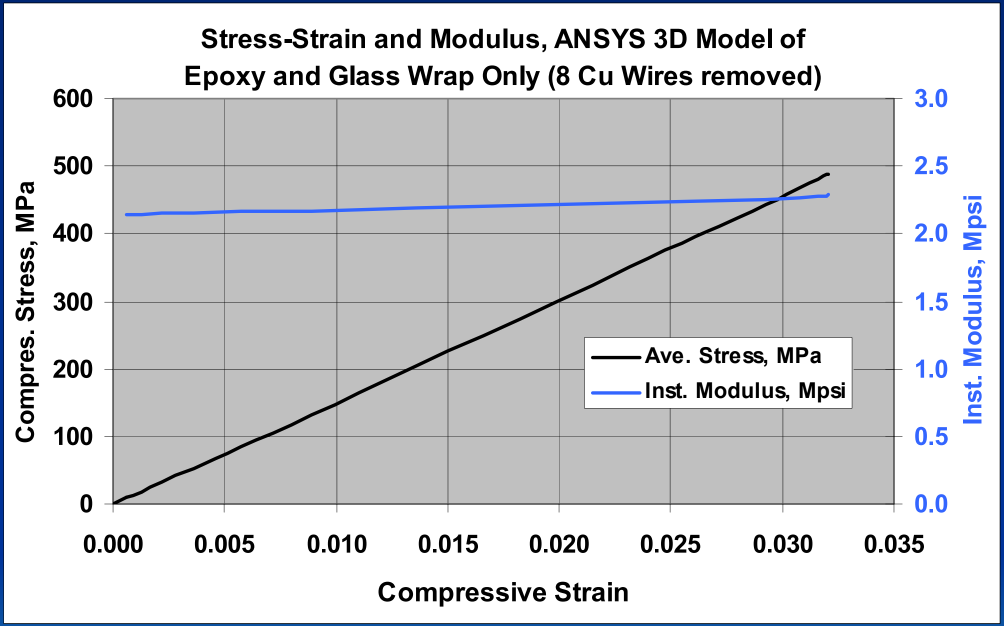
Remove the Epoxy & Glass, and the Cable gets very soft (0.3 Mpsi @ -0.2%)

- The model is compressed without the impregnating epoxy or glass.
- This allows the Cu strands to move more freely.
- The bare cable modulus is a strong function of strain.
- The modulus is 0.3 Mpsi or 1.0 Mpsi at -0.2% strain, depending on the definition of Area in the average stress calculation.



Remove the Cu, and the Epoxy & Glass get moderately soft

- The model is compressed without the Cu Strands.
- The composite modulus of the glass-epoxy drops to 2.2 Mpsi.
- Could it be that the actual impregnated cable behaves more like this than a Cu-Epoxy-Glass monolith?



Summary and Comments

- Strain Gage data is suspicious.
  - CTD admits this, but has not yet explained.
  - Stress-Strain plots & reported E values (+13 & -37 Mpsi) confirm this.
- Moduli based on LVDT data *looks reasonable*:
  - 1.1 Mpsi in compression (RT and 76K)
  - 2-3 Mpsi in Tension initially, with scatter above ~5 ksi
    - Some specimens soften abruptly.
- Non-Linear ANSYS model of 8-stranded cable:
  - Matches Rule of Mixtures hand-calc, which is stiffer than test results.
  - Shows importance of epoxy to stabilize the Cu strands.
  - Shows that conductor behaves like epoxy-glass composite *without* Cu.

Summary and Comments

- These inconsistencies raise the question of:
  - Impregnation quality or monolithic assumption of conductor composite.
  - LVTD data (although the Auburn data from CDR shows 1.2-1.7 Mpsi).
  - Modeling accuracy.
- Although a small yield-to-ultimate ratio is generally a good characteristic for a structural material, there is no test data which describes the electrical performance of the conductor as a function of stress or cyclic loading.
- Are expected loads *Primary* (must be carried by the structure, like EM) which could produce large deflections, or *Secondary* (self-limiting, like thermal) which produce essentially no deflections and lower stresses?