A Review of NCSX Conventional Coil Insulation Stresses

Presented by
Leonard Myatt

Relevant Project Memos

- "Insulation Shear Stresses in the Central Solenoid," December 10, 2003.
- "Detailed Electromagnetic-Structural Analysis of the NCSX PF4/5/6 Coils," February 18, 2004.
- "Detailed Electromagnetic-Structural Analysis of the NCSX TF Coils," March 17, 2004.

Each Memo Tells a Similar Story

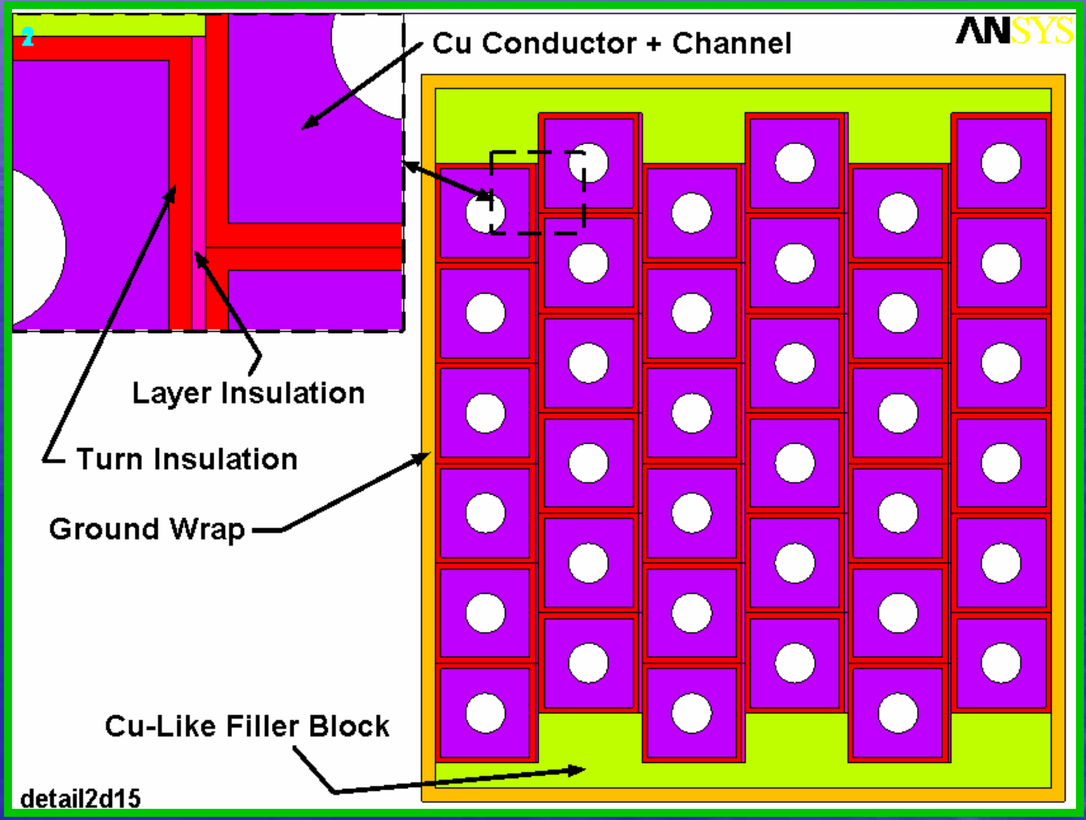
- SS Structural member stresses: OK
- Cu Conductor stresses: OK
- Insulation stresses…
  - Flat-Wise Compression: OK
  - In-Plane Tension: OK
  - In-Plane Compression: OK
  - Shear Stress: OK
  - Flat-Wise Tension: Above design value, Not OK

The Essence of the Problem

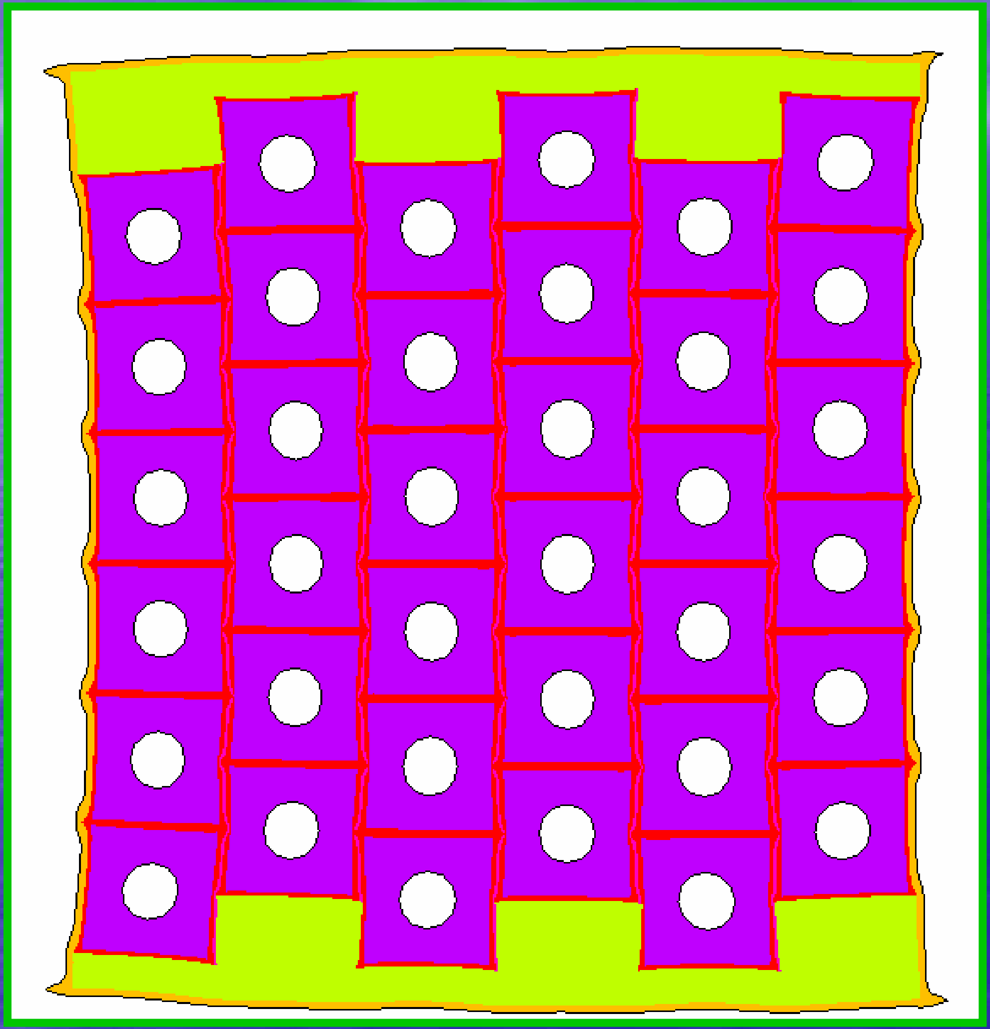
- The Winding Pack (WP) insulation (pre-impregnated S-2 glass with co-wound polyimide film) has orthotropic CTE (α) values which are much different than that of the Cu conductor (from 300 to 80K):
  - α_{Normal} (Insulation) = 25 to 28^{+} μ/K
  - $\alpha_{In\text{-}Plane}$ (Insulation) = 7 to 8 μ/K
  - $\alpha_{Isotropic}$ (Cu Cond.) = 14 μ/K

Let's look at this phenomenon with a Representative Solenoidal WP

- 6x6 conductor array built from:
  - 0.787"□, 0.354" hole
  - 49 mil turn insulation
  - 30 mil layer insulation
  - 120 mil Ground Wrap
  - Cu-Like Filler Blocks

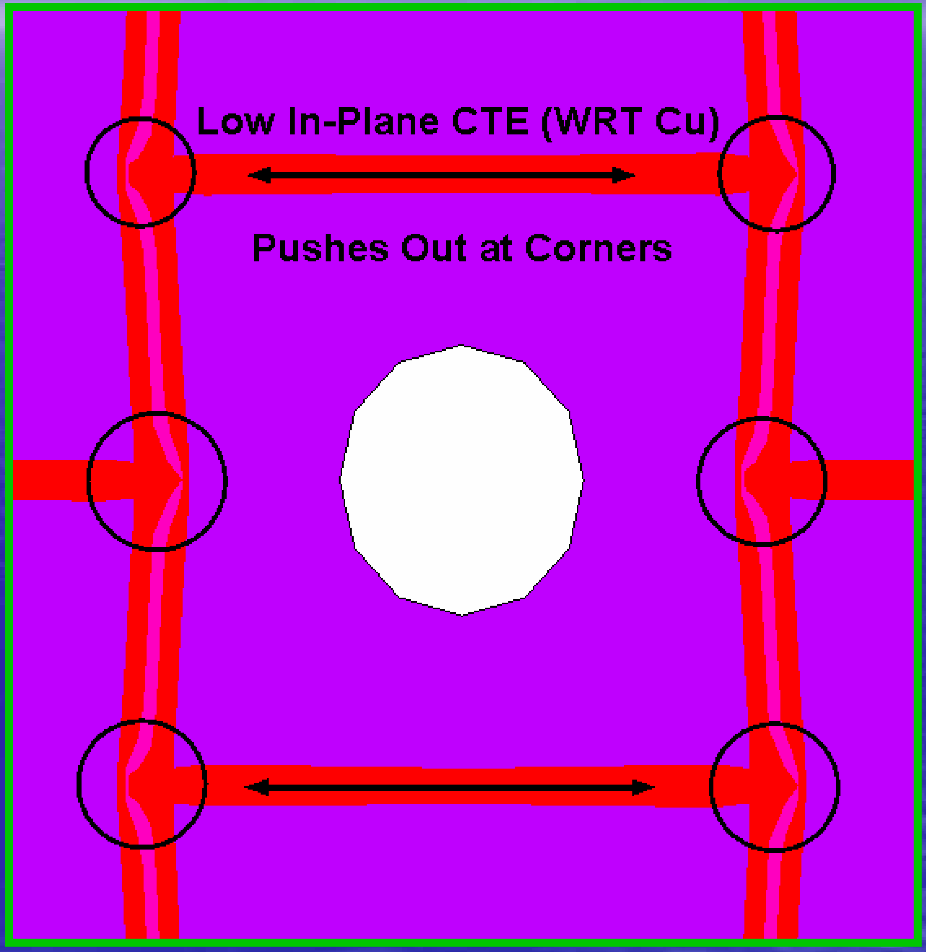


Representative Solenoid WP at 85K



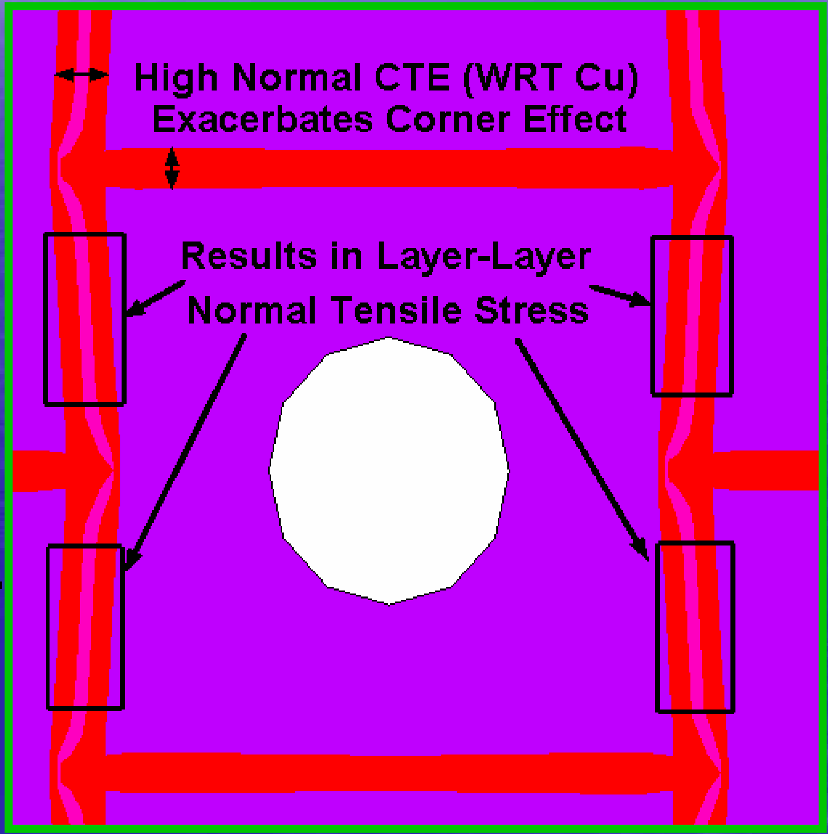
When the WP is Cooled to LN2: Part 1

- The Cu contracts more than low-α In-Plane Turn-Wrap Insulation.
- This produces deformations at the corners which push layers apart.



When the WP is Cooled to LN2: Part 2

- The Cu turns contract less than high-α Normal Turn-Wrap Insulation.
- The stiffer turns dictate the radial contraction of the WP.
- This puts the layer-to-layer insulation into normal tension.
- The condition is exacerbated by effects at the corners.

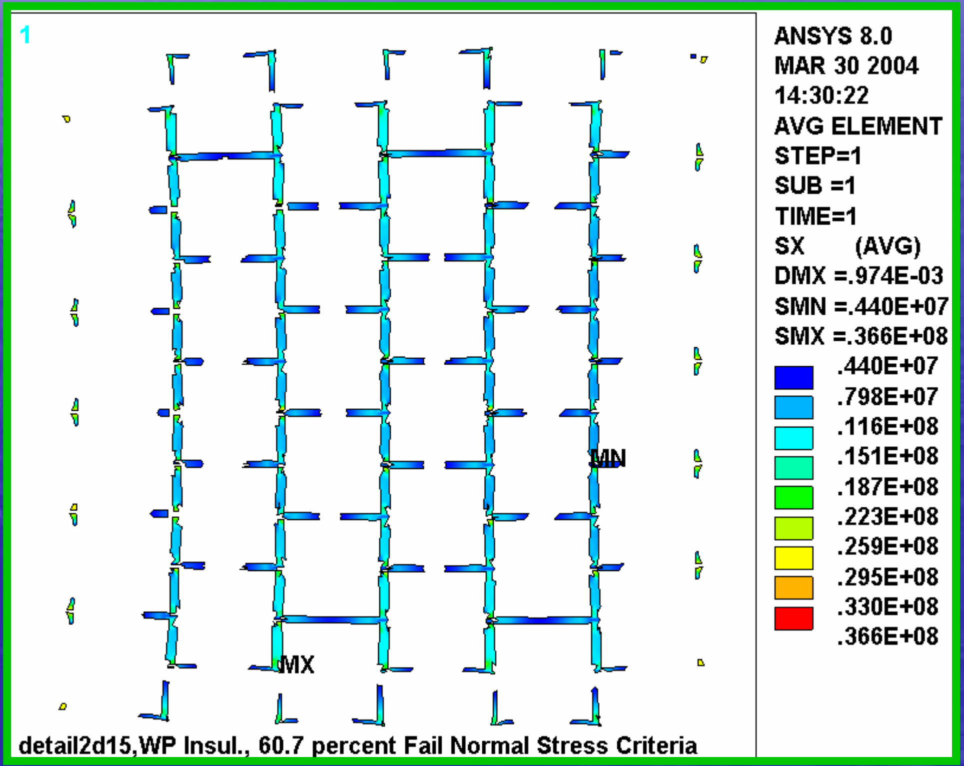


About the Normal Stress Allowable

- NCSX Structural Design Criteria (5/13/02) says: “In the absence of tensile test data normal to the plane of the glass, the allowable strain is 0.02%.”
- With a Normal elastic modulus of ~22 GPa, the allowable normal tensile stress is:
  - 0.0002 x 22 GPa = 4.4 MPa.
- There is presently no other defendable basis for applying this value. The actual limit will be a function of such variables as the glass weave, epoxy, surface prep and cure cycle. (Dick and Paul could extend this list.) Applicable test data would help.

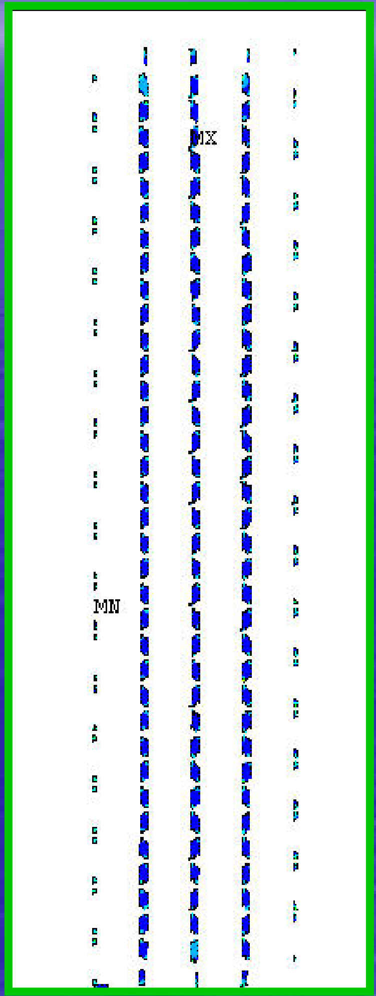
Normal Stress Contours in Elements with stresses > 4.4 MPa allowable

- Plot shows that Part 2 effect (high α_{Normal}) hurts layer-layer insulation more than Part 1 effect (low $\alpha_{In\text{-}Plane}$) hurts horizontal insulation.
- In this case, ~60% of the insulation has Normal stresses above 4.4 MPa.

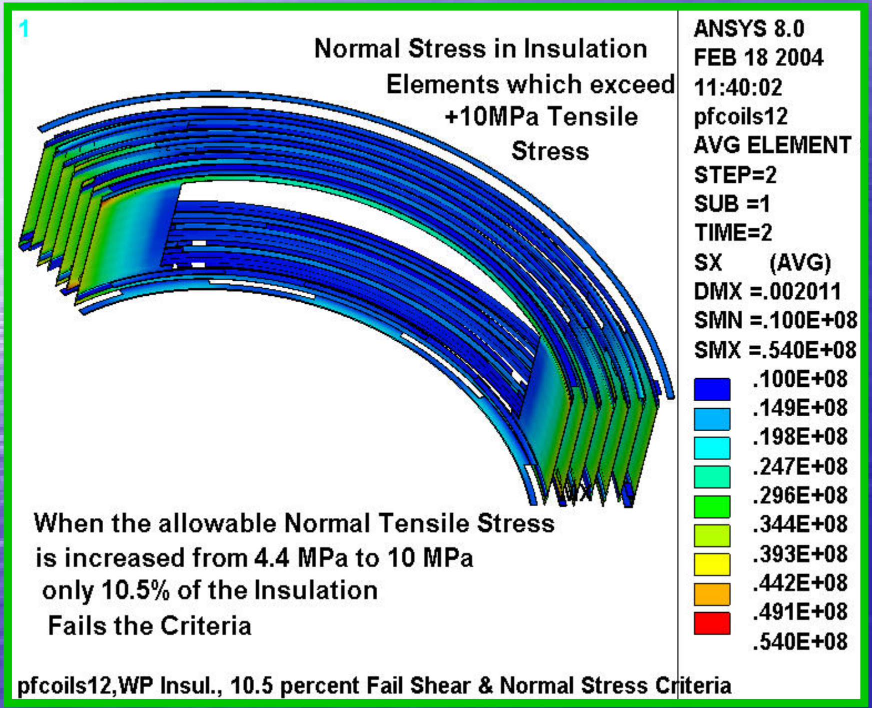


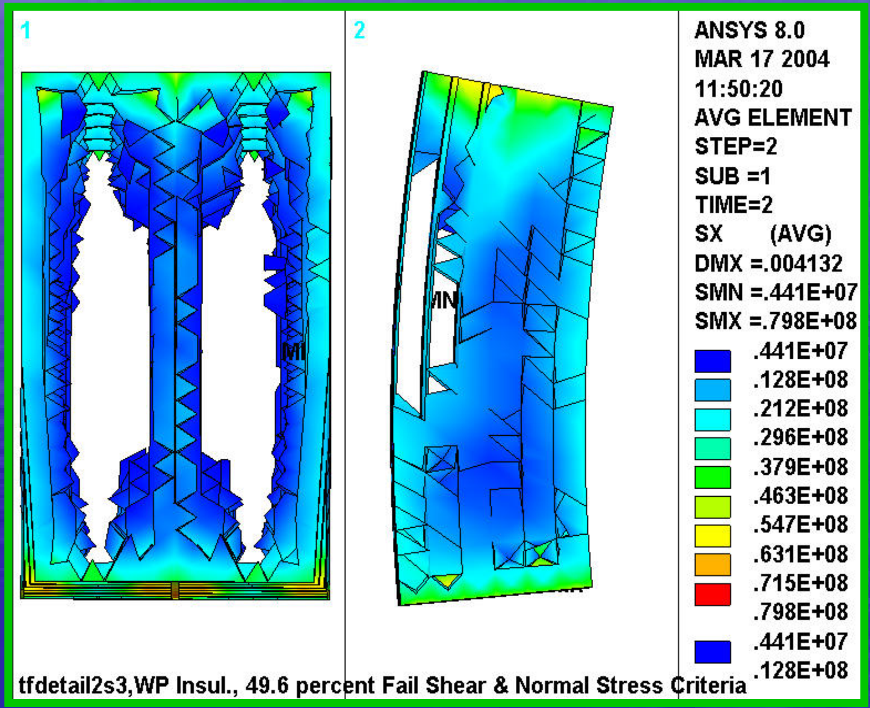
Vertical Compression in the CS Improves this Condition

- The CS Tie Rods provide significant vertical compression.
- This overcomes the modest vertical tensile stresses that develop in the horizontal insulation elements from Part 1 effects.
- Essentially none of the horizontal insulation elements exceed the normal stress criteria.
- On the other hand, the lack of a radial preload is evident in this plot of elements which “Fail” the normal stress criteria.



In PF4/5/6 and the TF, there is no preload, and 50-70% of the insulation has Normal tensile stresses above the nominal allowable.





When the nominal limit is increased to +10 MPa, ~90% of PF4 "Passes."

A locally detailed analysis of the TF coil indicates that ~50% of the insulations exceeds the 4.4 MPa limit.

TPX Insulation Tension Test Data

TPX THROUGH THICKNESS TENSION DATA SUMMARY						
Run No.	Reinforcement	Resin System	Barrier	Strength Average (MPa)	Standard Deviation	Coefficient of Variation
TT1A	TTI 3-d weave	Shell 826	None	52.5	6.7	0.13
TT1B	6781 8-h	Shell 826	None	57.3	2.5	0.04
TT2A	6781 8-h	CTD-112P	Kapton 200HA	29.5	10.2	0.35
TT2B	6580 8-h	CTD-112PF	Kapton 200HA	37.7	9.6	0.25
TT2C	6781 8-h	CTD-112P	None	28.2	1.0	0.04
TT3A	6781 8-h	CTD-112P	Kapton 200HA	20.1	7.9	0.39
TT3B	6580 8-h	CTD-112PF	Kapton 200HA	27.5	9.1	0.33
TT3C	6781 8-h	CTD-112P	None	24.4	3.7	0.15
TT4A	TTI 3-d weave	Shell 826	None	46.4	6.7	0.14
TT4B	6781 8-h	Shell 826	None	63.1	8.1	0.13

PA Sanger, "Final Report on Shear Strength under Compressive Load and Through Thickness Tension of TPX Insulating Materials," 14-950718-WEC-PSanger-01, Pittsburgh PA.

TPX Insulation Test Summary

- Sanger's Test Results Summary shows:
  - 3D S2 glass not as strong in tension or shear as 8 harness weave, *but still not too shabby*.
  - 3D glass has slightly higher compressive slope

Composite Type	Pure Interlaminar Tension (MPa)	Pure Interlaminar Shear (MPa)	Compressive Slope
3D S2 glass tape	46	52	0.7
8 harness satin weave S2 glass tape	60	95	0.5

PA Sanger, "Final Report on Shear Strength under Compressive Load and Through Thickness Tension of TPX Insulating Materials," 14-950718-WEC-PSanger-01, Pittsburgh PA.

General Comments on Test Results

- The use of Kapton generally reduces the tensile strength of the insulation layer.
- Shear strengths are independent of substrate material (316 SS or Incoloy 908).
  - *With similar surface prep, maybe we could expect similar results with the Cu conductor.*
- When Kapton is present, Shell 826 is stronger than CTD101K.
- When Kapton is not present, the two epoxies performed equivalently.

Properties used in TPX FEA (4K)

TPX adopted the 3D Glass. Check out what that does for the CTE orthotropy.

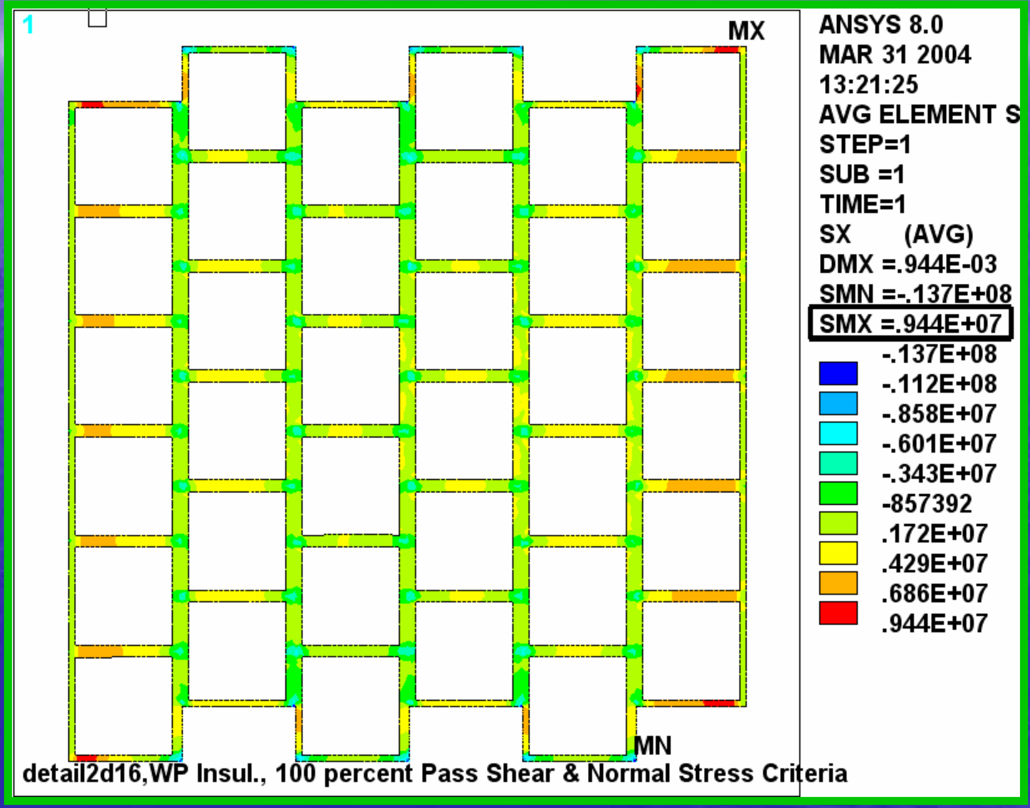
Table 2.0-1 Summary of Material Properties Used in the Analyses (4K)

Material (Ref #)	Shear Modulus (in-plane)	Shear Modulus (interlam.)	Young's Modulus (thru-thk)	Young's Modulus (in-plane)	Thermal Exp. Coef. (thru-thk)	Thermal Exp. Coef. (in-plane)	Poisson's Ratio
Incoloy 908 (1)	71 GPa		185 GPa		**5.9μ/K** (5.59)		0.299
316 LN (5)	81 GPa		205 GPa		**10.4μ/K** (10.3)		0.282
SC Cable(8)	0.23 GPa		Long/Tran:60/0.6 GPa		7.24μ/K		0.30
G11 Sheet (3)	11.6 GPa	9.0 GPa	24 GPa	36 GPa	24.9μ/K	8.3μ/K	0.26
Ground Wrap (7)	10.7 GPa	8.5 GPa	16 GPa	32 GPa	12μ/K	10μ/K	0.26
3D Glass Wrap (2)	10.7 GPa	8.5 GPa	16 GPa	32 GPa	12μ/K	10μ/K	0.26
3D Corner Fill (4)	10.7 GPa	8.5 GPa	16 GPa	32 GPa	12μ/K	10μ/K	0.26
Kapton Wrap (14)	0.37 GPa		4.0 GPa		15.8μ/K	13μ/K	0.34

RL Myatt, "Stress Analysis of the TF Conduit and Insulation for TPX," 13-950605-MIT-LMyatt-01, MIT, Cambridge, MA.

Representative Solenoid WP at 85K Revisited (now with 3D S2 glass)

- E/α_{Normal} = 16GPa/12μ/K
- $E/\alpha_{In\text{-}Plane}$ = 32GPa/10μ/K
- τ_0 =(52 MPa)(0.6 cyclic) ~ 30 MPa
- c_2 = 0.7
- $\sigma_\perp$ < (46 MPa)(1/3) = 15 MPa
- Plot shows:
  - $\sigma_\perp$ < 10 MPa
  - 100% of turn and layer insulation passes design criteria.



Summary Comments

- Clearly, the amount of anisotropy in the insulation's CTE values plays a major role in the stresses at the LN2 operating temp.
- Techniweave's 3D S-glass has almost isotropic CTEs, and may provide a way of avoiding the high stresses produced by the more traditional 2D glass weave.
- TPX test data shows good shear/compression/tension strength for 3D glass and epoxy systems.
- Up to date technical data on the 3D product is TBD.
- www.albint.com/web/albint_pub.nsf/Content/Specialty+Weaving is a good starting point.

Noteworthy

- TPX ultimately adopted a Kapton/3D glass slip-plane insulation system:
  - (2) ½-Lap Kapton Type H, no adhesive (t=0.025)
  - (1) ½-Lap 3D weave S-2 glass (t=0.356 mm)
    - Total Wrap Thickness, 0.812 mm (32 mils)
  - VPI with Shell 826 epoxy
- The "Large Scale Verification Test Program" qualified this system on 5x5 conductor array samples.
- The system is designed to allow micro-displacements between the insulation and the conductor, thus avoiding normal tensile stresses.
- The program is summarized in TPX CPDR Vol. 5, Manufacturing R&D (I still have a copy).