Design/Analysis of Metal/Composite Bonded Joints for Survivability at Cryogenic Temperatures

ISIM/JWST Composite Structure

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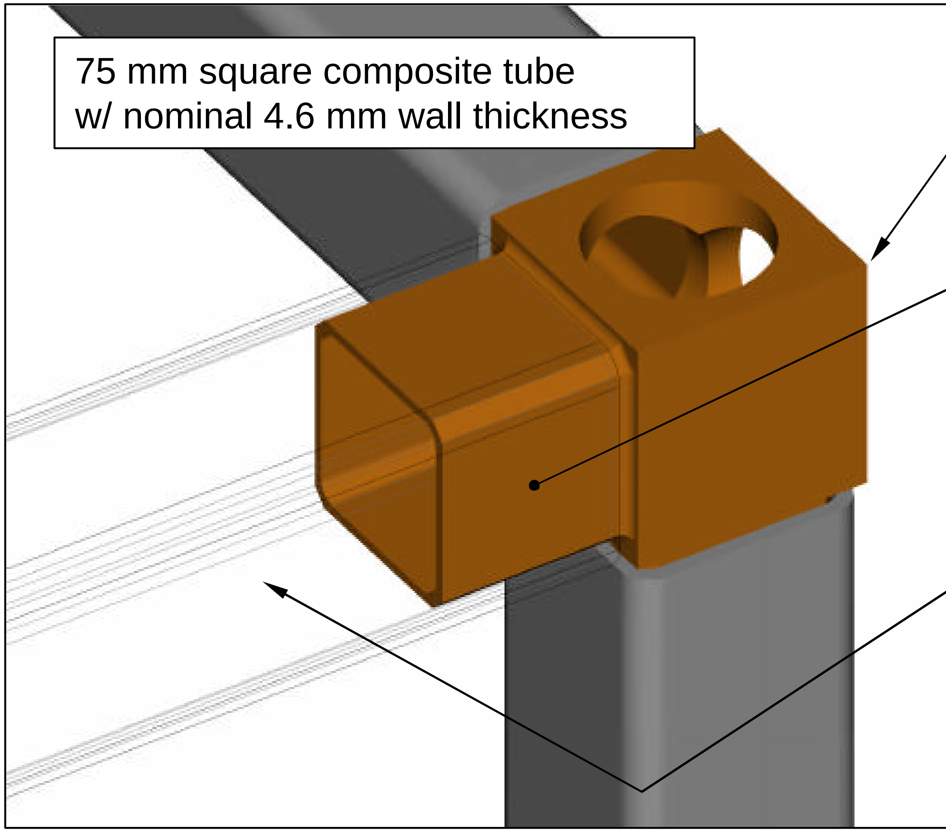
Design and Analysis Challenges
ISIM/JWST Metal/Composite Bonded Joints

- Design Requirements
  - Metal/composite bonded joints required at a number of nodal locations on the JWST/ISIM composite truss structure to accommodate bolted instrument interfaces and flexures.
  - Operational temperature at 30K (~ -400^{o}F); 263K total BTC from RT.
  - Composite truss tube with high axial stiffness (~30 msi) and low CTE (~ -0.9 ppm/K).
  - Multiple thermal cycles throughout design life of structure. In order to survive launch loads, joints cannot degrade more than an acceptable amount.

- Design/Analysis Challenges
  - Large thermal mismatch stresses between metal fitting and composite tube at cryogenic temperatures (30K).
  - Analysis and design experience is very limited for metal(titanium)/composite bonded joints at temperatures below liquid nitrogen (~80K).
  - Thermo-elastic material properties and strengths for composites and adhesives at 30K are not available and difficult to test for.

Baseline Joint Design Concept



Metal Fitting (Ti-6Al-4V, cryo grade)
E = 19.1 msi
α = +6.7 ppm/K

Adhesive Bond (EA9394)
E = 1.7 msi
G = 0.6 msi
α = 44.0 ppm/K
Fsu = 11.6 ksi (80 MPa)

Composite Tube
(M55J/954-6, $[45/0_3/-45/0_2]_s$)
E_{axial} = 32 msi
E_{hoop} = 4.1 msi
α_{axial} = -0.95 ppm/K
α_{hoop} = +5.2 ppm/K
S_{zz} = 2.9 ksi (20 MPa)
$S_{zx} = S_{yz}$ = 5.8 ksi (40 MPa)
} interlaminar strengths

- Stiffness and strength properties are given for 30K.
- Thermal expansion properties are secant CTE from RT to 30K.
- Adhesive and composite properties are preliminary and will be determined/verified by material testing.

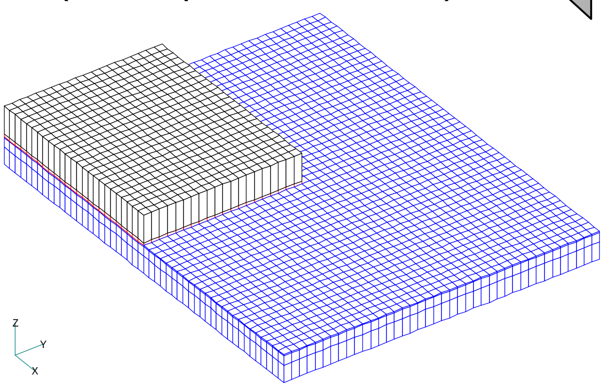
Preliminary Analysis Work

- Analysis Assumptions
  - All properties are end-state properties at 30K.
  - Non-linear effects, including plasticity and temperature dependent properties not considered.
  - The primary failure mode will be interlaminar (peel & shear) in the first few plies at the bonded interface.
- Analysis Techniques
  - Closed Form
    - Hart-Smith supported single lap joint solution
  - FEA
    - Equivalent adhesive springs (AAIAA paper 84-0913)
    - Plane stress/strain (for design studies including chamfer and adherend thickness sizing)
    - Solid Elements
      - All stress components captured (in-plane and interlaminar)
      - 3D orthotropic properties required
      - Computationally intensive
- Analytical Results
  - High interlaminar stresses will be induced by the large thermal load (BTC = -263K). Preliminary analysis shows stresses above allowables.
  - A detailed joint development testing program will be necessary to determine material properties at 30K, develop a stress interaction failure curve/criterion, and to correlate model parameters for accurate stress assessment.

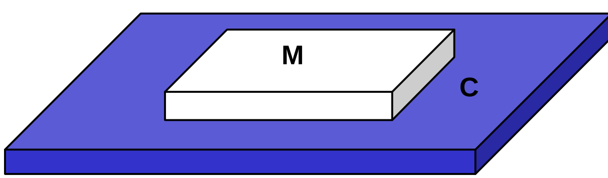
Testing/Correlation Methodology

- Purpose
  - Correlate FEA with test data and use correlated analysis for design of ISIM Joints.

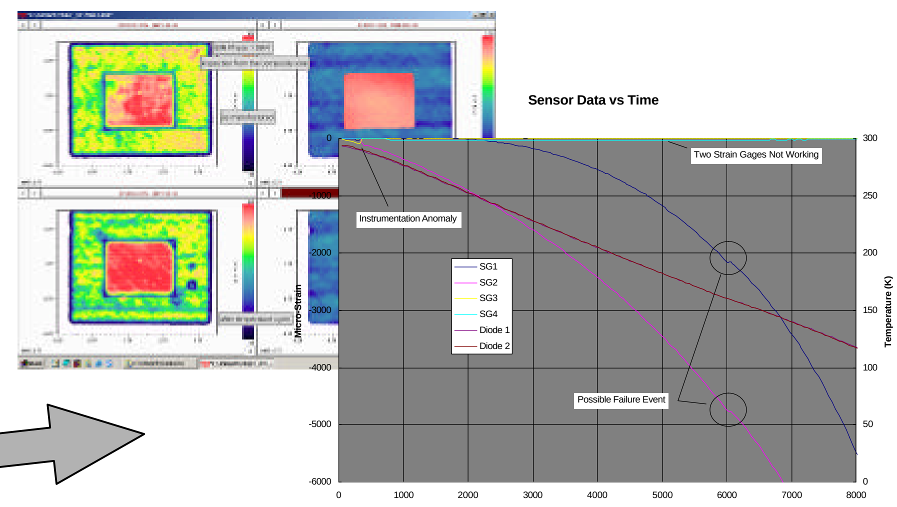
1) Perform preliminary FEA and design test coupons for different failure modes (shear, peel, interaction).



2) Cycle test coupons down to cryogenic temperatures and detect failure temperatures.



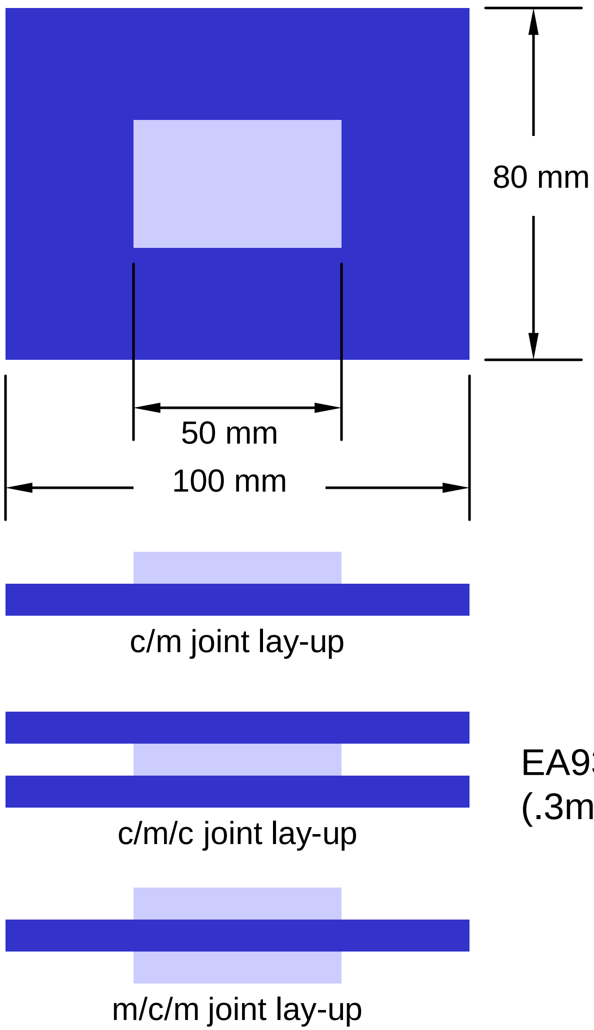
3) Inspect coupons and evaluate test data to determine failure modes and failure temperatures.



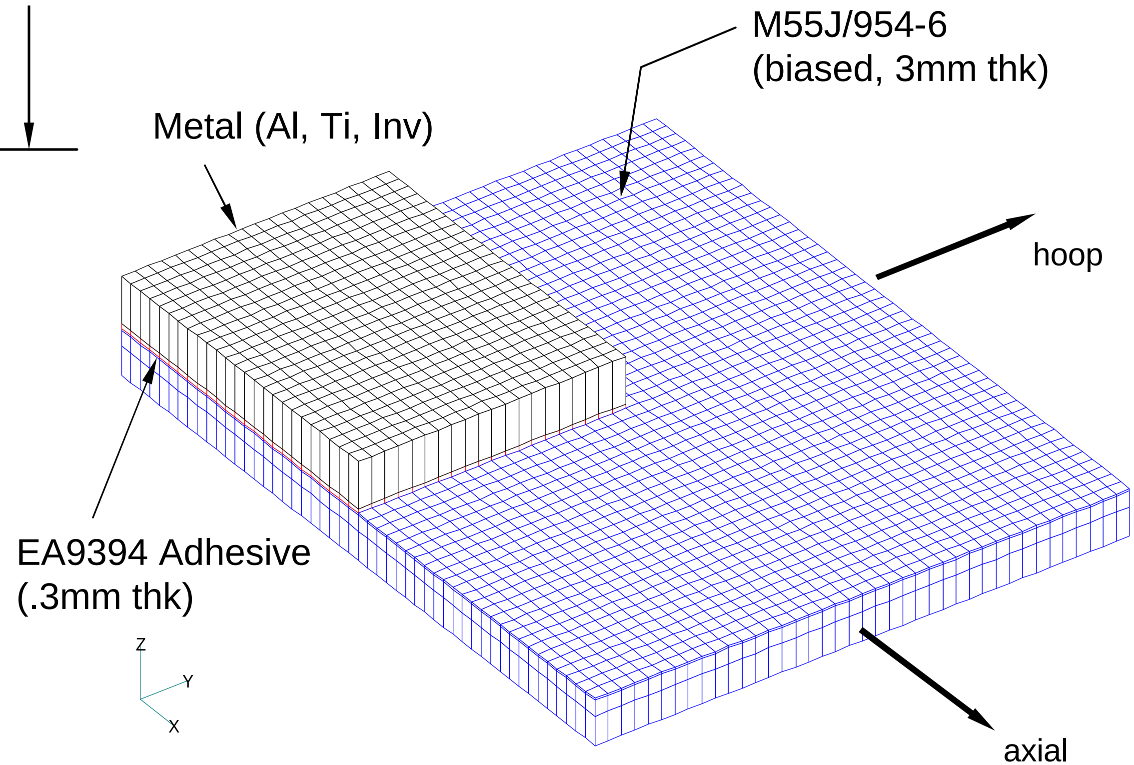
4) Adjust analytical models to match test data.
– obtain known material allowable stresses at failure temperature

Testing/Correlation Methodology

Failure Mode Coupon Configurations



- different coupon configurations to bias failure modes (shear, peel, interaction)
- 30K properties used
- composite edge stresses do not couple with bonded joint stresses

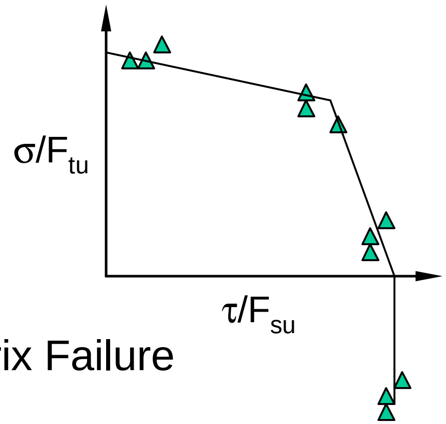


FEA ¼ Model w/ Symmetry Constraints

Testing/Correlation Methodology

Interlaminar Stress Interaction Failure Criterion

- Future Test Failure Curve/Criterion @ 30K
  - Based on test data from various failure mode coupons at or near 30K.
  - Margins on ISIM metal/composite joints will be based on test correlated failure curve.



- Current Failure Criterion in Use
  - Hashin's modified Tsai Wu Criterion for Matrix Failure

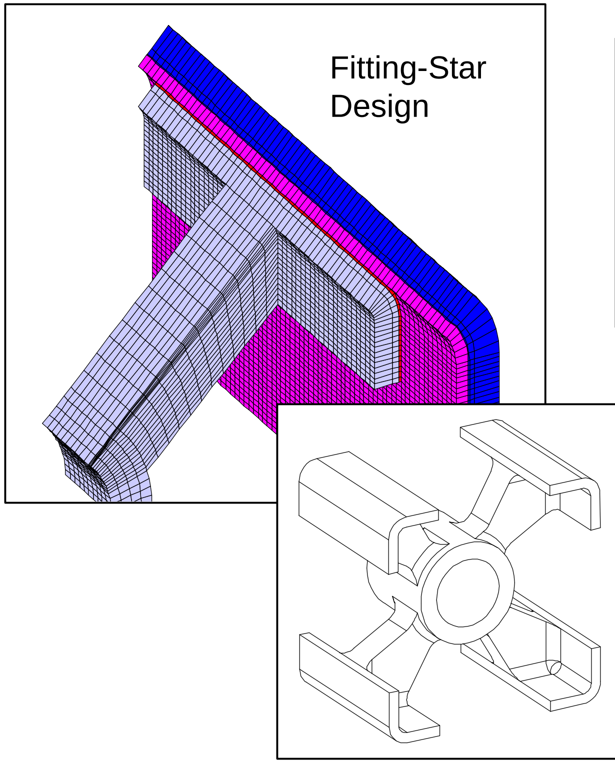
$$F_2\sigma_2 + F_{22}\sigma_2^2 + F_{66}\tau^2_{12} = 1$$

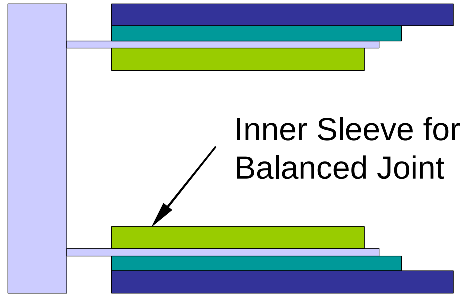
  - Interlaminar Stress Failure Criterion

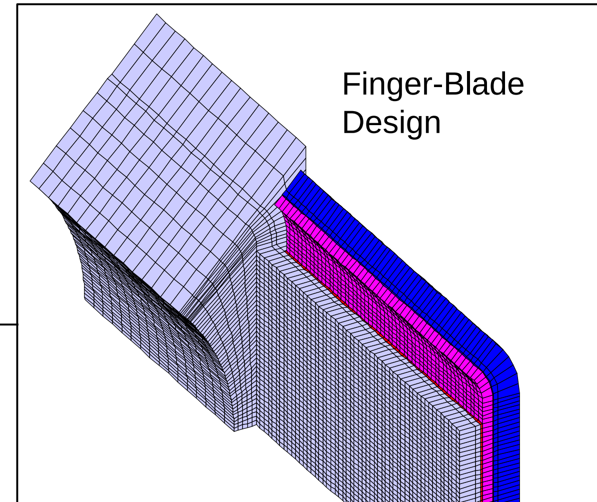
$$F_2\sigma_z + F_{22}\sigma_z^2 + F_{66}(\tau_{yz}^2 + \tau_{zx}^2) = 1$$

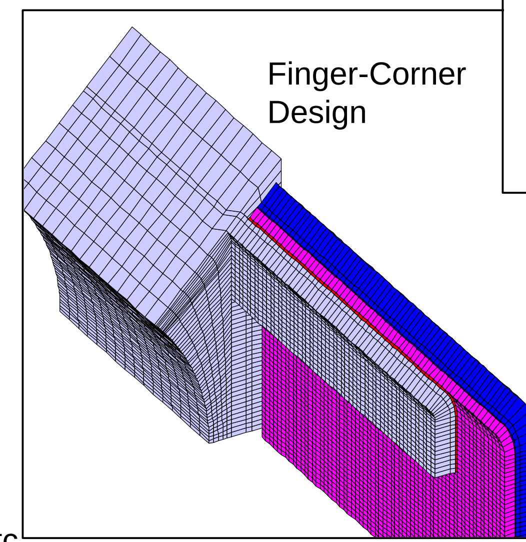
» F terms are material constants dependent on interlaminar strengths.

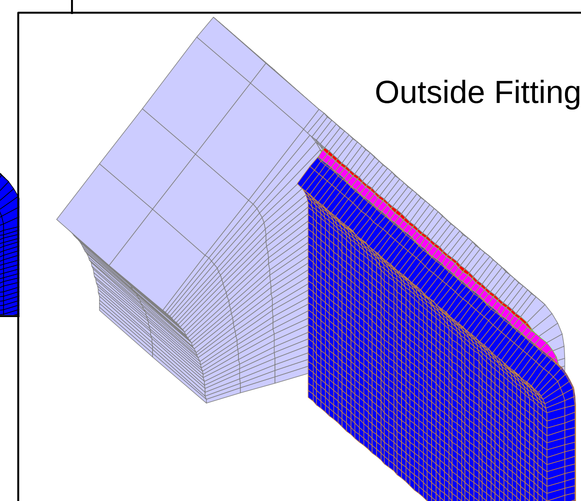
Joint Design Concepts Considered











- Configuration Variations
- Geometry Variations
  - Chamfers, thicknesses, overlaps, etc.
- Material Variations
  - Titanium, Invar, Aluminum
  - T300/954-6, E-Glass-Fabric/Epoxy
  - Various Lay-ups

Current Baseline Design/Analysis

New Baseline Joint Design Proposal

- Analytical studies show that in the titanium/composite joint much of the peel stresses are due to the contraction of the titanium fitting (positive CTE) and the expansion of the composite tube (negative hoop CTE). The shear stresses are dominated by the large axial CTE mismatch between the metal and composite.

- Propose a new design configuration to eliminate these effects using a “hybrid” laminate with a high positive hoop CTE and Invar (low CTE).

Material Properties at 30K

Property	Units	Ti	Invar 36	Baseline Laminate	Hybrid Laminate
E_X	msi	19.1	25.7	32	31.7
E_Y	msi			4.13	2.77
E_Z	msi			1.58	1.63
α^{secant}_X	μin/in/K	+6.7	+1.5	-0.95	-0.83
α^{secant}_Y	μin/in/K			+5.2	+10.7
α^{secant}_Z	μin/in/K			+42.4	+38.9

Baseline Laminate - $[45/0_3/-45/0_2]_{S3}$

Hybrid Laminate – $[45^2/0_3^1/-45^2/0_2^1]_{S3}$

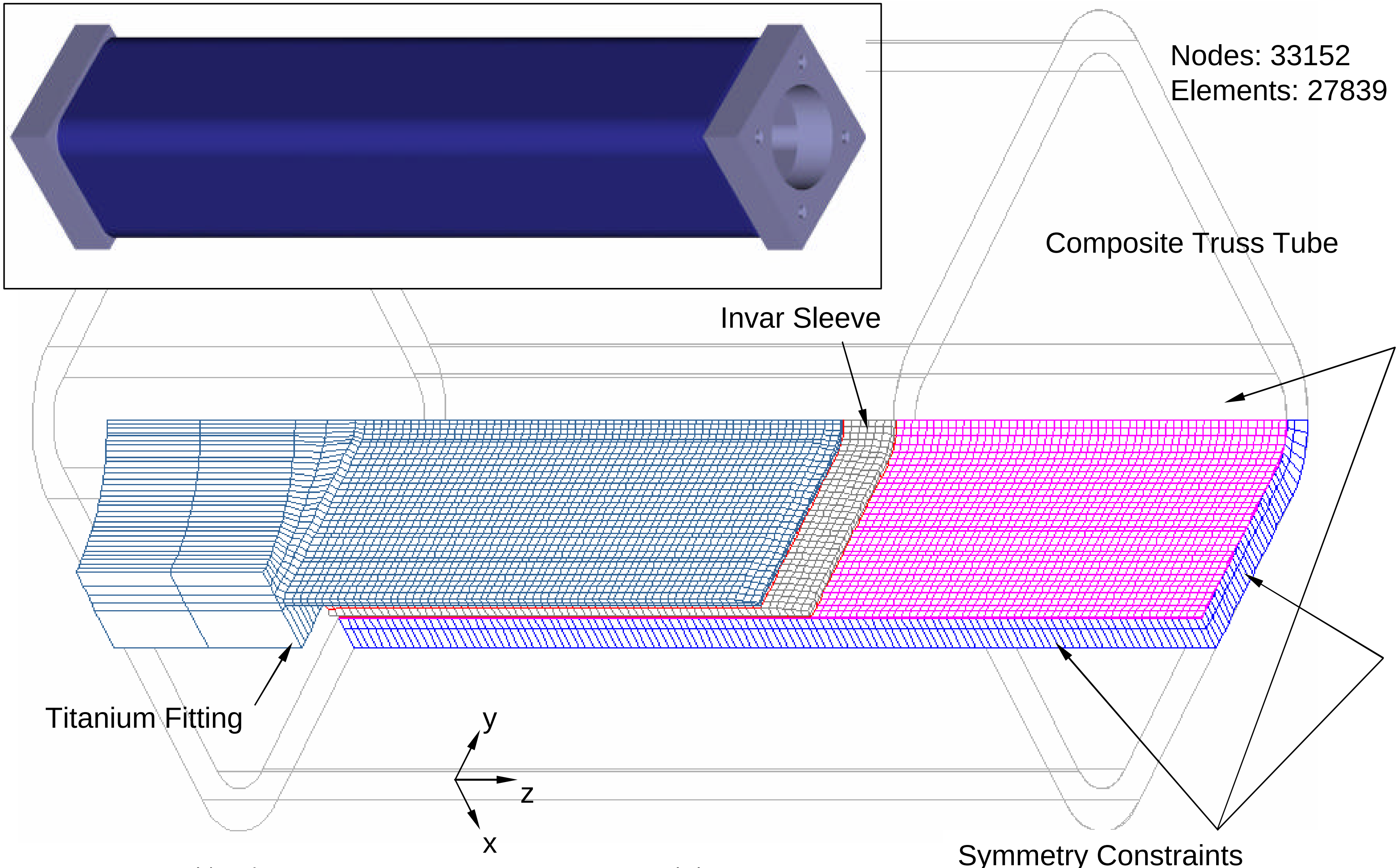
Superscripts

^{1}M55J/954-6

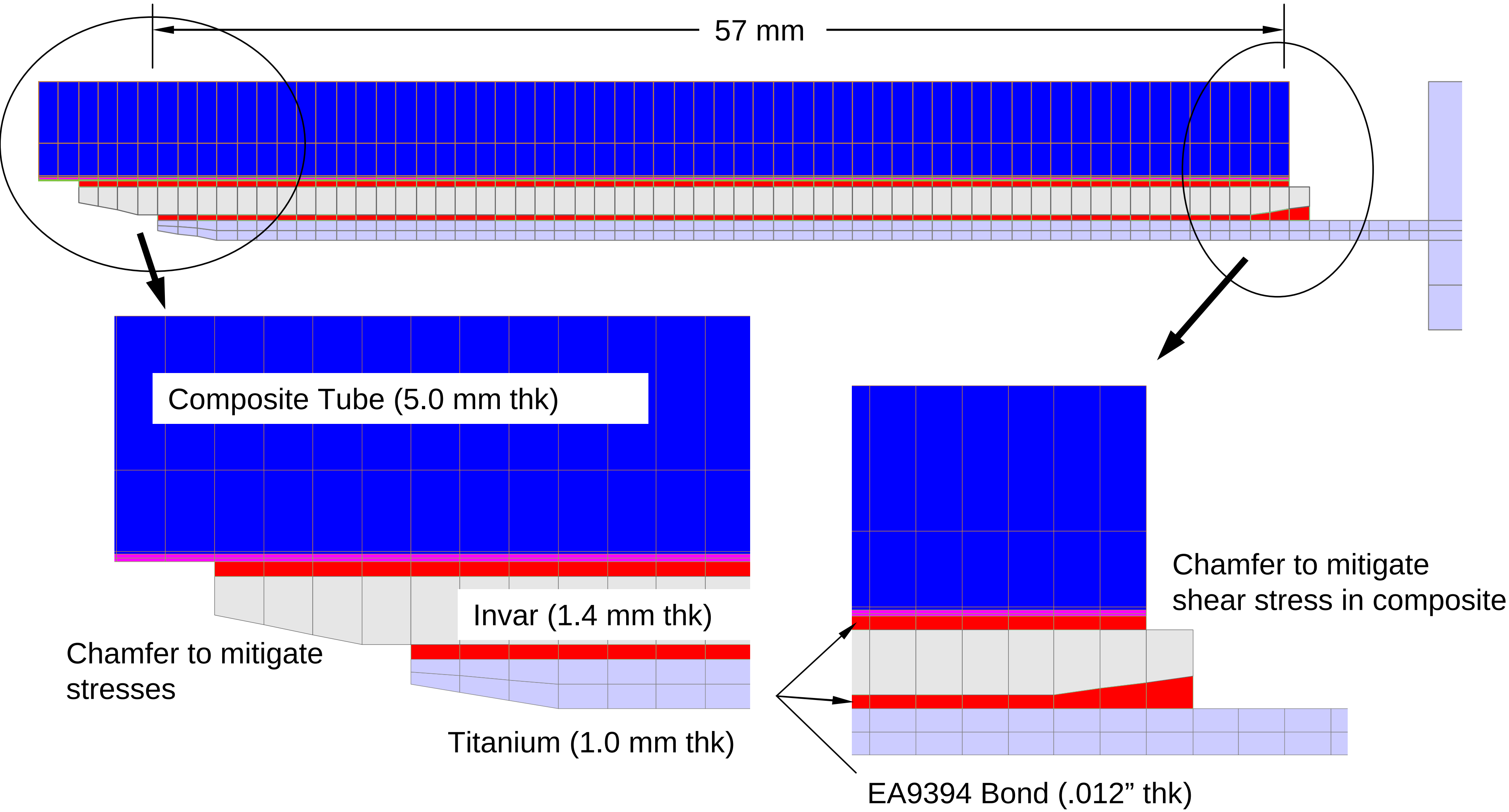
^{2}T300/954-6

Current Baseline Design/Analysis

Finite Element Model

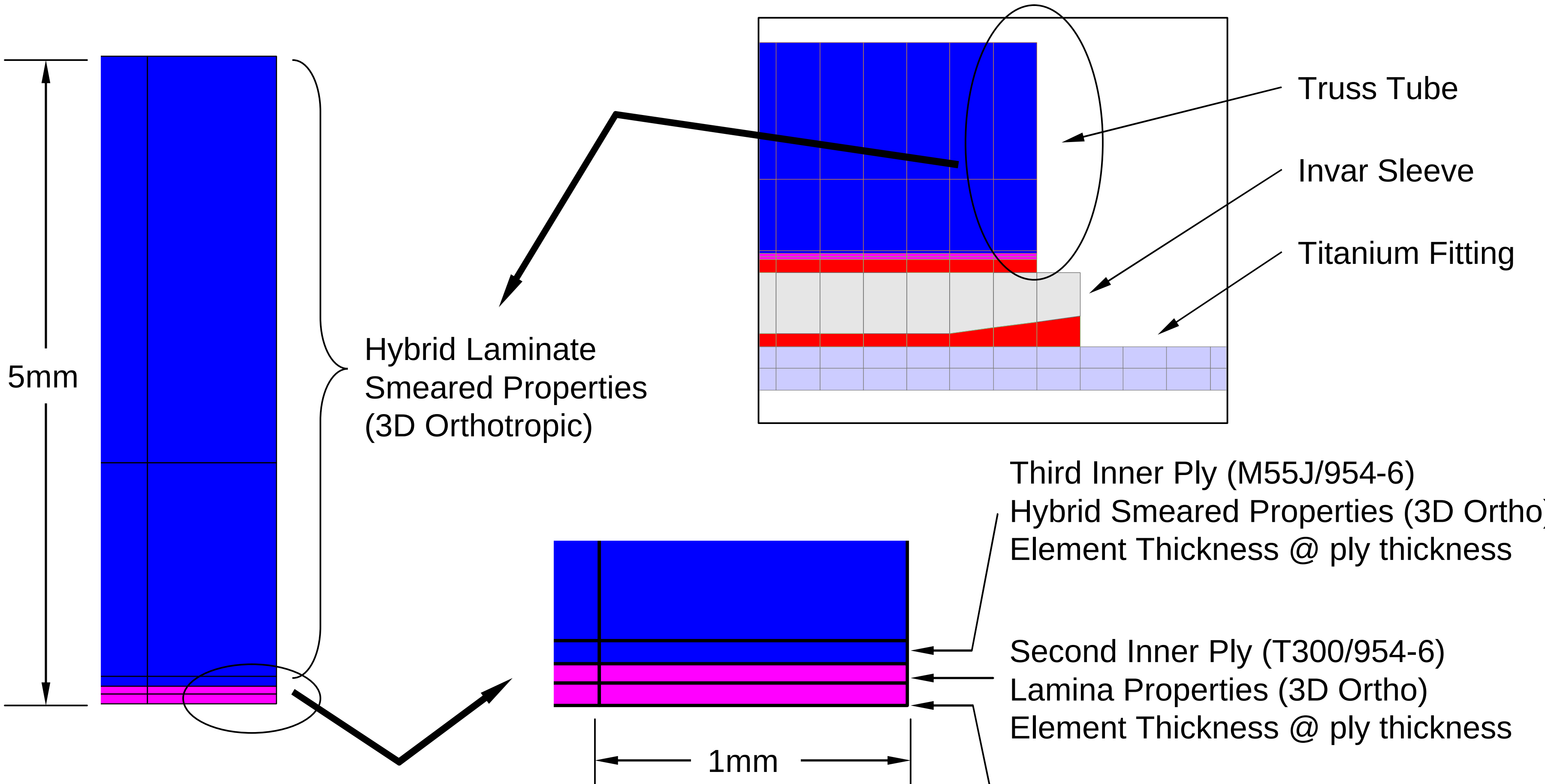


Current Baseline Design/Analysis
Finite Element Model



Current Baseline Design/Analysis

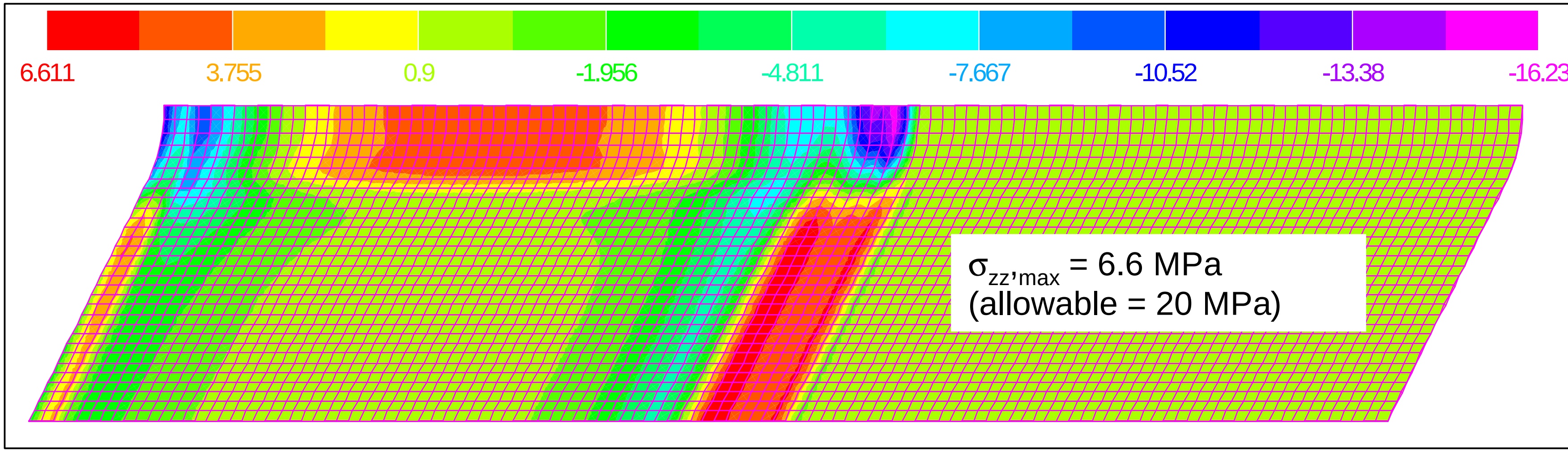
Finite Element Model

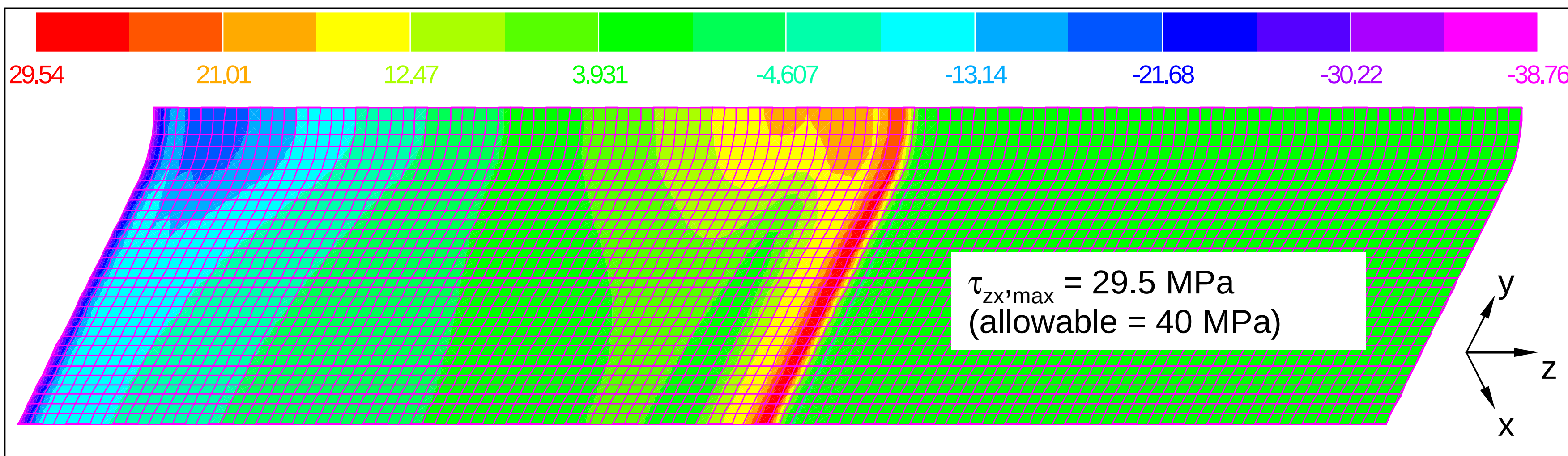


• Dimensions for elements will be tuned to correlate analysis with test data. Average element stresses are extracted.

Current Baseline Design/Analysis

3rd Ply Interlaminar Stress Countour Plots (DT = -263K)





Current Baseline Design/Analysis

Thermal Load (ΔT = -263K) Safety Factors

Joint Components	Stress Componenets	Dedicated T330 @ 45deg	Dedicated T300 @ 0deg
1st Ply (T300)	Max Peel Stress	14.6	10.8
	Max Shear Stress	45.4	38.9
	Interaction SF	1.42	1.56
3rd Ply (M55J)	Max Peel Stress	9.4	9.9
	Max Shear Stress	28.0	28.5
	Interaction SF	1.19	1.26
Adhesive (EA9394)	Max Peel	36.8	37.2
	Max Shear	62.1	63.2
	Shear SF	1.29	1.27

Material	Stress Componenets	Allowables (MPa)
M55J/954-6	Max Peel	20
	Max Interlaminar Shear	40
T300/954-6	Max Peel	30
	Max Interlaminar Shear	65
EA9394	Max Shear	80

Interaction SF's based on Hashin's modified Tsai-Wu

Conclusions & Future Work

- Material characterization testing and joint development testing are in progress. Test results will be critical for analysis correlation and the final design/analysis of the ISIM metal/composite bonded joints.
  - Phase A of the development test program has been completed. This initial phase included pathfinder coupons and failure detection proof-of-concept coupons. Test data from this phase appear to correlate well with preliminary analysis.
- An evaluation of strength degradation due to multiple thermal cycles will also be included in the joint development test program.
- An accelerated joint testing program based on the current baseline joint design will be conducted this summer (2004) in order to demonstrate the feasibility of joint survivability at cryogenic temperatures by PDR (September 2004).
- Alternate metal/composite bonded joints have been studied and developed and may be used as fallback designs if unable to demonstrate a working solution in the current baseline joint design.