FEMCI Workshop 2005

Correlating PMC-MMC (M46J/T300/M76 – AlSiC) Bonded Joint 3D FEA with Test

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Materials Testing

- **Part 1 = Process Testing**

  Test Material (6092/SiC/25p-T6) vs. Control (Al 6061)

  - **COMPLETED Surface preparation & bonding**

    Surface Prep : Bead blasted, cleaned, BR127 primed

    Average Cohesive Failure Strength : 4193 psi

    Published Loctite 9309-3 Shear Strength : 4200 psi

  - **COMPLETED "Wedge" Test for durability of bonded joint**
  - **COMPLETED "Conditioned Lap Shear" Testing for residual strength; equivalent 30% strength reduction for *both* adherends**
  - **COMPLETED Machining all AlSiC parts using diamond tooling and ESD**

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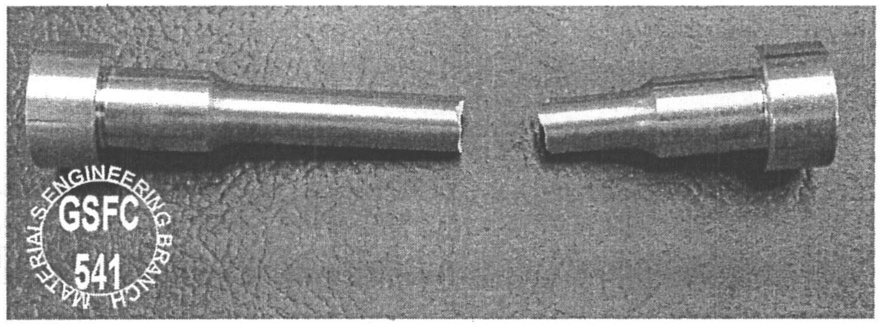
Materials Testing

- Part 2 = Mechanical Properties Verification

  Test Material, 6092/SiC/25p-T6

  - COMPLETED Tensile Testing (GSFC)

	Ult. Str. (ksi)	Yld. Str. (ksi)	Strain to Failure (%, 1 in)	
Ave.	74.62	60.73	4.88	DWA vendor data
Std. Dev.	2.86	2.98	0.98	
Ave.	76.5	63.9	2.3	GSFC Code 541 data
Std. Dev.	1.3	0.6	0.3	



  - COMPLETED CTE Testing (GSFC)

	CTE (µm/m-°C)			
	-125°C to 0°C	0°C to 125°C	-75°C to 25°C	
Ave.	12.0	16.0	12.0	GSFC Code 541 data
Std. Dev.	1.0	0.0	0.0	

	Room. Temp.	
Ave.	13.8	DWA vendor data

  - IN PROCESS - Stress Corrosion Crack Testing (MSFC); currently @ 72 days and 50-75% yield stress with no failures

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Materials Testing

- Part 2 = Mechanical Properties Verification; continued

Gr/Ep Truss tubes, T300/M46J/M76 (x6)

- COMPLETED Ultrasonic NDE (GSFC)
- COMPLETED Compression strength testing (GSFC)
  - Predicted laminate E, ν were 27.8 msi and 0.70, respectively
  - Tested laminate E, ν are 28.05 msi and 0.80, respectively
- COMPLETED Fiber volume assessment (Swales); 62% ave.

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Materials Testing

- **Part 3 = Joint Testing**
  - **6 of 6 finished Gr/Ep tubes assembled with AlSiC clevis end pieces**
    (GPM-TUBE-003, -005, -006 *and* -002, -004, -007)
  - **Test Method Overview**
    1. **Proof Tension Loading, all 6 tubes (@ 1.25*[Limit Load])**
       - **Limit Load = max. enveloped axial load, Jul'04 CLA results**
       - **COMPLETED successfully for 6 of 6 tubes**
    2. **Thermal Cycling, all 6 tubes (x20 cycles)**
       - **ΔT = 90 C (25 C to –65 C), design worst case flight predict**
       - **COMPLETED successfully for 6 of 6 tubes**
    3. **Proof Tension Loading, all 6 tubes (@ 1.25*[Limit Load])**
       - **Residual strength, post- thermal cycling**
       - **COMPLETED successfully for 6 of 6 tubes**

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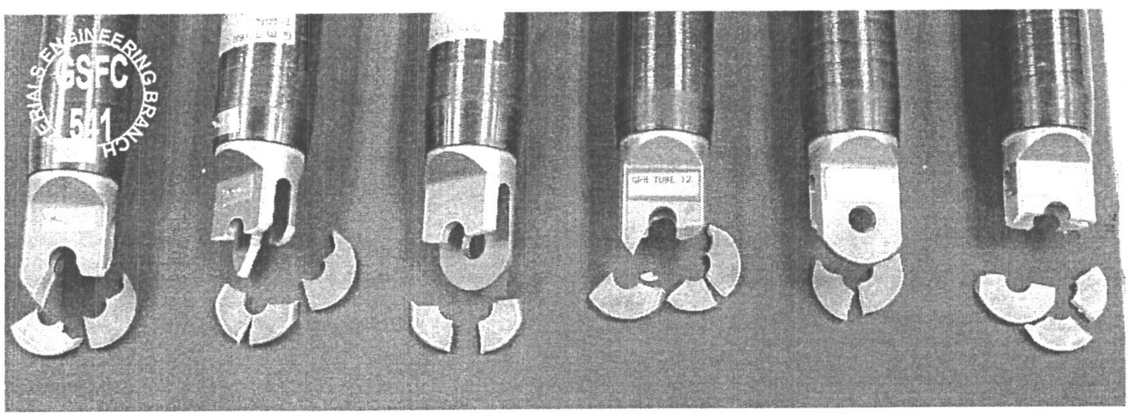
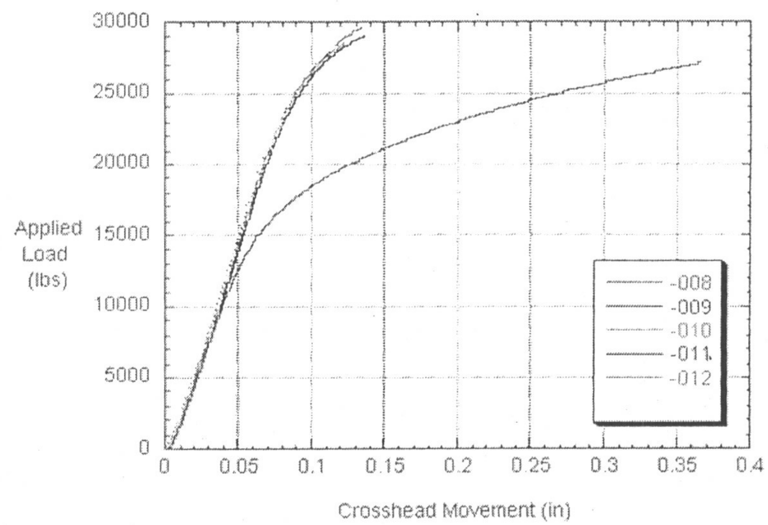
Materials Testing

- Part 3 = Joint Testing; continued
  4. Tension loading to failure, all 6 tubes
     - for statistical, quantitative assessment of residual strength
     - COMPLETED successfully for 6 of 6 tubes
       - Average Failure Load = 28.5 kip (equiv. Stress = 35.3 ksi)
       - > 3x design load (~8400 lb), which assumed bond failure
       - Actual Failure Mode = AlSiC material fracture
       - No indication of plastic deformation





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Materials Testing Status

- Part 1, Part 2, Part 3 – All Completed Successfully
- Post Test Status:
  - Codes 541, 543 agree to attempt to fail bonded joints in compression at -70 C
    - Code 547 is supporting this effort by removing the tangs from each tube assembly, leaving flats on both ends
    - Compression testing begun 4/27/05

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Materials Testing Simulations

- FEA using MSC/NASTRAN
  - Linear static solution
  - 3D brick elements and linear static solution
  - Quarter-symmetric model to reduce total DOF to ~467000
  - Output requests include stresses in all 6 direction for calculating Tsai-Hill, Tsai-Wu, and Hoffman ply failure margins
    - MATLAB code written to perform calculations externally
    - Actual Test Results vs. FEA-based margin calculations reveal that Tsai-Hill is best theory for predicting performance

- Hart-Smith A4EI Bonded Joint Analysis Tool (used originally to size tube taper and joint overlap length)
  - Being studied for treatment of circular joints; original FORTRAN based code treats planar joints only
    - Potential benefit: more accurate predictions; less tendency to over-design future hardware

Materials Testing Simulations

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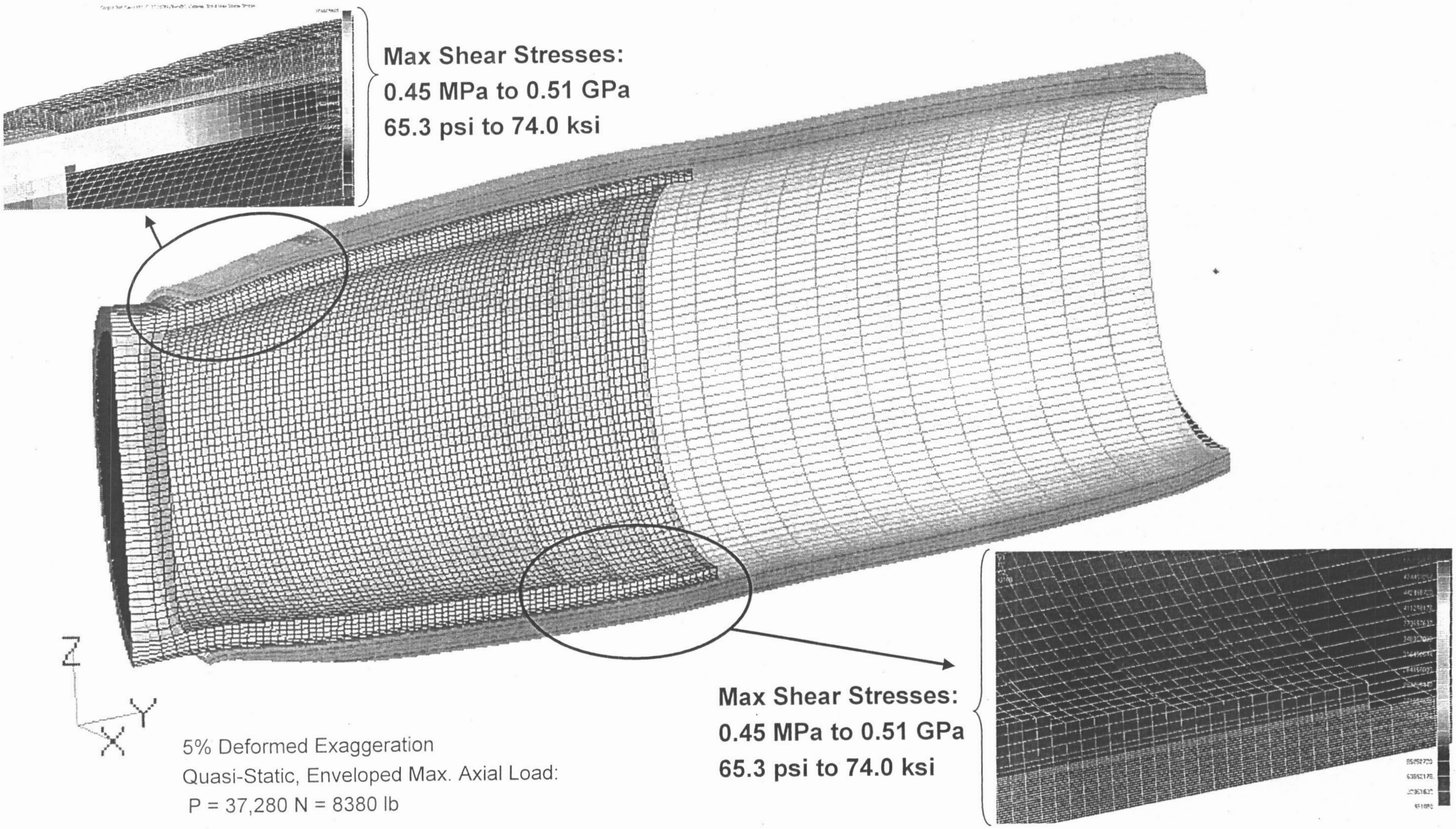
Output Set: Case101: F=37,280N (SymBC, Deformed(0.000347): Total Translation



5% Deformed Exaggeration

Quasi-Static, Enveloped Max. Axial Load:

P = 37,280 N = 8380 lb

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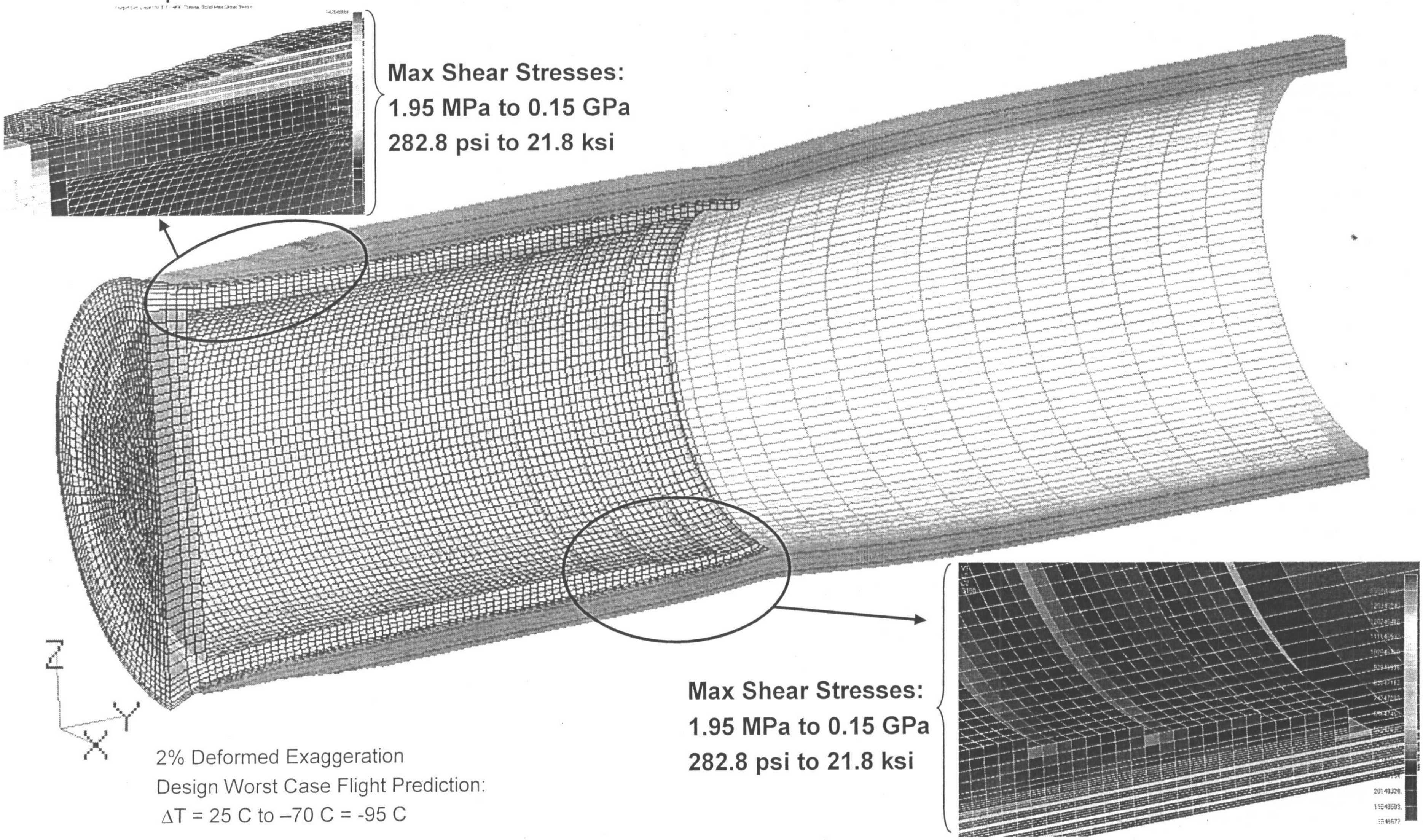
Materials Testing Simulations

Output Set: Case102: DT= -95K, Deformed(0.0000671): Total Translation



2% Deformed Exaggeration
Design Worst Case Flight Prediction:
ΔT = 25 C to –70 C = -95 C

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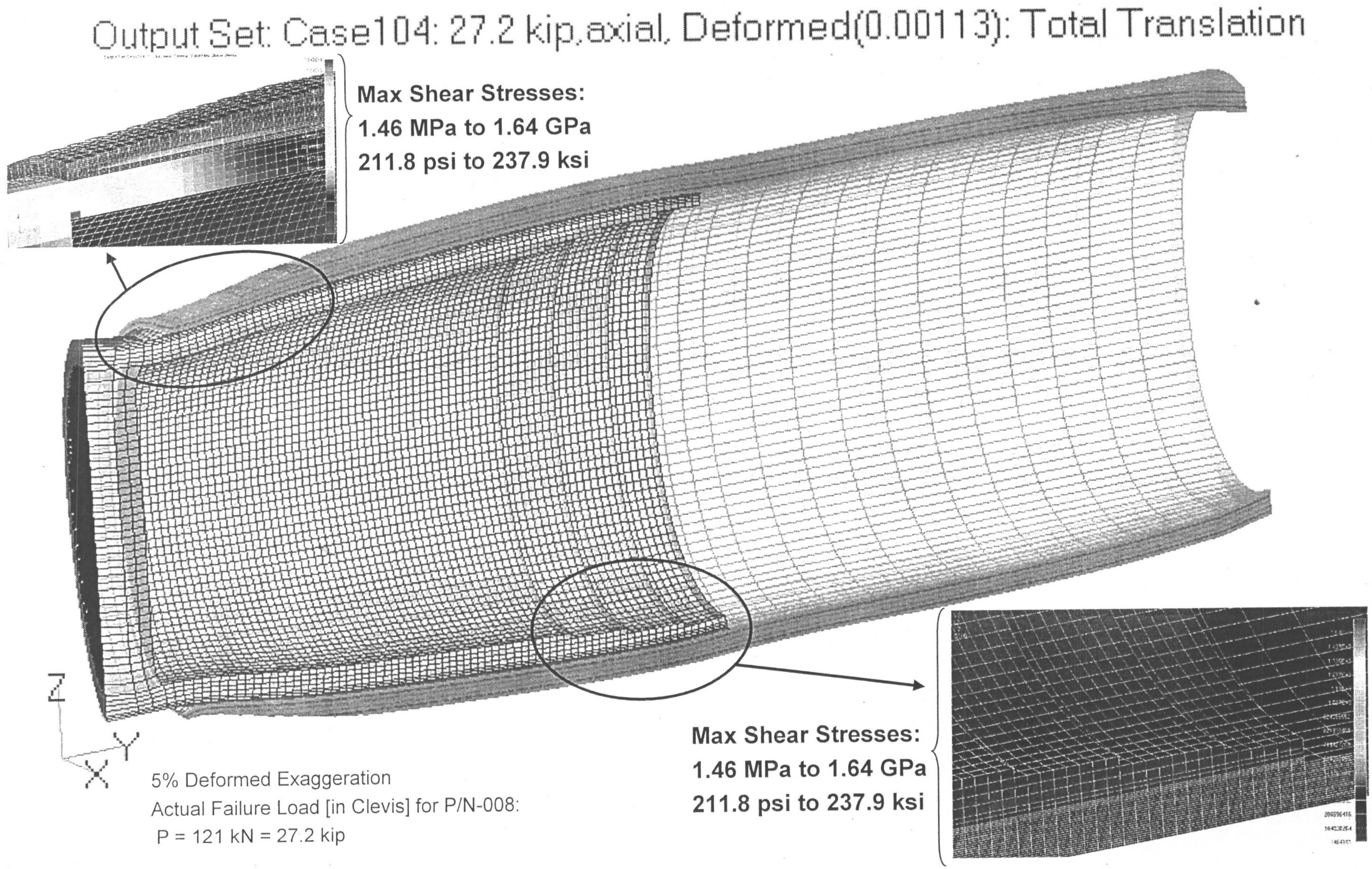
Materials Testing Simulations



5% Deformed Exaggeration

Actual Failure Load [in Clevis] for P/N-008:

P = 121 kN = 27.2 kip

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Materials Testing Simulations

- Un-factored and Factored Margins in Bond, based on FEA Resultants for 3 Load Cases:
  - [101] P = 8380-lb axial
  - [102] ΔT = -95 K
  - [104] P = 27.2 kip axial

- However, no failure in practice … FEA-based margin calculations are most accurate when based on predicted σ_{XY}

[EA 9309-3 Bond]
Associated Margins

	Load Case	[Global] VonMises	[Peak] VonMises	[Axial Shear] sigX	[Hoop Shear] sigY	[Comb. Shear] sigXY
8380-lb, axial	101	1.11	1.11	1.11	1.11	1.11
dT = -95K	102	0.36	-0.39	0.10	0.13	40.74
27.2-kip, axial	104	-0.05	-0.93	0.29	0.12	2.90

Associated (Factored) Margins [FF = 1.15, FU = 1]

	Load Case	[Global] VonMises	[Peak] VonMises	[Axial Shear] sigX	[Hoop Shear] sigY	[Comb. Shear] sigXY
8380-lb, axial	101	0.83	-0.77	-4.64	2.16	9.44
dT = -95K	102	0.19	-0.47	-0.04	-0.02	35.29
27.2-kip, axial	104	-0.18	-0.94	0.12	-0.03	2.39

Associated (Factored) Margins [FF = 1, FU = 1.5]

	Load Case	[Global] VonMises	[Peak] VonMises	[Axial Shear] sigX	[Hoop Shear] sigY	[Comb. Shear] sigXY
8380-lb, axial	101	0.41	-0.82	-3.79	1.43	7.01
dT = -95K	102	-0.09	-0.59	-0.26	-0.25	26.83
27.2-kip, axial	104	-0.37	-0.95	-0.14	-0.25	1.60

Associated (Factored) Margins [FF = 1.15, FU = 1.5]

	Load Case	[Global] VonMises	[Peak] VonMises	[Axial Shear] sigX	[Hoop Shear] sigY	[Comb. Shear] sigXY
8380-lb, axial	101	0.22	-0.84	-3.43	1.11	5.96
dT = -95K	102	-0.21	-0.64	-0.36	-0.35	23.20
27.2-kip, axial	104	-0.45	-0.96	-0.25	-0.35	1.26

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Materials Testing Simulations

- **Ply Failure Margins for Load Case 101**

Un-Factored ply	Tsai-Hill	Tsai-Wu	Hoffman		Factored [FF = 1, FU = 1.5] ply	Tsai-Hill	Tsai-Wu	Hoffman
1	0.986	0.628	0.642	< T300/M76 0° Layer >	1	0.959	0.397	0.417
2	0.969	0.454	0.474		2	0.906	0.146	0.172
3	0.974	0.506	0.527		3	0.922	0.221	0.252
4	0.977	0.54	0.559		4	0.931	0.269	0.298
5	0.985	0.583	0.67	< +45° Layer Orientation >	5	0.956	0.318	0.466
6	0.98	0.577	0.602		6	0.94	0.324	0.366
7	0.981	0.585	0.609		7	0.945	0.334	0.374
8	0.982	0.591	0.618		8	0.947	0.341	0.387
9	0.99	0.656	0.735	< -45° Layer Orientation >	9	0.971	0.43	0.567
10	0.983	0.592	0.629		10	0.949	0.342	0.405
11	0.983	0.593	0.629		11	0.949	0.343	0.404
12	0.982	0.587	0.623		12	0.948	0.334	0.395
13	0.98	0.54	0.596		13	0.94	0.259	0.355
14	0.989	0.622	0.677	< -45° Layer Orientation >	14	0.967	0.377	0.468
15	0.983	0.561	0.603		15	0.949	0.289	0.357
16	0.983	0.586	0.588		16	0.95	0.33	0.323
17	0.982	0.553	0.572		17	0.945	0.276	0.298
18	0.982	0.554	0.58	< +45° Layer Orientation >	18	0.945	0.275	0.308
19	0.972	0.528	0.515		19	0.917	0.24	0.202
20	0.971	0.516	0.504		20	0.913	0.223	0.185
21	0.967	0.495	0.482		21	0.901	0.191	0.15

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Materials Testing Simulations

- **Ply Failure Margins for Load Case 102**

	Un-Factored				Factored [FF = 1, FU = 1.5]		
ply	Tsai-Hill	Tsai-Wu	Hoffman		Tsai-Hill	Tsai-Wu	Hoffman
1	0.984	0.647	0.655	< T300/M76 0° Layer >	0.952	0.418	0.421
2	0.964	0.579	0.591		0.893	0.31	0.319
3	0.969	0.539	0.642		0.908	0.236	0.405
4	0.976	0.633	0.66		0.928	0.392	0.43
5	0.942	0.279	0.356	< +45° Layer Orientation >	0.827	-0.14	-0.039
6	0.982	0.681	0.693		0.946	0.47	0.483
7	0.973	0.618	0.657		0.919	0.367	0.426
8	0.972	0.614	0.653		0.917	0.361	0.42
9	0.947	0.299	0.393	< -45° Layer Orientation >	0.843	-0.116	0.016
10	0.97	0.594	0.642		0.912	0.329	0.402
11	0.98	0.652	0.697		0.942	0.419	0.491
12	0.97	0.598	0.641		0.91	0.335	0.4
13	0.97	0.564	0.63		0.912	0.279	0.382
14	0.95	0.338	0.433	< -45° Layer Orientation >	0.85	-0.064	0.076
15	0.972	0.607	0.639		0.915	0.351	0.397
16	0.963	0.594	0.64		0.891	0.33	0.4
17	0.963	0.608	0.648		0.889	0.353	0.415
18	0.949	0.377	0.471	< +45° Layer Orientation >	0.849	-0.007	0.132
19	0.968	0.618	0.621		0.905	0.372	0.367
20	0.998	0.863	0.871		0.995	0.767	0.78
21	0.961	0.639	0.642		0.883	0.407	0.403

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Materials Testing Simulations

- **Ply Failure Margins for Load Case 104**

Un-Factored					Factored [FF = 1, FU = 1.5]			
ply	Tsai-Hill	Tsai-Wu	Hoffman		ply	Tsai-Hill	Tsai-Wu	Hoffman
1	0.854	-0.006	0.028	< T300/M76 0° Layer >	1	0.565	-0.331	-0.308
2	0.666	-0.271	-0.229		2	0.006	-0.271	-0.274
3	0.714	-0.219	-0.176		3	0.15	-0.316	-0.3
4	0.748	-0.168	-0.12		4	0.249	-0.324	-0.283
5	0.849	-0.141	0.124	< +45° Layer Orientation >	5	0.551	-0.587	-0.144
6	0.792	-0.053	-0.005		6	0.38	-0.261	-0.19
7	0.803	-0.058	0.001		7	0.414	-0.296	-0.211
8	0.812	-0.052	0.023		8	0.44	-0.313	-0.196
9	0.886	-0.05	0.193	< -45° Layer Orientation >	9	0.661	-0.522	-0.121
10	0.818	-0.067	0.047		10	0.458	-0.36	-0.172
11	0.816	-0.115	0.06		11	0.454	-0.446	-0.152
12	0.809	-0.121	0.046		12	0.432	-0.438	-0.156
13	0.773	-0.226	-0.041		13	0.323	-0.511	-0.219
14	0.864	-0.124	0.108	< -45° Layer Orientation >	14	0.597	-0.588	-0.217
15	0.821	-0.148	-0.037		15	0.468	-0.491	-0.347
16	0.825	-0.094	-0.135		16	0.478	-0.44	-0.609
17	0.788	-0.206	-0.216		17	0.371	-0.553	-0.69
18	0.852	-0.12	-0.045	< +45° Layer Orientation >	18	0.561	-0.555	-0.503
19	0.733	-0.191	-0.315		19	0.206	-0.502	-0.881
20	0.671	-0.249	-0.401		20	0.021	-0.53	-0.991
21	0.634	-0.285	-0.449		21	-0.088	-0.543	-1.043

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Conclusions

- 3D finite element model predictions of PMC (M46J/T300/M76) ply failure are most accurate when assuming the Tsai-Hill failure criteria

- A4EI (Hart-Smith) bonded joint analysis tool:
  - Good for design purposes
  - Can be enhanced to optimize circular joint design

- High strength bonded joints between PMC and MMC adherends are possible
  - M46J/M76 to AlSiC using EA 9309-3
  - Post TVAC (20 cycles from R.T. to -65° C) residual strength is Full Capacity