TOUCHSTONE
RESEARCH LABORATORY, LTD.

METAL MATRIX COMPOSITE FILAMENT WINDING

Brian Gordon, Senior Program Manager
E-mail: blg@trl.com

METPREG™

Outline

- **Technology Overview**
  - Metal Prepregs
  - MMC Consolidation Methods
- **MMC Filament Winding**
- **Recent Results**
  - Hydrostatic Burst Testing
  - Axial Tension and Torsion Testing
  - Attachment Testing
  - Impact Testing
  - Pinned Closure Testing
- **MMC Design Tool Development**
- **Conclusions and Future Work**

Metal Prepreg Tape and Pultruded Shapes

Tape Width – 0.25 to 1.50”

Tape Thickness – 0.007 to 0.020”

Tubing – 0.25” OD, 0.015” wall

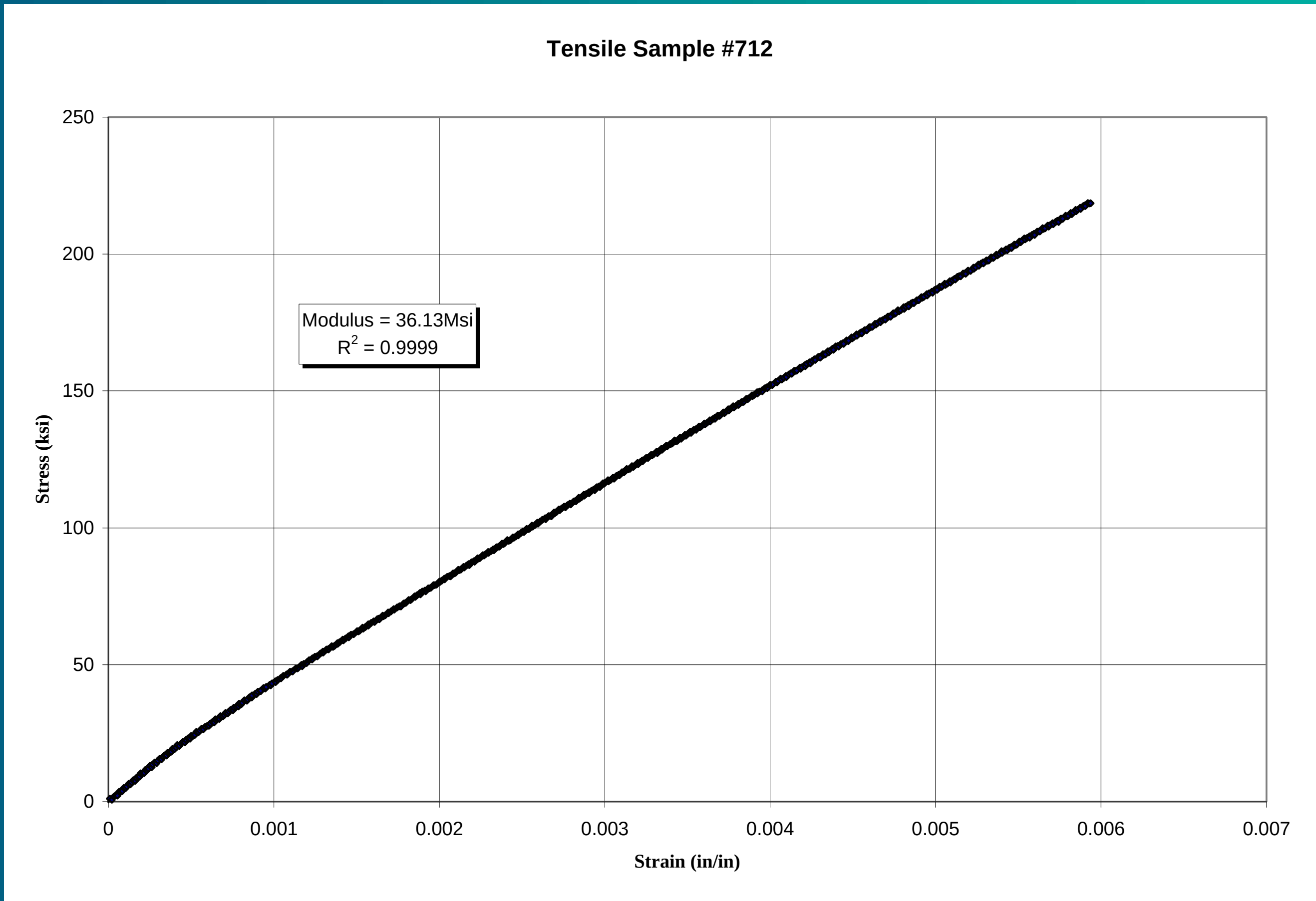
Angle – 0.375” per leg, 90° angle

Other sizes and shapes possible

Metal Prepreg Tape Properties

	V_f	Density (lb/in³)	Width (in)	Thickness (in)	F_1^{tu} (ksi)	E_1^t (Msi)	ε_1^{tu} (%)
Mean	0.50	0.119	0.377	0.0134	210	33	0.63

Material = Al_2O_3 fibers in pure Al
Temperature = RT
Environment = Air
Direction = [0]



Standard Tape:

Fiber volume of 50%

Width of 0.5 inch

Thickness of 0.015 inch

MMC Consolidation Methods

PROCESSING METHODS

Vacuum Furnacing
- Hand lay-up
- Weighted fixture
- Good for small parts
- Good for attachments

Vacuum Bagging
- Hand lay-up
- Evacuated fixture
- Larger components

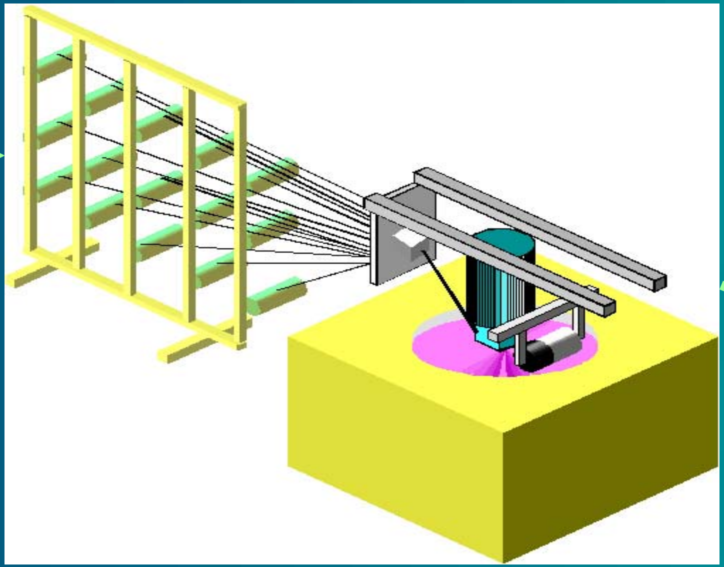
Adhesive Bonding
- Hand lay-up
- Room temperature cure
- Bag and autoclave

Tape/Fiber Placement
- Automated lay-up
- Cut/add/feed head
- Large complex components
- Out-of-autoclave

Hot Pressing
- Hand lay-up
- Controlled atmosphere
- Thicker components
- Higher fiber volume
- Flat and curved panels

Filament Winding
- Automated lay-up
- Higher fiber volume
- Large simple components
- Out-of-autoclave

Metal Prepreg Filament Winding



- **Analogous to PMC wet winding**
  - Based on MetPreg metal prepreg technology
  - Spools of fiber are put on creel
  - Tension is built into each tow
  - Fiber bundle is dipped into the liquid matrix (molten aluminum) to impregnate
  - Impregnated fiber bundle is laid onto the mandrel
- **Low-cost, flexible processing for MMCs**

MMC Filament Wound Components

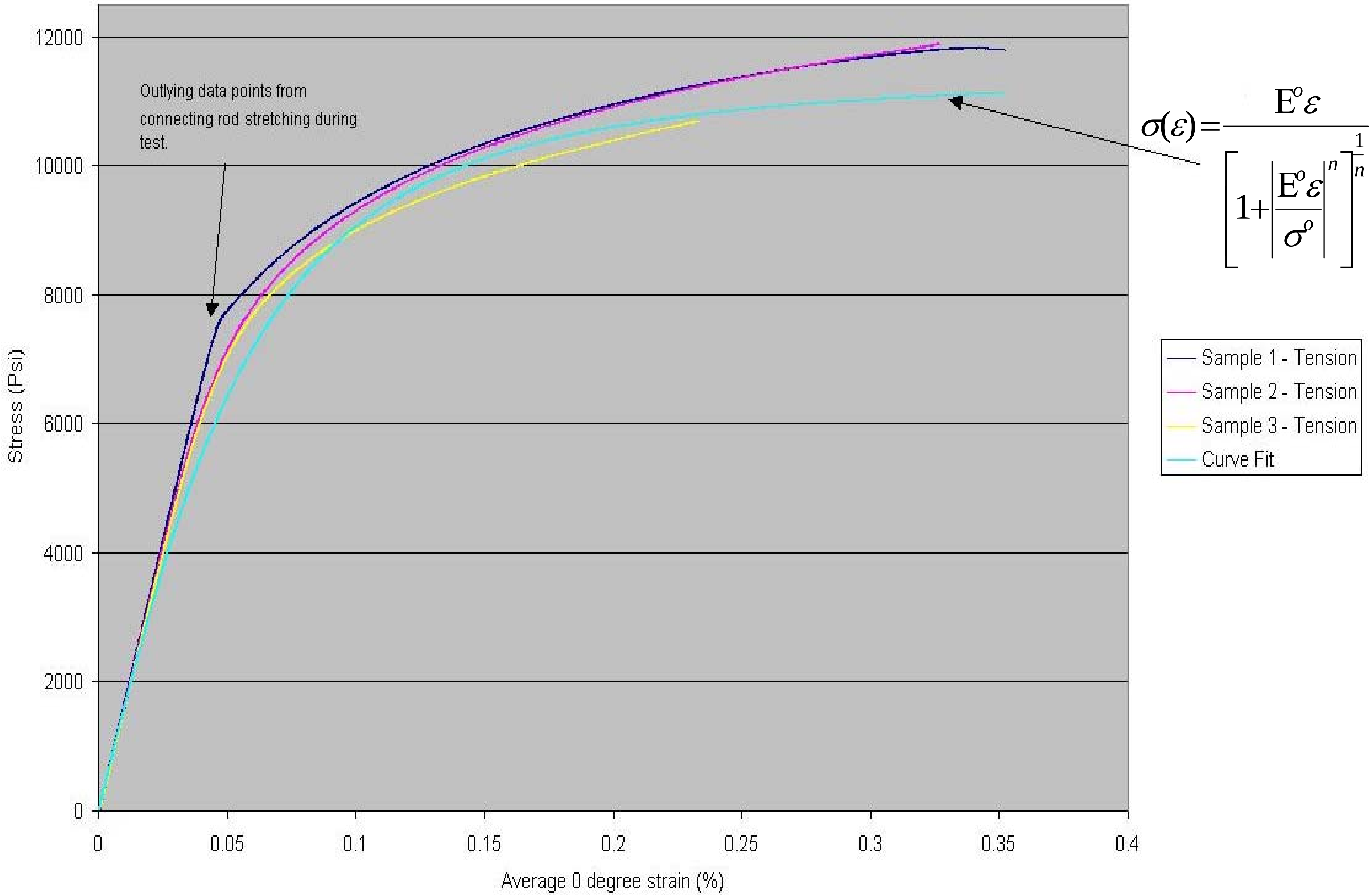
Fiber and Matrix Typical Properties

Property	Units	Fiber	Matrix
Chemical Composition	wt. %	>99 Al_2O_3	99.99 Al
Melting Point	°C °F	2000 3632	660 1220
Filament Diameter	μm in (10^{-4})	10-12 4-5	-
Crystal Phase		α- Al_2O_3	-
Density	g/cm^3 lb/in^3	3.9 0.141	2.7 0.098
Tensile Strength	MPa ksi	3100 450	40-50 6-7
Tensile Modulus	GPa Msi	380 55	62 9
Elongation	%	0.7-0.8	50-70
Thermal Expansion (100-1100°C)	ppm/°C ppm/°F	8.0 4.4	25 14

Axial Tension Test Results

Sample Number	E_{22} (Msi)	σ_{22} (ksi)	Strain @ Max Stress (%)
1	16.894	11.84	0.340
2	16.704	11.90	0.327
3	15.428	10.70	0.233
Average	**16.34**	**11.48**	**0.300**
Std. Dev.	**0.80**	**0.67**	**0.058**
Cv (%)	**4.88**	**5.9**	**19.5**

Tension Test Stress-Strain Curves

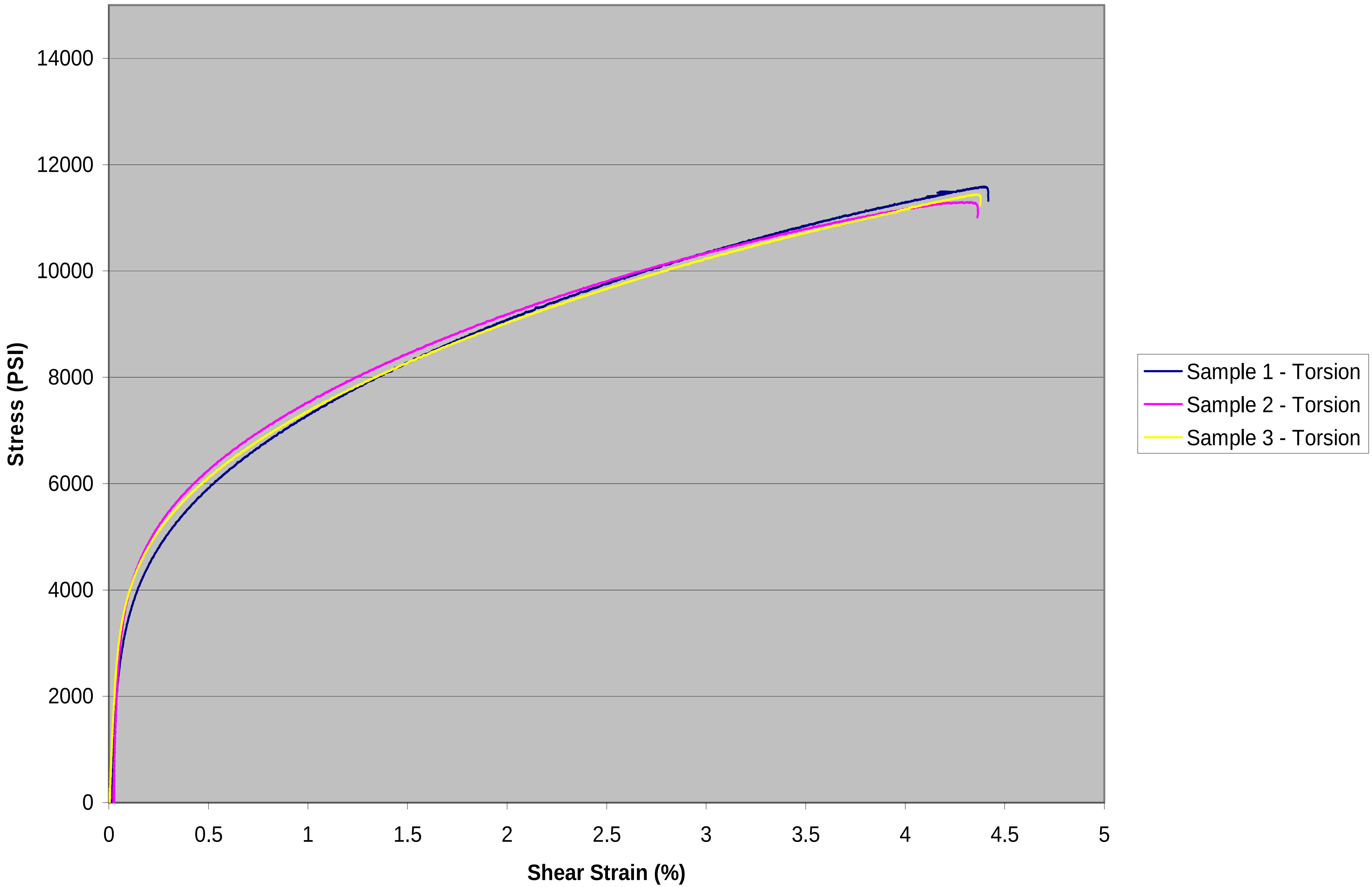


$$\sigma(\varepsilon)=\frac{E^{o}\varepsilon}{\left[1+\left|\frac{E^{o}\varepsilon}{\sigma^{o}}\right|^{n}\right]^{\frac{1}{n}}}$$

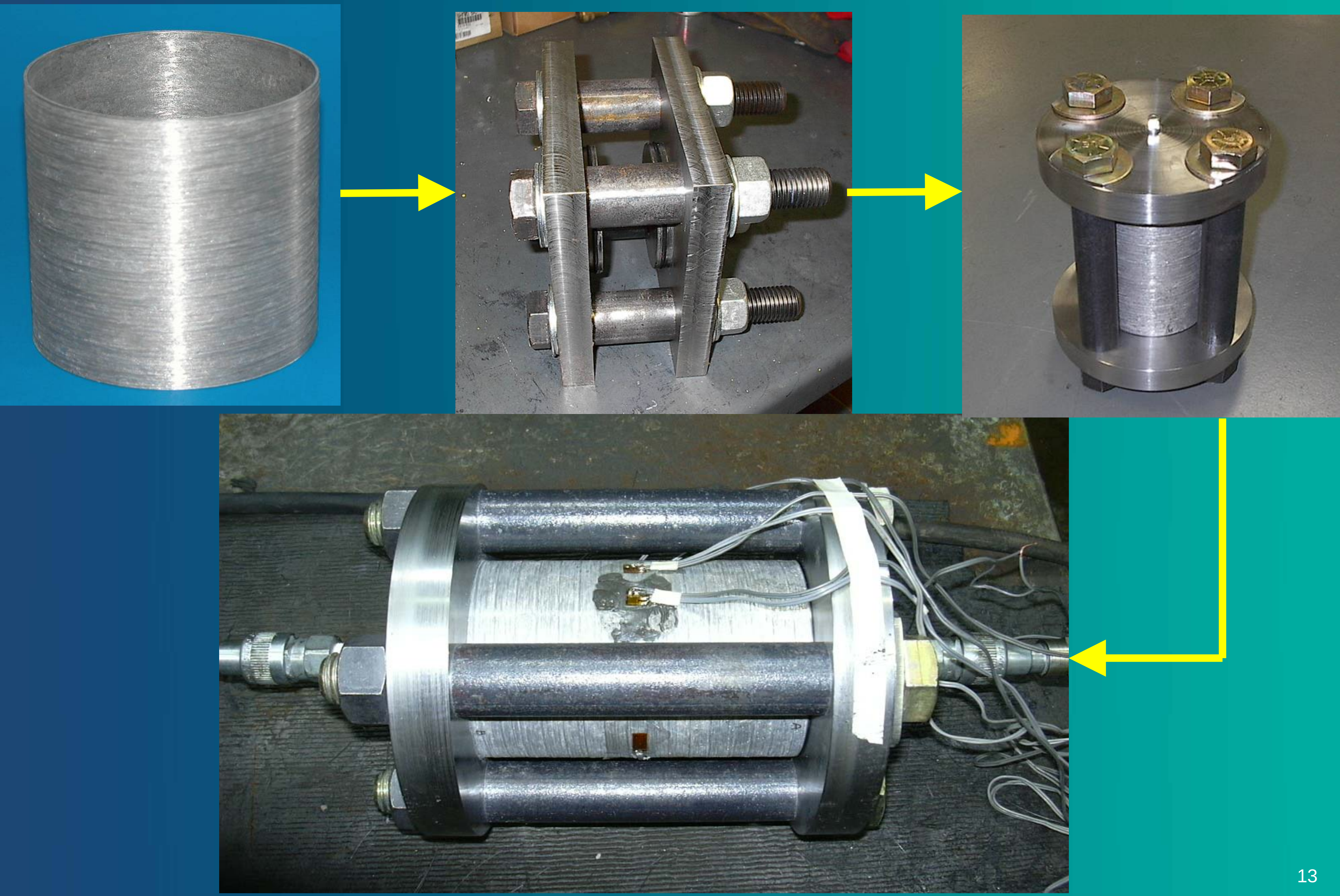
Torsion Test Results

Sample Number	G_{12} (Msi)	τ_{12} (ksi)	Strain @ Max Stress (%)
1	4.494	11.59	4.396
2	7.890	11.30	4.329
3	4.026	11.44	4.361
Average	**5.47**	**11.44**	**4.362**
Std. Dev.	**2.11**	**1.45**	**0.034**
Cv (%)	**38.55**	**1.3**	**0.8**

Torsion Test Stress-Strain Curves



Uniaxial Hydroburst Testing



Uniaxial Hydroburst Test Results

	Wall Thickness (in)	Length (in)	Inner Radius (in)	Fiber Volume Fraction	Burst Pressure (psi)	Delivered Lamina Strength (psi)	Delivered Fiber Strength (psi)
Hoop Only $[89]_4$	0.051	6.000	2.000	0.33	2700	105,882	320,856

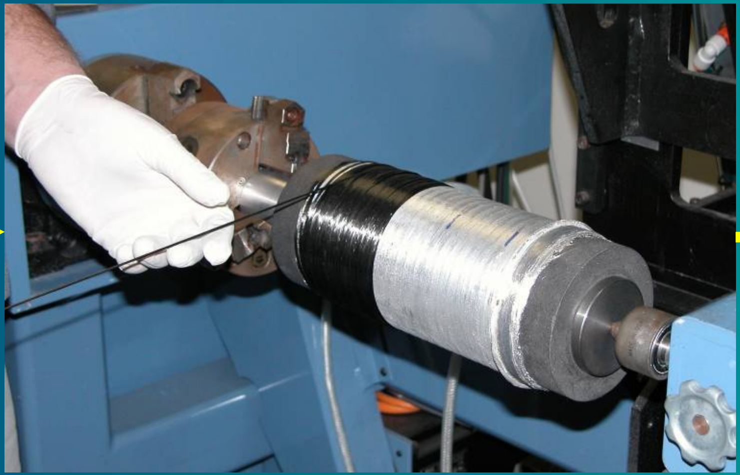
$$\text{Delivered Lamina Strength} = \frac{pr}{t}$$

$$\text{Delivered Fiber Strength} = \frac{pr}{tVf}$$

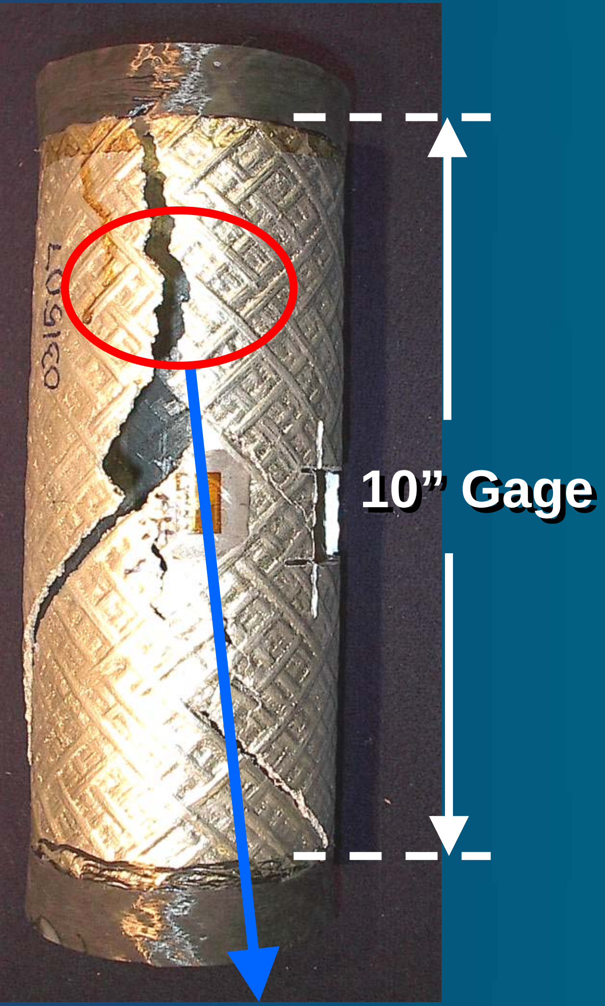
$$\text{Translation Efficiency} = \frac{\text{Delivered Fiber Strength}}{\text{Theoretical Fiber Strength}}$$

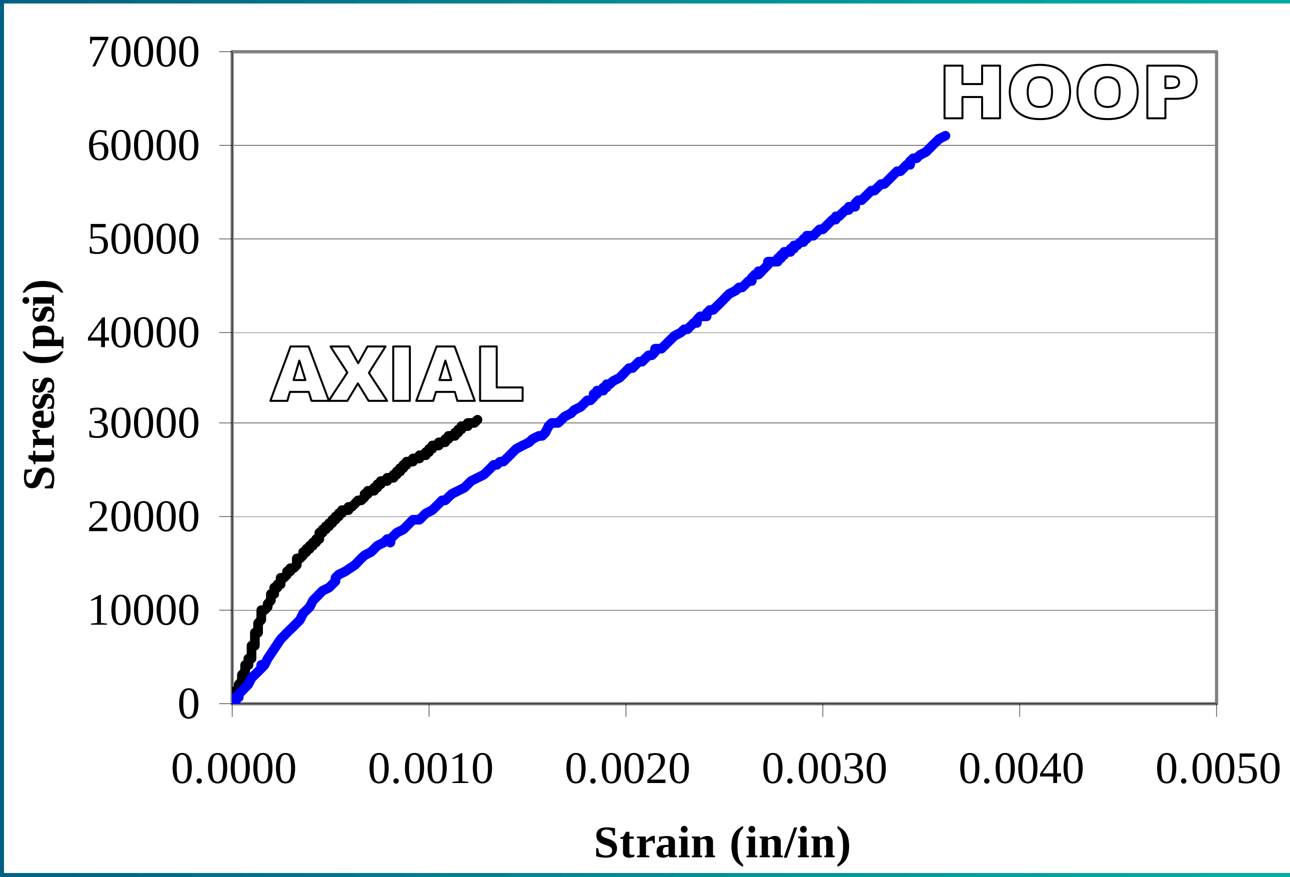
80% Translation Efficiency

Biaxial Hydroburst Testing



Cylinder Stress-Strain Response [±45/89/89/±45] Biaxial Hydroburst

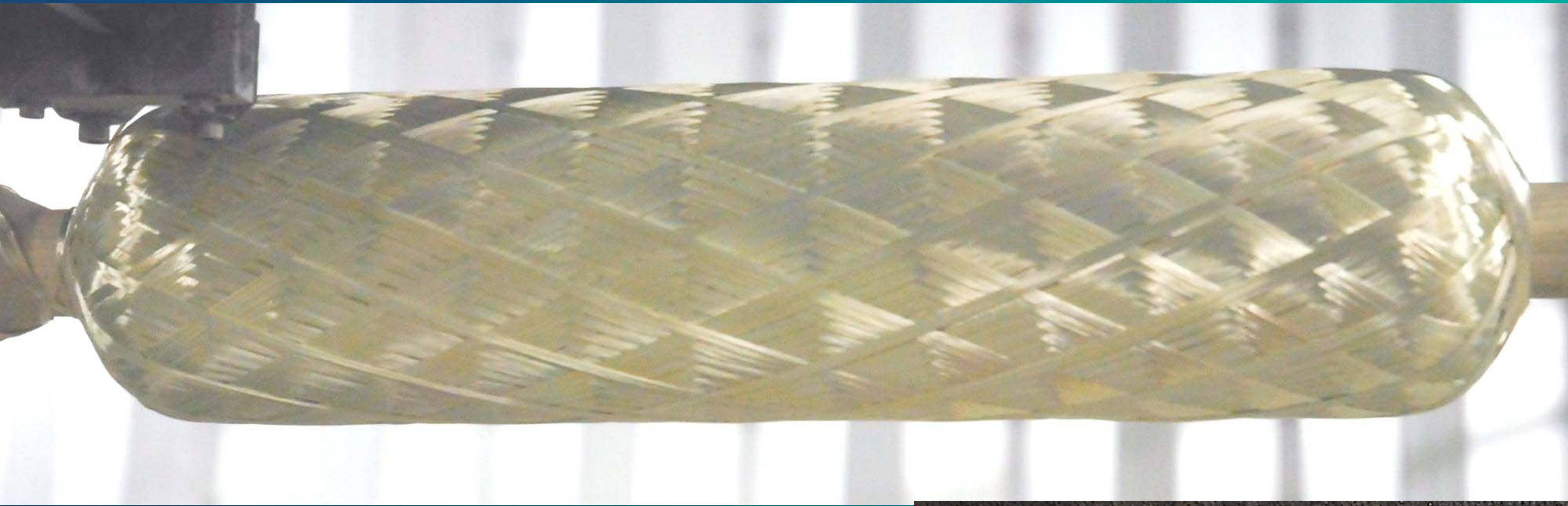




Failure Driven by Hoop Stress

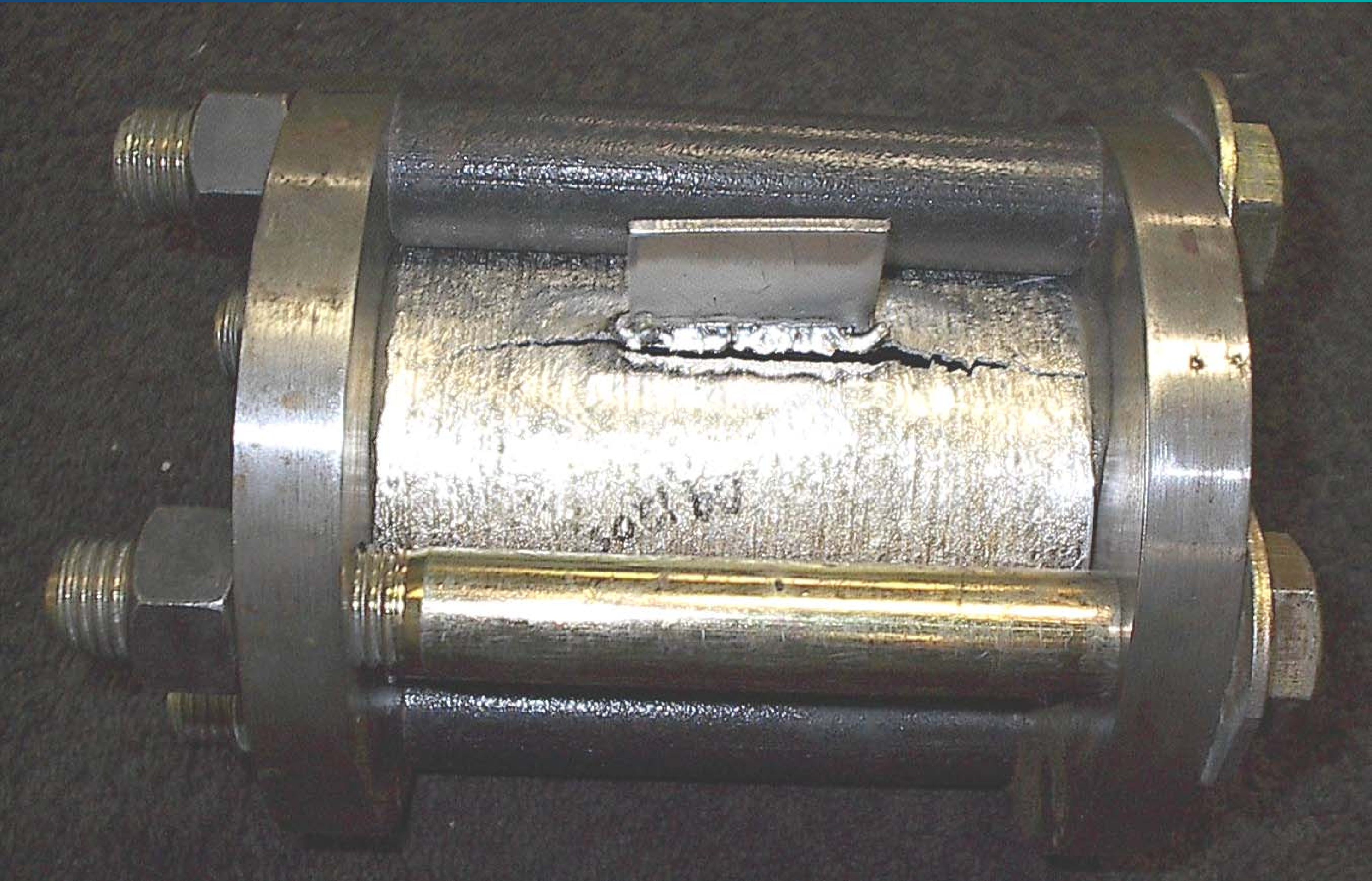
Process Developments

- Low-angle helical winding - 20°



- Integrally Wound Domes and Skirts

Attachment Test



Attachment Test Summary

	Wall Thickness (in)	Fiber Volume Fraction	Burst Pressure (psi)	Delivered Hoop Stress (psi)	Hoop Fiber Stress (psi)	Translation Efficiency (%)
Recent Cylinder Tests	0.050	0.43	2812	111,843	263,174	66
MIG	0.051	0.42	2235	87,087	207,349	52
Pulse MIG	0.052	0.42	2030	78,839	189,989	48

Bolt Hole Test

Cylinder ID	Burst Pressure (psi)	Delivered Hoop Stress (psi)	Hoop Fiber Stress (psi)	Translation Efficiency (%)
100505	1078	40,679	104,306	26
101005	1257	50,280	125,700	31

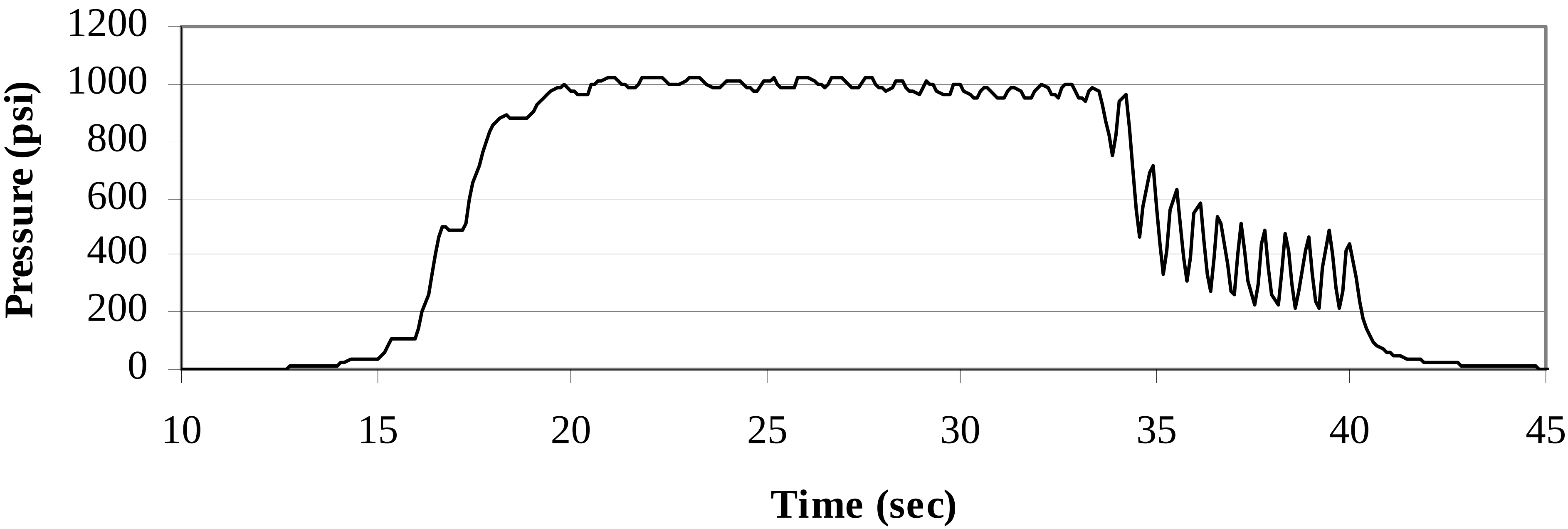
Impact Test

- 6-ply cylinders
- 2-lb weight
- 0.625-inch indenter
- Drop heights of 6 and 12 inches
- Hydroburst testing after impact

Cylinder ID	Drop Height (in)	Burst Pressure (psi)	Delivered Hoop Stress (psi)	Hoop Fiber Stress (psi)	Translation Efficiency (%)
100405	6	1686	64,846	162,115	41
100605	12	1065	40,189	100,472	25

Pinned Closure Test

Pinned Closure Test Summary



- Tests were to establish baseline properties
- Detailed stress analysis not yet completed
- AT 1000 psi internal pressure, the stress in the MMC near each hole would be over 56 ksi
- This is comparable to a quasi-isotropic PMC
- Lower helical angle would dramatically effect the results

MMC Design Tool Development

- Design tool for modeling MMC behavior is being developed for predicting properties of cylinders
- Fiber strength adjusted to match burst pressure from uniaxial hydroburst tests (first row of table)
- Model predictions show good agreement with biaxial experimental data when the failure mode is hoop fiber failure (rows two and four)
- Other failure modes, such as helical fiber or matrix failure, show slight discrepancy from experimental results (row three)
- Model validation and modification is on-going

Cylinder Lamination	Assumed Fiber Strength (ksi)	Assumed Translation Efficiency	Predicted Burst Pressure (psi)	Actual Burst Pressure (psi)	Percent Difference (%)
90_4	249	0.62	2813	2812	0
90_4	249	0.62	728	777	-6
90/±45/90	249	0.62	1728	1472	17
±45/90/90/±45	249	0.62	3250	3393	-4

Preliminary IM Modeling Results

Design Description	Maximum predicted fiber stress as a fraction of the allowable fiber stress	IM test being modeled
Instantaneous response to design loads at 75ºF	0.925, ***Failure not predicted***	None
Instantaneous response to design loads at 300ºF	0.978, ***Failure not predicted***	Fast cookoff
Instantaneous response to design loads at 500ºF	1.42, ***Failure predicted***	Fast cookoff
30 min. stress-rupture response to design loads at 300ºF	1.49, ***Failure predicted***	Slow cookoff

Conclusions

- Scale-up of MMC filament winding process to 23-inch overall cylinder length has been completed
- Good translation of fiber properties has been achieved with a 10-inch gage length
- Longer process length makes helical fiber angles of ±20° achievable
- MMC Design Tool being validated through experimental results
- MMC Design Tool and burst test results being used to design cylinders for IM testing

Future Work

- Determine the effect on pressure vessel performance with varying helical ply angle
- Refine the process for winding integral end domes, bosses, and skirts
- Design and produce cylinders for IM testing
- Look for additional partners interested in teaming up on SBIR programs to further develop MMC filament wound pressure vessels, storage tanks, space structures, and flywheels

Questions?

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