Polymer Composite Material Screening for a Cryotank Application

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Welcome Slide

- Joseph Pinakidis
- NASA Glenn Research Center – Cleveland, OH
- Michigan State University & Purdue University
- Aerospace Materials Engineer
- Background in mechanical testing, characterizing aerospace materials, composites, and manufacturing
- Baseball fan (go Cubs and Guards), sand volleyball, and voracious reader

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Motivation

- Interest in a more fuel-efficient and lower carbon emission airspace transportation
- Liquid hydrogen (LH2) propulsion technology is attractive for its higher energy density than traditional fuels and fewer carbon-based emissions [1]
- Significant design considerations to overcome such as fuel tank sizing, storage at cryogenic temperatures (-253 °C/20 K), and operational safety
- Carbon fiber reinforced polymer (CFRP) composites can be leveraged for their high strength-to-weight ratio which increases efficiency of transport vehicles [2]

[1] Yusaf et al., 2022.
[2] Otto et al., 2022.

Background

- Matrix microcracking is the primary driver for permeation leaks and failure within composite cryotanks, particularly when subjected to stress at cryogenic temperatures [3], [4]
- NASA's Commercially viable Hydrogen Aircraft for Robust Growth in Efficiency (CHARGE) Project was formed to address these challenges for air and space missions
- Toughened resin epoxies and thermoplastics are being investigated to improve cryogenic mechanical performance to withstand refueling cycles, flight loads, and environmental conditions (e.g. hydrogen embrittlement)
- In previous work, NASA's Composite Cryotank Technology Development (CCTD) Project successfully manufactured two composite LH2 tanks for space application that passed thermal cycling, permeation, and burst tests [5]

[3] Hodge, 2001.
[4] Manu et al., 2022.
[5] Jackson et al., 2015.

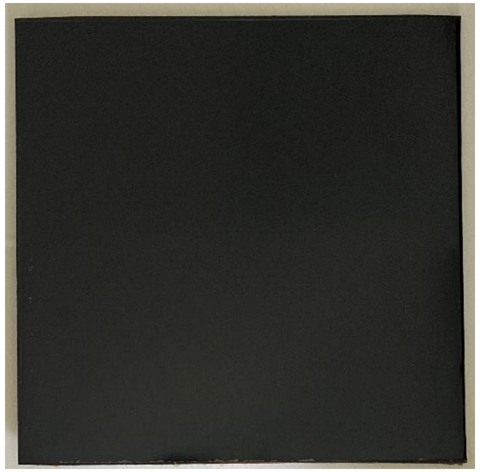
Focus of This Work

- Perform a mechanical screening of relevant composite materials to inform cryotank design decisions
- Determine the effect, if any, of cryogenic thermal cycling on static and fatigue performance
- Provide publicly available data as a starting point for other entities
- Liquid nitrogen (LN2) was used for thermal cycling efforts (-196 °C/77 K)in this work due to time and cost constraints (compared to LH2 at -253 °C/20 K)

Materials

- Composite materials:
  1. Thermoplastic (TP): T1100 carbon fiber (CF)/TC1225 low-melt polyaryletherketone (LM-PAEK), 145 gsm, 34% resin content, Toray Advanced Composites
  2. Thermoset (TS): T1100 /3960 toughened epoxy, 192 gsm, 34% resin content, Toray
  3. Hybrid (TS/VEIL): T1100 CF/3960 toughened epoxy prepreg with a thermoplastic polyurethane (TPU) melt spun veil between every ply, 15 gsm, Hills Inc.

TP quasi-isotropic panel.



TS quasi-isotropic panel.

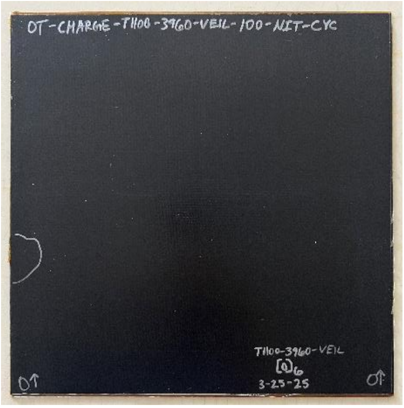
One ply of T1100/3960 prepreg.

+

TPU veil added in between each ply.

Repeat x15

=



Hybrid TS/TPU Veil Composite.

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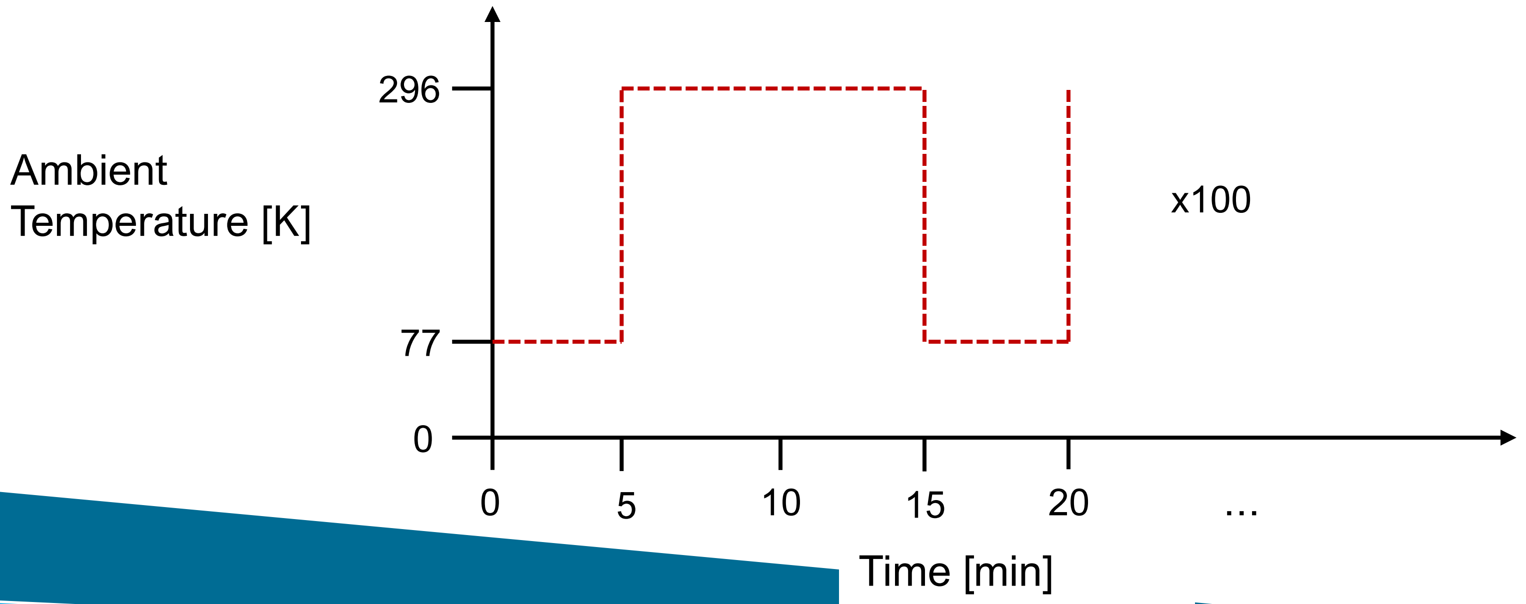
LN2 Thermal Cycling Methodology

- LN2-cycling methodology (Experior Laboratories):
  - Submerged in LN2 (-196 °C/77 K) for 5 min.
  - Pull from bath, equilibrate to room temperature (RT, 23 °C/296 K) for 10 min.
  - Repeat for 100 cycles per coupon

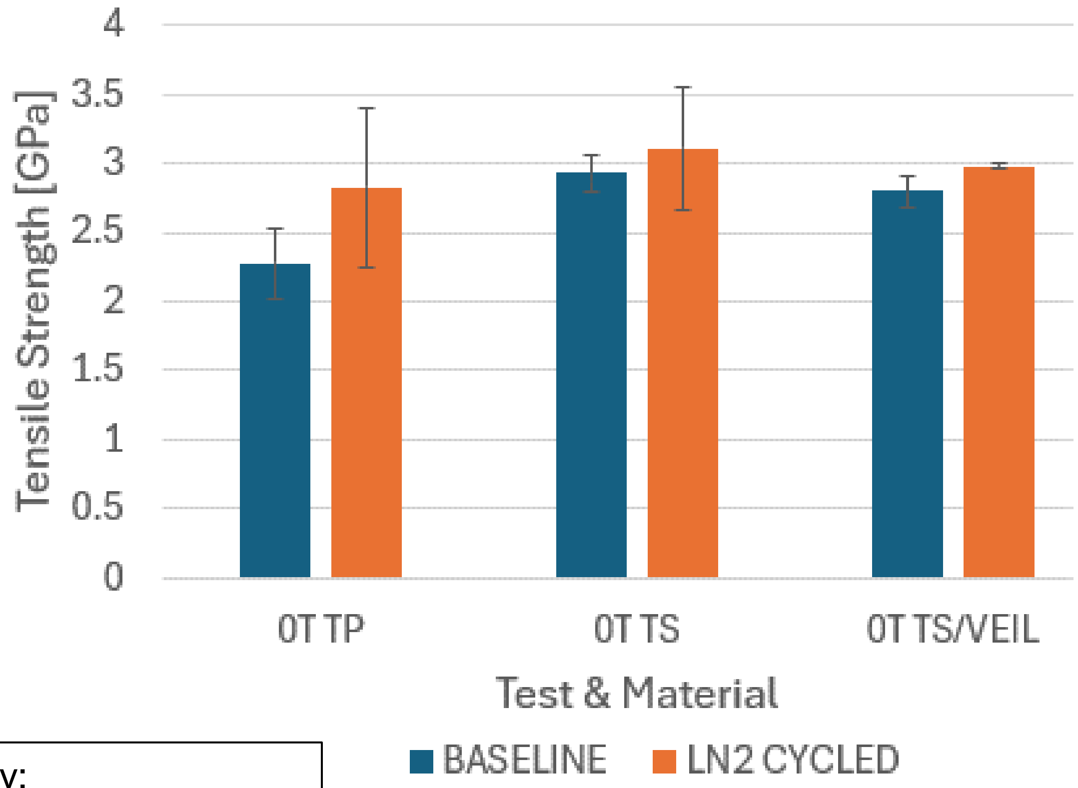


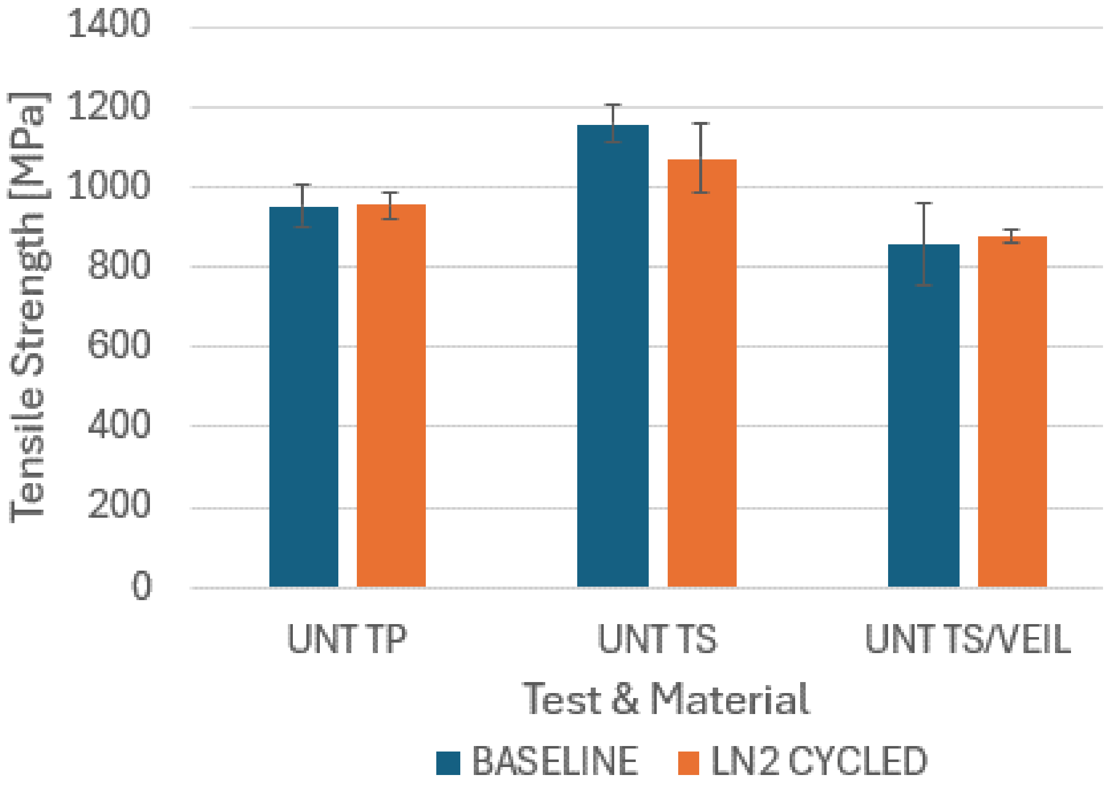
Mechanical Testing Methods

Abbr.	Test	ASTM Standard	Layup	Coupon Size [in]	Condition	Specimen	Materials
90T	Lamina Tension [90 degree]	D3039	[0]6	10.0 x 0.5	Baseline	7	2
0T	Lamina Tension [0 degree]	D3039	[0]6	10.0 x 0.5	Baseline	7	3
					LN2 Cycled	7	3
UNT	Laminate Tension	D3039	[45,0,-45,90]2S	10.0 x 1.0	Baseline	7	3
					LN2 Cycled	7	3
0C	Lamina Compresion	D6641	[0]14	5.50 x 0.5	Baseline	5	2
					LN2 Cycled	5	2
UNC	Laminate Compresion	D6641	[45,0,-45,90]3S	5.50 x 0.5	Baseline	5	2
					LN2 Cycled	5	2
IPS	In-Plane Shear	D3518	[+45/-45]4S	10.0 x 1.0	Baseline	7	3
					LN2 Cycled	7	3
TTF	Tension-Tension Fatigue	D3479	[45,0,-45,90]2S	10.0 x 1.0	Baseline	7	2
					LN2 Cycled	7	2

*Note: All tests conducted at RT.

Results – Tensile Data



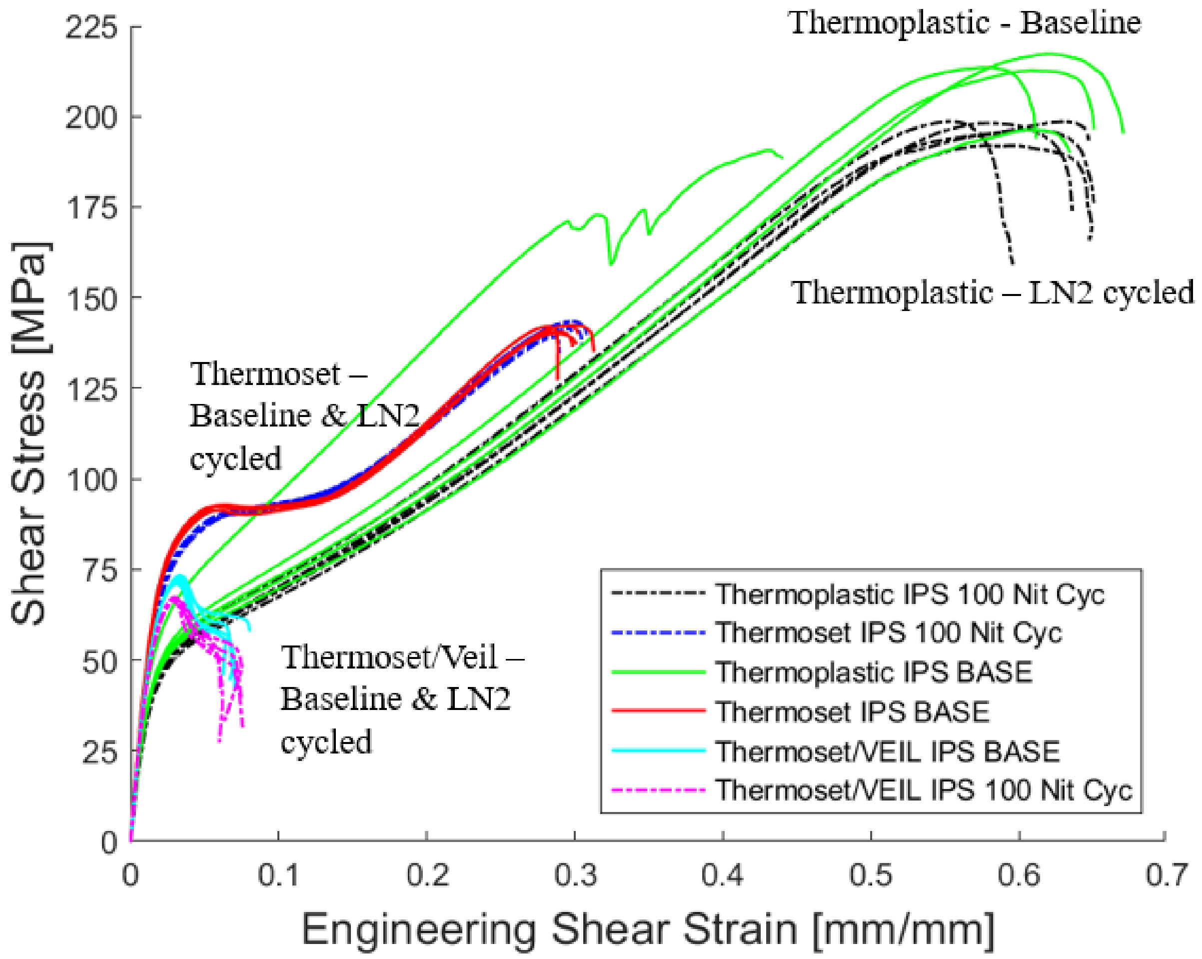


Key:
- TP – Thermoplastic
- TS – Thermoset
- TS/VEIL - Hybrid

90° tensile tests were completed at RT to support modeling efforts:

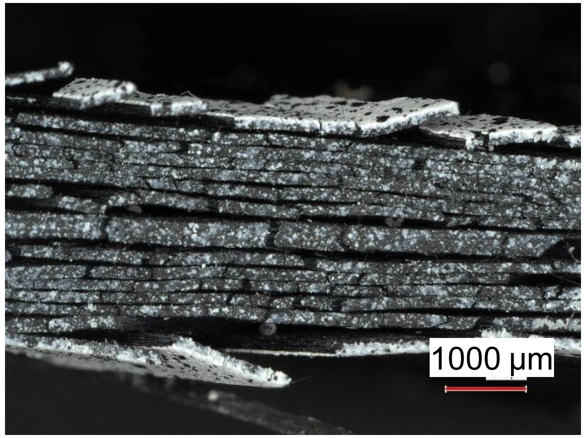
- TP: avg. strength: 89.2 ± 16.1 MPa, avg. modulus: 7.76 ± 0.16 GPa
- TS: avg. strength: 49.1 ± 4.9 MPa, avg. modulus: 8.66 ± 0.32 GPa

Results – In-Plane Shear Data

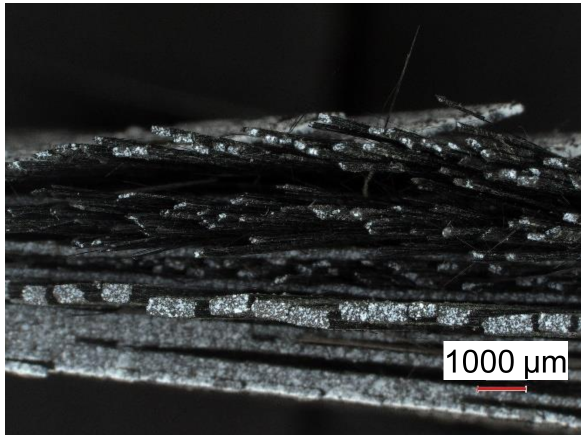


Failed IPS LN2-cycled coupons.

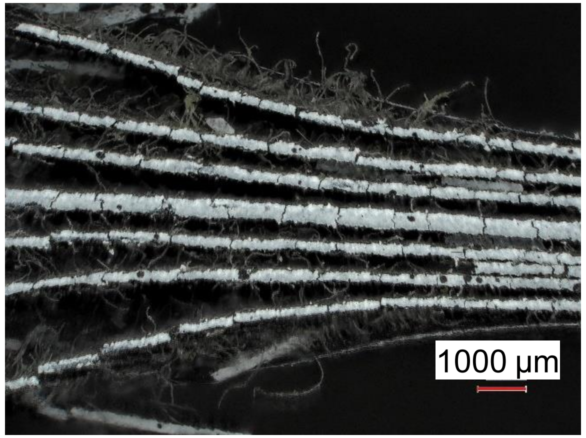
Microscopy – In-Plane Shear Failure



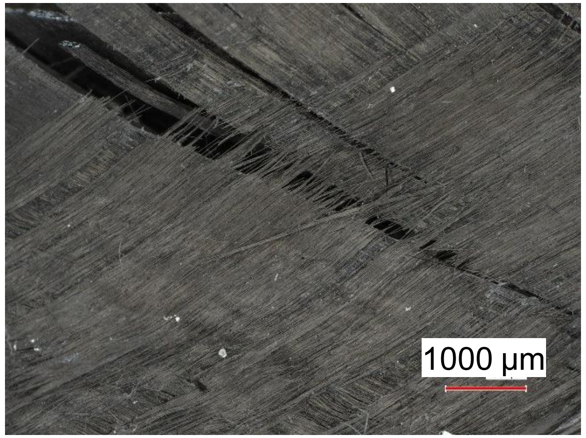
Side view



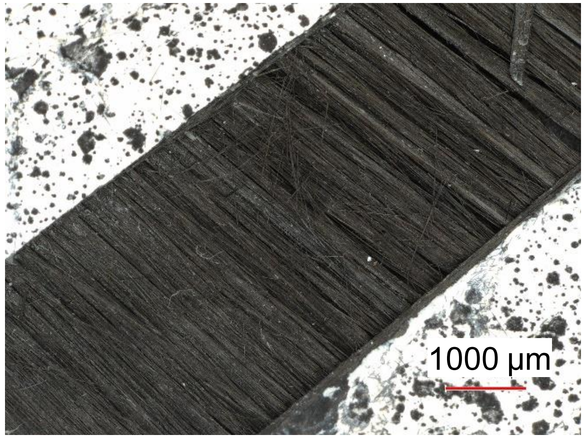
Side view



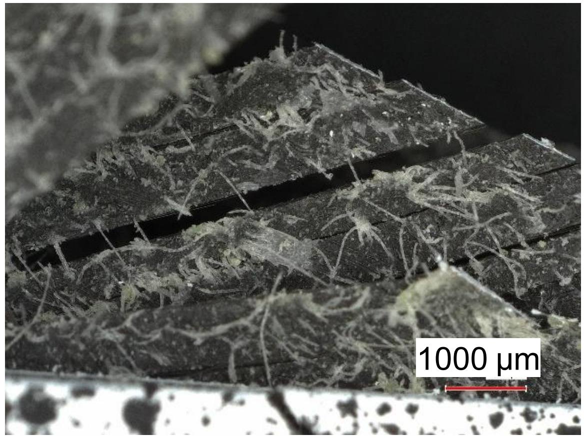
Side view



Top view



Top view



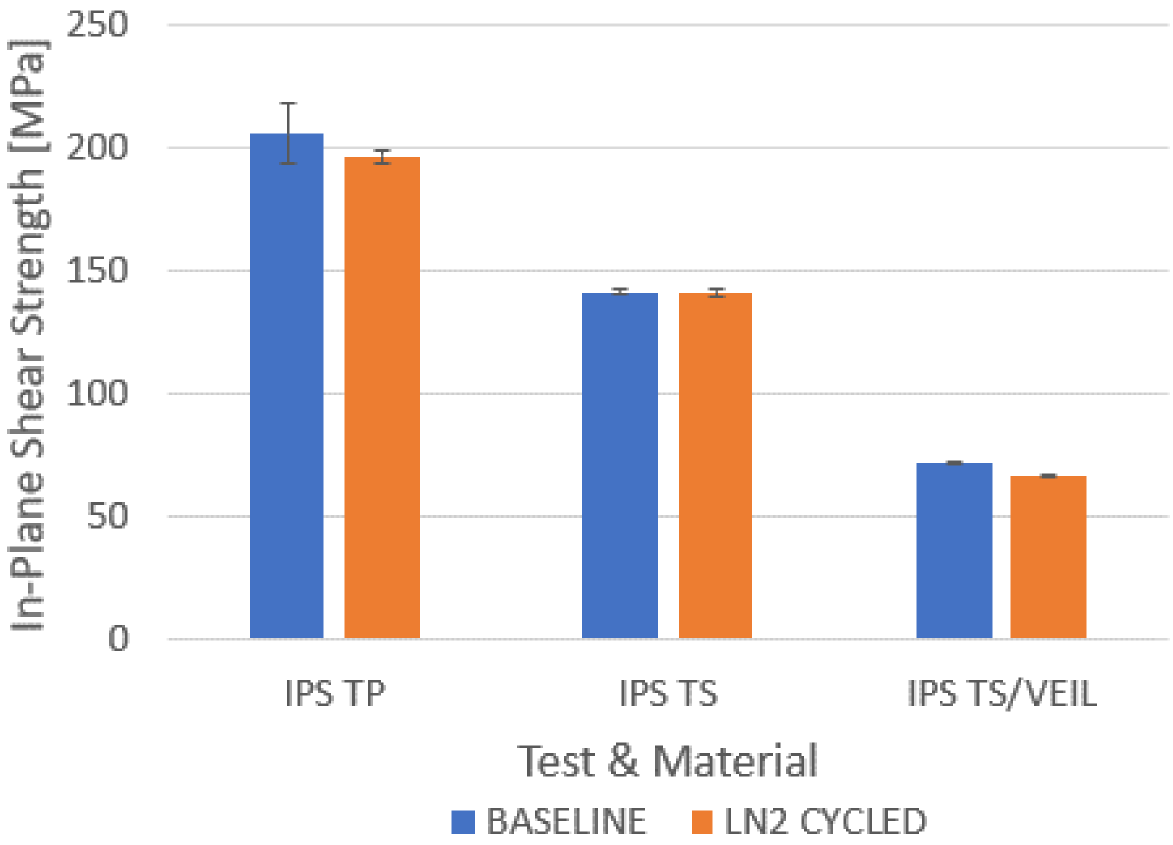
Top view

Thermoplastic

Thermoset

Thermoset/Veil

Results – In-Plane Shear (cont.)



Key:
- TP – Thermoplastic
- TS – Thermoset
- TS/VEIL - Hybrid

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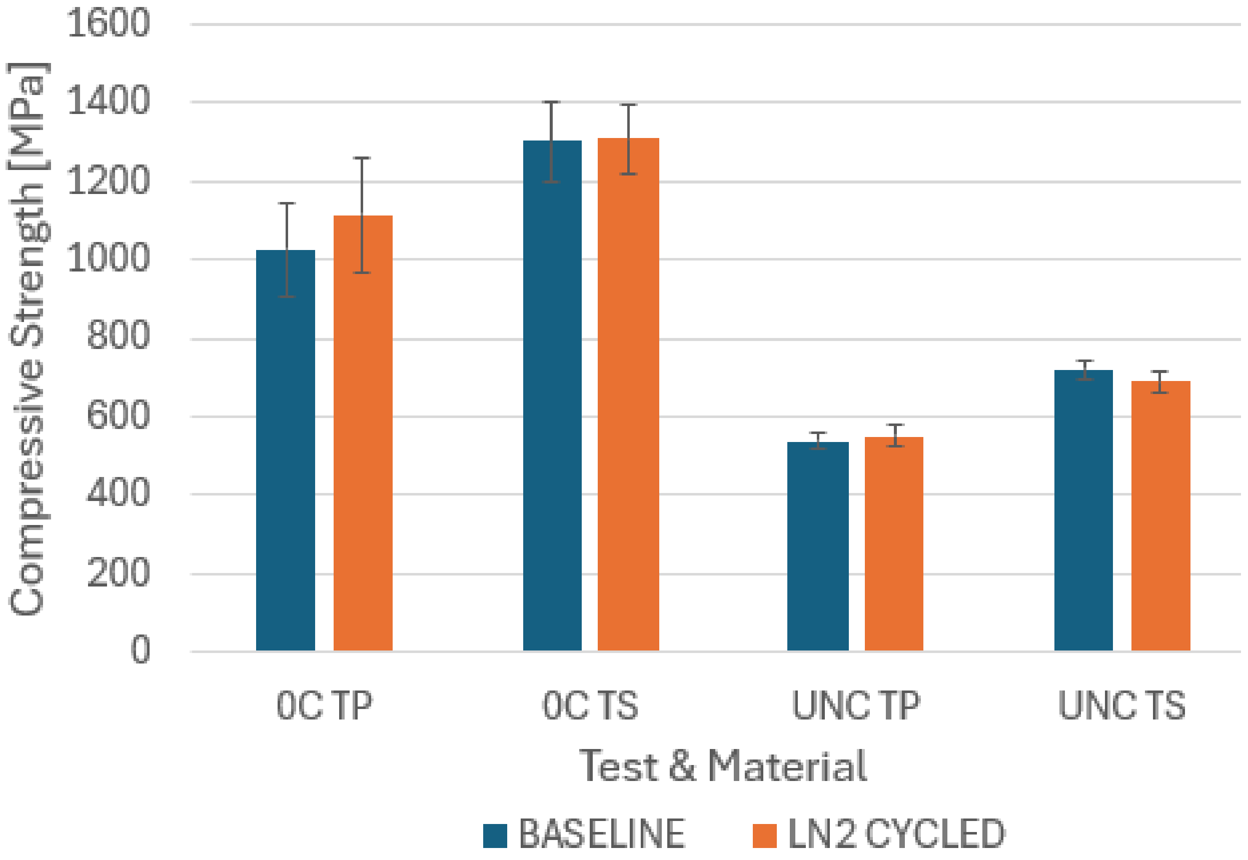
Results – Compression Data



Key:
- TP – Thermoplastic
- TS – Thermoset

*Note: No hybrid tested due to poor performance and project constraints.

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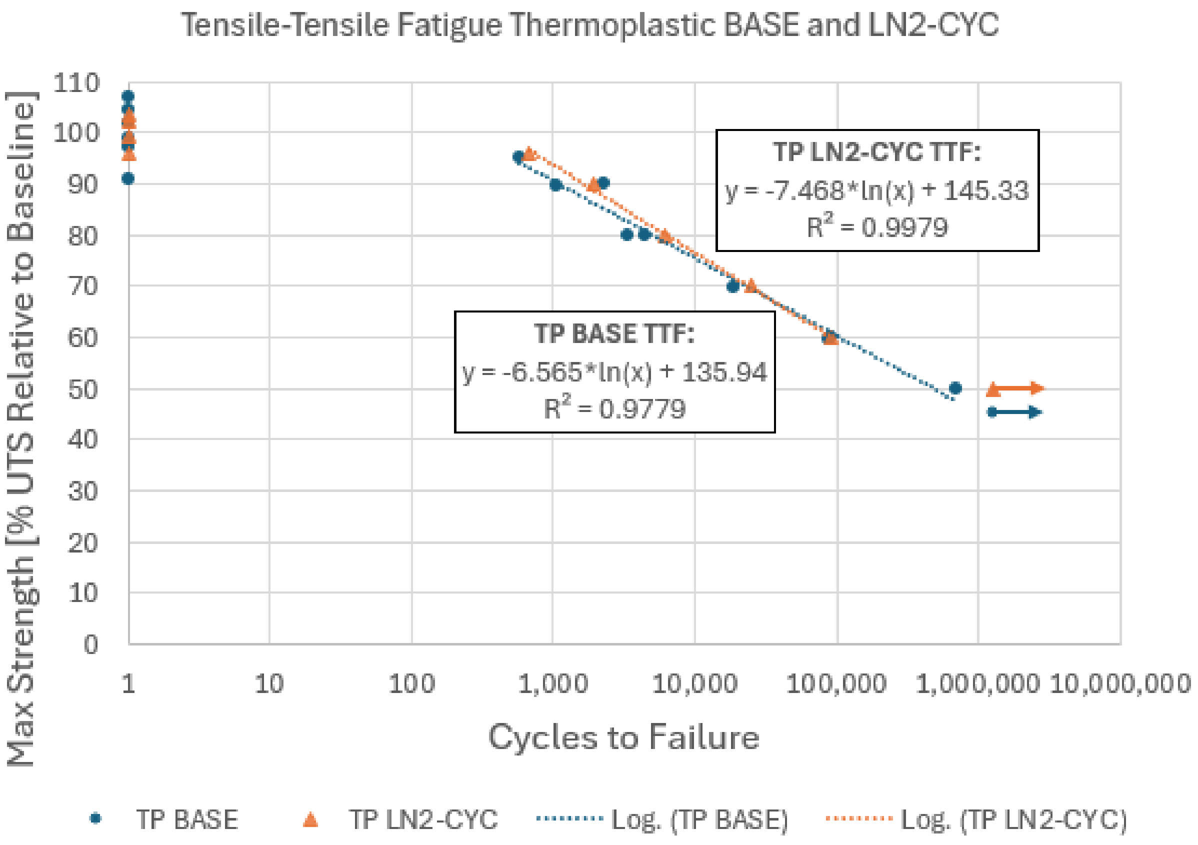
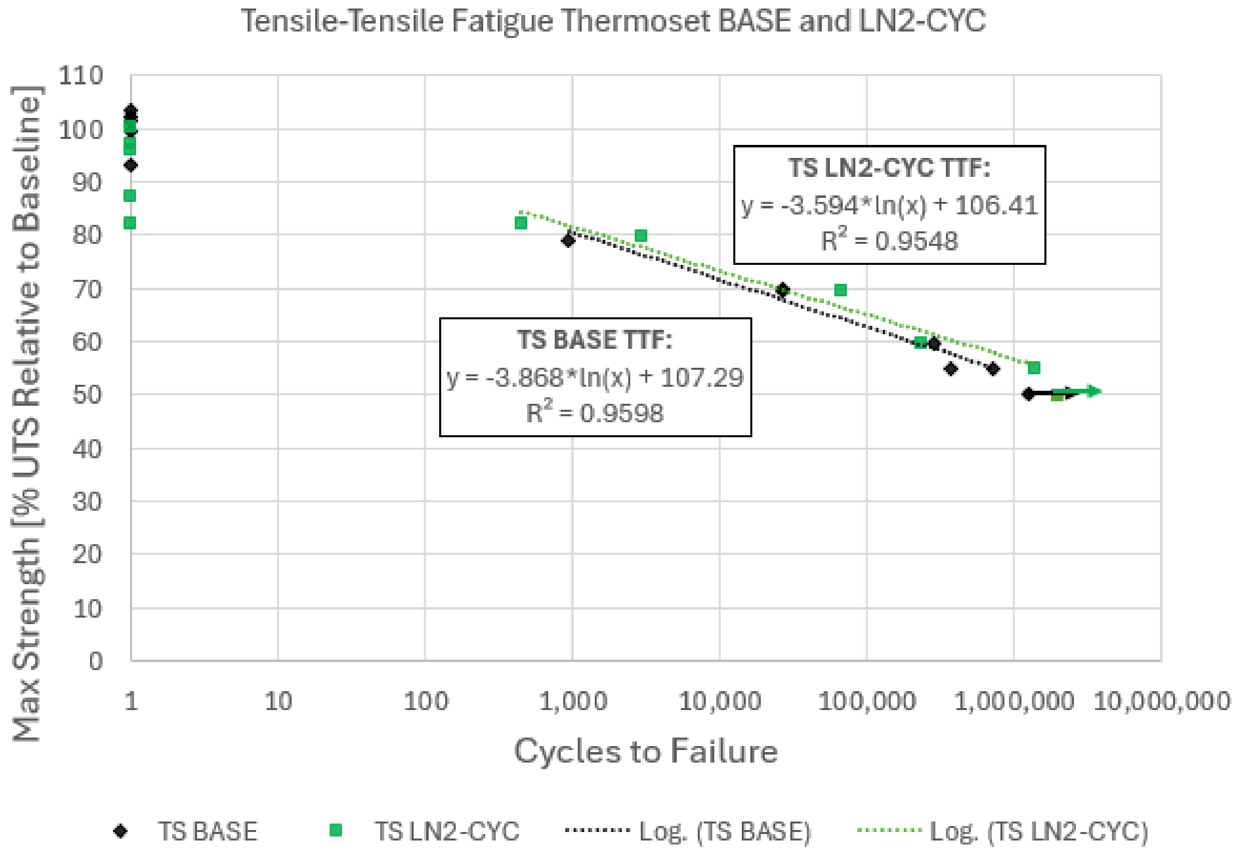
Results – Tensile-Tensile Fatigue Data





- Tested at a frequency of 5 Hz and load ratio of 0.1
- Delam and matrix cracking typically observed in early cycles

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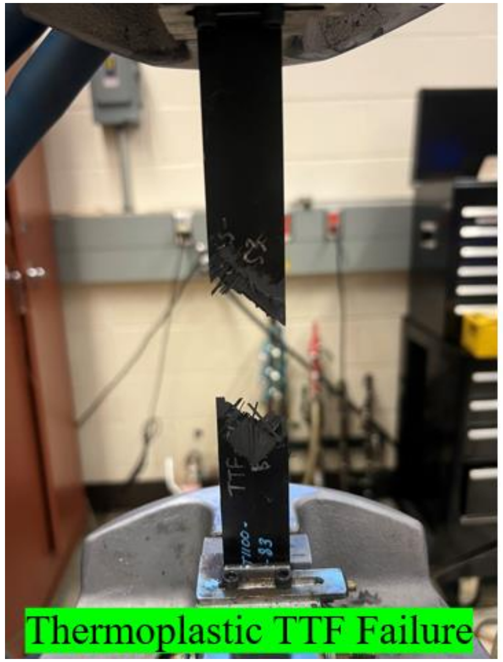
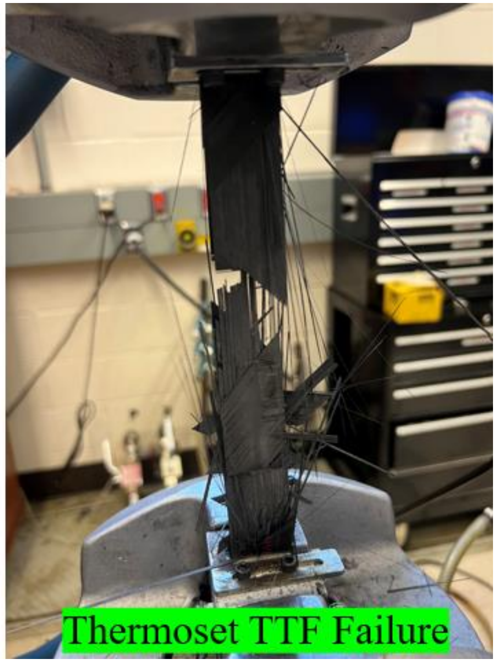
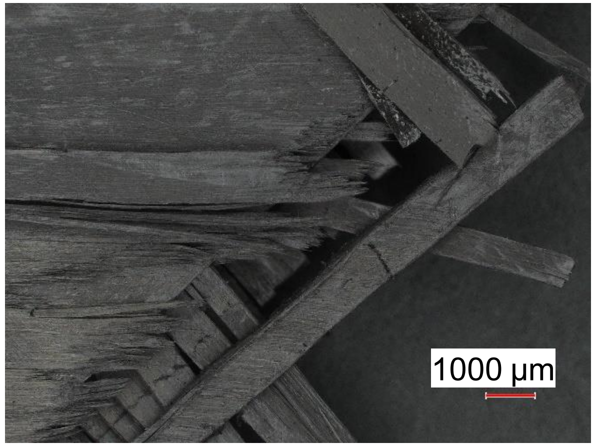
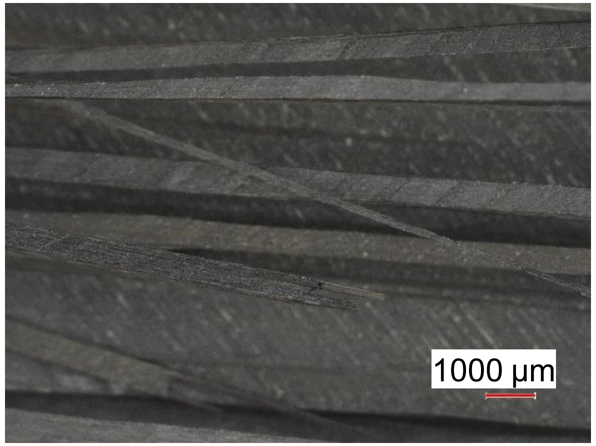
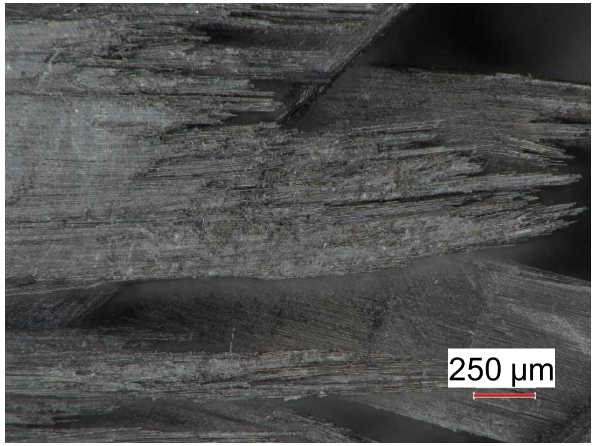
Results – Tensile-Tensile Fatigue Failure

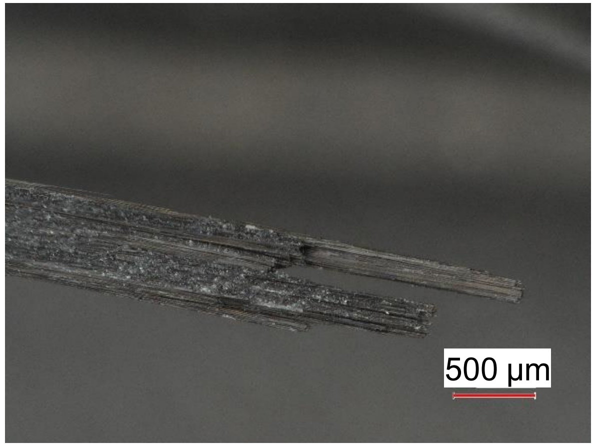












Thermoplastic

Thermoset

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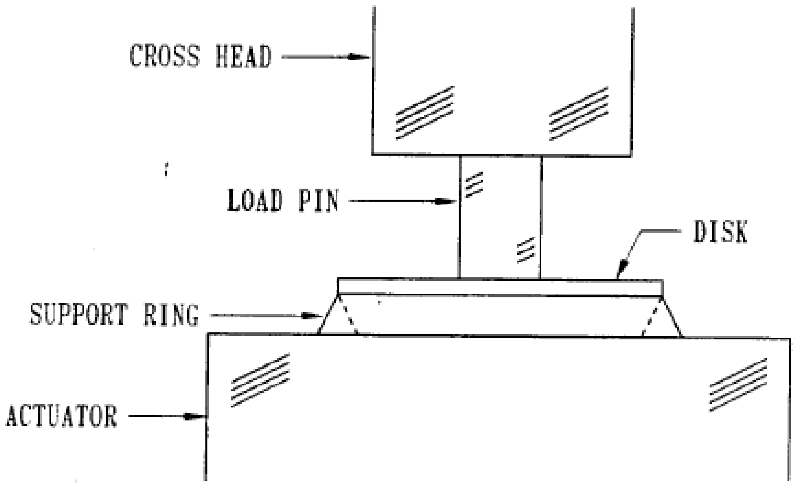
Conclusions

- Material screening completed for a TP, TS, and hybrid TS/TPU Veil composite
- Significant challenges and knockdown factors of the hybrid composite in its premature state due to poor interfacial bonding
- Minimal effects of LN2-cycling compared to baseline for all mechanical tests
- Negligible effects of LN2-cycling on fatigue performance, fit to a log-linear relationship
- Captured data will inform material down-selection and modeling efforts for an LH2 cryotank

Next Steps & Future Work

- Planned mechanical tests of the neat matrix (LM-PAEK & 3960 resin) and CF composites at LH2 temperature of 20 K
  - Toughness, tension, thermal expansion, fatigue, thermal conductivity, burst testing
  - Inform modeling efforts
- Modified tensile-tensile fatigue to minimize edge effects
  - Utilize strain gauges to capture change in stiffness, indicative of microcracking
- Other thermal cycling ideas include soaking material for longer in cryo and thermal cycling under bi-axial loading conditions
- Manufacture a sub-scale cryotank part



Loading arrangement of a biaxial disk specimen [6].

[6] Cavallaro & Tsangarakis, 1995.

References

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[2] Otto, M., Chagoya, K. L., Blair, R. G., Hick, S. M., & Kapat, J. S., "Optimal hydrogen carrier: Holistic evaluation of hydrogen storage and transportation concepts for power generation, aviation, and transportation." *Journal of Energy Storage*, *55*, (2022), 105714.

[3] Hodge, A. J., "Evaluation of microcracking in two carbon-fiber/epoxy-matrix composite cryogenic tanks." (No. NAS 1.15: 211194, NASA/TM- 20010080458). National Aeronautics and Space Administration, (2001).

[4] Manu, M., et al., "Review on development of effective carbon fiber based cryogenic storage tank materials for space applications." (March 15, 2022). Proceedings of the International Conference on Aerospace & Mechanical Engineering (ICAME 21), Available at SSRN: https://ssrn.com/abstract=4057984 or http://dx.doi.org/10.2139/ssrn.4057984

[5] Jackson, J. R., Vickers, J., & Fikes, J., "Composite cryotank technologies and development 2.4 and 5.5 m out of autoclave tank test results." (No. M15-4801 NASA/TM- 20150021410). National Aeronautics and Space Administration, (2015).

[6] Cavallaro, P., Gee, L., & Tsangarakis, N. (1995). *Biaxial Testing of Composites. A Study of the Disk Specimen* (No. ARLTR690).