

POLYMER COMPOSITE MATERIAL SCREENING FOR A CRYOTANK APPLICATION

Joseph J. Pinakidis, Sandi G. Miller
NASA Glenn Research Center
Cleveland, OH/USA

ABSTRACT

Composite cryotanks will play a key role in enabling the next generation of efficient aircraft. Carbon fiber reinforced polymer (CFRP) composites have the benefits of reduced weight and potentially higher structural strength compared to traditional metallic fuel tanks. A material screening study was conducted to inform material selection for liquid hydrogen (LH2) fuel storage. Three composite materials were considered because of their aerospace grade toughness, strength, and existing data to compare against. These materials were a thermoplastic low-melt polyaryletherketone (LM-PAEK)/carbon fiber (CF), thermoset/CF, and hybrid thermoset/thermoplastic polyurethane (TPU) veil/CF composite. Mechanical screening tests included tension, compression, in-plane shear (IPS), and tensile-tensile fatigue. Each material was tested at both a baseline (no liquid nitrogen/LN2 cycling) and 100 LN2-cycled conditions to determine the knockdown factor, if any, of each material when exposed to environmental loading effects in a cryotank. Results show minimal effects of the LN2-cycling compared against baseline values. The three materials behaved similarly in tension; however, the thermoplastic/CF had the highest IPS toughness. The hybrid thermoset/TPU/CF composite had the lowest IPS strength, compressive strength, and toughness. LN2-cycling had minimal effects on tensile-tensile fatigue performance of the thermoplastic/CF material. Mechanical data was captured to guide material down selection for future commercially viable hydrogen aircraft design.

Keywords: composites, testing, cryotank

Corresponding author: Joseph J. Pinakidis, joseph.pinakidis@nasa.gov

1. INTRODUCTION

There is an interest towards developing more fuel-efficient and lower carbon emission airspace transportation by leveraging hydrogen propulsion technology. The main appeal of using liquid hydrogen fuel is its abundance, higher energy density than traditional fuels, and no carbon-based emissions, although it still does produce nitrous oxide pollutants [1]. Liquid hydrogen (LH2) has a roughly three times higher energy density (123 MJ/kg) than traditional fuels such as kerosene (43 MJ/kg), but its volumetric energy density (8.5 MJ/m³) is roughly four times lower than kerosene (32 MJ/m³) and needs to be stored at very low temperatures (around -253 °C) to remain

Notice for Copyrighted Information

This manuscript is a work of the United States Government authored as part of the official duties of employee(s) of the National Aeronautics and Space Administration. No copyright is claimed in the United States under Title 17, U.S. Code. All other rights are reserved by the United States Government. Any publisher accepting this manuscript for publication acknowledges that the United States Government retains a non-exclusive, irrevocable, worldwide license to prepare derivative works, publish, or reproduce the published form of this manuscript, or allow others to do so, for United States government purposes.

*SAMPE Conference Proceedings. Seattle, WA, April 27-30, 2026.
Society for the Advancement of Material and Process Engineering – North America.*

(DOI will be added by SAMPE)

in liquid form [2]. To leverage this alternative fuel there are significant design considerations that must be accounted for in future air and space craft such as fuel tank size, storage at cryogenic temperatures, and operational safety. Carbon fiber reinforced polymer (CFRP) composites are an attractive material choice for this cryogenic fuel storage because of their high strength-to-weight ratio. These lightweight fuel tanks increase the efficiency for transport vehicles [3], which can help meet aeronautics and space goals such as on-orbit propellant depots and long duration flights.

NASA's Commercially viable Hydrogen Aircraft for Robust Growth in Efficiency (CHARGE) project is working to address challenges associated with cryogenic fuel storage for air and space missions. The project is funded by the Aeronautics Mission Research Directorate and brings together a team with aircraft design, modeling, thermal storage engineering, material science, and manufacturing experience. The motivation of this work is to perform a material screening of relevant composite materials to provide mechanical data needed for design selection, and discover the effects, if any, that cryogenic thermal cycling could have on static and fatigue performance. Liquid nitrogen (LN2) was used to thermally cycle materials due to cost and time constraints of the project. All subsequent mechanical tests were performed at room temperature (23°C).

Matrix microcracking is a primary driver for permeation and failure in composite cryotanks, therefore CFRP composites must be tough enough to withstand thousands of refueling cycles, flight loads, and environmental conditions (hydrogen embrittlement) [4]. When a composite laminate is stressed, particularly at cryogenic temperatures, damage modes such as matrix microcracking are known to occur [5], [6]. Mitigating microcracking is essential for composite cryotanks because it negatively affects fatigue life and permeation leaks, contributing to boil-off and safety concerns. Hence, toughened resin epoxies and thermoplastics are being investigated to improve cryogenic mechanical properties and prevent cryogenic pressure deformation and microcrack propagation [7], [8]. This is why a thermoplastic, toughened thermoset, and hybrid thermoset/thermoplastic interlayer carbon fiber composite materials were selected for this study. In a previous study, NASA's Composite Cryotank Technology Development (CCTD) project successfully manufactured two composite LH2 cryotanks that validated an estimated 33% weight savings and 30% cost saving projection compared to aluminum lithium tanks [9]. This effort demonstrated the use of an out-of-autoclave (OoA) IM7 carbon fiber/Cytec 5320-1 toughened epoxy resin that passed a manufacturing, thermal cycling, permeation, and burst test. It was found that permeation could be reduced with the use of thin-ply in the cryotank wall [10]. Thus, there is demonstrated technological promise in this area and this material screening serves as the next step in expanding mechanical characterization that will guide the design process.

2. EXPERIMENTAL METHODS

2.1 Materials

The purpose of this material screening was to gather data on candidate composite materials to evaluate their applicability for a composite cryotank. Three different composite materials were selected for this study due to their aerospace-grade strength and existing data in literature. The first was a thermoplastic (TP) composite prepreg consisting of T1100 carbon fiber (CF) and

TC1225 low-melt polyaryletherketone (LM-PAEK), 145 grams per square meter (gsm), 34% resin content, obtained from Toray Advanced Composites (Morgan Hill, CA). The second was a thermoset (TS) composite prepreg comprised of T1100 CF and 3960 toughened epoxy, 192 gsm, 34% resin content, also from Toray. The third composite was a hybrid of the T1100 3960 prepreg and a thermoplastic polyurethane (TPU) melt spun veil, 15 gsm, procured from Hills Inc. (Melbourne, FL). The TPU veils were used as interlayer between every ply of T1100/3960 in the hybrid composite panel layup.

2.2 Liquid Nitrogen Cycling

Liquid nitrogen (LN2) was used for thermal cycling of coupons instead of liquid hydrogen (LH2) for cost and time restraints of the project. Coupons were sent to Experior Laboratories (Oxnard, CA). The individual coupons were submerged in LN2 at approximately -196 °C for 5 min., pulled from the bath, and equilibrated to room temperature (RT) at approximately 23 °C for 10 minutes. This process was repeated for 100 cycles for each coupon.

2.3 Mechanical Testing Methods

All mechanical tests were performed in accordance with ASTM Standards and at room temperature (23 °C). The full mechanical screening test matrix is detailed in Table 1. The tests will be referred to by their abbreviation for the remainder of the paper. The hybrid veil composite was only tested in certain tests due to relatively poor performance. The thermoplastic and thermoset composite materials were tested in every test. For reference, the 0° direction in mechanical tests refers to the carbon fiber reinforcement being aligned with axial movement direction (fiber-dominated response), and 90° refers to carbon fibers being perpendicular to crosshead movement (matrix-dominated response). Un-notched tension (UNT) and un-notched compression (UNC) abbreviations were used to identify un-notched quasi-isotropic coupons.

Table 1. Test matrix for all material testing in the CHARGE project.

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	Lamina 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	Lamina 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

2.3.1 Tensile-Tensile Fatigue

Tensile-tensile fatigue (TTF) testing was conducted on a Material Test System 810. Each quasi-isotropic TTF coupon was loaded and gripped in the machine, then ramped at 500 N/s to the calculated mean force. Once this force level was reached, the correct amplitude would trigger to ensure that the coupon oscillated at a frequency, f , of 5 Hz in tension-tension to maintain a load ratio, R , of 0.1. Prior to the test, mean force and amplitude [N] were calculated in a spreadsheet to achieve the desired stress level. In all cases, baseline and LN2-cycled, coupons were normalized based on percentage of average maximum stress [MPa] of the baseline material system in un-notched compression (UNC). This was reported on the y-axis as % ultimate tensile strength (UTS) relative to baseline.

3. RESULTS

Mechanical results were captured for each of the three composite materials as a part of this material screening. Although all the tests were conducted at room temperature, each material had a baseline and 100 LN2 cycled counterpart to directly compare against. In nearly every case, the LN2 cycled coupons were within scatter in strength compared to the baseline counterpart, Table 2. The standard deviation error bars overlap which indicates that the difference is likely not significant. The same trend is observed for the modulus in which there is similar values for both the baseline and 100 LN2 cycled coupons, except for the IPS test in which the modulus values for LN2 cycled materials were slightly lower than baseline. The modulus values are presented in Table 3.

Table 2. Summary strength data for each material and test. Values are $\pm$ one standard deviation.

	Condition	0T [MPa]	90T [MPa]	UNT [MPa]	0C [MPa]	UNC [MPa]	IPS [MPa]
TP	Baseline	2280 $\pm$ 265	89.2 $\pm$ 16.1	952 $\pm$ 54	1025 $\pm$ 117	538 $\pm$ 21	206.1 $\pm$ 11.8
	100 LN2 Cycled	2829 $\pm$ 581	N/A	955 $\pm$ 33	1114 $\pm$ 147	551 $\pm$ 25	196.7 $\pm$ 2.8
TS	Baseline	2934 $\pm$ 127	49.1 $\pm$ 4.9	1157 $\pm$ 47	1302 $\pm$ 102	719 $\pm$ 21	141.5 $\pm$ 1.1
	100 LN2 Cycled	3109 $\pm$ 437	N/A	1072 $\pm$ 88	1309 $\pm$ 88	690 $\pm$ 27	141.7 $\pm$ 1.7
Hybrid	Baseline	2799 $\pm$ 107	N/A	855 $\pm$ 102	N/A	N/A	72.1 $\pm$ 0.9
	100 LN2 Cycled	2982 $\pm$ 24	N/A	877 $\pm$ 16	N/A	N/A	66.7 $\pm$ 0.5

Table 3. Summary modulus data for each material and test. Values are $\pm$ one standard deviation.

	Condition	0T [GPa]	90T [GPa]	UNT [GPa]	0C [GPa]	UNC [GPa]	IPS [GPa]
TP	Baseline	163.5 $\pm$ 11.5	7.76 $\pm$ 0.16	57.7 $\pm$ 1.9	154.1 $\pm$ 3	55.3 $\pm$ 1.3	3.61 $\pm$ 0.22
	100 LN2 Cycled	172.2 $\pm$ 14.2	N/A	57.6 $\pm$ 1.9	150.2 $\pm$ 2.9	57.7 $\pm$ 1.8	3.31 $\pm$ 0.13
TS	Baseline	187.1 $\pm$ 27.7	8.66 $\pm$ 0.32	62.1 $\pm$ 1.8	153.4 $\pm$ 1.2	59.4 $\pm$ 0.2	4.93 $\pm$ 0.14
	100 LN2 Cycled	164.7 $\pm$ 3.9	N/A	61.1 $\pm$ 1.6	149.9 $\pm$ 1.8	58.4 $\pm$ 1.4	4.59 $\pm$ 0.14
Hybrid	Baseline	160.7 $\pm$ 6.8	N/A	57.8 $\pm$ 2.3	N/A	N/A	4.54 $\pm$ 0.11
	100 LN2 Cycled	153.9 $\pm$ 1.6	N/A	56.4 $\pm$ 2.8	N/A	N/A	4.36 $\pm$ 0.07

3.1 Tensile Data

The 90° tensile test is a matrix dominated test and provides valuable information to the project's modeling effort. The 90T baseline TP coupons had an average tensile strength of 89.2 MPa with standard deviation of 16.1 MPa, and modulus of $7.76 \text{ GPa} \pm 0.16 \text{ GPa}$. The 90T baseline TS coupons had an average tensile strength of $49.1 \text{ MPa} \pm 4.9 \text{ MPa}$, and modulus of $8.66 \text{ GPa} \pm 0.32 \text{ GPa}$.

The 0T and UNT (quasi-isotropic) results support the trend observed in literature that tensile strength increases at lower temperatures due to both a reduction in polymer chain mobility, and resin contraction around the fiber leading to a stronger bond between the fiber and matrix [11]. Although tests in this work were completed at RT and not cryogenic temperature, the 0T results indicate that there may be residual effects such as matrix densification and changes to the fiber-matrix interface still present from the LN2-cycling. This is observed in Figure 1 where a slight increase in unidirectional tensile strength was recorded for all LN2-cycled 0T tests compared to baseline. Similar strengths were found between LN2-cycled and baseline coupons for UNT tests in Figure 2. All data is within the error scatter ($\pm$ one standard deviation) when comparing data between baseline and LN2-cycled coupons of a certain material.

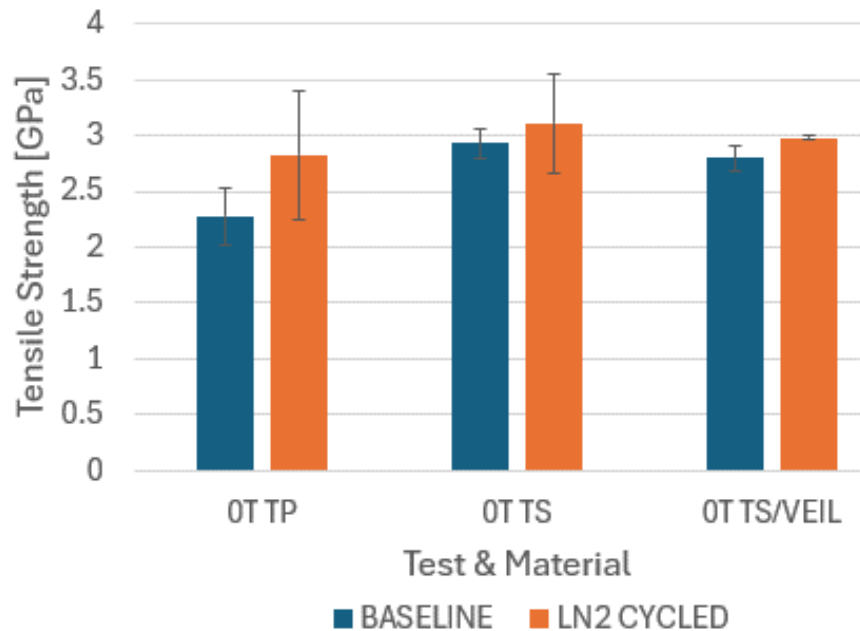


Figure 1. Tensile strength for unidirectional tensile (0T) tests at baseline and LN2 cycled conditions $\pm$ one standard deviation. Materials tested were a TP, TS, and hybrid TS/veil composite.

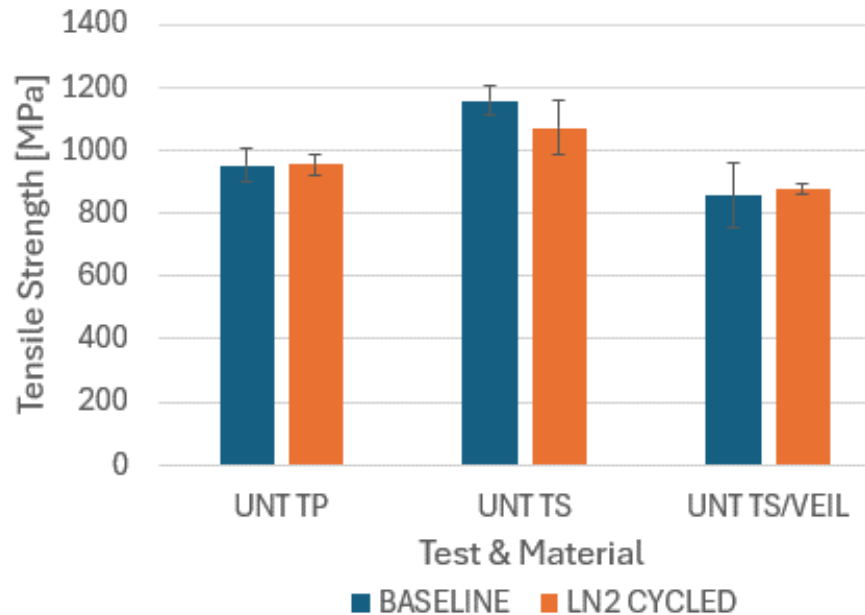


Figure 2. Tensile strength for un-notched tensile (UNT) quasi-isotropic tests at baseline and LN2 cycled conditions $\pm$ one standard deviation. Materials tested were a TP, TS, and hybrid TS/TPU veil composite.

3.2 Compression Data

Unidirectional (OC) and un-notched quasi-isotropic (UNC) compression testing was completed for both the TP and TS materials. Five coupons were tested for compression strength and three coupons were wired with uni-axial strain gauges to collect modulus values. Despite being LN2-cycled at low temperature ($\sim 196^{\circ}\text{C}$), compression tests at RT yielded the same or slightly higher compressive strength, see Figure 3. All data was within the scatter.

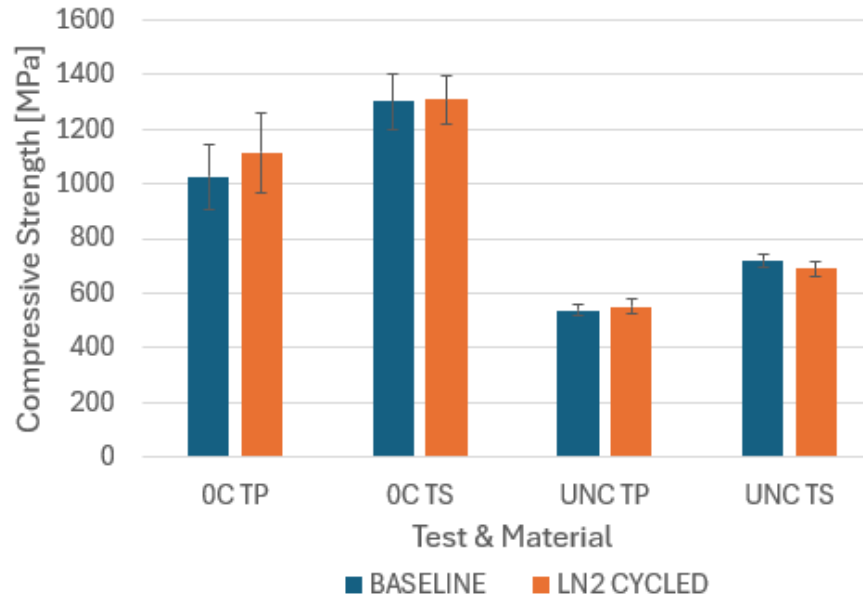


Figure 3. Compressive strength for unidirectional (0C) and un-notched quasi-isotropic (UNC) compression tests at baseline and LN2 cycled conditions $\pm$ one standard deviation. Materials tested were a TP and TS composite.

3.3 In-Plane Shear Data

In-plane shear tests demonstrated the greatest distinction in performance between the three materials. The TP material had the lowest yield strength but was the toughest material as it generally failed around 60% strain, which was expected for the thermoplastic matrix. The TS had a higher yield strength and roughly half the strain-to-failure, failing at approximately 30% strain with a lower maximum shear stress. The thermoset/veil hybrid composite performed the worst in this test, with failure occurring shortly after yielding of the composite. This is likely due to the lower strength TPU veils between plies and potentially interlaminar void content due to the TPU veil. These results are best visualized in the shear stress vs. engineering strain plot in Figure 4.

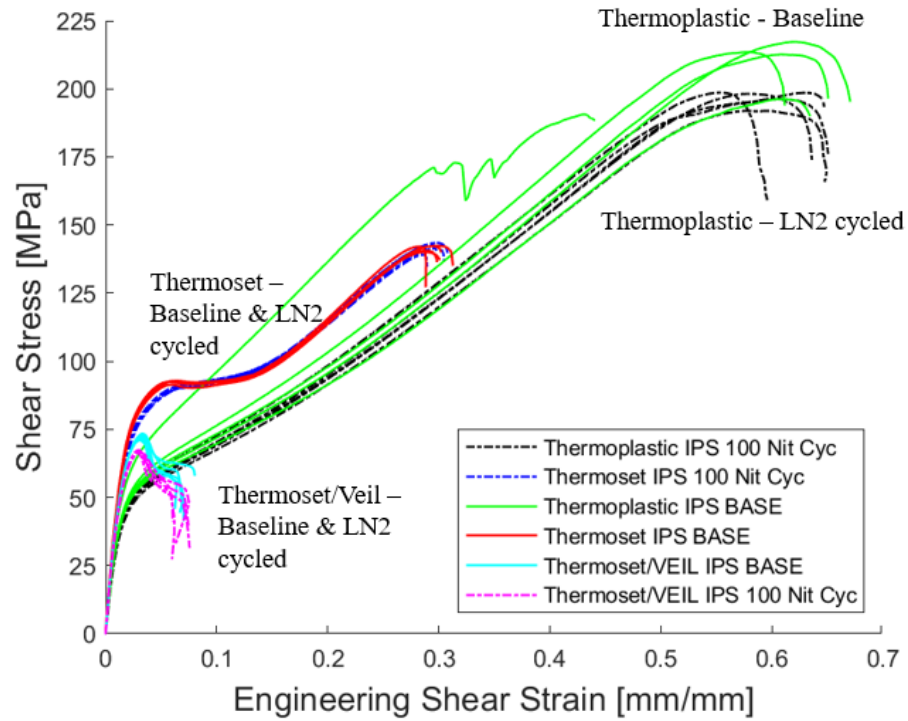


Figure 4. Shear stress vs. strain for in-plane shear (IPS) tests at baseline and LN2 cycled conditions. Materials tested were a TP, TS, and hybrid TS/veil composite.

The ductility of each material system is best visualized through the fractured coupons after taken to failure. The TP was the most ductile, followed by the TS, and finally the hybrid was the most brittle in shear before delamination occurred. Representative failed coupons are highlighted below in Figure 5.

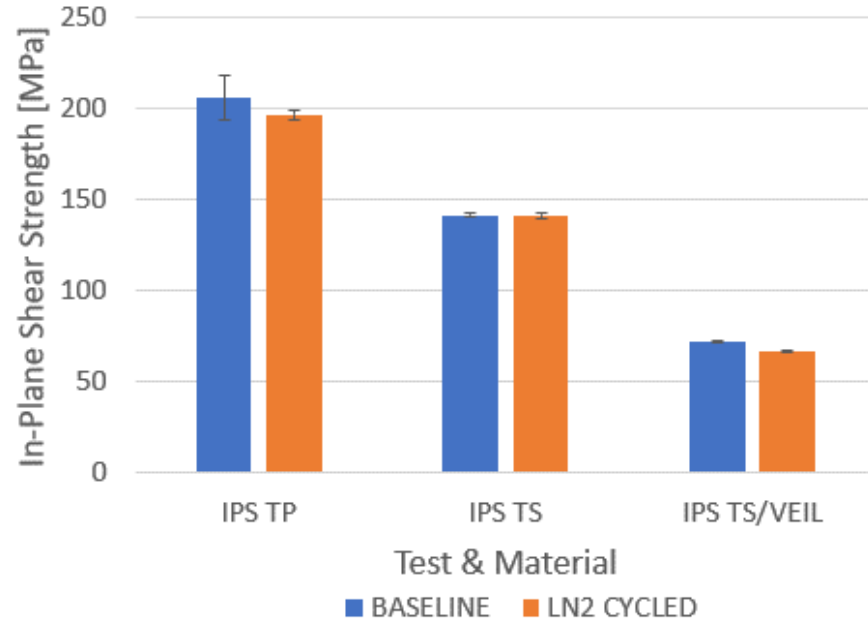


Figure 6. Shear strength for in-plane shear (IPS) tests at baseline and LN2 cycled conditions $\pm$ one standard deviation. Materials tested were a TP, TS, and hybrid TS/TPU veil composite.

3.4 Tensile-Tensile Fatigue Data

A tensile-tensile fatigue curve was generated for the thermoplastic (TP) composite material at both baseline and LN2-cycled conditions. The data is reported as a normalized percent of the UTS on the y-axis versus the logarithmic fatigue life, N (number of cycles), of the coupon on the x-axis. The data points plotted for one cycle in the S-N curve are the UNT tensile strength data from this same study. While additional data points are required to fully capture the scatter, the S-N curve in Figure 7 presents clear evidence that there is minimal effect on tensile-tensile fatigue life for the LN2-cycled coupons compared to the baseline for thermoplastic composite coupons. Arrows on the curve represent a runout above 10^6 cycles. An important note on this testing is that delamination was visually observed in the coupon in most cases once the test began cycling at 5 Hz. This damage grew over time, evolving into further delamination and fiber pull-out throughout testing. In this data, “failure” is recorded as the time when the coupon clearly broke into two pieces, but the author notes that the coupon experienced significant damage prior to this catastrophic event throughout the test. Therefore, this data should be used to provide insight into relative material performance and comparative purposes between baseline and LN2-thermally cycled coupons. The cycles to failure, N , reported should not be used as representative for a hydrogen cryotank application, since the cryotank would be one continuous piece and thus not subjected to edge effects as a test coupon is. Future testing should focus on monitoring strain in a load-controlled test to identify modulus drop off, critical failure strain, and runout strain levels.

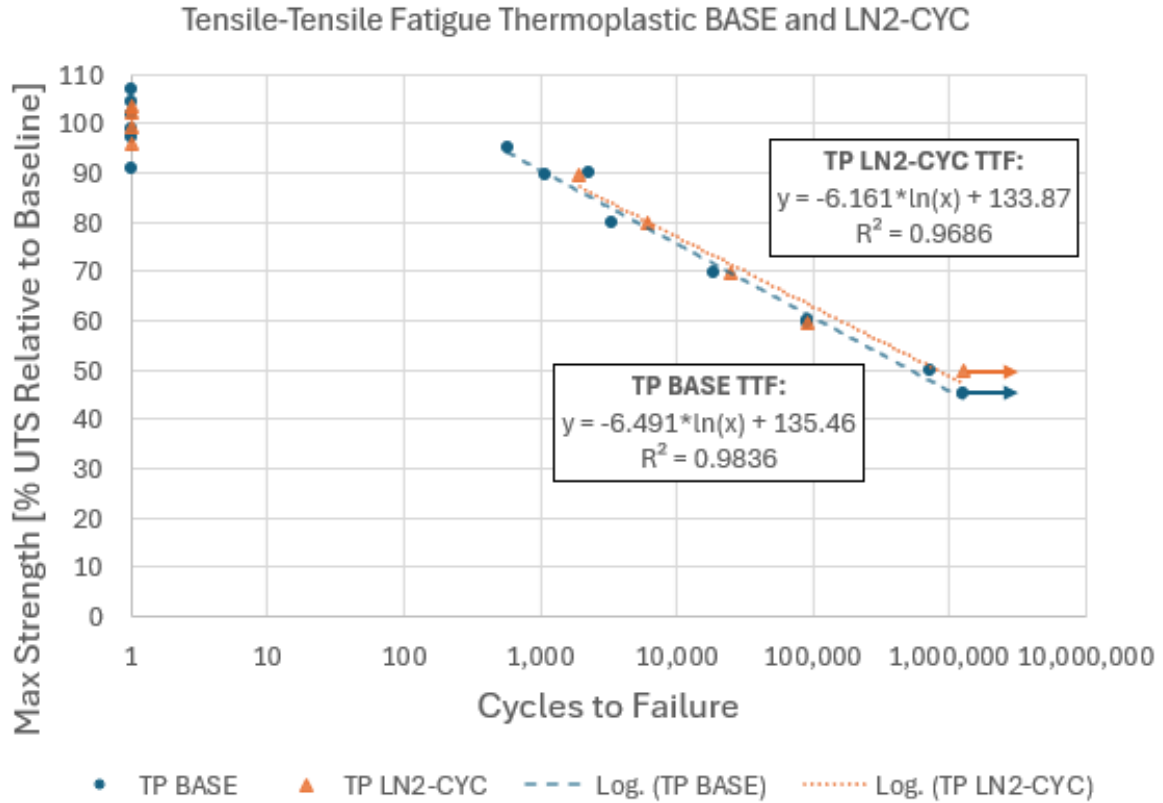


Figure 7. Tensile-tensile fatigue (TTF) S-N curve of the thermoplastic composite at baseline and LN2-cycled conditions. Arrows represent a runout above 10^6 cycles.

The material strength and load combination were fit according to a log-linear law, which is a simple and clean method to summarize the data [12]. The slope, m , is the fatigue strength degradation exponent, and R^2 represents the quality of the fit. Both R^2 values are above 0.9 which represents a strong fit, and the fatigue strength degradation exponents vary only by approximately 5%. Work has been started on the TTF thermoset and hybrid materials but remains ongoing at time of this report. In many cases, delamination and matrix cracking was the primary failure mode that evolved over time into other modes such as fiber pull-out and fiber breakage. This aligns with literature findings in that fatigue failure of CFRP composites tends to be a matrix-dominated failure mode event [13]. Images of failed thermoplastic and thermoset coupons are shown in Figure 8 for reference.

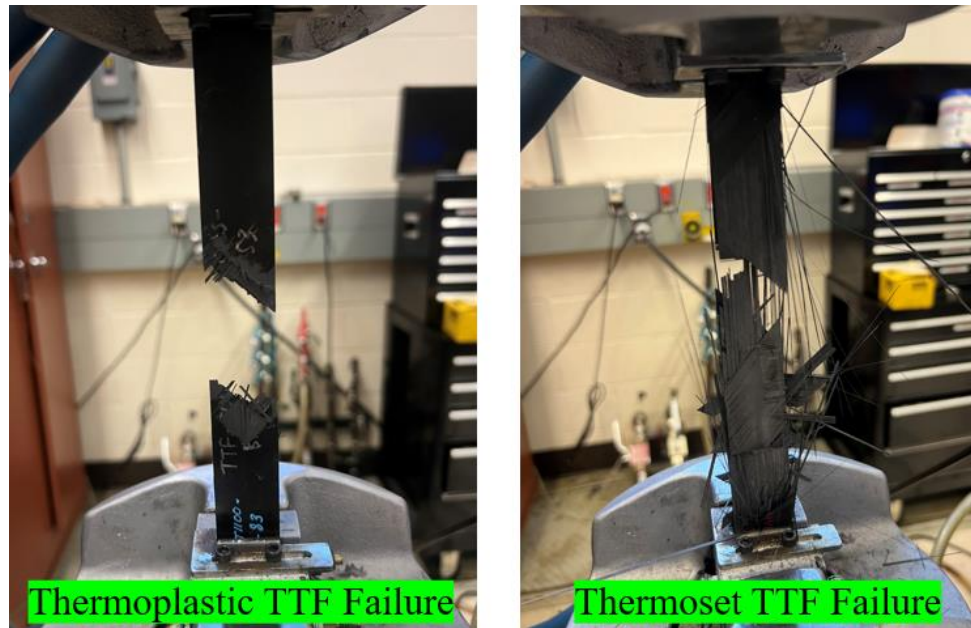


Figure 8. Failure mode of a baseline thermoplastic (left) and thermoset (right) TTF coupon.

4. CONCLUSIONS

This work captured the mechanical data for a thermoplastic/CF, thermoset/CF, and hybrid thermoset/TPU veil/CF composite material as part of a material screening for a liquid hydrogen fuel cryotank within the NASA CHARGE Project. Mechanical tests included tension, compression, in-plane shear, and tensile-tensile fatigue. For each test, coupons were tested at a baseline (no LN2 cycling) and LN2-cycled condition to determine the effect, if any, of environmental thermal conditioning on the composite materials. Liquid nitrogen was used for this study due to cost and time constraints of the project.

Mechanical results show minimal effects of the LN2 cycling on coupons compared to baseline values in all tests, demonstrating that the coupons were not damaged by LN2 cycling. Tensile strengths were similar across all three materials. The thermoplastic/CF composite had the highest ductility and toughness in IPS testing. Significant challenges and knockdown factors were found for the hybrid thermoset/TPU veil/CF composite as it had the lowest compressive strength, IPS strength, and strain at IPS failure. This was most likely due to the low TPU strength and poor interfacial bonding between the dissimilar thermoset/CF prepreg plies and thermoplastic TPU veils. Tensile-tensile fatigue testing was completed for the thermoplastic/CF material at both baseline and LN2-cycling conditions. There were minimal effects of the LN2-cycling on fatigue performance, and the curves were fit to a log-linear relationship. Overall, mechanical data was successfully captured and will inform future material down-selection and modeling efforts for a liquid hydrogen cryotank. Future tests include letting the composite material soak for longer in liquid nitrogen prior to testing, and thermal cycling under bi-axial loading conditions to simulate the pressurized environment of a cryotank. Ultimately, a manufacture of a full tank is

recommended to perform liquid hydrogen thermal cycling, permeation, and burst validation testing for liquid hydrogen fuel storage.

5. REFERENCES

- [1] Yusaf, T., Fernandes, L., Abu Talib, A. R., Altarazi, Y. S., Alrefae, W., Kadirgama, K., ... & Laimon, M., "Sustainable aviation—Hydrogen is the future." *Sustainability*, 14(1), 548, (2022).
- [2] Diaconu, T. M., "Integration and design of cryogenic hydrogen fuel systems for sustainable commercial aviation." *INCAS Bulletin*, 16(4), (2024), pp. 11-27.
- [3] 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.
- [4] Boddorff, A. K., "Choosing the Right Stuff: Material Selection for Liquid Hydrogen Aircraft Cryotanks." (No. NASA/TM-20250007133). National Aeronautics and Space Administration, (2025).
- [5] 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).
- [6] 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>
- [7] Dagdag, O., & Kim, H., "Cryogenic Impact on Carbon Fiber-Reinforced Epoxy Composites for Hydrogen Storage Vessels." *Journal of Composites Science*, 8(11), (2024), 459.
- [8] Grogan, D. M., Brádaigh, C. Ó., McGarry, J. P., & Leen, S. B., "Damage and permeability in tape-laid thermoplastic composite cryogenic tanks." *Composites Part A: Applied Science and Manufacturing*, 78, (2015), pp. 390-402.
- [9] McCarville, D. A., Guzman, J. C., Jackson, J. R., & Birkland, J. O., "Design, manufacture and test of cryotank components." *Comprehensive composite materials II*, 3(M17-6280), (2017).
- [10] 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).
- [11] Sági, Z., & Butler, R., "Properties of cryogenic and low temperature composite materials—A review." *Cryogenics*, 111, 103190, (2020).
- [12] Michel, S. A., Kieselbach, R., & Martens, H. J., "Fatigue strength of carbon fibre composites up to the gigacycle regime (gigacycle-composites)." *International journal of fatigue*, 28(3), (2006), pp. 261-270.

- [13] Feng, Y., Ma, B., Zhang, T., Zhang, T., He, Y., & Jiao, S., “Reliability fatigue life and A new S–N curve model of composite laminates under tensile-tensile fatigue load.” *Applied Composite Materials*, 28(1), (2021), pp. 129-148.