

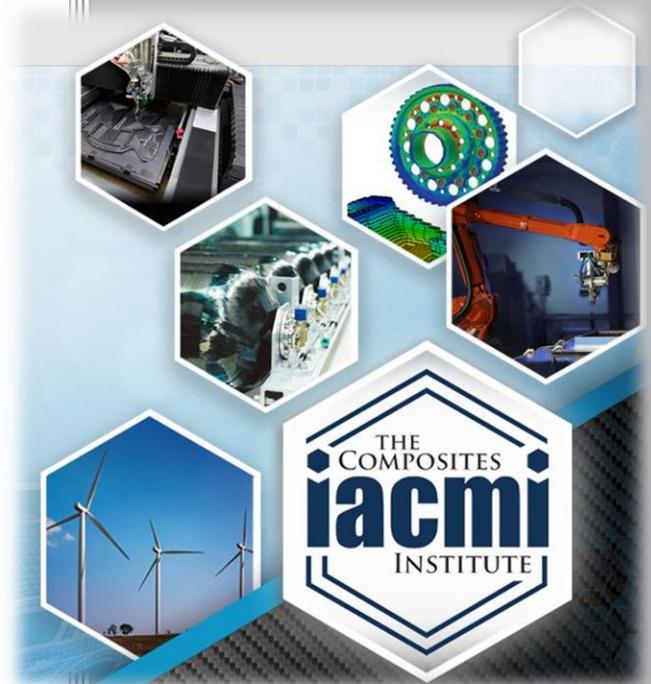
# Spinning Chopped Fiberglass Scrap into Continuous Technical Yarns for Reuse

Author: Ryan Ginder, UTK  
Warren Smith, UTK  
Jessica McKinney, UTK  
Stephen Nolet, TPI

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# Spinning Chopped Fiberglass Scrap into Continuous Technical Yarns for Reuse

Principal Investigators: Ryan Ginder – University of Tennessee Knoxville (UTK) & Stephen Nolet – TPI Composites (TPI)

## Organizations:

- University of Tennessee, Knoxville (UTK); 505 Summer Place – UTT 946, Knoxville, TN 37902-2807; [rginder@vols.utk.edu](mailto:rginder@vols.utk.edu)
- TPI Composites (TPI), 373 Market St, Warren, RI 02885; [snolet@tpicomposites.com](mailto:snolet@tpicomposites.com)

Prepared by:  
Institute for Advanced Composites Manufacturing Innovation  
Knoxville, TN 37932  
Managed by Collaborative Composite Solutions, Inc.

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# 1. EXECUTIVE SUMMARY

The overwhelming majority of fiber reinforced polymer composites are made with fiberglass reinforcement. Fiberglass (primarily E glass and E-CR glass although sometimes higher-grade S glass or R glass) is inexpensive, readily available in continuous filament tows, fabrics, and chopped “matchsticks”, and meets the performance needs of many different industrial sectors. Fiberglass’s near ubiquity means that large quantities of fiberglass manufacturing waste are generated every year. Due to the waste’s low value and inexpensiveness of new filament, this waste stream is generally landfilled or downcycled into applications like concrete fillers. However, recent work done by The University of Tennessee, Knoxville (UTK) and TPI Composites, Inc. (TPI) with recycled end-of-life fiberglass has shown that it is possible to take discontinuous fiberglass and spin it back into continuous technical yarns. This conversion back into a robust continuous form factor enables fiberglass reuse for many new, previously impossible high value, high throughput applications. As a demonstration, the team used a fiberglass prototype yarn made from a recycled wind turbine blade to filament wind the airframe and nose cone of a small rocket, which received the CAMX 2022 Ace Award for Market Growth: Composites Sustainability. If this technology could be made to work for readily available manufacturing glass waste and a growing market demand established, the resulting market pull could provide the outlet necessary to justify the capital expenditure to begin end-of-life composites recycling.

In this project, the team proposes to adapt its fiberglass yarn spinning technology for the conversion of manufacturing waste into continuous technical yarns for added value products. The goals of the team will be to:

- Produce fiberglass yarns with up to 50 wt% manufacturing waste as an input feedstock target (25 wt% as a minimum) comingled with acrylic and/or phenolic staple fibers
- Produce plied yarns with nominal linear density of 2000-4000 tex at least 200-300 yards in length
- Demonstrate yarn suitability for composites manufacturing by running pultrusion trials for a 100mm wide electric vehicle (EV) battery separator component

Fiberglass manufacturing scrap, consisting of different lengths of chopped tow (e.g., roving used in pultrusion startup, chopper gun waste, basement glass) has a bundled, sized form factor, significantly different from recycled fiber’s fluffy, staple form format. The UTK team will determine what preprocessing and textile machine settings are necessary for manufacturing scrap waste to be ring spun into yarn. As part of this process, UTK will comingle the waste fiber with polymer fibers, specifically chopped acrylic and separately phenolic fiber, to help facilitate the spinning process and compatibilize the yarn for later resin infusion. These staple fiber yarns can then be further plied with themselves or with continuous fiberglass or polymer tow to ensure they have sufficient strength to within stand the tension requirements of pultrusion. The resulting prototype yarns will be used initially for making composite test panels to assess infusion and mechanical performance. UTK will then prepare and ship additional yarn to TPI for a pultrusion manufacturing trial with the goal of assessing initial suitability for production of an EV battery separator component. At the project’s end, the team will report on its assessment of the prototype fiberglass yarn for pultrusion manufacturing and provide a basic cost analysis.

## 2. INTRODUCTION

Many, if not most, manufacturing processes for producing glass reinforced composites are designed around using continuous tows of glass filament as their material input because that is how virgin fiberglass itself is produced. However, many of these processes also involve chopping the glass into discontinuous ‘matchsticks,’ which results in chopped process offal no longer being suitable for recycling back into the original manufacturing process. As short, chopped fibers, this manufacturing scrap has fewer pathways for potential reuse and in many cases is simply landfilled. Recent advances in the processing of recycled fiberglass from end-of-life recycling, however, indicate new possibilities for this scrap by potentially restoring it to a continuous form factor.

To meet the challenges of fiberglass composites recycling, UTK has developed its own pyrolysis-based recycling method which yields recycled fiberglass from sources like wind blades and car parts with a white, fluffy consistency similar to cotton staple fiber. While UTK has been able to demonstrate successful use of this recycled fiber in typical chopped fiber applications, such as nonwoven fabrics and thermoplastic compounding, it like virtually all other sources of recycled fiberglass was originally limited in its reuse potential by being in a discontinuous form factor. However, thanks to support from industry partner TPI, UTK has implemented its own in-house technical yarn spinning line, producing the world’s first prototype continuous recycled fiberglass product. Conversion of recycled fiberglass into a continuous yarn has opened new application spaces previously impossible with recycled materials that also naturally lend themselves to low cost, high throughput manufacturing. Furthermore, as we can blend other fiber types with the fiberglass during yarn production, we are able to make yarns that are inherently compatible with different matrix resin types, such as incorporating acrylic fibers into the yarn for use in infusions with Elium resin. As an initial demonstration of this yarn’s potential, UTK produced a small functional launch vehicle by filament winding a rocket nose cone and airframe for TPI using recycled fiberglass from a GE 37m wind turbine blade. Said launch vehicle, shown in Fig. 1, received CAMX’s 2022 Market Growth: Composites Sustainability ACE award.

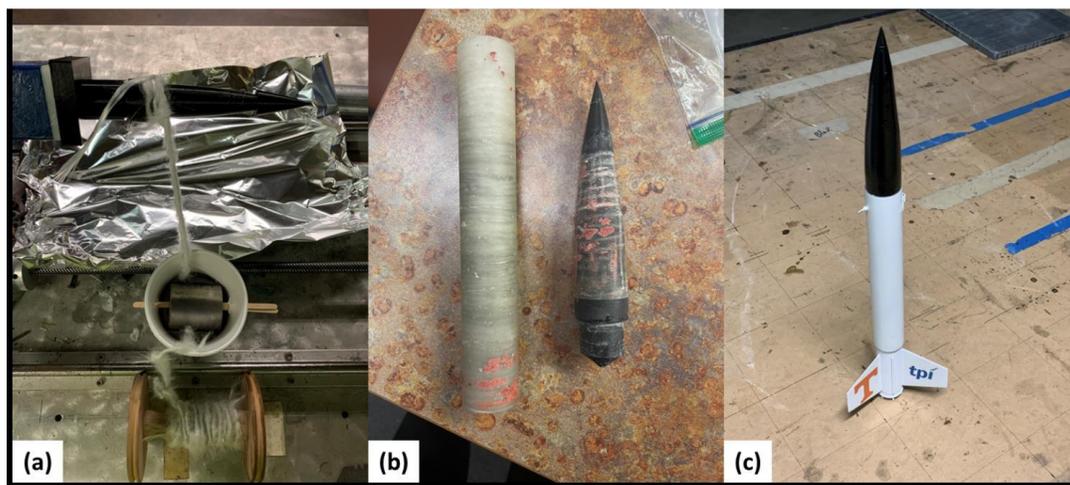


Fig. 1. (a) technical yarn made from recycled fiberglass being filament wound into a rocket nose cone, (b)

final rocket air frame and nose cone parts made from filament winding, (c) final assembled launch vehicle

This same yarn fabrication process should be extendable to manufacturing scrap tow waste for similar results. Therefore, we propose to branch off our existing recycled fiberglass yarn program to explore conversion of chopped fiber tow waste into similar continuous reclaimed yarns. Using offal supplied from TPI's manufacturing operations, UTK will research methods of dispersing these chopped 'matchstick' bundles into a more filamentized form factor necessary for the fiber to be carded and spun into consistent yarns without significant material breakage. Additional work will also likely be required to select fiber length and loading for the hybridized polymer fibers to help facilitate spinning as many chopped fiberglass sources have lengths insufficient for spinning on their own. Resulting prototype yarn material properties will be characterized by UTK and TPI. Promising yarn formulation candidates can then be further demonstrated in a composite reuse application like automotive components.

### 3. BACKGROUND

As previously referenced, our team's initial development of recycled fiberglass technical yarns first began with the recovery of recycled materials from wind blades. For example, our own team's past work using pyrolysis proved able to reclaim a high purity (suitable for remelt), high aspect ratio, high stiffness recycled fiberglass at 0.9 kg CO<sub>2</sub> eq/kg recycled fiber from a one ton pilot reactor. Unfortunately, the recovered fibers from this process and others have a fluffy, staple fiber consistency making the material unsuitable for traditional composites manufacturing techniques designed with continuous filament tow input in mind (e.g., pultrusion, filament winding). Collaborating with TPI Composites, our team found a solution to this problem by processing recycled glass staple fibers on textile equipment to spin new, continuous yarns. As a first crude test, we used artisanal, hand-operated carding and spinning equipment to create a prototype fiberglass yarn. We then successfully filament wound this into the functional rocket depicted back in Fig. 1. While the market for fiberglass model rockets may be small, this test proved that the yarn could be used to create a stiff tube. This made it theoretically suitable for large scale use as electrical conduit in infrastructure (e.g., the US power grid consists of nearly 7 million miles of transmission and distribution lines). Therefore, we set out to: (1) reformulate and prove scalability of our recycled fiberglass yarn on mechanized equipment and (2) filament wind small sections of proof-of-concept conduit to assess application viability inline with National Electrical Manufacturers Association (NEMA) Standards Publication TC 14-2002 *Reinforced Thermosetting Resin Conduit (RTRC) and Fittings*.

Yarn fabrication followed two main processing steps: carding and ring spinning. Initially, waste fiberglass was placed onto a conveyor along with prechopped acrylic fibers and fed into a carding machine to produce an aligned web called a sliver. This sliver was then taken and fed into a ring spinning machine to produce a single strand yarn. This yarn could be used as is or further plied with additional yarn and/or virgin continuous filament for additional bulk and performance. The team found it could produce a relatively consistent prototype yarn with linear densities of ~1000 tex. Images of the spinning process can be found in Fig. 2 followed by example output yarn Fig. 3.



Fig. 2. UT's minimill mechanized spinning line consisting of carding and drawing of recycled fiberglass mixed with other fiber types (pictured is an early trial blending with wool) into a sliver followed by sliver drawing then twisting and tensioning into yarn.

Having scaled a demonstration recycled fiberglass yarn, the team turned to filament winding of 6" long conduit sections to see how close to the standard we could achieve. While NEMA TC 14-2002 contains a veritable laundry list of materials tests and potential geometries, the team focused its testing on replicating a 1" trade size conduit within our equipment capabilities relevant to underground electrical distribution. The first test examined the dimensional tolerances for our selected trade size and confirmed that yarn processability with epoxy would be sufficient to meet NEMA size requirements. Another example test focused on compressibility. Under NEMA, a composite conduit must survive 4.45kN of compressive load when sandwiched between two steel plates and not experience more than a 25% reduction in inner diameter. As can be seen from Fig. 4, not only was conduit made from a single ply of recycled fiberglass yarn able to outperform the maximum load of the 100% acrylic yarn control specimen by 64%, but it achieved 95% of the required load to meet the standard. Even though it did not reach the target, the measured 14% reduction in inner diameter at failure suggests that the tube would have also met this requirement. Visual examination of our samples revealed tube failure occurring at especially thin sections of yarn. This was not terribly surprising. Typically when producing yarn, one feeds multiple slivers from the carding process into a drawing/roving machine (which we do not have for budgetary reasons) to improve material consistency before ring spinning. However, should the improved consistency somehow not be insufficient, the team demonstrated that in the worst case the yarn can meet the standard by plying with a reduced quantity of virgin glass filament. The team proceeded to then validate where possible that the conduit passed NEMA's other relevant tests such as laminate separation in boiling water and water absorption. Tests where a passing result would be guaranteed (e.g., halogen content test) were assumed to pass at this stage. As a final practical use test, we proceeded to take one of the conduit pieces, connect it with a standard junction box, and pull cable through it shown in Fig. 3.

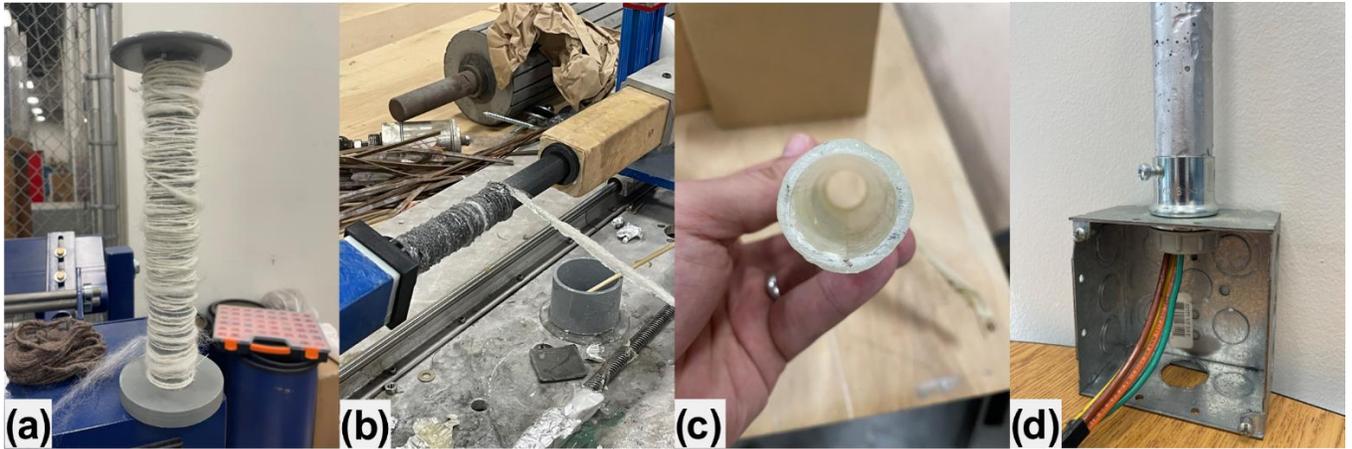


Fig. 3. Images of (a) ~1000 tex recycled fiberglass yarn made with 55% waste fiberglass content input, (b) manual winding of epoxy coated yarn, (c) cured prototype 1" trade size conduit, (d) painted composite conduit mated to traditional metal junction box with pulled through cabling.

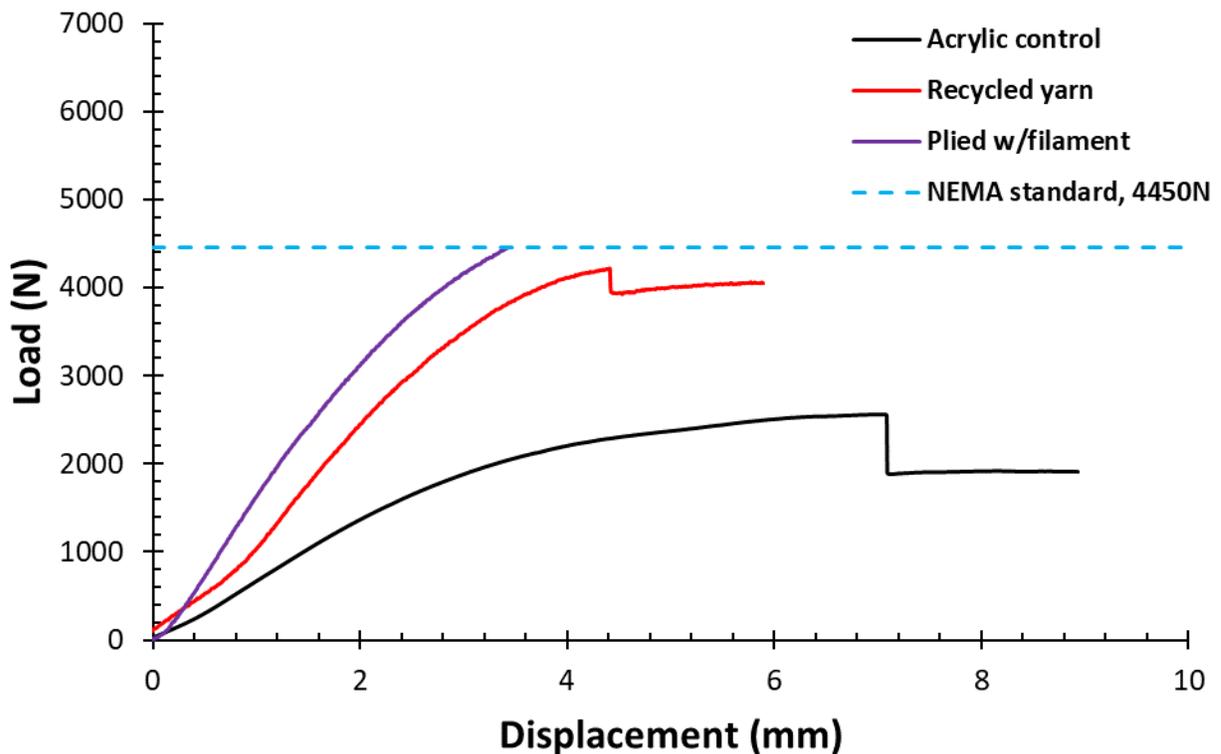


Fig. 4. Load-displacement curves during conduit compression testing indicating significant yarn stiffness and tenacity improvement from recycled fiberglass commingling over pure acrylic.

## 4. RESULTS AND DISCUSSION

As noted in the previous section, up until this point all of the team's previous testing had focused on sources of recycled fiberglass for yarns reclaimed at end of life. Given the limited availability of such materials, for this project the team shifted its focus towards reuse of purely manufacturing scrap material with the goal of

repurposing the waste such that it could be go back into the manufacturing process itself. For this fiberglass waste from on of TPI’s pultrusion facilities producing EV battery separators was collected from the line and shipped to UTK for reprocessing into yarn. This waste, in Fig. 5, was chopped into nominally 3” lengths and then cofed along with 1”, crimped, 15 dpf acrylic fiber sourced from Minifibers, Inc into a mechanical carding system at a 50 wt% / 50 wt% split. While blends with up to 60 wt% fiberglass were achievable, the team selected the 50 wt% loading for further yarn production to avoid any of the linear density inconsistencies that emerged at higher loadings as noted in the previous background conduit application testing. The slivers obtained from the carding process were then ring spun to produce a 1000 tex acrylic/fiberglass hybrid yarn. For later pilot testing, this recycled yarn was then plied with a virgin 1000 tex OC Adventex fiberglass tow to produce a final plied yarn with norminal 2000 tex density required for part pultrusion. Approximately 2.2km of final plied yarn, shown in Fig. 5, was produced to allow for the pultrusion of new EV battery separator parts in place of some of the virgin fiberglass tow lines normally used.

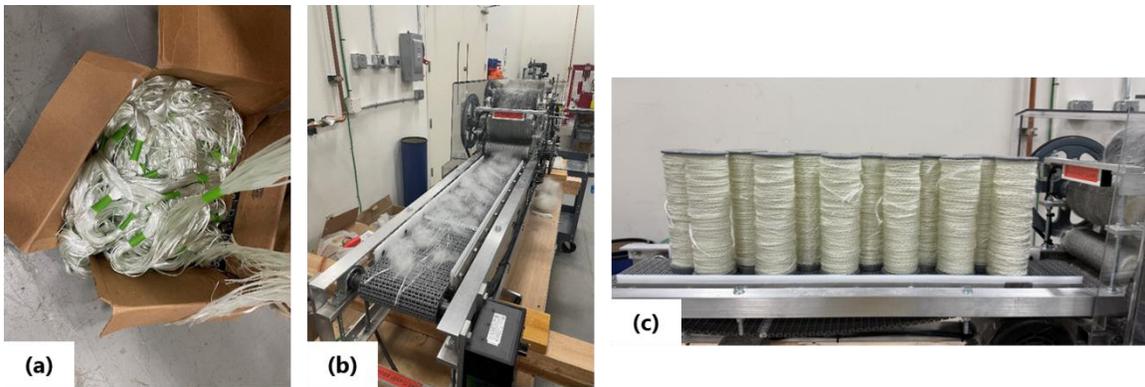


Fig. 5. (a) Starting pultrusion waste received from TPI for reuse, (b) Recovered fiberglass co-processed w/ acrylic at 50/50 wt% loading, (c) 2.2 km of 1000 tex acrylic/fiberglass yarns plied with additional 1000 tex filament sent to TPI for pultrusion.

Prior to pilot pultrusion trials, the test yarn was handlaid up and vacuum infused into unidirectional panels to check for resin compatibility and sufficient mechanical performance. Specimen yarn was laid up and infused into the panels depicted in Fig. 6 using Eponol Resin from Westlake (Hexion) and cured for at least 8 hours at 80°C. After machining out test specimens, the resulting composite was tested for tensile performance under ISO 527-5 with measured average properties of Stress at Break 234.7 MPa, Strain at Break 1.34%, and Modulus 19,869 MPa. Shear properties were also tested according to ASTM D7078 with average performance measured at Ultimate Strength 57.2 MPa, Shear Chord Modulus 3,301 MPa, and 0.2% Offset Shear Strength 41.4 MPa. Full details, images, and data from the relevant testing are presented in the Appendix. Comparison of these mechanical properties with the application specifications indicated that the yarn was suitable for the EV battery separator pultrusion application and so the hybrid yarns were spliced into the production line and ran to produce parts.

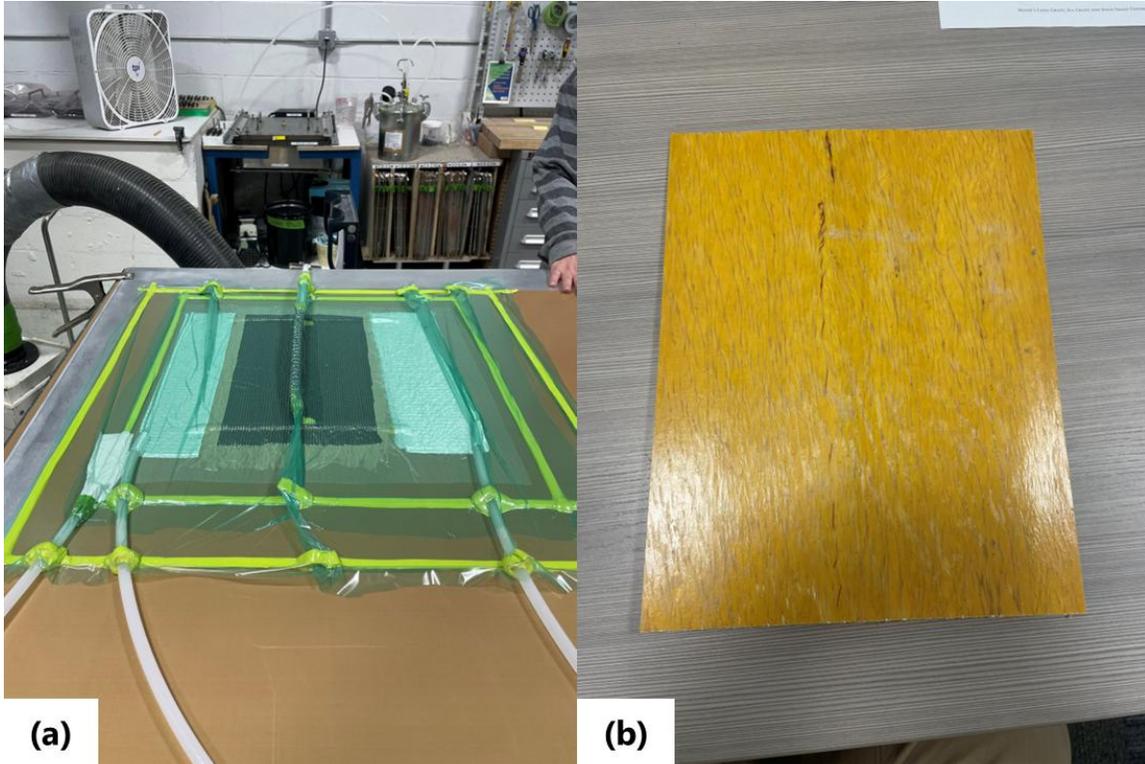


Fig. 6. (a) infusion layup configuration for test panel fabrication, (b) typical cured phenolic-fiberglass yarn panel result.

As shown in Fig. 7, the recycled yarns were mounted on the pultrusion line to replace some of the virgin fiberglass tows going into the phenolic resin. The yarns were pulled to make 150 mm wide by 1.8 mm plates at a pull rate of 72 cm/min. Initially there was a problem during startup as the recycled yarns had originally been connected together via weaver's knots to reach the total lengths needed for processing; these knots had difficulty passing through the narrow die and so were cut out and the yarns instead directly spliced together eliminating the problem. Knots removed, the yarns successfully ran through the die ultimately producing ~40 two-meter long parts shown in Fig. XYZ.

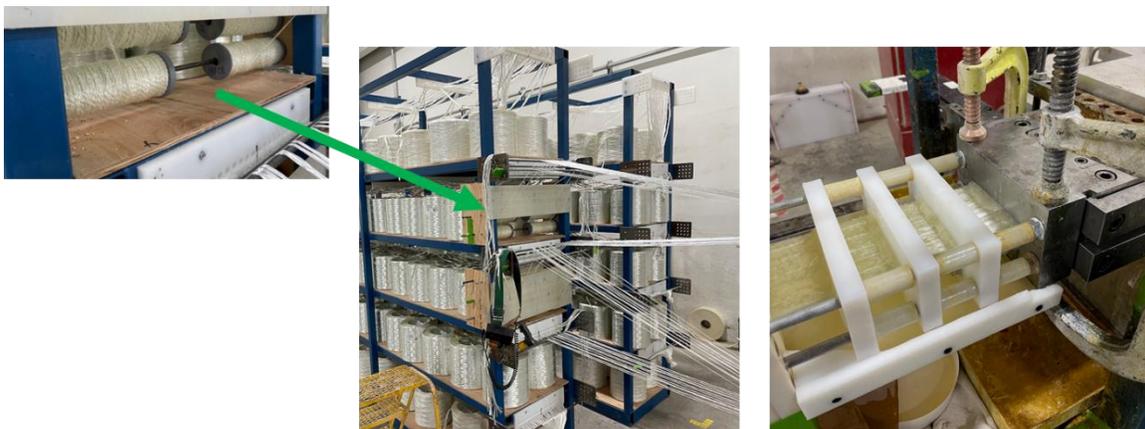


Fig. 7. Mounting configuration of hybrid yarns alongside virgin tows feeding into the pultrusion die.

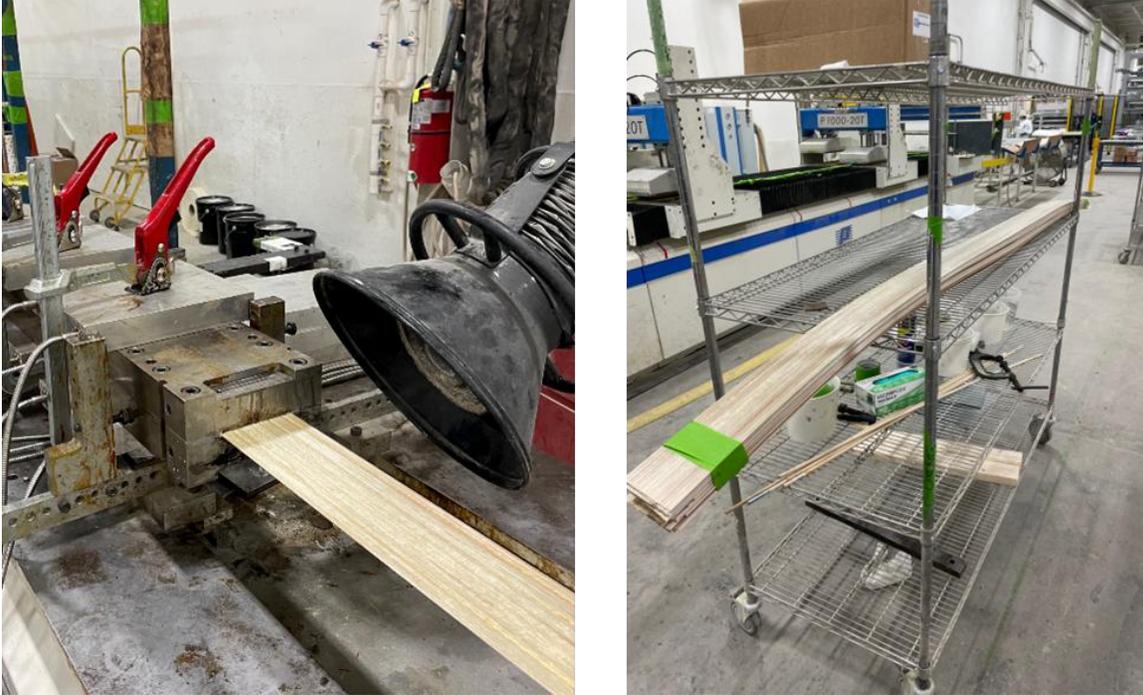


Fig. 8. Pultruded panels exiting the die and after curing and cutting into 2m lengths.

With successful pultrusion of the desired part, a preliminary part cost analysis was conducted. This analysis was completed using the following assumptions:

- A pultruded part has nominal dimensions of 2 m by 150 mm by 3 mm,
- One finished EV battery enclosure requires 5 two-meter long pultruded parts,
- Pultruded panels have ~60% fiber vol fraction with phenolic resin representing the remainder,
- Raw materials represent ~33% of the total cost of a part.

The cost differential for a virgin filament versus yarn part was then calculated assuming 50% replacement of virgin to recycled tow with an upper bound yarn cost 2x that of virgin material (real yarn cost expected to be closer to texturized roving in cost). This calculation yield a relative part cost increase of 11.86% for the recycled yarn made part with an accompanying recovered content relative increase of 37.83 wt%. This ratio of 1% cost increase for 3.2 wt% increase in recovered content suggests an attractive value proposition for original equipment manufacturers like automotive OEMs looking for more recycled content in their products. Within the specific context of this specific application, it was estimated utilizing the waste fiber for pultruded yarn could supply enough separators for ~225,000 EV enclosures with a current market value of ~\$270MM.

Table. 1. Preliminary Part Cost Analysis Results.

<b>Part Dimensions</b>	
Length	2m
Width	150mm
Height	3mm
<b>Est. Part Cost</b>	
Virgin Only yarn	\$6.41
50% yarn-fiber	\$7.17
Part Cost Relative Increase	11.86%
Recovered Content Relative Increase	37.83wt%
Recovered Content to Cost Ratio	3.2% : 1%

## 8. CONCLUSIONS

- First, this project has demonstrated that it is physically possible to mechanically recycle fiberglass production scrap into new hybrid yarns for reuse in some manufacturing contexts, eliminating waste and yielding more product.
- Successful pultrusion with the 1.8 mm thick die used in this project suggests promise for wider applications with thicker cross-sections and greater recycled material content.
- Successful pultrusion with phenolic suggests the recycled yarn should also work with easier resin systems (e.g., polyester, vinylester)
- Materials recovery and circular application reuse via yarn production yielded an attractive recovered content to cost increase ratio of 3.2 wt% : 1% cost, which suggests potential economic viability in applications such as automotive.
- Within the context of the specific target application in this project, it was estimated that yarn reuse could potentially be used to produce ~225,000 EV battery enclosures with a current market value of ~\$270MM.

## 10. APPENDIX

Test identification

Plastics - Determination of tensile properties  
 Part 5: Test conditions for unidirectional fibre-reinforced plastic composites

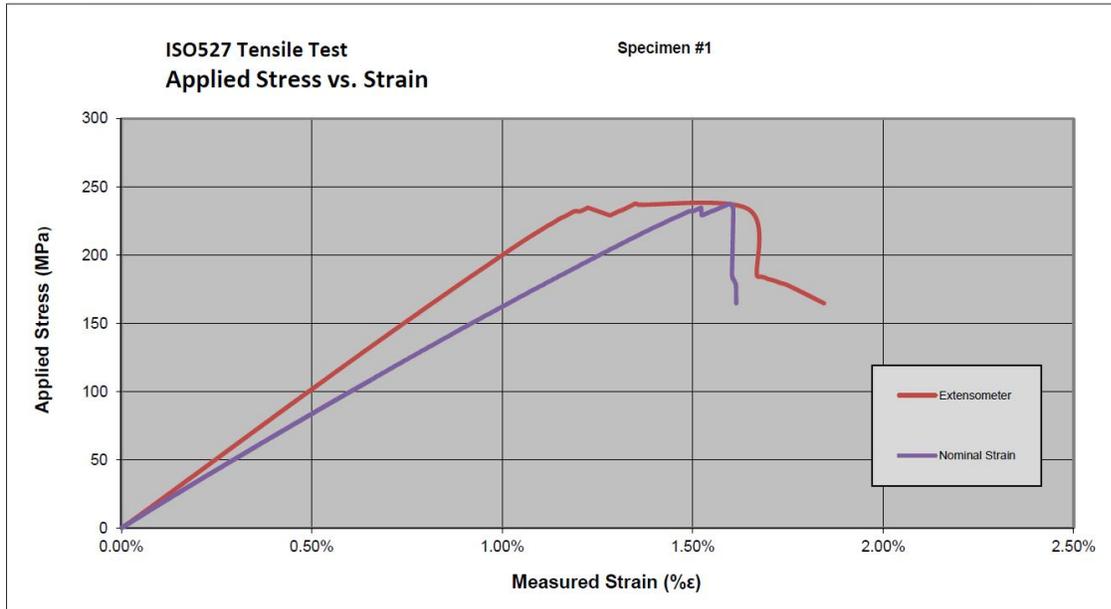
ISO 527-1:2019(E)  
 ISO 527-5

Identification of material tested

Mat Type	Vendor p/n	Description	Vendor	Lot/Batch #
Reinforcements	TEX 1900	Yarn-Filament hybrid tow - single strand 50/50 glass acrylic	University of Tennessee	Unknown

Test Results

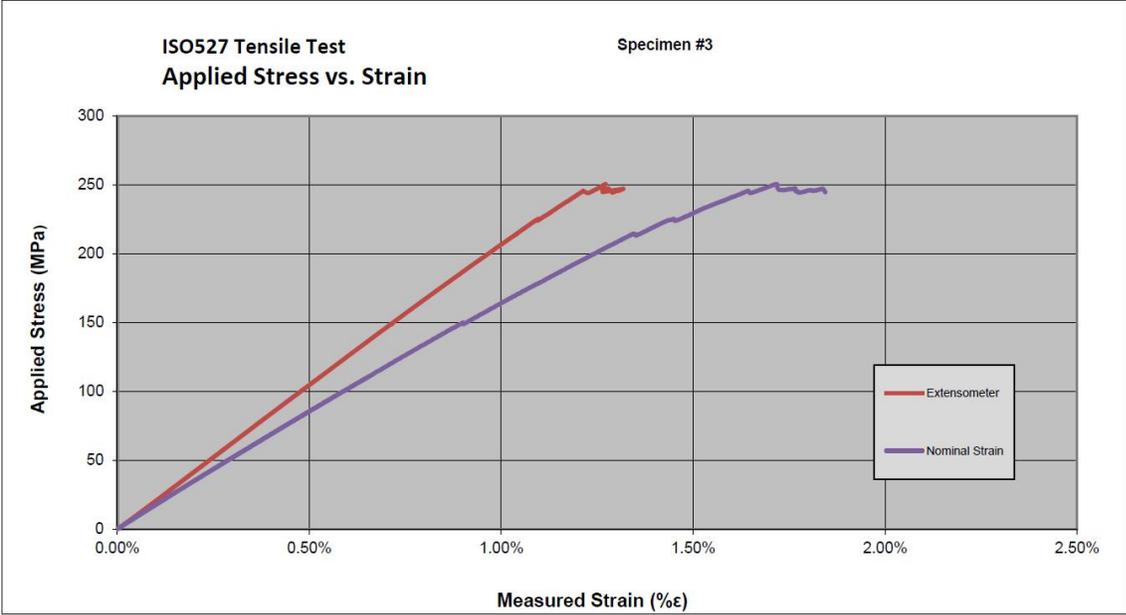
Specimen	Cross-section (mm <sup>2</sup> )	Stress at break (MPa)	Strain at break (%ε)	Nominal Strain at break (%)	Strength (MPa)	Strain at Strength (%ε)	Modulus (MPa)	Comments & Failure Mode
1	28.39	237.8	1.35%	N/A	N/A	N/A	20,439	AGB
2	31.25	215.6	1.26%	N/A	N/A	N/A	18,170	AWT
3	25.74	250.6	1.27%	N/A	N/A	N/A	21,055	AWB
4	32.63	217.4	1.14%	N/A	N/A	N/A	20,427	AGB
5	28.17	252.2	1.69%	N/A	N/A	N/A	19,256	AGM
AVG:		234.7	1.34%	-	-	-	19,869	
MIN:		215.6	1.14%	-	-	-	18,170	
STDEV:		17.6	0.21%	-	-	-	1152	
% STDEV:		7.5%	15.5%	-	-	-	5.8%	



Results

Max Load:	6752 N
Stress at Break:	237.8 MPa
Strain at Break:	1.35%
Nominal Strain at Break:	N/A
Strength:	N/A
Strain at Strength:	N/A
Stress at yield:	N/A
Strain at yield:	N/A
Modulus (Gage 1):	#N/A
Modulus (Extensometer):	20439 MPa
Poisson's Ratio:	#N/A

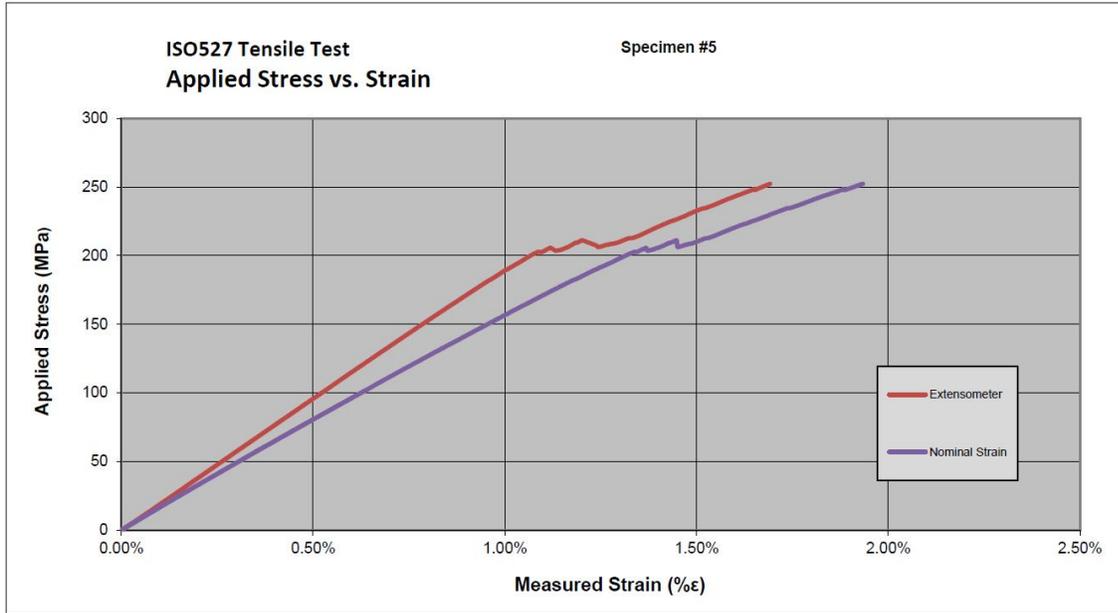




*Results*

<b>Max Load:</b>	6451 N
<b>Stress at Break:</b>	250.6 MPa
<b>Strain at Break:</b>	1.27%
<b>Nominal Strain at Break:</b>	N/A
<b>Strength:</b>	N/A
<b>Strain at Strength:</b>	N/A
<b>Stress at yield:</b>	N/A
<b>Strain at yield:</b>	N/A
<b>Modulus (Gage 1):</b>	#N/A
<b>Modulus (Extensometer):</b>	21055 MPa
<b>Poisson's Ratio:</b>	#N/A





*Results*

Max Load:	7106 N
Stress at Break:	252.2 MPa
Strain at Break:	1.69%
Nominal Strain at Break:	N/A
Strength:	N/A
Strain at Strength:	N/A
Stress at yield:	N/A
Strain at yield:	N/A
Modulus (Gage 1):	#N/A
Modulus (Extensometer):	19256 MPa
Poisson's Ratio:	#N/A

Test identification

Shear Properties of Composite Materials by V-Notched Rail Shear Method

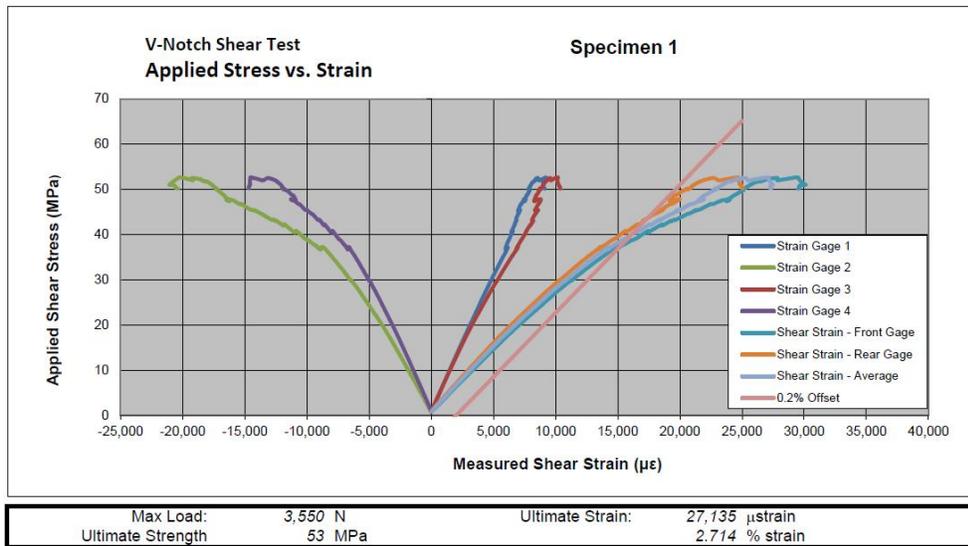
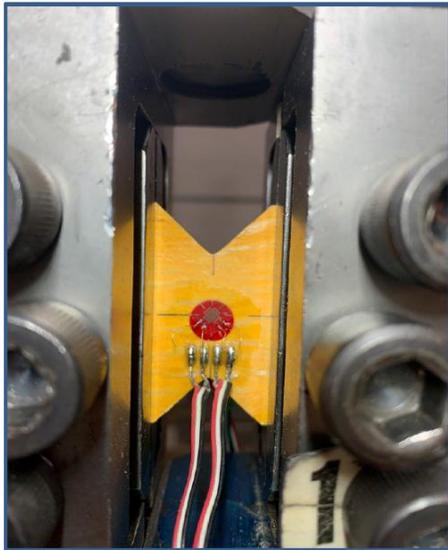
ASTM D7078-D7078M-20

Identification of material tested

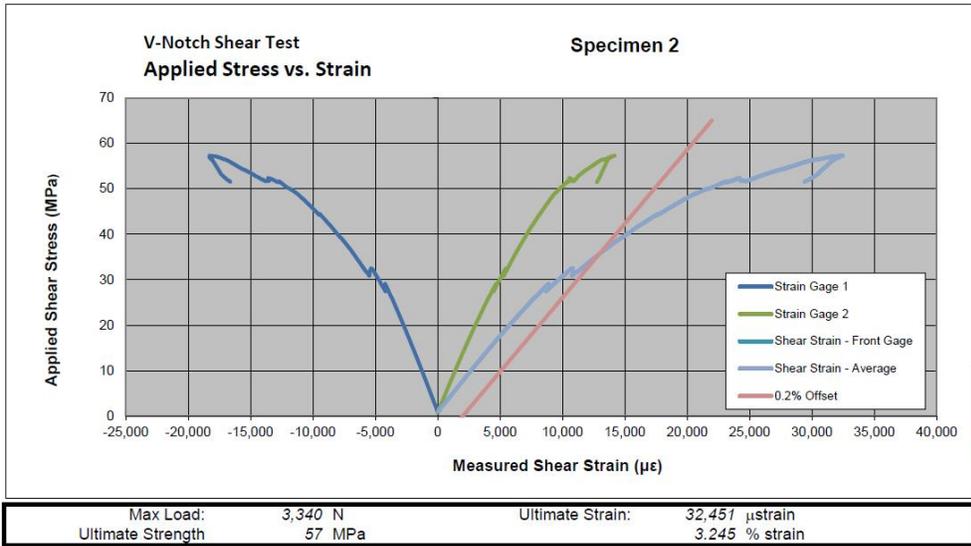
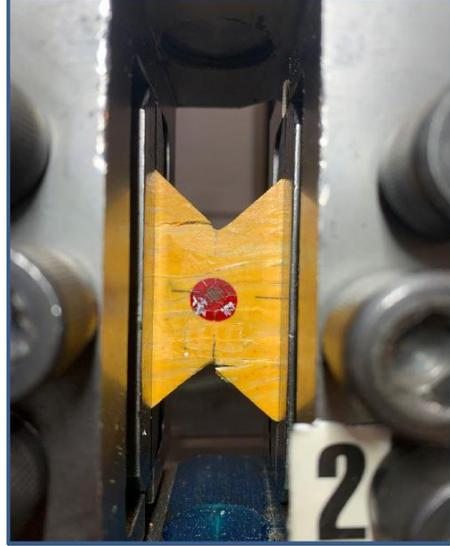
Mat Type	Vendor p/n	Description	Vendor	Lot/Batch #
Reinforcements	TEX 1900	Yarn-Filament hybrid tow - single strand 50/50 glass acrylic	University of Tennessee	Unknown

Test Results

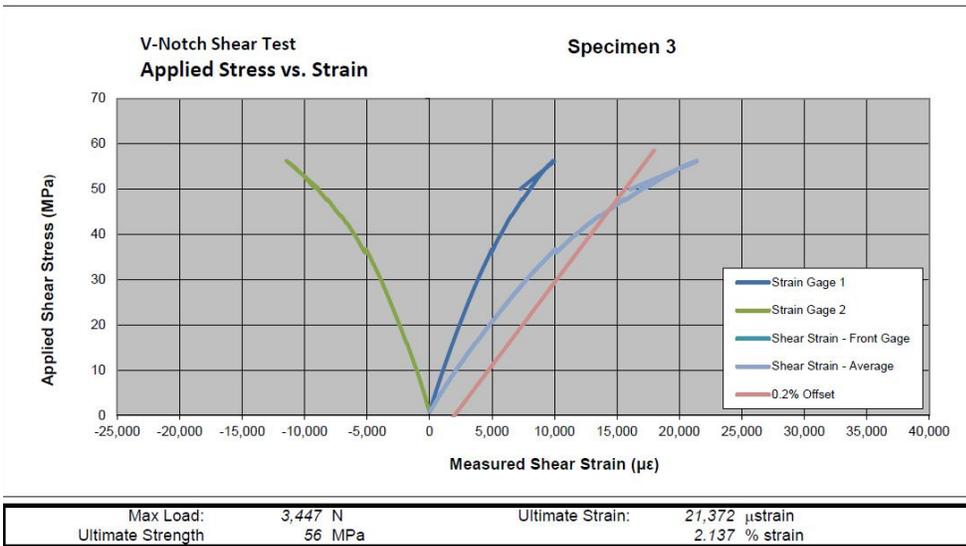
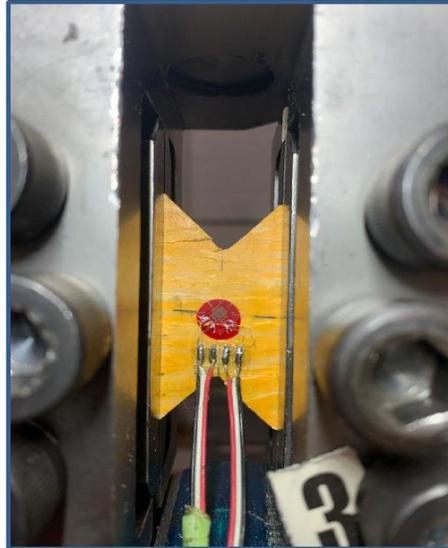
Specimen	Area (mm <sup>2</sup> )	Max Load (N)	Ult. Strength (MPa)	Ult. Strain (mstrain)	Shear Chord Modulus (MPa)	0.2 % Offset Shear Strength (MPa)	Failure Mode		
							1st	2nd	3rd
1	2.20	3,550	52.6	27,135	2833	40.2	H	G	N
2	1.90	3,340	57.3	32,451	3255	35.7	H	G	N
3	1.99	3,447	56.2	21,372	3661	45.3	H	G	A
4	2.04	4,109	65.9	33,134	3502	39.8	H	G	N
5	1.96	3,439	56.9	21,634	3451	46.4	H	G	A
6	2.05	3,430	54.2	26,868	3106	40.8	H	G	N
Average:		3,552	57.2	27,099	3,301	41.4			
Minimum Individual Value:		3,340	52.6	21,372	2,833	35.7			
Standard Deviation:		281	4.6	5,055	300.6	3.93			
Coefficient of Variation:		7.9%	8.0%	18.66%	9.11%	9.49%			
Characteristic Value:		2,902	47	15,388	2,605	32			



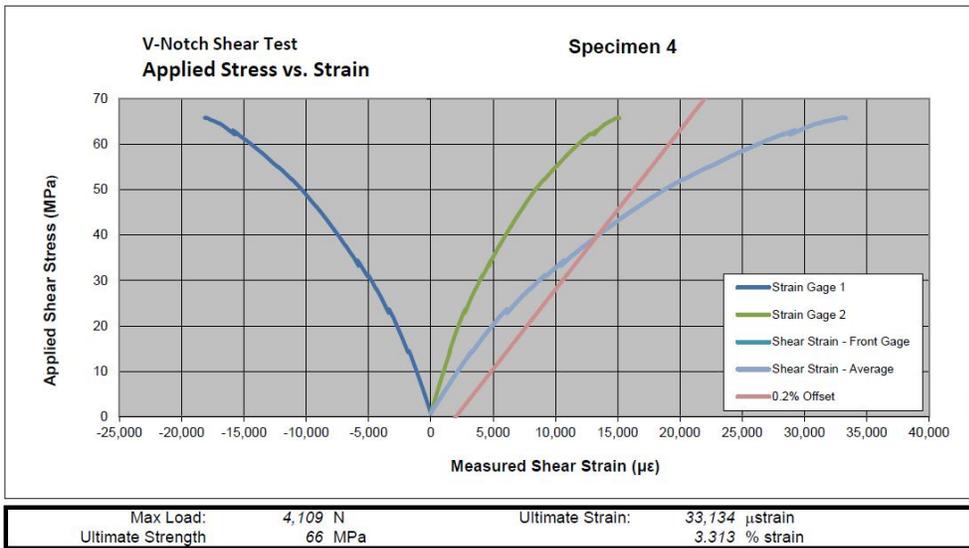
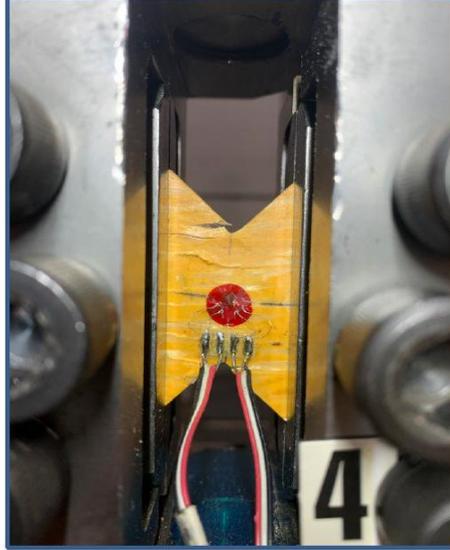
Shear Chord Modulus (MPa)	
Average	2833
Front Gage	2719
Rear Gage	2958
Twist	4.2%
1998 to 5994 average µε	



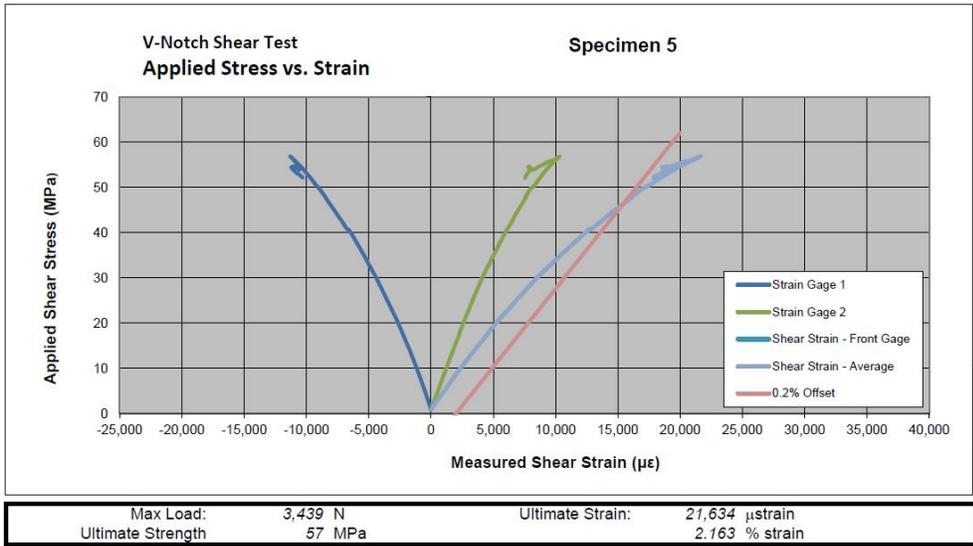
Shear Chord Modulus (MPa)	
Average	3255
Front Gage	3255
Rear Gage	#N/A
Twist	#N/A
1996 to 5994 average με	



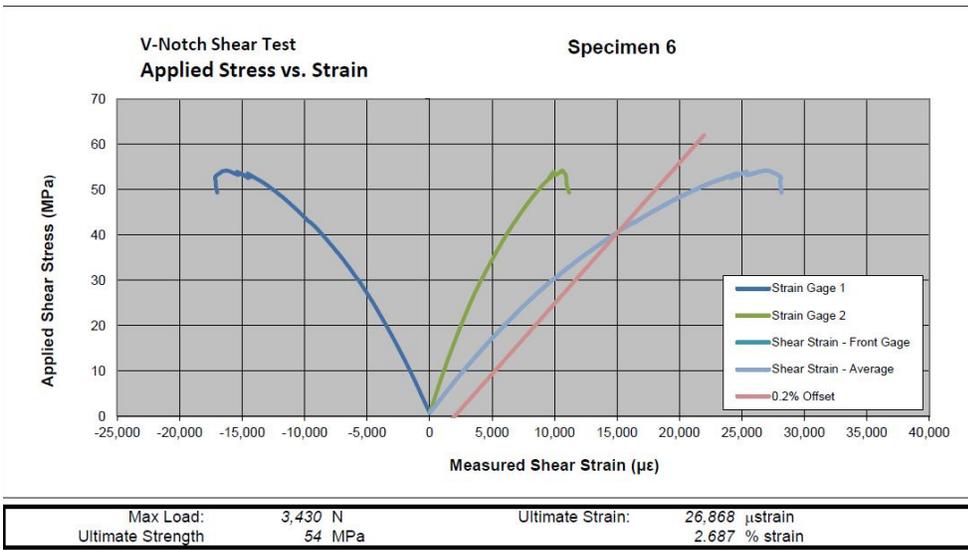
Shear Chord Modulus (MPa)	
Average	3661
Front Gage	3661
Rear Gage	#N/A
Twist	#N/A
1996 to 5992 average $\mu$ ε	



Shear Chord Modulus (MPa)	
Average	3502
Front Gage	3502
Rear Gage	#N/A
Twist	#N/A
<i>1999 to 5990 average με</i>	



Shear Chord Modulus (MPa)	
Average	3451
Front Gage	3451
Rear Gage	#N/A
Twist	#N/A
<i>1994 to 6000 average µε</i>	



Shear Chord Modulus (MPa)	
Average	3106
Front Gage	3106
Rear Gage	#N/A
Twist	#N/A
<i>1999 to 5996 average µε</i>	