3-D Static Elastic Constants and Strength Properties of a Glass/Epoxy Unidirectional Laminate

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Abstract

This report presents the results of static tensile, compressive and shear stress-strain tests in the three primary material directions for a unidirectional laminate typical of wind turbine blade construction. Test coupons were machined from six-ply (in-plane properties) and 80-ply laminates prepared by resin infusion of Vectorply E-LT-5500 unidirectional glass fabric (containing about 6% transverse glass backing strands) with Epikote MGS RIMR 135/Epicure MGS RIMH 1366 epoxy resin. Results are given for elastic constants, strengths, and best-fits to stress-strain curves.

Property Summary

The material directions and coupon orientations are described in Figure 1. Average elastic constants and strengths are given in Table 1 in the material principal directions. Properties are averages for coupons with the same stress direction, but orthogonal coupon orientations, such as LTZ and ZLT, which are given separately in the following sections.

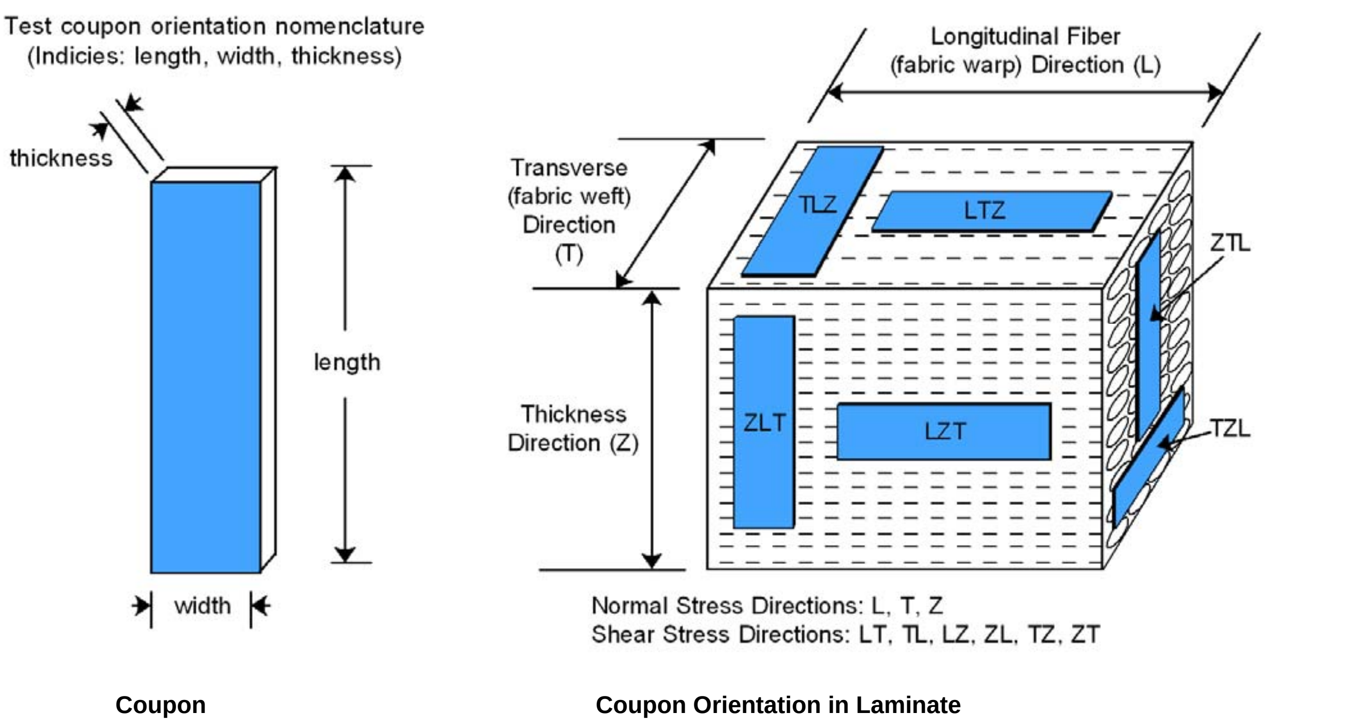


Figure 1. Coupon orientation indices and location in thick laminate.

Table 1. Average 3-D elastic and strength properties for thick unidirectional glass fabric/epoxy laminate and for neat resin.

LAMINATE ELASTIC CONSTANTS[1]	V_F = 56.8 – 58.2%
Tensile Modulus E_L (GPa)	44.6
Tensile Modulus E_T (GPa)	17.0
Tensile Modulus E_Z (GPa)	16.7
Compressive Modulus E_L (GPa)	42.8
Compressive Modulus E_T (GPa)	16.0
Compressive Modulus E_Z (GPa)	14.2
Poisson Ratio ν_{LT}	0.262
Poisson Ratio ν_{LZ}	0.264
Poisson Ratio ν_{TL}	0.079
Poisson Ratio ν_{TZ}	0.350
Poisson Ratio ν_{ZL}	0.090
Poisson Ratio ν_{ZT}	0.353
Shear Modulus G_{LT} (GPa)	3.49
Shear Modulus G_{LZ} (GPa)	3.77
Shear Modulus G_{TL} (GPa)	3.04
Shear Modulus G_{TZ} (GPa)	3.46
Shear Modulus G_{ZL} (GPa)	3.22
Shear Modulus G_{ZT} (GPa)	3.50

[1]Tensile and compressive moduli and Poisson's ratios determined from best fit line between 0.1% and 0.3% strain; shear moduli calculated from best fit line between 0.2% and 0.6% shear strain.

LAMINATE STRENGTH PROPERTIES	STRESS DIRECTION	STRENGTH (MPa)	ULTIMATE STRAIN (%)
Tension	L	1240	3.00
Tension[1]	T	43.9	0.28
Tension	Z	31.3	0.21
Compression	L	-774	-1.83
Compression	T	-179	-1.16
Compression	Z	-185	-1.44
Shear[2]	LT	55.8	5.00
Shear[2]	LZ	54.4	5.00
Shear	TL	52.0	4.60
Shear[2]	TZ	45.6	5.00
Shear	ZL	33.9	1.10
Shear	ZT	28.4	0.81

[1]Transverse tension properties given for first cracking (knee) stress
[2]Shear values given for 5% strain following ASTM D5379

Neat Resin Properties	
Tensile Modulus (GPa)	3.53
Poisson's Ratio	0.347
Compression Modulus (GPa)	2.98
Shear Modulus (GPa)	0.990
0.2% Offset Tensile Yield Stress (MPa)	41.0
Ultimate Tensile Strength (MPa)	76.3
Ultimate Tensile Strain (%)	4.20
0.2% Offset Compressive Yield Stress (MPa)	-64.7
Ultimate Compressive Strength (MPa)	-91.0
Ultimate Compressive Strain (%)	-5.38
0.2% Offset Shear Stress (MPa)	26.1
Shear Stress at 5% Strain (MPa)	37.7

Experimental Methods

Materials and Processing

The unidirectional glass fabric/epoxy laminates were composed of Vectorply E-LT-5500 infused with Epikote MGS RIMR 135/Epicure MGS RIMH 1366 (100 to 30 mass ratio) epoxy resin. While the primary (warp) reinforcing strands are in the longitudinal direction, the fabric also contains about 6% transverse (weft) backing glass strands to which the warp strands are stitched; the backing strands are irregularly spaced, as shown in the transmitted light photographs in Figure 2. Warp strands are PPG 4400 Tex with Hybon 2026 sizing. There is sufficient backing strand content to significantly influence the properties in some directions. The areal weights of the fabric construction are detailed in Table 2; since the fabric is not strictly unidirectional, it is designated 0_b. The stacking of fabric and strands in the 80 ply laminate is shown in Figure 3 for a transverse slice. The internal structure is very heterogeneous on the scale of many 12.7 mm wide coupons, and transverse strands vary as to the number present in the coupon cross-section.

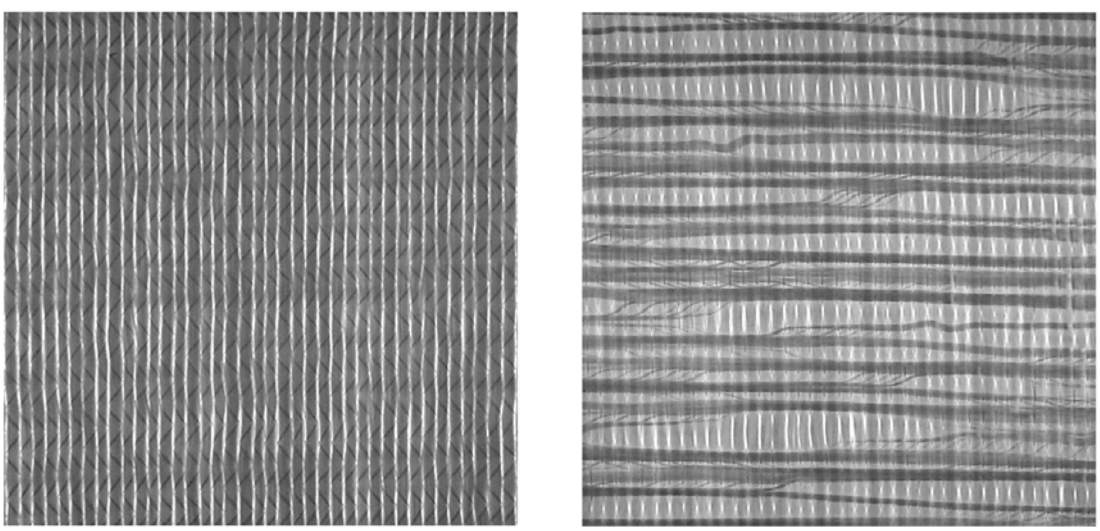


Figure 2. Transmitted light photographs of Vectorply E-LT-5500 (Front and Back)

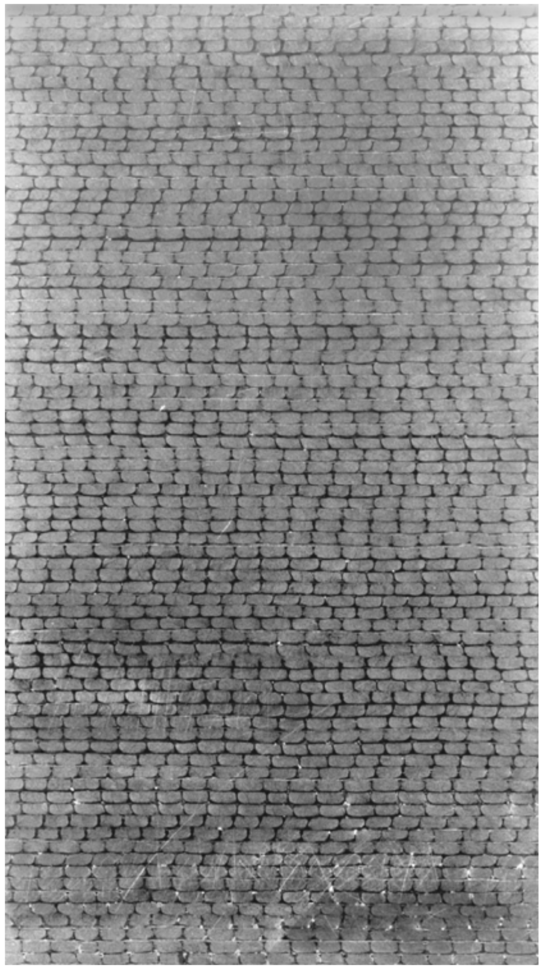


Figure 3. Through-thickness fabric strand stacking for infused 80 ply laminate (50 mm wide x 90 mm high slice).

Table 2. Fabric Construction

Manufacturer and Product Designation	Fiber Areal Weight, g/m²						
	Total	0°	90°	-45°	+45°	mat	stitch
Vectorply E-LT-5500	1875	1728	114	0	0	0	33

Properties were determined from 6-ply laminates for in-plane (L, T, LT, TL) properties to reduce possible effects of machining. Properties with a thickness (Z) direction stress were determined from an 80-ply thick laminate, with test coupons removed by wet machining with a diamond edge saw.

The 80-ply thick laminate, $(0_b)_{80}$, 79 cm long by 27 cm wide by 9.2 cm in thickness, was carefully cure monitored to reduce cure errors related to the curing exotherm. After the room-temperature infusion was completed, the laminate was initially cured on a RT aluminum mold plate until the exotherm subsided (about 12 hrs), then the mold plate temperature was raised to 70°C (mold surface temperature) for 12 hours, de-molded and placed in a post curing oven at 70°C for another 12 hours. Four thermocouples were placed in the laminate for temperature monitoring, detailed in Figure 4. The 6-ply laminate, $(0_b)_6$, used for in-plane properties was cured at RT for 24 hours, followed by a 12 hour post-cure at 70ºC. Table 4 gives fiber content and ply-thickness data for the two laminates.

Table 3. Fiber Volume Fraction (ASTM D2584)

Number of Layers	Fiber Volume Fraction, V_F			Thickness, Average mm/ply
	Average,%	STD	COV	
6-ply laminate	56.8	0.34	0.6	1.19
80-ply laminate	58.2	0.52	0.9	1.16

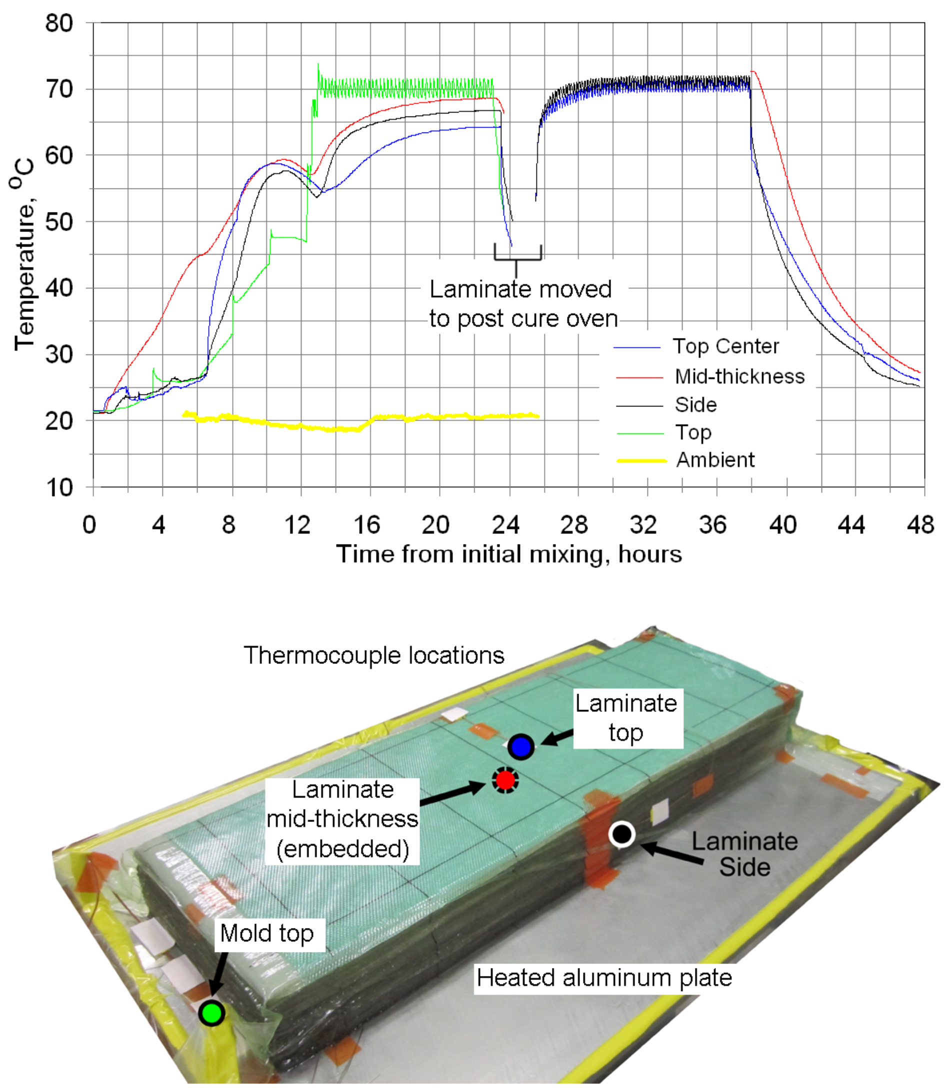


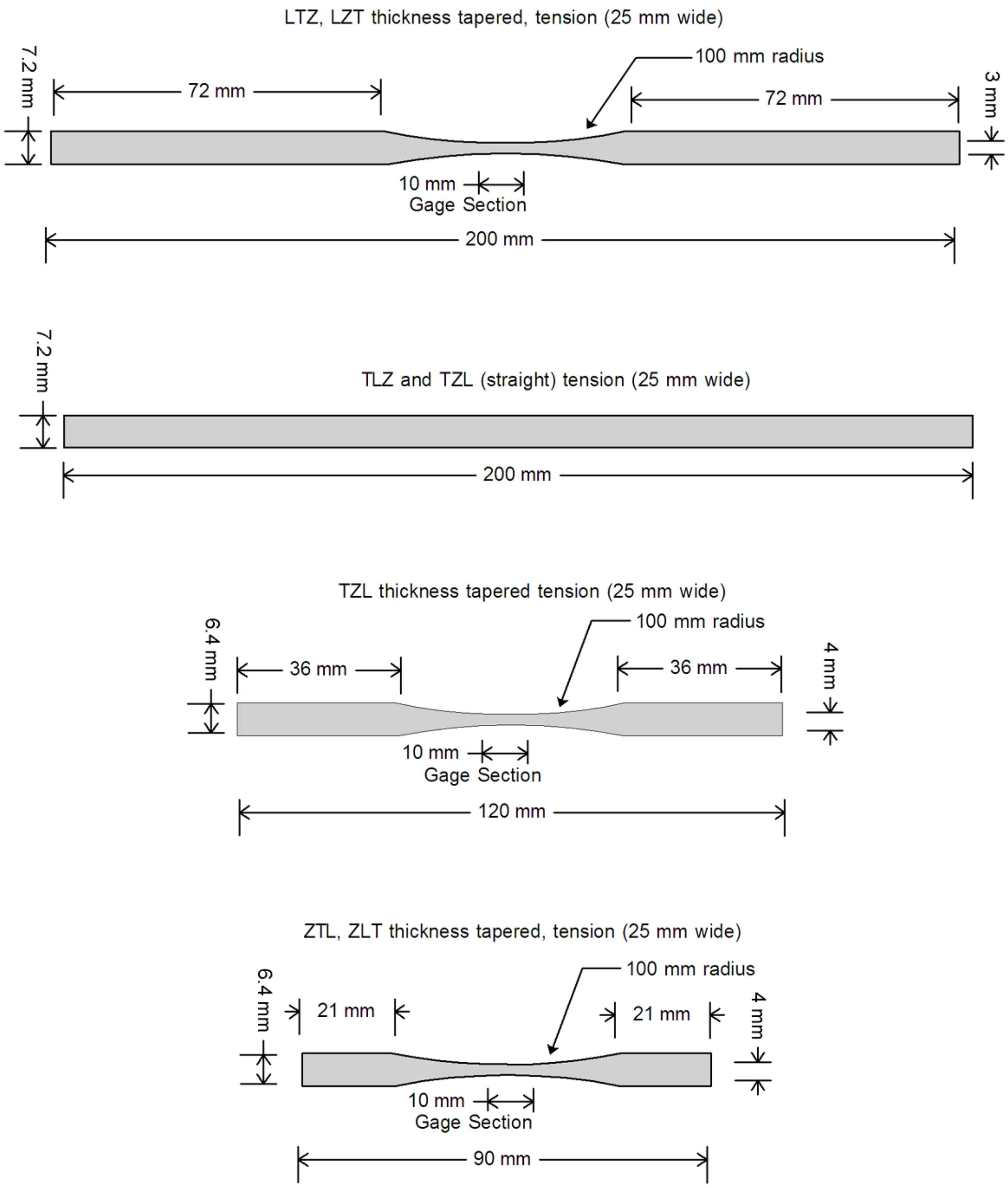
Figure 4. Laminate infusion photograph and temperature traces during cure and post-cure from thermocouples at the indicated positions for the 80-ply laminate.

Test Methods

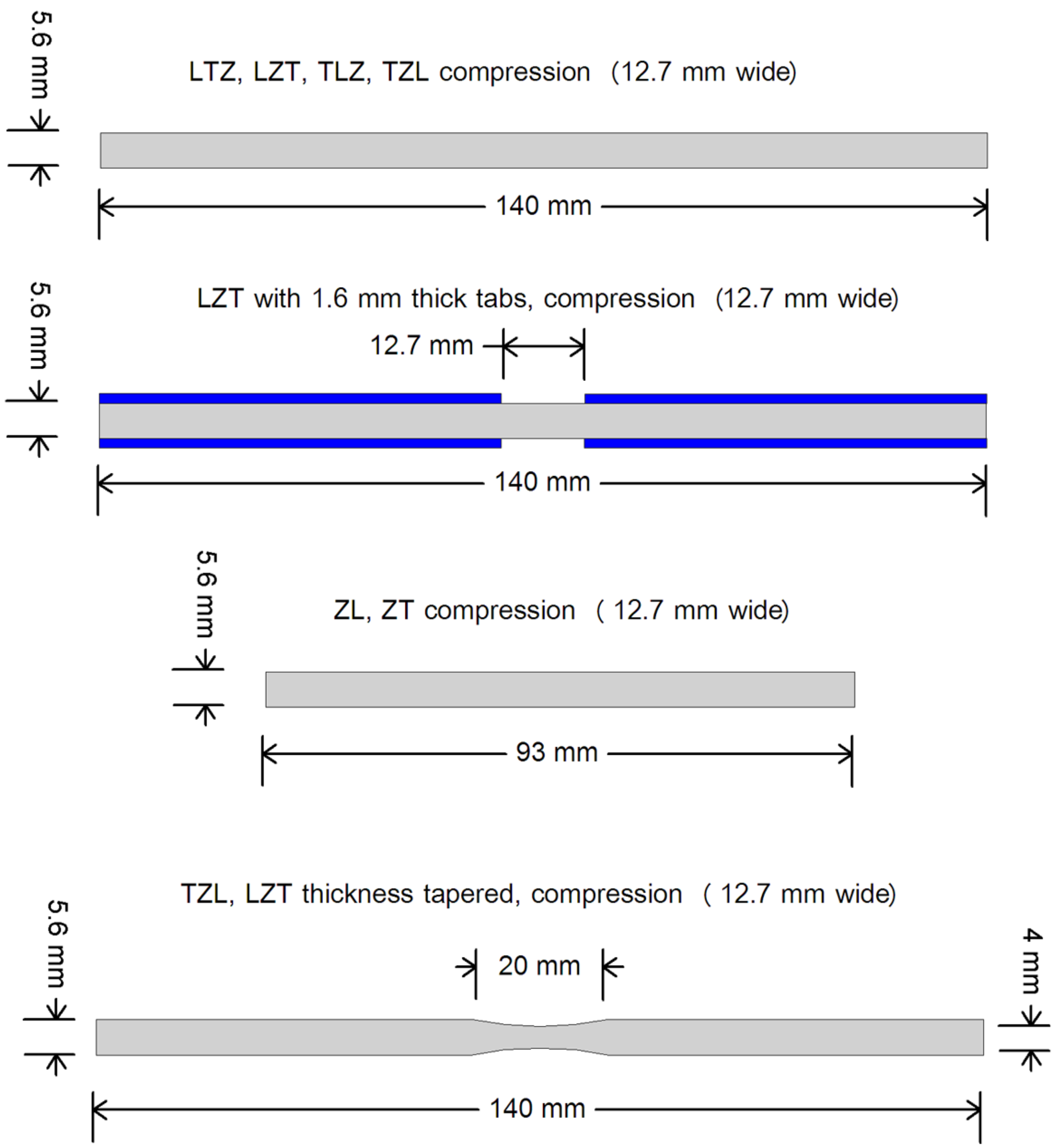
Tests were conducted on an Instron 8562 servo-electric test system at a displacement ramp rate of 0.025 mm/s. Axial strains were determined with Micro-measurements Group C2A-06-125LW-120 strain gages for tensile and compressive strains, and C2A-06-062LT-120 strain gages for transverse (Poisson's ratio) and shear strains. For the compression coupons, strains were calculated as the average of gages were on both (width) faces.

A variety of test coupon geometries were used following the indicated test standards, with deviations from standard geometries such as added tabs or thickness tapering to obtain gage section failures. Figure 4 gives the various coupon geometries.

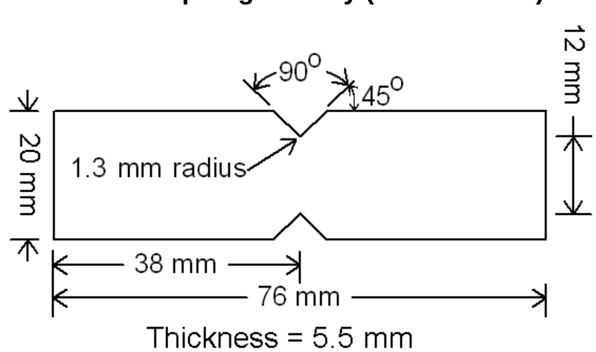
Tensile coupon geometries (ASTM D3039 and D638 with variations)



Compression coupon geometries (ASTM D6641)



Shear coupon geometry (ASTM D5379)



Neat Resin Coupon Geometries

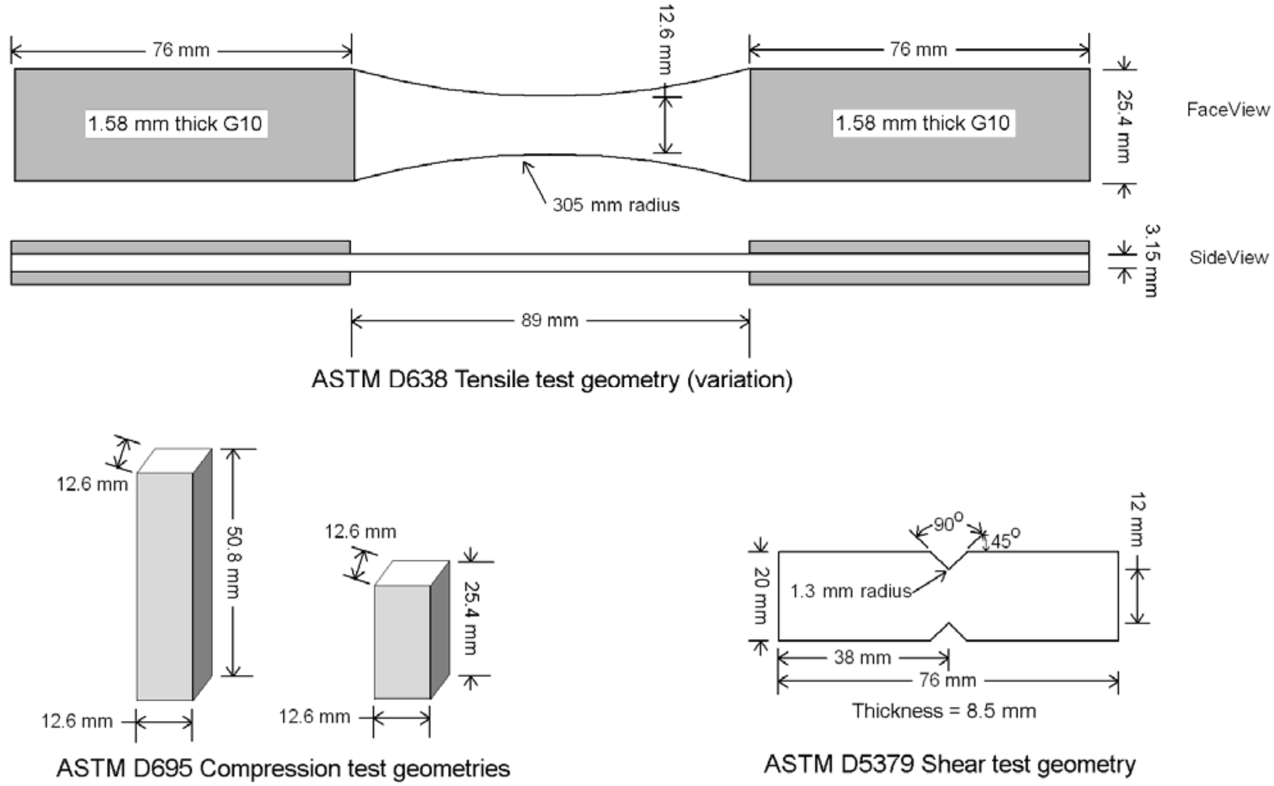


Figure 4. Test coupon geometries.

Results and Discussion

Table 4 gives detailed results for each coupon orientation and stress direction. Normal stress tests used the two orthogonal coupon orientations each for L, T, and Z direction stresses, indicated in Figure 1. These results are averaged for the property listings in Table 1, but are listed separately in Table 4. Major nonlinearities occur in the transverse tension and shear tests. In transverse tension, a knee in the stress-strain curves is observed at the stress where resin cracking occurs parallel to the warp direction strands, if the weft direction backing strands remain in-tact; separate results are given for the first cracking stress and strain. Stress-strain curves are nonlinear over most of the stress range in shear, so 0.2% offset data are given where values could be determined. Shear results are limited to 5% shear strain or less by ASTM D5379, so the stress at 5% strain is listed instead of ultimate values.

Individual test stress-strain data and best fit stress-strain curves are given in Appendix A, and tabular individual test data are given in Appendix B. Figure 5 compares the best fit stress-strain curves for various cases, with fit equations given in Table 5. Figure 6 gives photographs of failed coupons for each case. Cases with greater scatter evident in Appendix A such as transverse and thickness direction tension (Figures c-f) and ZL and ZT shear (Figures q and r) reflect differences in the number of transverse strands in the gage section, local strand packing features (Figure 3) or the location of the V-notch in the shear coupon relative to the transverse strand position.

There do not appear to be significant differences between coupons taken from the 6-ply laminate (LTZ and TLZ) compared to those sectioned from the 80-ply laminate (LZT and TZL). The longitudinal tension coupons were each machined with a radius (Figure 4), while the other LTZ and TLZ coupons used as-molded surfaces. The fiber content was slightly higher for the 80-ply laminate (Table 3).

Table 4. Detailed Test Results

Tensile Properties

Stress Direction	Coupon Orientation	$E_{Tension}$, GPa				Poisson's Ratio				Ultimate Tensile Stress, MPa			Failure strain, %		
			Avg	SD	COV		Avg	SD	COV	Avg	SD	COV	Avg	SD	COV
L	LTZ	E_L	43.2	2.1	4.9	ν_{LT}	0.262	0.01	3.2	1180	66	5.6	2.92	0.13	4.4
L	LZT		45.9	2.0	4.4	ν_{LZ}	0.264	0.02	7.3	1293	20	1.6	3.08	0.13	4.2
T	TLZ	E_T	17.2	2.0	12	ν_{TL}	0.079	0.01	17	73.0	3.7	5.0	0.45	0.03	6.5
T	TZL		16.7	0.73	4.4	ν_{TZ}	0.350	0.02	6.5	65.5	9.6	15	1.09	0.57	53
Z	ZLT	E_Z	16.3	2.1	13	ν_{ZL}	0.090	0.02	20	32.6	1.6	4.8	0.23	0.02	8.7
Z	ZTL		17.0	2.3	14	ν_{ZL}	0.353	0.06	16	29.9	3.5	12	0.19	0.05	28
----	Neat Resin	E	3.53	0.08	2.2	ν	0.347	0.01	1.7	76.3	0.63	0.83	4.2	0.50	12

First cracking (knee) tensile stress and strain

Stress Direction	Coupon Orientation	First cracking stress, MPa			Strain at First cracking, %		
		Avg	SD	COV	Avg	SD	COV
L	LTZ	--	--	--	--	--	--
L	LZT	--	--	--	--	--	--
T	TLZ	44.0	3.2	7.3	0.27	0.04	16
T	TZL	43.8	6.2	14	0.29	0.06	22
Z	ZLT	--	--	--	--	--	--
Z	ZTL	--	--	--	--	--	--

Compression Properties

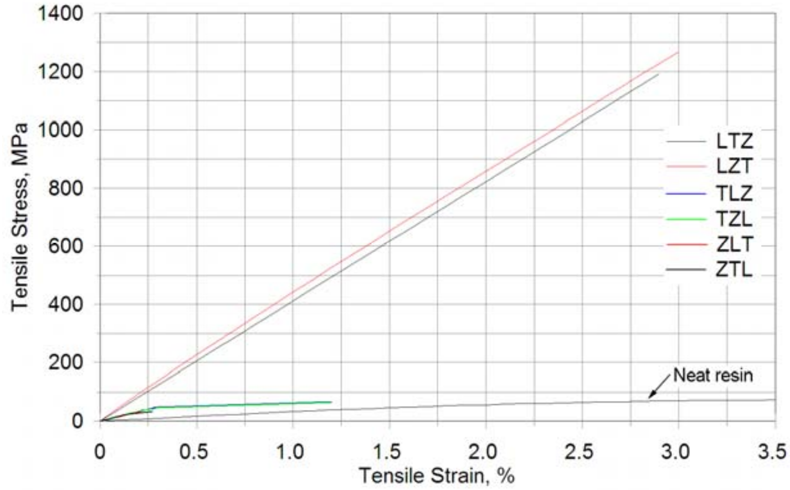
Stress Direction	Coupon Orientation	$E_{Compression}$, GPa			Ultimate Compressive Stress, MPa			Failure Strain, %		
		Avg	SD	COV	Avg	SD	COV	Avg	SD	COV
L	LTZ	42.5	2.3	5.4	-750	42	5.5	-1.78	0.17	9.5
L	LZT	43.1	1.8	4.1	-797	66	8.3	-1.87	0.25	13
T	TLZ	16.4	1.8	11	-189	3.7	2.0	-1.18	0.15	13
T	TZL	15.6	1.3	8.6	-168	24	14	-1.13	0.13	12
Z	ZLT	13.8	0.79	5.7	-180	6.3	3.5	-1.44	0.10	6.6
Z	ZTL	14.6	1.2	8.0	-189	7.2	3.8	-1.44	0.10	6.8
----	Neat Resin	2.98	0.02	0.70	-91.0	1.3	1.4	-5.38	0.37	6.9

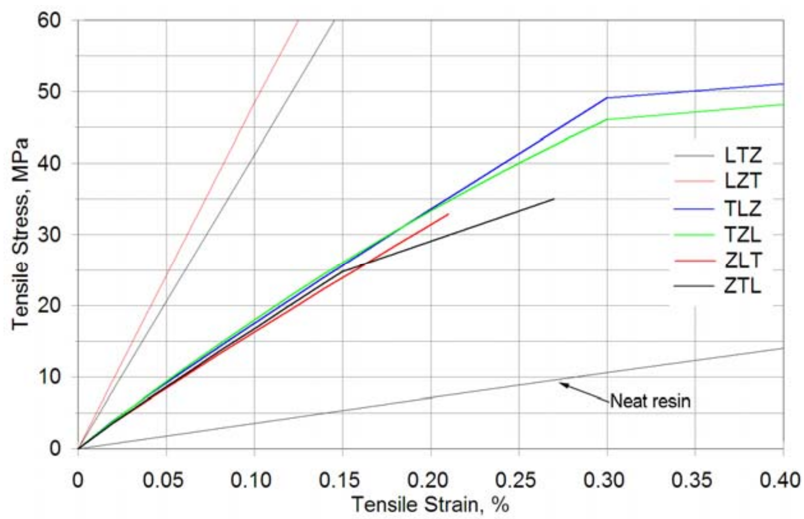
Shear Properties

Stress Direction	Coupon Orientation	Shear Modulus[1], G, GPa				0.2% Offset Stress, MPa			Maximum Shear Stress, MPa			Maximum[2] Shear Strain at Maximum Stress, %		
			Avg	SD	COV	Avg	SD	COV	Avg	SD	COV	Avg	SD	COV
LT	LTZ	G_{LT}	3.49	0.39	11	38.7	3.8	9.7	55.8	0.79	1.4	5	--	--
LZ	LZT	G_{LZ}	3.77	0.25	6.6	39.1	2.8	7.1	54.4	2.4	4.4	5	--	--
TL	TLZ	G_{TL}	3.04	0.37	12	38.0	4.3	11	52.0	1.7	3.3	4.6	0.30	6.5
TZ	TZL	G_{TZ}	3.46	0.51	15	36.3	3.6	9.9	45.6	3.0	6.6	5	--	--
ZL	ZLT	G_{ZL}	3.22	0.38	12	--	--	--	33.9	5.5	16	1.1	0.28	25
ZT	ZTL	G_{ZT}	3.50	0.44	13	--	--	--	28.4	3.6	13	0.81	0.25	31
----	Neat Resin	G	0.99	0.19	19	26.1	4.1	16	37.7	2.0	5.3	5	--	--

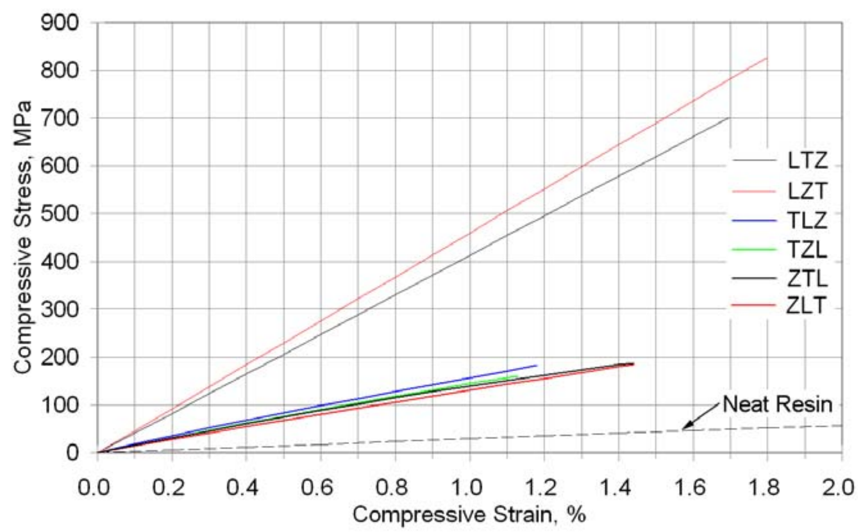
[1]Shear modulus calculated from best fit line between 0.2% and 0.6% shear strains.
[2]ASTM D5379 limits the maximum shear strain to 5%.

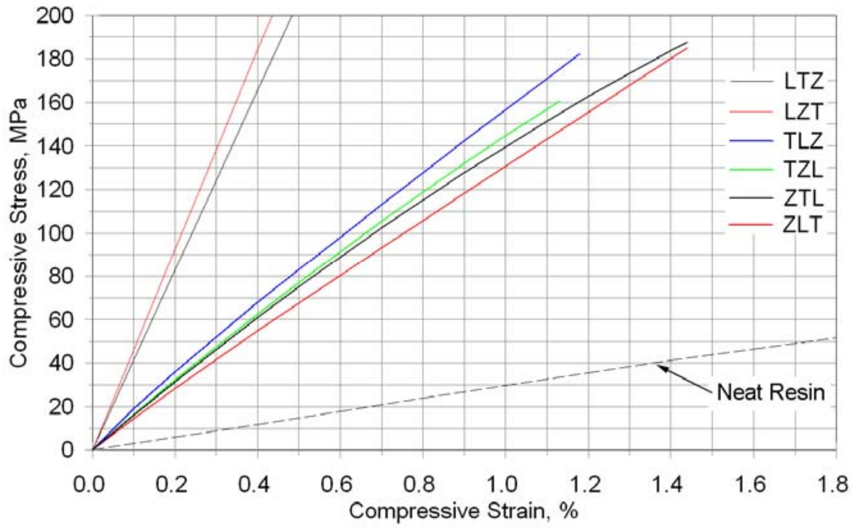
(a) Tensile Best Fit Stress-Strain Curves (Two Scales)





(b) Compression Best Fit Stress-Strain Curves (Two Scales)





(c) Shear Best Fit Stress-Strain Curves

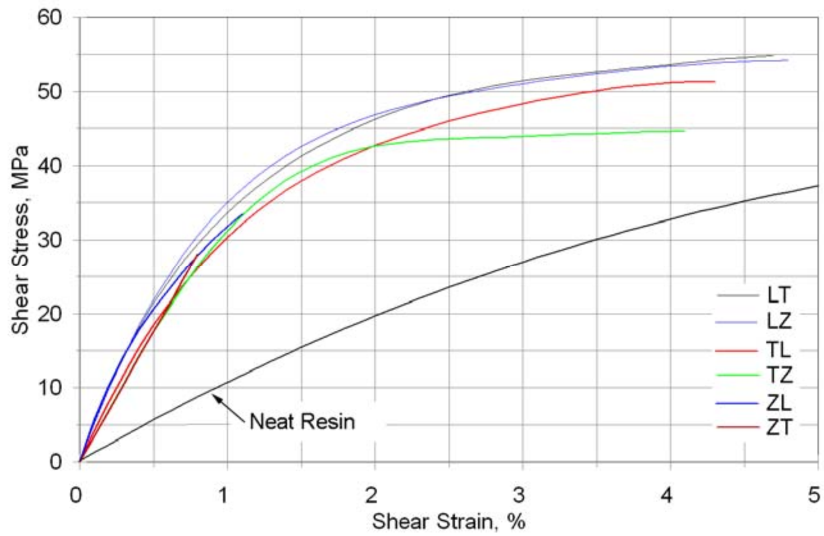


Figure 5 (a, b, c). Best fit stress-strain curves from Appendix A, curve fits in Table 5.

Table 5. Best fit stress-strain curve fits.

Tensile Stress-Strain Curve Best Fit Equations

Stress Direction	Coupon Orientation	Tensile Stress Best Fit Equations
L	LTZ	Stress (MPa) = 411.36(%strain)
L	LZT	Stress (MPa)= 441.67(%strain)$^{0.96}$
T	TLZ	Stress (MPa)=152.32(%strain)$^{0.94}$ for 0 – 0.3% strain Stress (MPa) = 19.53(%strain)+43.26 for 0.3 – 1.2% strain
T	TZL	Stress (MPa)= -130.83(%strain)^{2} + 192.87(%strain) for 0-0.3% strain Stress (MPa) = 21.01(%strain)+39.79 for 0.3 – 1.2% strain
Z	ZLT	Stress (MPa)= 144.9(%strain)$^{0.95}$
Z	ZTL	Stress (MPa)= 153.06(%strain)$^{0.96}$ for 0-0.15% strain Stress (MPa) = 85.33(%strain)+11.96 for 0.15 – 0.27% strain
	Neat Resin	Stress (MPa)= 0.1448(%strain)^{4} - 1.1038(%strain)^{3} - 2.1641(%strain)^{2} + 36.005(%strain)

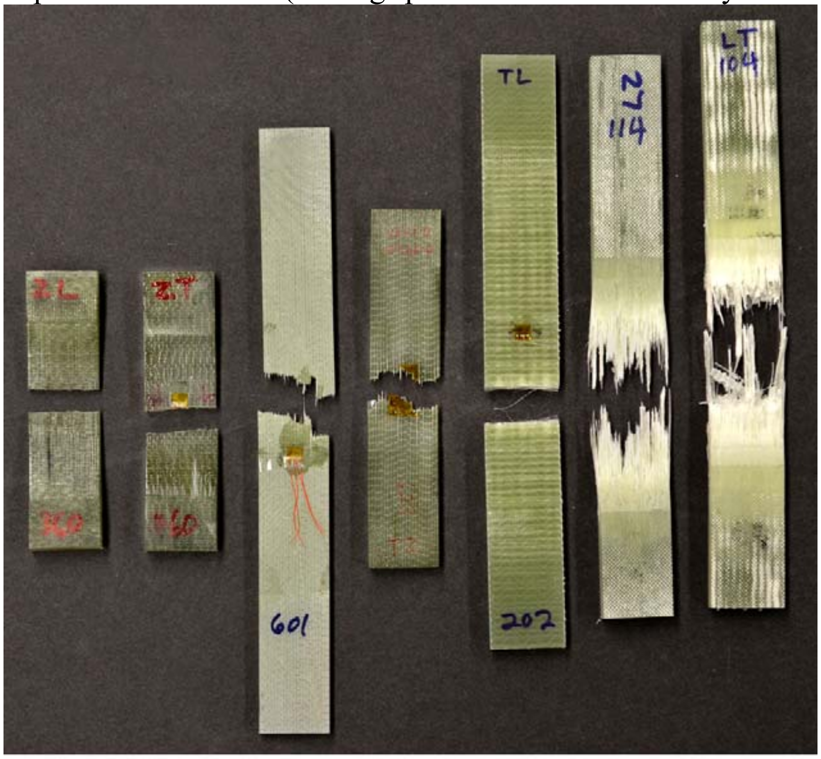
Compression Stress-Strain Curve Best Fit Equations

Stress Direction	Coupon Orientation	Compressive Stress Best Fit Equations
L	LTZ	Stress (MPa) = 412.95(%strain)
L	LZT	Stress (MPa) = -23.901(%strain)^{2} + 469.19(%strain)
T	TLZ	Stress (MPa) = 156.67(%strain)$^{0.9135}$
T	TZL	Stress (MPa) = -19.415(%strain)^{2}+164.07(%strain)
Z	ZLT	Stress (MPa) = 130.8(%strain)$^{0.951}$
Z	ZTL	Stress (MPa) = -20.956(%strain)^{2}+160.7(%strain)
	Neat Resin	Stress (MPa) = 0.1438(%strain)^{4} - 1.6118(%strain)^{3} + 2.1803(%strain)^{2} + 29.189(%strain)

Shear Stress-Strain Curve Best Fit Equations

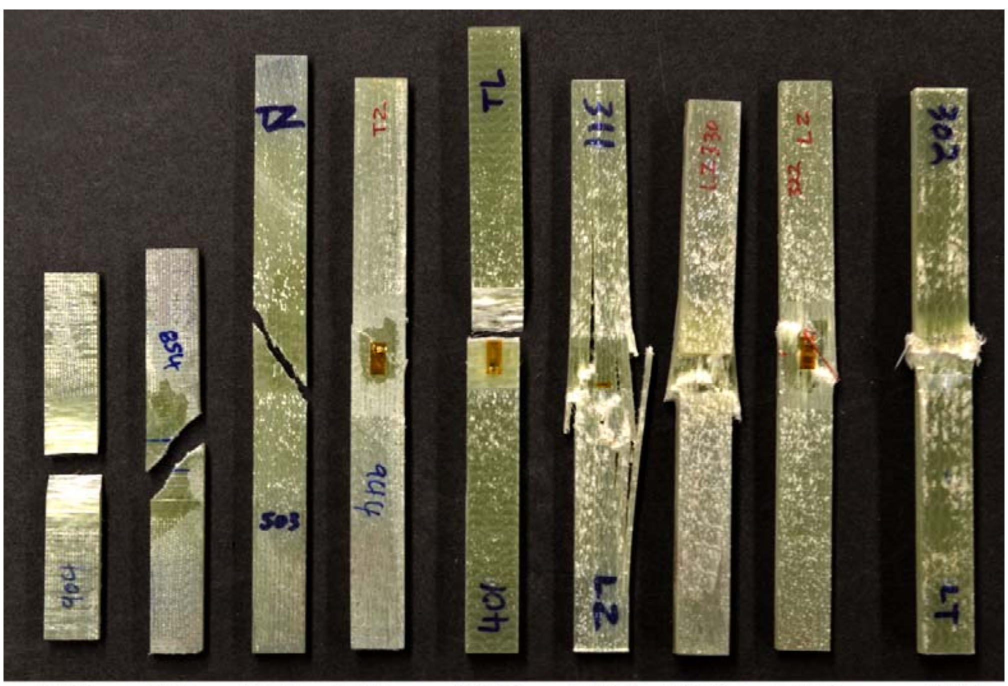
Stress Direction	Coupon Orientation	Shear Stress Best Fit Equations
LT	LTZ	Shear Stress (MPa) = -0.034(%strain)^{6} + 0.5624(%strain)^{5} – 3.7974(%strain)^{4} + 14.06(%strain)^{3} – 33.504(%strain)^{2} + 56.362(%strain)
LZ	LZT	Shear Stress (MPa) = 0.0328(%strain)^{5} - 0.7284(%strain)^{4} + 6.1254(%strain)^{3} - 25.332(%strain)^{2} + 54.909(%strain)
TL	TLZ	Shear Stress (MPa) = -0.2925(%strain)^{4} + 3.6075(%strain)^{3} – 17.746(%strain)^{2} + 44.791(%strain)
TZ	TZL	Shear Stress (MPa) = 0.0634(%strain)^{6} -1.0294(%strain)^{5} + 6.1689(%strain)^{4} - 15.38(%strain)^{3} + 6.5506(%strain)^{2} + 34.848(%strain)
ZL	ZLT	Shear Stress (MPa) = -19.231(%strain)^{4} +56.534(%strain)^{3} – 69.789(%strain)^{2} + 64.356(%strain)
ZT	ZTL	Shear Stress (MPa) = 35.097(%strain)
	Neat Resin	Shear Stress (MPa) = 0.0023(%strain)^{4} – 0.03(%strain)^{3} – 0.5587(%strain)^{2} + 10.608(%strain)

Tensile Coupon Failure Photos (some grip areas removed for analysis after testing)



ZLT ZTL TZL TZL tapered TLZ LZT LTZ

Compression Coupon Failure Photos



ZLT ZTL TZL TZL tapered TLZ LZT LZT tabs LZT tapered LTZ

Shear Coupon Failure Photos

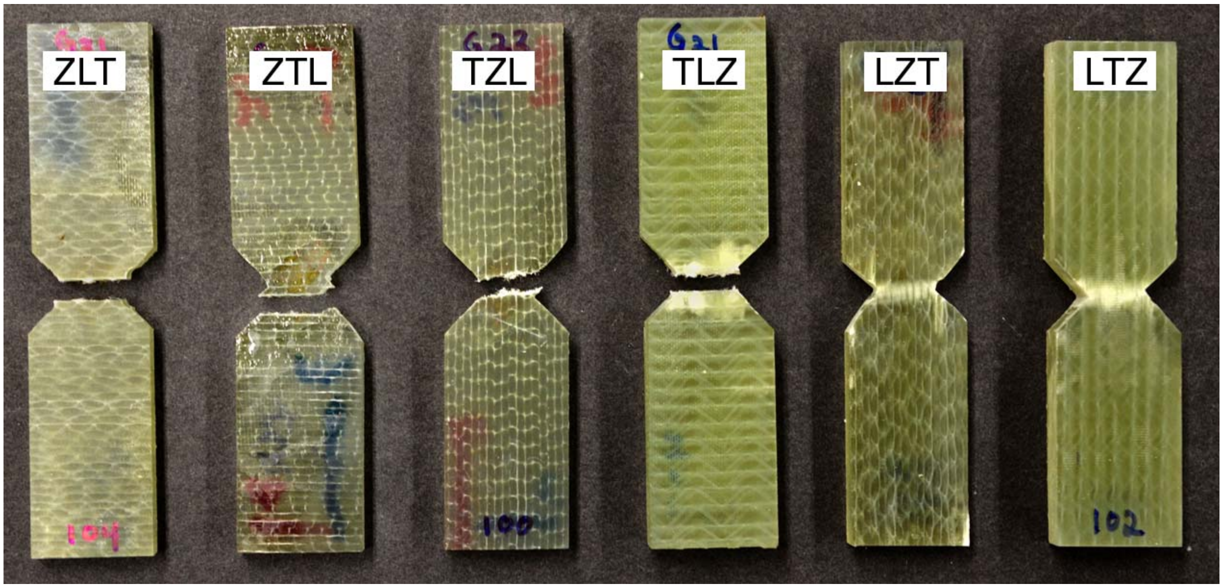
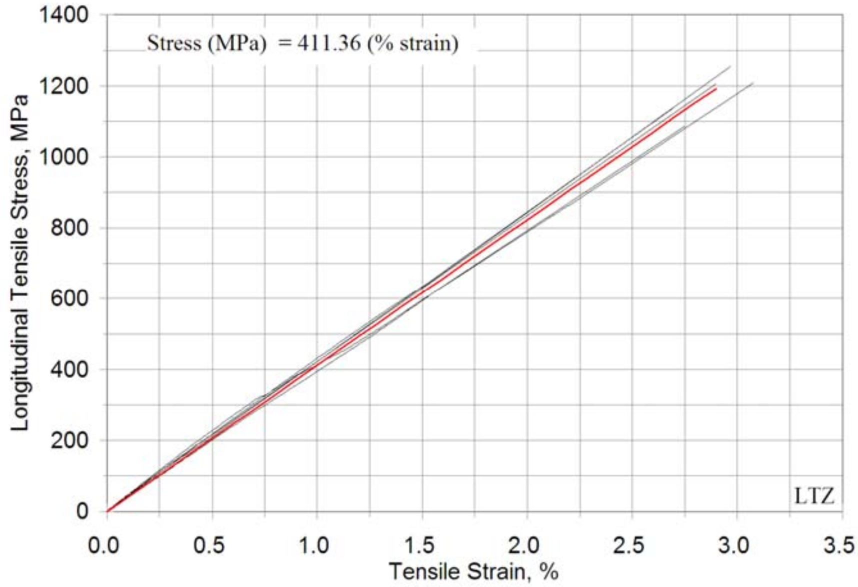
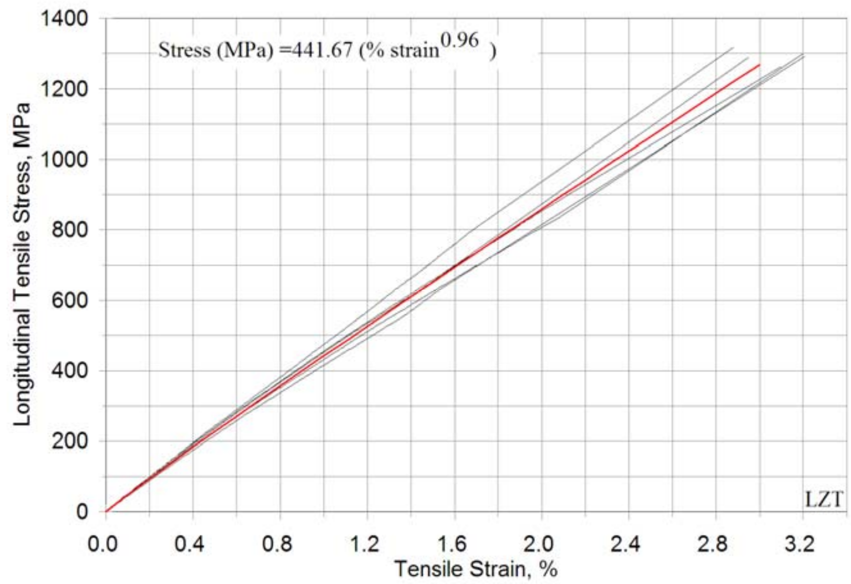


Figure 6 (a, b, c). Failed Coupon Photographs

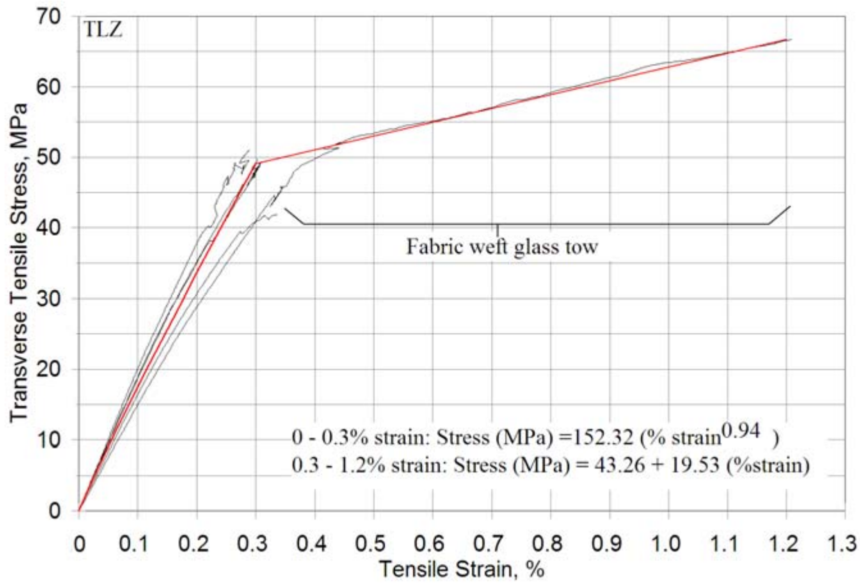
Appendix A. Stress-strain curves for individual tests with best fit curves



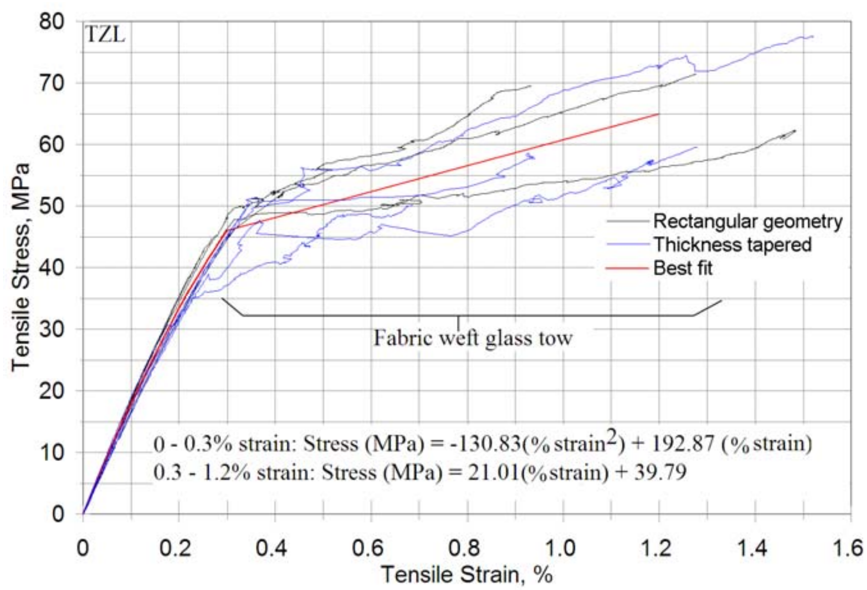
(a) Longitudinal tension, LTZ coupon orientation



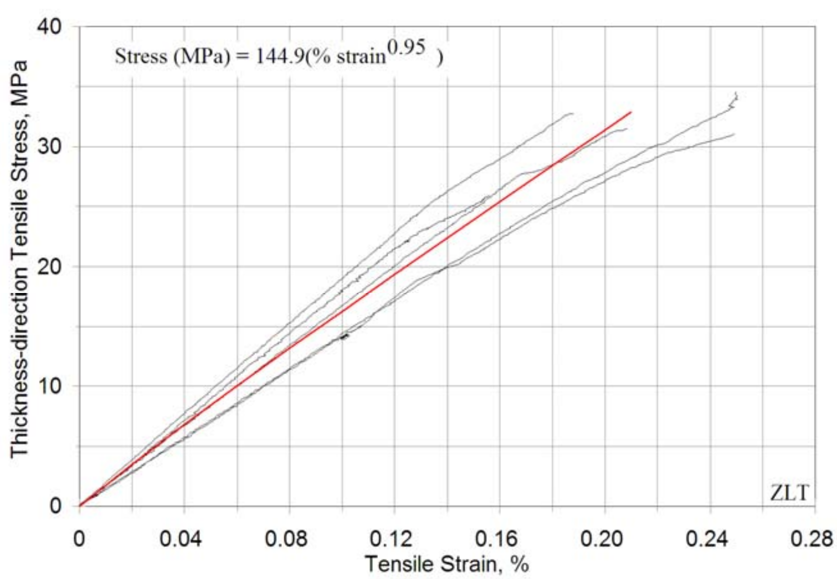
(b) Longitudinal tension, LZT coupon orientation



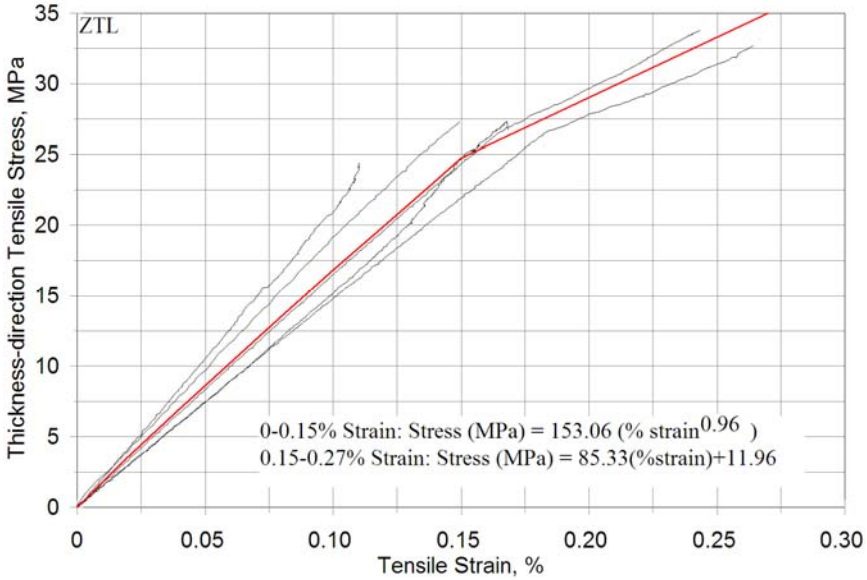
(c) Transverse tension, TLZ coupon orientation



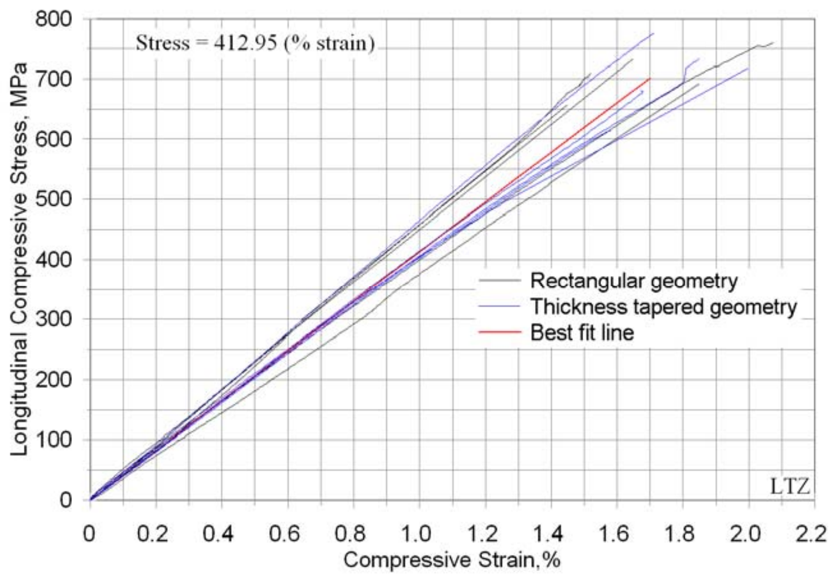
(d) Transverse tension, TZL coupon orientation



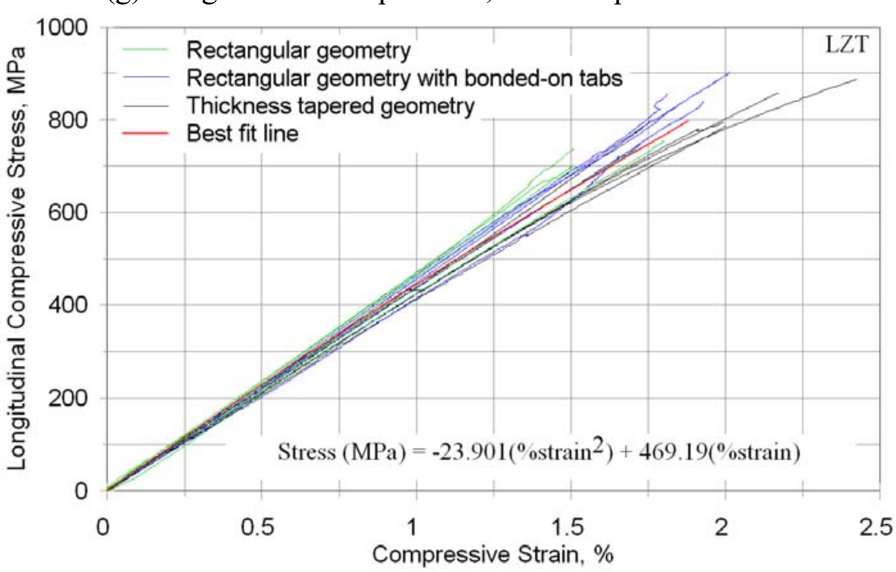
(e) Thickness direction tension, ZLT coupon orientation



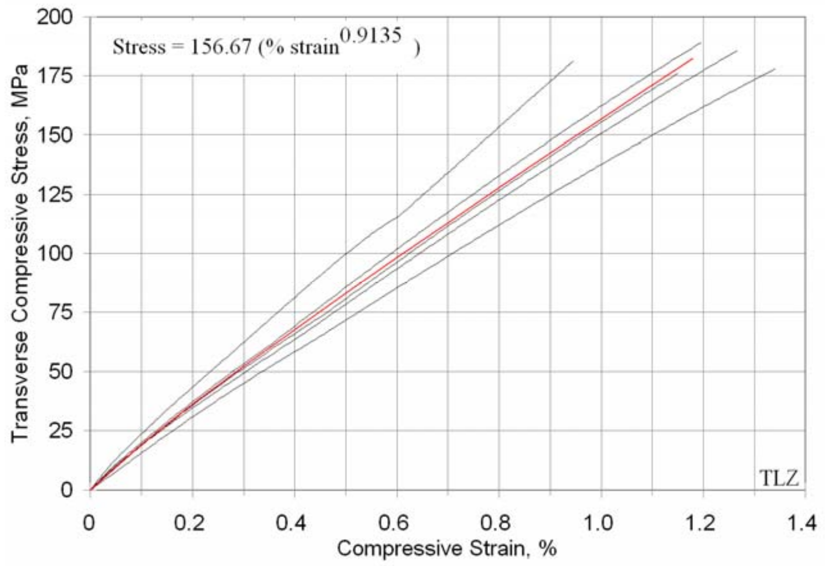
(f) Thickness direction tension, ZTL coupon orientation



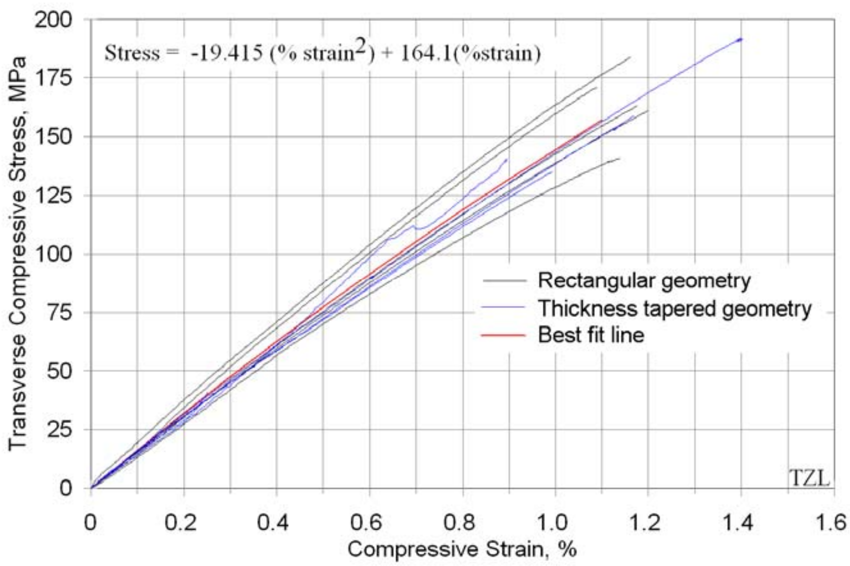
(g) Longitudinal compression, LTZ coupon orientation



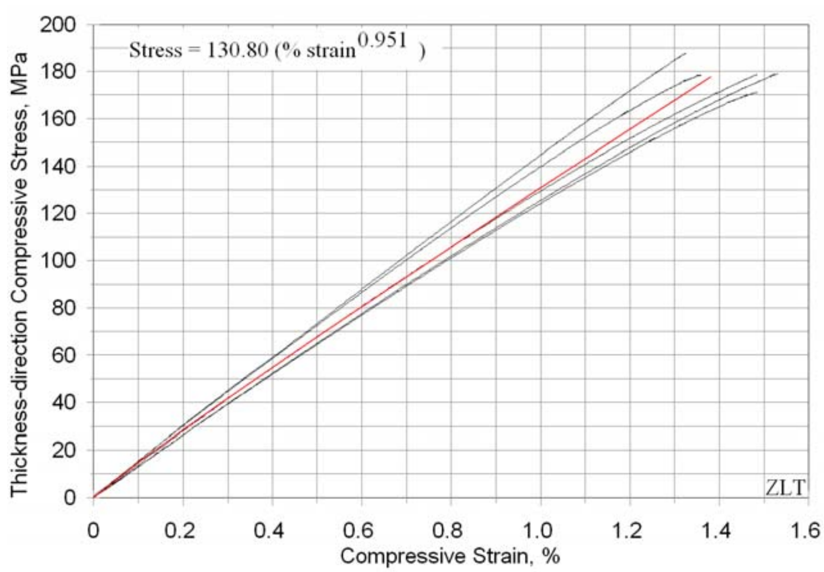
(h) Longitudinal compression, LZT coupon orientation



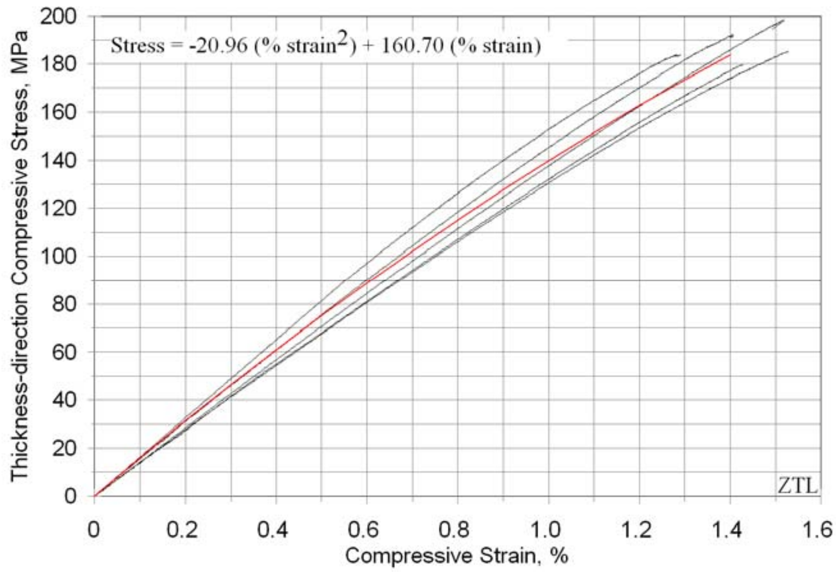
(i) Transverse compression, TLZ coupon orientation



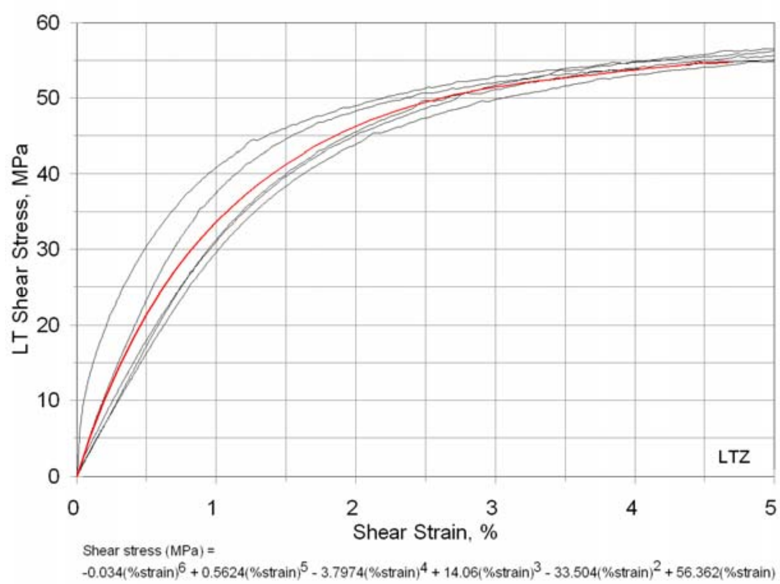
(j) Transverse compression, TZL coupon orientation



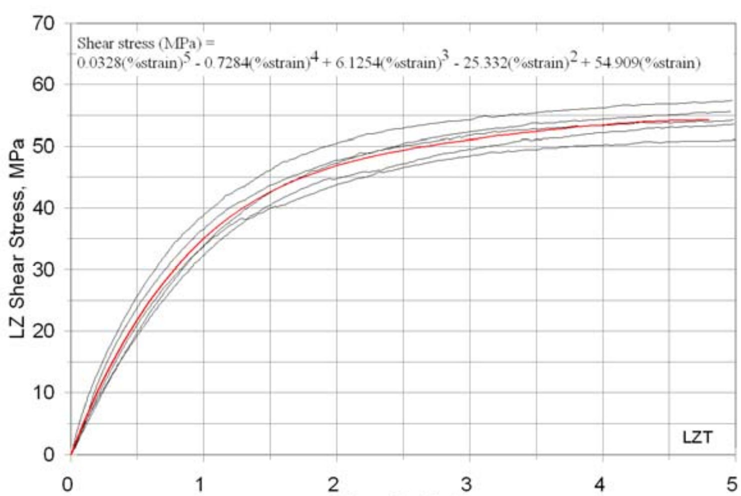
(k) Thickness direction compression, ZLT coupon orientation



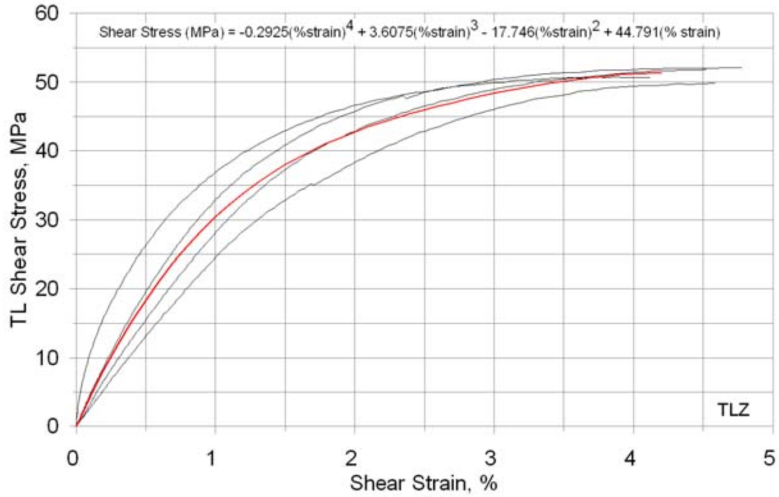
(l) Thickness direction compression, ZTL coupon orientation



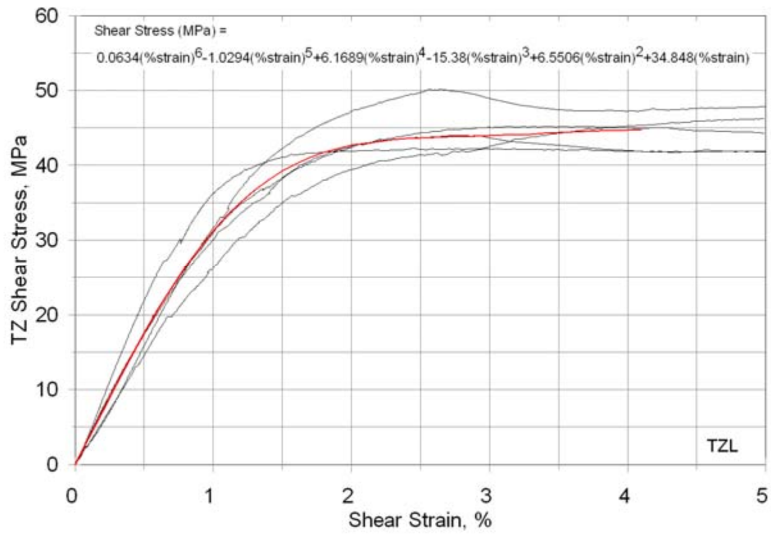
(m) LT shear direction, LTZ coupon orientation



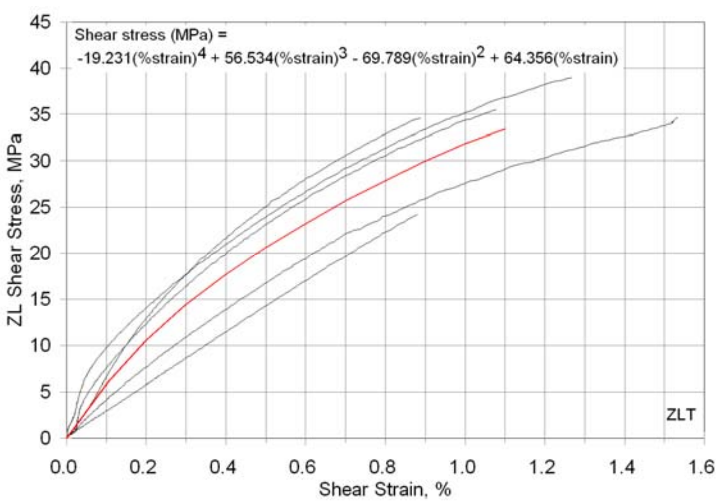
(n) LZ shear direction, LZT coupon orientation



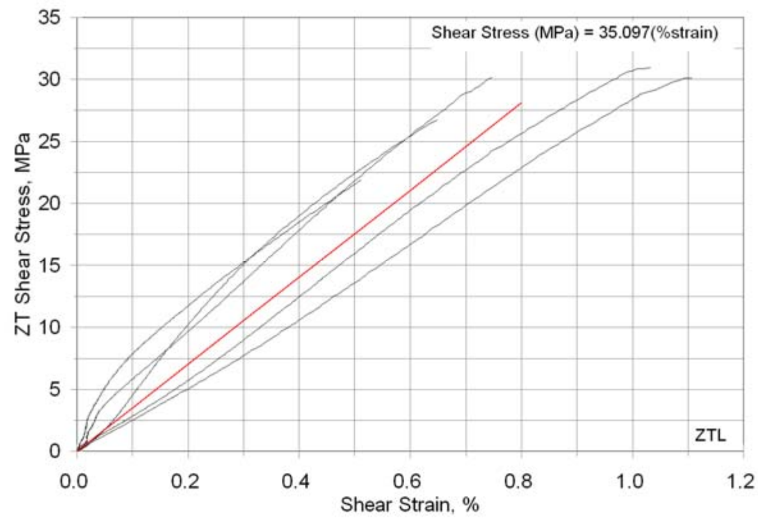
(o) TL shear direction, TLZ coupon orientation



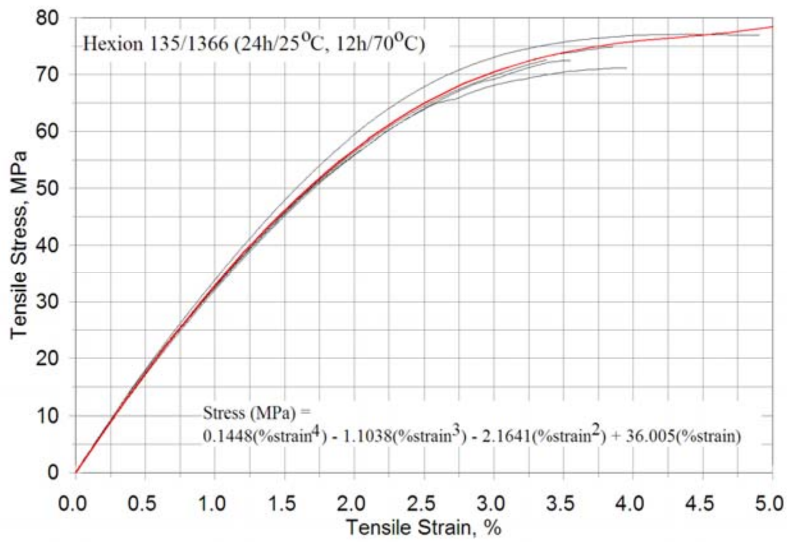
(p) TZ shear direction, TZL coupon orientation



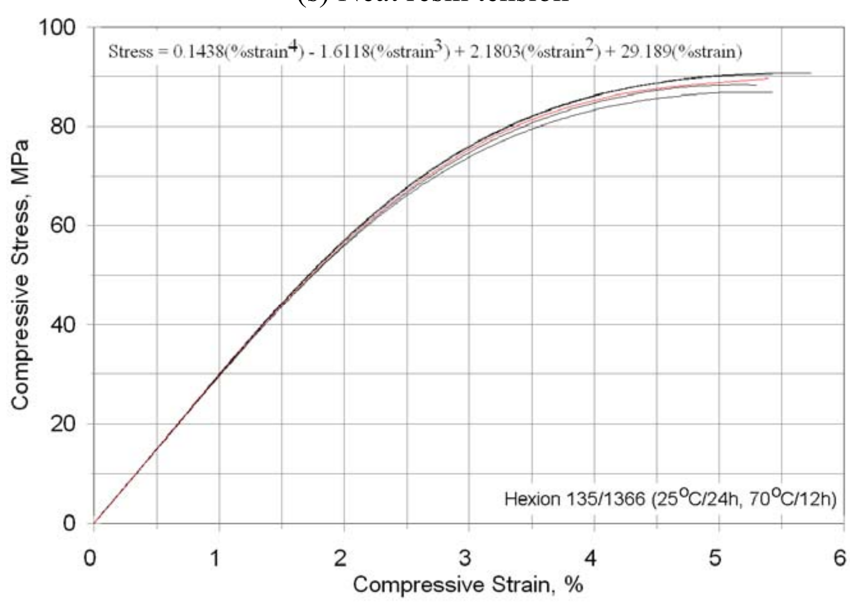
(q) ZL shear direction, ZLT coupon orientation



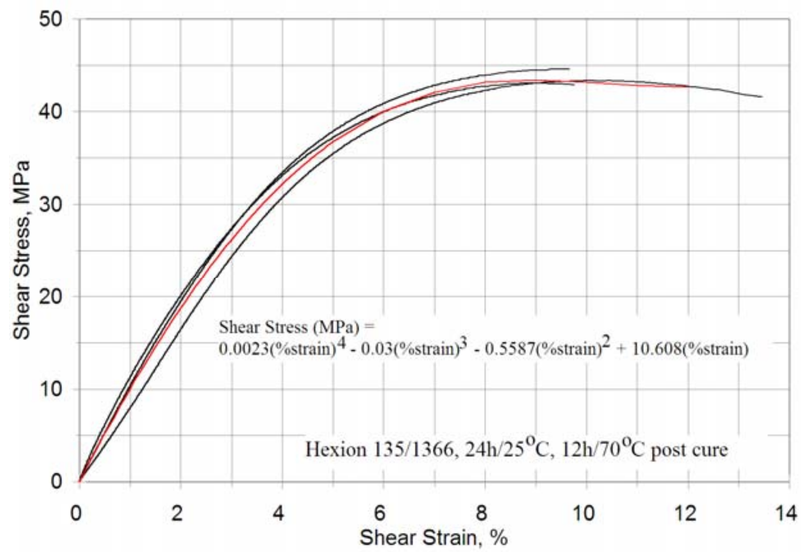
(r) ZT shear direction, ZTL coupon orientation



(s) Neat resin tension



(t) Neat resin compression



(u) Neat resin shear

Appendix B.
Individual Tensile Test Results

Stress Direction	Direction	Coupon	Ultimate Tensile Stress, MPa	E, GPa	Max. Strain, %	Poisson's Ratio	First crack Stress, MPa	First crack Strain, %	Notes
L	LTZ	LT100	1209	40.2	3.1	0.270	--	--	
L	LTZ	LT101	1256	43.7	3.0	0.251	--	--	
L	LTZ	LT102	1139	42.7	2.8	0.260	--	--	
L	LTZ	LT103	1087	46.2	2.8	0.262	--	--	
L	LTZ	LT104	1206	43.4	2.9	0.272	--	--	
L	LZT	LZ110	1300	44.9	3.2	0.281	--	--	
L	LZT	LZ111	1294	43.0	3.2	0.242	--	--	
L	LZT	LZ112	1318	48.1	3.0	0.245	--	--	
L	LZT	LZ113	1263	47.0	3.1	0.280	--	--	
L	LZT	LZ114	1290	46.5	2.9	0.274	--	--	
T	TLZ	TL200	73.9	18.0	0.46	0.091	46.3	0.33	
T	TLZ	TL201	76.9	19.6	0.42	0.088	41.0	0.22	
T	TLZ	TL202	66.9	14.6	0.47	0.084	44.8	0.31	
T	TLZ	TL203	73.4	15.7	0.47	0.058	39.5	0.25	
T	TLZ	TL204	71.8	18.2	0.41	0.074	46.3	0.26	
T	TZL	TZ600	69.7	17.6	0.93	0.349	40.6	0.23	
T	TZL	TZ601	61.0	17.5	0.25	0.389	42.1	0.25	
T	TZL	TZ602	72.0	16.2	1.28	0.372	46.2	0.31	
T	TZL	TZ603	63.5	17.8	0.27	0.357	44.8	0.27	
T	TZL	TZ604	57.4	16.9	1.45	0.308	43.7	0.25	
T	TZL	TZ620	50.9	16.8	0.69	0.346	30.7	0.19	tapered
T	TZL	TZ621	59.8	16.6	0.94	0.335	51.0	0.37	tapered
T	TZL	TZ622	78.3	16.0	1.75	0.340	49.0	0.38	tapered
T	TZL	TZ623	81.4	16.0	1.90	0.351	50.7	0.36	tapered
T	TZL	TZ624	60.5	15.8	1.44	0.375	39.0	0.26	tapered
Z	ZLT	ZL360	33.3	18.8	0.21	0.110	--	--	
Z	ZLT	ZL361	31.2	17.9	0.23	0.102	--	--	
Z	ZLT	ZL362	31.6	14.1	0.25	0.081	--	--	
Z	ZLT	ZL363	31.9	16.7	0.21	0.065	--	--	
Z	ZLT	ZL364	35.0	14.3	0.25	0.093	--	--	
Z	ZTL	ZT460	27.5	18.8	0.15	0.415	--	--	
Z	ZTL	ZT461	26.8	20.1	0.14	0.408	--	--	
Z	ZTL	ZT462	27.7	15.4	0.17	0.284	--	--	
Z	ZTL	ZT463	34.3	16.2	0.24	0.347	--	--	
Z	ZTL	ZT464	33.1	14.6	0.26	0.310	--	--	
		Resin1	76.2	3.43	3.8	0.345			
		Resin2	75.7	3.58	3.8	0.343			
		Resin3	76.7	3.52	4.0	0.342			
		Resin4	77.2	3.63	5.0	0.357			
		Resin5	75.8	3.49	4.2	0.346			

Individual Compression Test Results

Stress Direction	Direction	Coupon	Ultimate Compressive Stress, MPa	E_C, GPa	Min. Strain, %	Notes
L	LTZ	LT300	-703	44.6	-1.3	
L	LTZ	LT301	-770	40.9	-1.9	
L	LTZ	LT302	-746	42.3	-1.8	
L	LTZ	LT303	-714	41.0	-1.7	
L	LTZ	LT304	-710	46.3	-1.6	
L	LTZ	LT310	-852	---	-2.0	Bonded tabs
L	LTZ	LT311	-750	---	-1.8	Bonded tabs
L	LTZ	LT312	-791	---	-1.9	Bonded tabs
L	LTZ	LT313	-706	---	-1.7	Bonded tabs
L	LTZ	LT314	-808	---	-1.9	Bonded tabs
L	LTZ	LT320	-750	40.3	-1.9	tapered
L	LTZ	LT321	-734	41.8	-1.8	tapered
L	LTZ	LT322	-739	40.9	-1.8	tapered
L	LTZ	LT323	-721	40.7	-1.9	tapered
L	LTZ	LT324	-748	46.1	-1.7	tapered
L	LZT	LZ320	-801	41.9	-2.0	tapered
L	LZT	LZ321	-860	42.3	-2.2	tapered
L	LZT	LZ322	-790	41.3	-2.0	tapered
L	LZT	LZ323	-889	44.5	-2.4	tapered
L	LZT	LZ324	-796	42.3	-2.0	tapered
L	LZT	LZ330	-858	45.1	-1.8	Bonded tabs
L	LZT	LZ331	-839	45.4	-1.9	Bonded tabs
L	LZT	LZ332	-748	40.0	-1.7	Bonded tabs
L	LZT	LZ333	-904	44.8	-2.0	Bonded tabs
L	LZT	LZ334	-840	43.4	-1.9	Bonded tabs
L	LZT	LT320	-750	40.3	-1.9	tapered
L	LZT	LT321	-734	41.8	-1.8	tapered
L	LZT	LT322	-739	40.9	-1.8	tapered
L	LZT	LT323	-722	40.7	-1.9	tapered
L	LZT	LT324	-748	46.1	-1.7	tapered
L	LZT	LT310	-852	--	-2.0	Bonded tabs
L	LZT	LT311	-750	--	-1.8	Bonded tabs
L	LZT	LT312	-791	--	-1.9	Bonded tabs
L	LZT	LT313	-706	--	-1.7	Bonded tabs
L	LZT	LT314	-808	--	-1.9	Bonded tabs
L	LZT	LZ310	-701	42.4	-1.5	
L	LZT	LZ311	-697	45.5	-1.5	
L	LZT	LZ312	-757	40.5	-1.8	
L	LZT	LZ313	-742	43.6	-1.9	
L	LZT	LZ314	-739	43.7	-1.5	
T	TLZ	TL401	-185	16.3	-1.2	
T	TLZ	TL402	-193	16.6	-1.2	
T	TLZ	TL403	-192	14.7	-1.3	
T	TLZ	TL404	-185	19.2	-0.94	
T	TLZ	TL405	-190	15.1	-1.3	
T	TZL	TZ500	-173	18.1	-1.1	
T	TZL	TZ501	-168	15.7	-1.2	
T	TZL	TZ502	-185	17.6	-1.2	
T	TZL	TZ503	-173	14.9	-1.2	
T	TZL	TZ504	-142	14.4	-1.1	
T	TZL	TZ940	-211	14.5	-0.99	tapered
T	TZL	TZ941	-193	14.9	-1.4	tapered
T	TZL	TZ942	-160	14.2	-1.2	tapered
T	TZL	TZ943	-143	16.0	-0.95	tapered

T	TZL	TZ944	-134	15.8	-0.98	tapered
Z	ZLT	ZL900	-177	14.5	-1.4	
Z	ZLT	ZL901	-173	13.0	-1.5	
Z	ZLT	ZL902	-180	13.1	-1.5	
Z	ZLT	ZL903	-182	13.6	-1.5	
Z	ZLT	ZL904	-190	14.7	-1.3	
Z	ZTL	ZT850	-194	15.2	-1.4	
Z	ZTL	ZT851	-186	13.6	-1.5	
Z	ZTL	ZT852	-200	14.2	-1.5	
Z	ZTL	ZT853	-185	16.3	-1.3	
Z	ZTL	ZT854	-182	13.6	-1.4	
		Resin1	-91.1	2.98	-5.8	
		Resin2	-88.5	2.94	-5.3	
		Resin3	-89.7	2.98	-5.5	
		Resin4	-90.4	2.99	-4.8	
		Resin5	-90.6	2.99	-5.5	
		Resin6	-93.2	--	-6.7	
		Resin7	-92.1	--	-6.4	
		Resin8	-91.8	--	-6.4	
		Resin9	-91.9	--	-6.1	
		Resin10	-91.3	--	-6.7	
		Resin11	-91.1	--	-6.1	

Individual Shear Test Results

Stress Direction	Direction	Coupon	0.2% Offset Shear Stress, MPa	Maximum Shear Stress, MPa	Shear Strain at Maximum Stress[1], %	G, GPa
LT	LTZ	I12_100	44.2	56.5	5	3.42
LT	LTZ	I12_101	35.0	54.9	5	3.15
LT	LTZ	I12_102	40.8	55.2	5	4.15
LT	LTZ	I12_103	36.1	56.7	5	3.47
LT	LTZ	I12_104	37.4	55.6	5	3.28
LZ	LZT	I13_100	36.1	51.0	5	3.76
LZ	LZT	I13_101	38.2	55.7	5	3.73
LZ	LZT	I13_102	39.1	54.3	5	3.94
LZ	LZT	I13_103	38.3	53.6	5	3.38
LZ	LZT	I13_104	43.6	57.4	5	4.03
TL	TLZ	I21_100	39.0	54.4	5	3.09
TL	TLZ	I21_101	37.5	52.3	4.6	2.84
TL	TLZ	I21_102	37.7	52.4	4.8	3.49
TL	TLZ	I21_103	32.0	50.0	4.6	2.54
TL	TLZ	I21_104	44.0	51.0	4.2	3.26
TZ	TZL	I23_100	37.1	45.2	5	3.28
TZ	TZL	I23_101	37.8	42.2	5	4.31
TZ	TZL	I23_102	34.6	44.0	5	3.26
TZ	TZL	I23_103	31.2	46.3	5	2.95
TZ	TZL	I23_104	40.7	50.2	5	3.52
ZL	ZLT	I31_100	---	34.8	0.89	3.79
ZL	ZLT	I31_101	---	35.0	1.5	2.96
ZL	ZLT	I31_102	---	39.3	1.3	3.15
ZL	ZLT	I31_103	---	35.9	1.1	3.38
ZL	ZLT	I31_104	---	24.6	0.88	2.82
ZT	ZTL	I32_100	---	30.3	0.75	4.02
ZT	ZTL	I32_101	---	30.5	1.1	2.93
ZT	ZTL	I32_102	---	22.6	0.51	3.25
ZT	ZTL	I32_103	---	27.2	0.65	3.82
ZT	ZTL	I32_104	---	31.3	1.0	3.47
	Resin	H4	23.8	38.0	5	1.04
	Resin	H5	30.8	35.5	5	0.78
	Resin	H6	23.6	39.5	5	1.16

[1] ASTM D5379 limits the maximum shear strain to 5%.