Mechanical Characterization of Stretch Broken Carbon Fiber Materials – IM7 Fiber in 8552 Resin

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ABSTRACT

Interest in aligned discontinuous fiber materials has increased significantly in recent years as they facilitate new and more cost effective forming techniques for complex shaped composite parts compared to continuous fiber systems. Recent developments in the stretch break process led to enhanced formability of stretch broken carbon fiber (SBCF) materials, in particular those with intermediate modulus (IM) fibers.

A comprehensive test matrix was developed to compare the mechanical performance of stretch broken IM fiber based composites with 8552 matrix resin to those made with continuous reinforcement. Properties tested at ambient conditions, cold temperature dry, and elevated temperature wet environments include 0° and 90° tension, 0° compression, open-hole tension and compression, in-plane and short beam shear, compression after impact, and pin bearing response.

The results of the mechanical property testing demonstrate equivalency of a wide range of strength and stiffness related properties of the stretch broken IM7/8552 material form compared to the material form with continuous reinforcement.

1. INTRODUCTION

Prior work conducted in Hexcel's Navy-funded SBCF programs has been published at the 2005, 2006, 2007, and 2009 SAMPE spring conferences. The continued development of Hexcel's stretch break process led to stretch broken (SB) IM7 fiber with an average broken filament length as short as 5 cm and improved deformability [1]. Details of technology demonstrations of bead-stiffened panels and 3D woven preforms can be found in [2,3,4].

With the introduction of the SB (2.0") IM7 fiber in early 2008, testing of mechanical properties became a major effort within the current Navy-funded SBCF program, awarded at the end of December 2007. The test matrices included a wide range of properties, which were selected based on material specifications of interest. Results on mechanical performance testing of IM7/8552 with stretch broken and continuous reinforcement at ambient conditions (RTD) had been presented and discussed in [5]. The current paper includes the test data obtained at the cold temperature dry (CTD) and elevated temperature wet (ETW) environments.

2. EXPERIMENTATION

2.1 Stretch Breaking of IM7 Carbon Fiber

A detailed description of Hexcel stretch break technology can be found in [1]. The Generation 2 Stretch Break Machine (SB2 Machine) was utilized to manufacture stretch broken IM7 tows at a spacing of the two break zones of 5.08 cm (2.0 inch) each, designated SB (2.0”) IM7-GP 12K.

Three different lots of unsized IM7 12K were used as feed fiber, of which one fiber lot (3593-7A referred to as Lot A) served also as the continuous reinforcement control. Table 1 provides information on fiber properties, shown as lot averages of the continuous feed fiber.

Table 1. IM7 12K Feed Fiber Information

IM7 12K Fiber Lot Number		3593-7A **Lot A**	4144-7E **Lot B**	4326-7B **Lot C**
Tow Tensile Strength	[MPa] (ksi)	5636	5672	5596
Tow Tensile Modulus	[GPa] (Msi)	273	277	277
Fiber Density	[g/cm^3]	1.782	1.776	1.777

2.2 UD Prepreg Tape Manufacture

All IM7/8552 prepregs – both with stretch broken and continuous reinforcement – were manufactured on commercial prepreg lines at Hexcel’s SLC Matrix facility. The resin used was commercial film, also manufactured by Hexcel SLC Matrix utilizing standard operating procedures. Nominal resin content was 35% for both SB and continuous materials

For the Initial Test Matrix, 30.48 cm (12 inch) wide IM7/8552 prepreg of nominal 145 g/m^2 FAW (fiber areal weight) was manufactured with continuous (control) and stretch broken reinforcement from Lot A, and stretch broken reinforcement from Lot B.

Table 2. Information on Prepreg for the Initial Test Matrix

Prepreg Designation		UDC 08-001	SBT 08-003	SBT 08-004
Feed Fiber Designation Stretch Break Run No. SBR-		Lot A Control	Lot A 08-003	Lot B 08-004
Fiber Areal Weight	[g/m^2]	144.3	145.1	146.9
Resin Content	[%]	35.3	35.7	35.1

Note: In the prepreg designation, "UDC" stands for uni-directional continuous, while "SBT" stands for stretch broken tape.

For the Full Test Matrix, 60.96 cm (24 inch) wide IM7/8552 prepreg of nominal 160 g/m^2 FAW was manufactured with continuous (control) and stretch broken reinforcement from Lot A, and stretch broken reinforcement from Lot B.

Table 3. Information on Prepreg for the Full Test Matrix

Prepreg Designation		UDC 08-002	SBT 08-005	SBT 08-007	SBT 08-006
Feed Fiber Designation Stretch Break Run No. SBR-		Lot A Control	Lot A 08-007	Lot B 08-009	Lot C 08-008
Fiber Areal Weight	[g/m^2]	158.2	162.2	160.1	159.5
Resin Content	[%]	36.2	37.3	36.8	37.0

2.3 Panel and Test Specimen Fabrication, Environmental Conditioning, Testing, and Data Reduction

These tasks were performed by the National Institute for Aviation Research (NIAR) at Wichita State University (WSU). Panels were fabricated from as-made prepregs, using the standard 177 °C (350 °F) HexPly® 8552 cure cycle.

Table 4 below lists the properties tested, testing methods (standards), ply sequence (lay-up), and number of coupons tested for both the Initial and Full Test Matrix.

The abbreviations RTD, CTD, and ETW in Table 4 define the test conditions and moisture conditioning of wet test specimens:

RTD: Room Temperature Dry testing conducted at laboratory ambient condition, 21° ± 6°C (70° ± 10°F)

CTD: Cold Temperature Dry testing at -54° ± 3°C (-65° ± 5°F)

ETW: Elevated Temperature Wet testing at 82° ± 3°C (180° ± 5°F) after wet conditioning in an environment of 82° ± 3°C (180° ± 5°F) and a relative humidity of 85% ± 3%.

Specimen dry-out was conducted in an oven at 104° ± 3°C (220° ± 5°F).

The specimens were considered "Dry", when the average percent change in moisture content for three consecutive weighings was less than 1.0% of the total percent increase in weight.

Calculations of the test values were made in accordance with the respective ASTM or SRM standard. Final reported test values for strength and modulus – where applicable – are reported as normalized to 60% fiber volume. The cured ply thickness method was applied for fiber volume normalization, i.e. the calculated test values were multiplied by the actual specimen thickness divided by the nominal specimen cured ply thickness x number of plies.

Table 4. Mechanical Property Test Matrices

Panel Designation (Property)	**Method**	**Ply Sequence**	**Initial**	**Full Test Matrix**		
			RTD	CTD	RTD	ETW
0° Tensile Strength 0° Tensile Modulus 0° Poisson's Ratio	ASTM D 3039	$[0]_8$	6 -	6 6	6 6	6 6
Open Hole Tension Strength Open Hole Tension Modulus	ASTM D 5766	$[+45/0/-45/90]_{2S}$	6	6	6	6
0° Compression Strength 0° Compression Modulus	ASTM D 6641	$[90/0/90]_7$ $[0]_{20}$	6	6	6	6
OH Compression Strength OH Compression Modulus	ASTM D 6484	$[+45/0/-45/90]_{2S}$	6	6	6	6
Compression after Impact Strength	SRM-2	$[+45/0/-45/90]_{4S}$	4	-	4	-
Short Beam Shear Strength	ASTM D 2344	$[0]_{16}$	6	6	6	6
In-Plane Shear Strength In-Plane Shear Modulus	ASTM D 3518	$[+45/-45]_{2S}$	-	6	6	6
90° Tensile Strength 90° Tensile Modulus	ASTM D 3039	$[90]_{16}$	-	6	6	6
Bearing Response Procedure A	ASTM D 5961	$[+45/0/-45/90]_{2S}$	-	6	6	6

2.4 Analysis of Variance (ANOVA)

The statistical analysis of the property test data was performed by Flightware, Inc. [6]. The numerical procedures generally followed the guidelines defined in reference [7]. Much of the statistical analysis was performed directly in the ASAP (AGATE Statistical Analysis Program) data reduction spreadsheets developed by WSU/NIAR for this purpose [7]. The first phase of data analysis was performed within the ASAP spreadsheet, as described in sections 2.4.1 to 2.4.4 below.

2.4.1 Data Normality

Checks for data normality for each condition were performed using the Anderson-Darling [8] test and the method of Normal Scores.

2.4.2 Batch Pooling

Checks were performed to determine if the data from each SBCF material batch belongs to the same population using the k-Sample Anderson Darling Test [9]. Checks were conducted at significance levels of 0.050, 0.025 and 0.010.

2.4.3 Outlier Determination

Within any batch and environment, a determination of data Outliers was performed per the procedures defined in reference [7]. In the event a data Outlier was identified, it was removed from the data set and the statistics were then recalculated.

2.4.4 Analysis of Variance

An analysis of variance (ANOVA) was performed for each environmental condition and each property using the statistical procedures embodied in the XLSTAT spreadsheet [10]. The significance of the differences between all batch permutations within one environmental condition (i.e. pairwise comparison) for a given property was calculated using Tukey's HSD (Honestly Significant Difference) test [11] at a confidence level of 95% ($\alpha = 0.05$).

For sub-ambient (CTD) and hot-wet (ETW) conditions, differences were examined between one batch of Continuous material and three SBCF batches. For most RTD properties, differences were examined between two batches of Continuous material with five SBCF batches.

2.4.5 Material Equivalence

A Stretch Break "Retention Factor" was calculated to express material equivalence between mean values of SBCF batches and those of Continuous material:

$$\text{SB Retention Factor (RF)} = \frac{SBCF\ Mean}{Continuous\ Mean}$$

Where the ANOVA indicated a statistically significant difference exists between one or more batches of SBCF material from Continuous material, the property and its batch mean value(s) are correspondingly highlighted in the mechanical property data tables in the Appendix.

3. RESULTS

A summary of the mechanical property data is provided in Tables 7, 8, 9 (see section 7. Appendix) for CTD, RTD, and ETW environments, respectively. Basic data statistics – mean value and standard deviation – are presented for the individual batches. For the (nominal) number of data points used per batch and condition, see Table 4.

The ANOVA results are included in the Tables 7 to 9, using color codes as defined in the legends below of the tables. Several observations can be made:

- For many properties most of the SBCF batches were statistically equivalent to the Continuous batch(es).

- For almost all properties within one environment where significant differences were noted, these differences were consistent within one property/environment, i.e. either consistently higher or lower than the Continuous value.

  The only exception to this was in ETW SBS Strength, where one SBCF batch was significantly higher and one SBCF batch was significantly lower than the Continuous value.

Figures 1 to 3 present the SB Retention Factor for each environment, as defined in section 2.4.5. The error bars illustrate the calculated ± 1 σ standard deviation for each dataset to provide a graphic representation of scatter overlap.

3.1 Strength Comparison

3.1.1 Fiber-Dominated Properties

Figure 1 presents the SB Retention Factor (RF) for all fiber-dominated strength properties. With two exceptions, the mean SBCF material strength is at least equivalent to the mean Continuous material strength.

- The SB Retention Factor for the CTD 0° Tensile Strength comes to 0.941. The RF for all three SBCF batches were lower than the one Continuous batch, with one of the SBCF batches (SBT08-005) significantly lower.

- The SB Retention Factor for the CTD Open Hole Tensile (OHT) Strength comes to 0.996. While the RF for one of the three SBCF batches (SBT08-007) was lower than the one Continuous batch, SBT08-006 compensated without being significantly higher than the one Continuous batch.

It is worth noting that the SB Retention Factor for both 0° Tensile Strength and OHT Strength is increasing from CTD to RTD to ETW environment, while this trend is reversed for 0° compression strength.

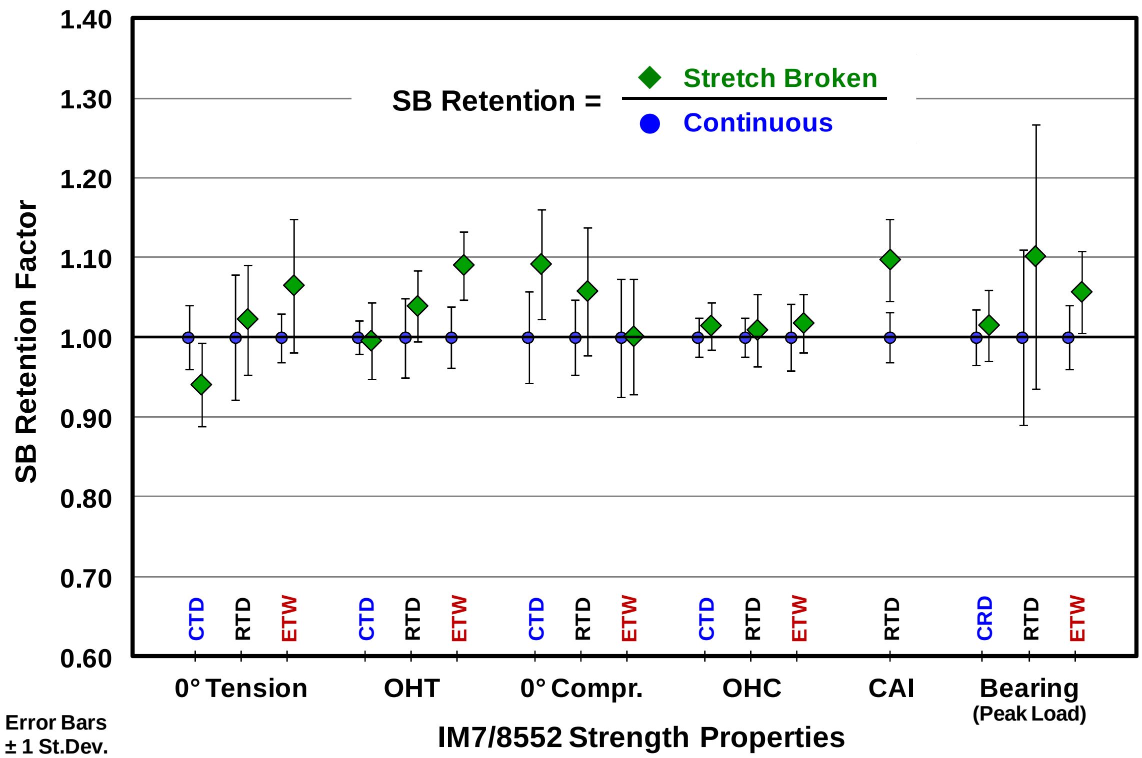

Figure 1: SB Retention Factors of IM7/8552 Fiber-Dominated Strength Properties

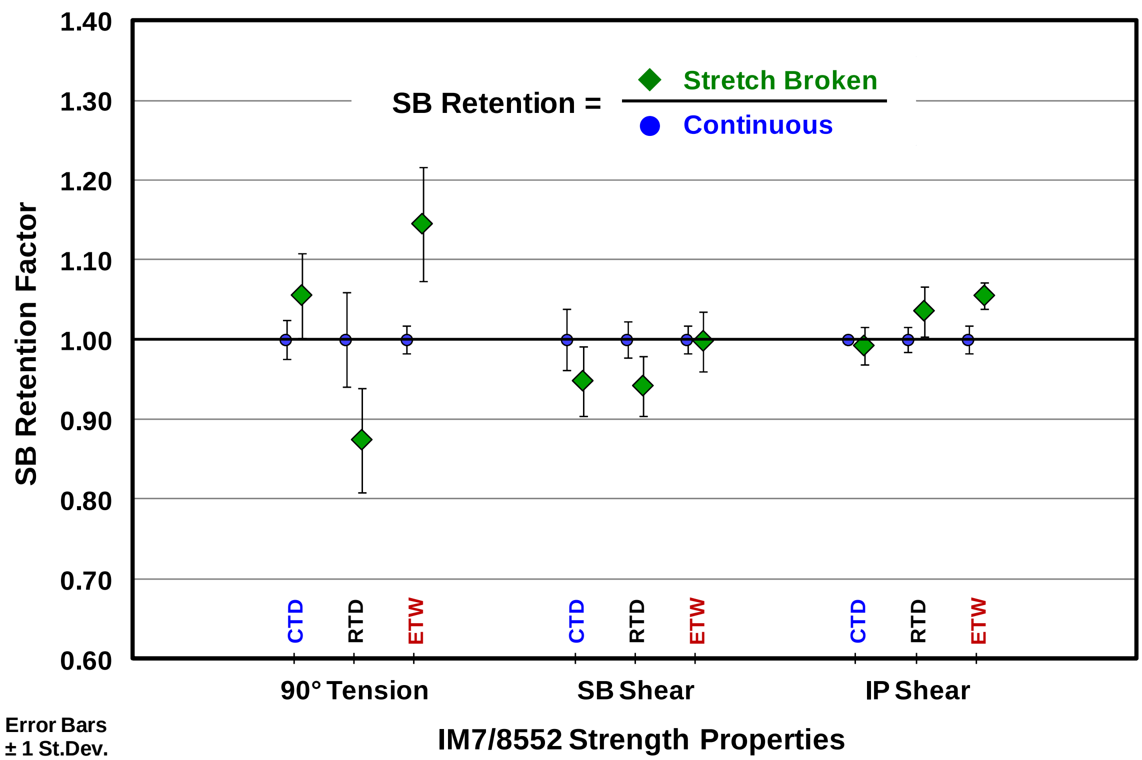

Figure 2: SB Retention Factors of IM7/8552 Matrix-Dominated Strength Properties

Although not identified as outliers, all RTD Bearing Strength data of batch SBT08-007 appears unusually high, 30% to 40% higher than for Continuous material and the other two SBCF batches at the same condition. No explanation is currently available, but will be investigated in future work.

3.1.2 Matrix-Dominated Properties

Figure 2 presents the SB Retention Factor for matrix-dominated strength properties.

The SB Retention Factors for the 90° Tensile Strength are inconsistent for the three environments. Compared to the Continuous CTD batch mean value, the Continuous RTD batch mean value was relatively high, contributing to the drop of the RTD SB Retention Factor to 0.874.

The Short Beam Shear Strengths for the SBCF material at the CTD and RTD environments are significantly lower than those for the Continuous material. The difference of 5.8% at RTD is approximately the same as what was found for SBCF-based AS4/8552 and AS4/M73 samples, but not for SBCF-based AS4/M65 materials [12].

3.2 Stiffness Comparison

Figure 3 presents the SB Retention Factor for stiffness properties.

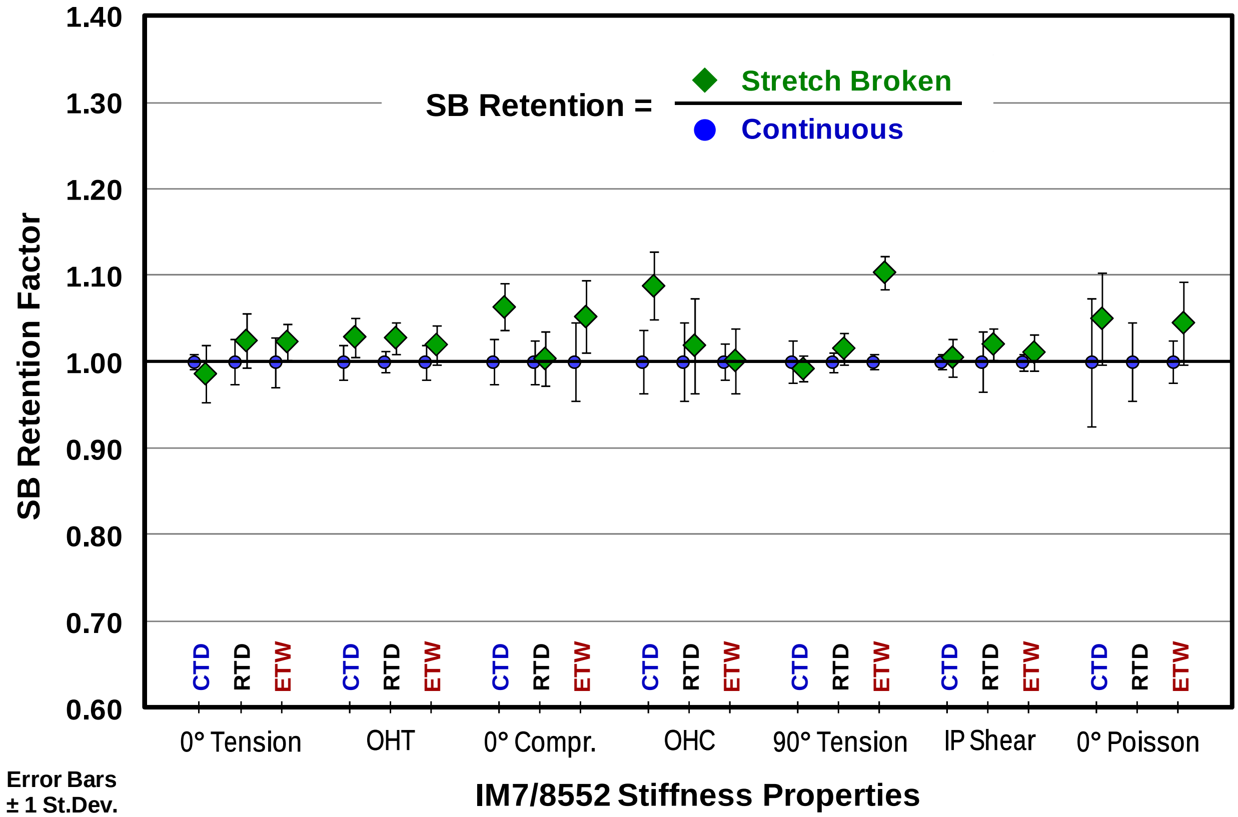

Figure 3: SB Retention Factors of IM7/8552 Stiffness Properties

At a confidence level of 95% (α = 0.05), all stiffness properties are statistically at least equivalent to Continuous material. This is also valid for the 0° tension modulus at CTD condition (RF = 0.986) and the 90° tension modulus at CTD condition (RF = 0.992).

4. SUMMARY

The Navy-funded SBCF program included the generation of an extensive set of mechanical property data of the Stretch Broken IM7/8552 material form for comparison with the material form with Continuous reinforcement. Property testing was performed at three environmental conditions – Cold Temperature Dry (CDT), Room Temperature Dry (RTD), and Elevated Temperature Wet (ETW) at 82 °C (180 °F).

In all cases, stiffness of the SBCF IM7/8552 material was statistically equivalent to the Continuous material.

In most cases, strength of the SBCF IM7/8552 material was statistically equivalent to the Continuous material.

The following strength properties –listed in Table 5 below – exhibited a slight, but statistically significant reduction due to at least one (1) SBCF batch mean compared to the Continuous mean value:

Table 5. Strength Properties Exhibiting a Slight Statistically Significant Reduction

Environment (Domination)	Strength Property	SB Retention Factor		
		Worst Batch	Average	Best Batch
CTD (Fiber)	0° Tensile	0.911	0.941	0.951
CTD (Fiber)	OH Tensile	0.951	0.996	1.048
RTD (Matrix)	90° Tensile	0.848	0.874	0.900
CTD (Matrix)	Short Beam Shear	0.906	0.948	0.980
RTD (Matrix)	Short Beam Shear	0.896	0.942	0.965
ETW (Matrix)	Short Beam Shear	0.959	0.998	1.038
CTD (Matrix)	In-Plane Shear	0.965	0.992	1.012

In some cases, the average SB Retention Factor is very close to 1.00, i.e., the data from SBCF batches seem not to differ from Continuous material, indicating that there is no “Stretch Break” effect on properties. In those cases, a conservative approach for design purposes would be to use SB Retention Factors of SBCF batches that are significantly lower than the Continuous material.

A number of strength properties – listed in Table 6 below – exhibited no statistically significant difference between any SBCF batch and Continuous material:

Table 6. Strength Properties Exhibiting No Statistically Significant Difference

Environment (Domination)	Strength Property	SB Retention Factor		
		Worst Batch	Average	Best Batch
CTD (Fiber)	OH Compression	1.000	1.015	1.031
ETW (Fiber)	OH Compression	1.004	1.018	1.042
ETW (Fiber)	Bearing (Peak)	1.022	1.057	1.098
CTD (Matrix)	90° Tension	1.046	1.055	1.061

In all other cases, the analysis indicated that the SBCF strength of at least one batch, and often of more than one batch, exceeded the mean strength of the Continuous material by margins that were statistically significant. To be conservative, this SBCF "strengthening effect" should be ignored and an SB Retention Factor = 1.00 should be assigned in these cases.

5. ACKNOWLEGDEMENTS

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7. APPENDIX

Table 7: CTD Mechanical Property Data

CTD Data \ **Reinforcement**		**Contin.**	**Stretch Broken**		
IM7/8552		UDC08	SBT08	SBT08	SBT08
Prepreg Designation		-002	-005	-006	-007
Feed Fiber Designation		Lot A	Lot A	Lot C	Lot B
0° Tensile Strength	MPa	2811	2562	2681	2687
Standard Deviation		112	156	152	54
0° Tensile Modulus	GPa	163.8	164.7	157.4	162.5
Standard Deviation		1.5	5.4	4.8	3.2
Poisson's Ratio		0.320	0.335	0.325	0.347
Standard Deviation		0.024	0.020	0.015	0.015
Open Hole Tensile Strength	MPa	449	443	470	427
Standard Deviation		9.4	13.9	14.0	5.7
Open Hole Tensile Modulus	GPa	63.2	64.5	66.6	63.9
Standard Deviation		1.3	0.9	0.9	0.9
0° Compressive Strength	MPa	1780	1961	2031	1820
Standard Deviation		163	70	129	140
0° Compressive Modulus	GPa	137.8	148.8	150.5	144.8
Standard Deviation		3.9	1.4	3.5	4.8
OH Compressive Strength	MPa	377	389	377	381
Standard Deviation		1.3	11.0	13.2	7.9
OH Compressive Modulus	GPa	54.3	57.2	61.3	58.7
Standard Deviation		2.0	2.4	1.5	0.6
90° Tensile Strength	MPa	75.6	80.3	79.1	80.1
Standard Deviation		3.5	3.5	4.9	5.0
90° Tensile Modulus	GPa	10.1	9.9	10.1	10.1
Standard Deviation		0.25	0.11	0.08	0.18
In-Plane Shear Strength	MPa	114.3	110.3	115.6	114.2
Standard Deviation		0.25	2.18	0.73	1.29
In-Plane Shear Modulus	GPa	5.59	5.61	5.67	5.58
Standard Deviation		0.05	0.09	0.17	0.09
Interlaminar Shear Strength	MPa	173.1	156.8	169.7	166.1
Standard Deviation		6.7	5.8	4.6	2.6
Bearing Strength (Peak)	MPa	1103	1089	1101	1166
Standard Deviation		38.1	41.3	20.2	45.2
Bearing Strength (2% Offset)	MPa	1072	1067	1077	1130
Standard Deviation		40.1	35.1	26.0	39.4

Legend: Same Population* | High* | Low*

*) Stretch Broken versus Continuous at a Confidence Level of 95% ($\alpha = 0.05$)

Table 8: RTD Mechanical Property Data

RTD Data \ Reinforcement		Continuous		Stretch Broken				
IM7/8552		UDC08	UDC08	SBT08	SBT08	SBT08	SBT08	SBT08
Prepreg Designation		-001	-002	-003	-004	-005	-006	-007
Feed Fiber Designation		Lot A	Lot A	Lot A	Lot B	Lot A	Lot C	Lot B
0° Tensile Strength	MPa	2528	2689	2662	2644	2543	2903	2570
Standard Deviation		90	264	214	78	168	104	53
0° Tensile Modulus	GPa	159.7	159.5	166.8	164.8	161.8	164.0	158.7
Standard Deviation		3.6	5.2	8.7	5.0	1.5	1.9	1.3
Poisson's Ratio		0.337	0.337	0.338	0.347	0.337	0.330	0.322
Standard Deviation		0.019	0.010	0.023	0.025	0.016	0.010	0.011
Open Hole Tensile Strength	MPa	414	443	445	429	459	462	433
Standard Deviation		15.5	16.4	19.7	20.7	14.6	13.4	7.9
Open Hole Tensile Modulus	GPa	61.2	60.9	63.1	62.0	62.8	63.2	62.6
Standard Deviation		0.9	0.6	1.3	1.0	0.8	1.4	1.0
0° Compressive Strength	MPa	1573	1569	1529	1618	1606	1805	1769
Standard Deviation		65	90	96	83	107	63	59
0° Compressive Modulus	GPa	148.3	143.9	152.0	146.0	142.7	146.7	144.6
Standard Deviation		2.1	3.7	4.0	0.4	2.7	3.9	3.7
OH Compressive Strength	MPa	324	332	321	323	353	331	333
Standard Deviation		7.6	7.0	12.3	15.0	7.3	6.7	7.2
OH Compressive Modulus	GPa	53.1	56.5	55.3	56.0	51.8	59.5	56.9
Standard Deviation		2.0	1.6	2.0	2.2	1.1	1.8	2.4
90° Tensile Strength	MPa		82.6			70.1	74.4	72.2
Standard Deviation			4.9			6.0	1.3	5.1
90° Tensile Modulus	GPa		8.8			8.78	9.10	8.82
Standard Deviation			0.10			0.08	0.07	0.09
In-Plane Shear Strength	MPa		88.4			91.0	90.4	92.5
Standard Deviation			1.2			1.1	2.3	2.3
In-Plane Shear Modulus	GPa		4.57			4.67	4.66	4.66
Standard Deviation			0.16			0.07	0.09	0.10
Interlaminar Shear Strength	MPa	138.4	139.1	132.6	134.3	124.3	129.9	133.9
Standard Deviation		2.3	4.1	1.9	1.0	4.11	4.33	3.12
CAI Strength	MPa	185.1	193.2	197.0	199.2	206.7	216.4	218.3
Standard Deviation		5.5	3.1	3.5	5.8	5.5	7.7	8.1
Bearing Strength (Peak)	MPa		759			731	770	1001
Standard Deviation			83.8			96.0	75.6	39.1
Bearing Strength (2% Offset)	MPa		683			655	738	957
Standard Deviation			82.2			111.0	65.4	38.1

Legend: N/A | Same Population* | High* | Low*

*) Stretch Broken versus Continuous at a Confidence Level of 95% (α = 0.05)

Table 9: ETW Mechanical Property Data

ETW Data \ Reinforcement		Contin.	Stretch Broken		
IM7/8552		UDC08	SBT08	SBT08	SBT08
Prepreg Designation		-002	-005	-006	-007
Feed Fiber Designation		Lot A	Lot A	Lot C	Lot B
0° Tensile Strength	MPa	2308	2215	2627 (High)	2529 (High)
Standard Deviation		71	132	83 (High)	85 (High)
0° Tensile Modulus	GPa	158.3	163.5	161.9	160.3
Standard Deviation		4.5	4.9	1.3	2.3
Poisson's Ratio		0.362	0.381	0.375	0.378
Standard Deviation		0.009	0.014	0.026	0.016
Open Hole Tensile Strength	MPa	435	474 (High)	484 (High)	467
Standard Deviation		16.8	13.4 (High)	19.0 (High)	26.2
Open Hole Tensile Modulus	GPa	59.8	61.5	61.3	60.1
Standard Deviation		1.19	0.77	1.66	1.33
0° Compressive Strength	MPa	1356	1364	1439 (High)	1269
Standard Deviation		100	81	76 (High)	58
0° Compressive Modulus	GPa	138.8	141.4	147.7	149.2 (High)
Standard Deviation		6.2	6.2	5.1	4.3 (High)
OH Compressive Strength	MPa	267	278	269	268
Standard Deviation		11.05	8.56	4.69	12.77
OH Compressive Modulus	GPa	57.0	58.4	57.1	55.9
Standard Deviation		1.21	1.56	1.35	2.67
90° Tensile Strength	MPa	29.2	30.8 (High)	35.9 (High)	33.6 (High)
Standard Deviation		0.49	1.07 (High)	0.84 (High)	1.17 (High)
90° Tensile Modulus	GPa	6.6	7.4 (High)	7.2 (High)	7.3 (High)
Standard Deviation		0.05	0.08 (High)	0.10 (High)	0.12 (High)
In-Plane Shear Strength	MPa	50.7	53.8 (High)	53.2 (High)	54.5 (High)
Standard Deviation		0.65	0.55 (High)	1.02 (High)	0.71 (High)
In-Plane Shear Modulus	GPa	3.31	3.39	3.33	3.33
Standard Deviation		0.03	0.06	0.05	0.08
Interlaminar Shear Strength	MPa	75.3	78.2 (High)	72.2 (Low)	74.7
Standard Deviation		1.3	1.6 (High)	1.0 (Low)	1.6
Bearing Strength (Peak)	MPa	829	848	911 (High)	884 (High)
Standard Deviation		32.9	34.5	46.5 (High)	37.3 (High)
Bearing Strength (2% Offset)	MPa	799	811	798	783
Standard Deviation		31.4	39.0	45.1	100.7

Legend: Same Population* (light green); High* (green); Low* (red)

*) Stretch Broken versus Continuous at a Confidence Level of 95% ($\alpha = 0.05$)