DiscoTex®: Highly Formable Carbon Fiber Fabric

Elizabeth K. Goodine
Pepin Associates
15 Log Home Rd
Greenville, ME 04441

ABSTRACT

The aerospace structures community continues to face manufacturing, performance, and weight challenges designing highly curved composite structures. Aligned discontinuous fiber composites afford the design community the freedom to design these types of parts. The challenge of these systems is that there is a general lack of reliable material properties and manufacturing experience for given systems. Pepin Associates, Inc., with funding from the Defense Acquisition Challenge Program, is completing a program that will generate a material specification and material property averages for a particular system in both stretched and un-stretched conditions.

1. INTRODUCTION

Whenever a new way of processing composites is introduced, the structures community is understandably skeptical. Usually the first questions asked are “What are the properties?” and “Is the process controlled, documented, and capable of reproducing reliably consistent material?” All new material systems face a long and expensive road to qualification and acceptance within the structures community. A descriptive analysis of the material and its performance, up to this point, is described below.

1.1 DiscoTex®: Aligned Discontinuous Fibers

DiscoTex® is an aligned, discontinuous composite reinforcement material that allows fabrication of complex composite structures. DiscoTex® fabric is woven from continuous tow that has been cut into discrete, uniform lengths and held together with a continuous water-soluble binder. The resulting tow is referred to as continuous discontinuous tow, or CD tow. Figure 1 illustrates the break-down of a single strand of CD tow. Carbon, glass and ceramic have been used to make CD tow. The Challenge Program evaluated a DiscoTex® fabric system of AS4-GP 3K Carbon pre-pregged with 977-3 Aerospace Grade Resin with glass tracers. The glass tracers are inserted at specific intervals in the warp and fill directions to note the orientation of a given ply under non-destructive evaluation (NDE).

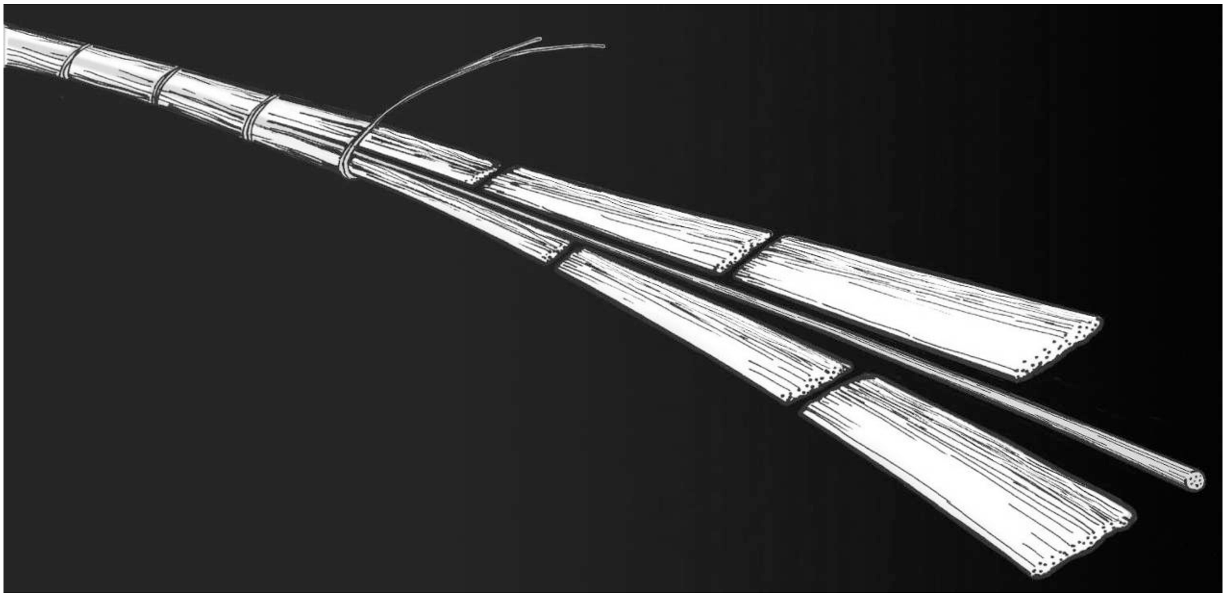

Figure 1: Schematic of CD Tow

The discontinuous nature of the CD-Tow is what allows it to form complex shapes and curvatures. Below are images of a fighter aircraft fuel-dump fairing. This part is currently in production using continuous carbon fabric prepreg. It takes two technicians four hours to lay the prepreg onto the tool. Pepin Associates, Inc. supplied DiscoTex® prepreg to the manufacturer to fabricate a demonstration fairing. One technician was able to lay up nine plies of this prepreg in a flat preform and then form this lay-up to the fairing shape in 30 minutes. By using DiscoTex®, the lay-up time for this part can be significantly reduced.

The formability of DiscoTex® is a welcome progression in the composites industry. In addition to saving fabrication time and labor, it enables designers to extend their parameters and develop new designs that may have been limited by fabrication issues.

1.2 Defense Acquisition Challenge Program Scope

This program consisted of the following tasks:

- Producibility studies
- Binder/resin compatibility
- Mechanical screening tests to evaluate the effects of two levels of residual binder and three levels of stretching.
- Mechanical Testing of three production lots of material
- NDI and photomicrograph evaluations
- Generation of a material specification (BMS)

Fighter Aircraft Fuel Dump Fairing	Side View of Fairing

Figure 2: Nine plies of DiscoTex® formed simultaneously on a demonstration part.

2. EXPERIMENTATION

2.1 Residual Binder

The purpose of the binder is to promote handling of the CD Tow so that it can be woven into fabric. After the CD Tows are woven into DiscoTex® fabric, it is washed to remove the binder and is then dried before being rolled onto cardboard tubes for storage. Approximately 1% by weight of the fabric of binder remains on the fabric. An initial set of test data was collected to investigate the effects of high (4% by weight) and production level (1% by weight) residual binder on the resin system.

2.1.1 Residual Binder Chemical Analysis

The fact that some residual binder remains on the fabric after the wash process necessitates a study of resin and binder chemical compatibility. Two concerns are being addressed; 1) Does the binder react with the resin to interfere with the cure or to produce chemicals that would cause porosity at cure temperatures, and 2) What amount of binder would have to be present to reduce properties? To answer these questions, glass transition temperatures (Tg) and degree of cure (DOC) have been evaluated for samples of resin that contain progressively more binder by weight until changes were observed.

Boeing Technology Phantom Works gathered mechanical property data for the two levels of residual binder. *Various tests including TGA, DSC, GC/MS, and FTIR were performed on the binder alone. Once the chemistry of the binder was established, it was mixed with the resin and it’s glass transition temperature (Tg) and degree of cure (DOC) were tested. The test matrix and results are shown below in Table 1 and Table 2 respectively. Boeing’s resin/binder conclusion states, “Typically, if less energy is released, it would be expected that less material would be cured and the Tg would be lower. In this case, however, reaction energy is lost but without effecting cure until 3% [binder] is reached.” Therefore, the amount of residual binder left on the DiscoTex® fabric as specified in the process control documents has no effect on the cured composite.

*TGA Thermal Gravimetric Analysis: Measures the glass transition temperature (Tg) and mass loss due to heating.
*DSC Differential Scanning Calorimetry: Degree of cure, amount of heat required to cure, and Tg of a heat cure system.
*GC/MS: Separation and identification of compounds in the binder.
*FTIR Fourier Transform Infrared Spectroscopy: Determine if reactions take place between binder and water.

Table 1: Residual binder chemical tests.

Cure	**Glass Transition Temp. (Tg) °C**	**Degree of Cure (DOC) %**
977-3 resin, no binder	Tg = 195	86
977-3 resin, 1% binder	Tg = 196	86
977-3 resin, 2% binder	Tg = 197	86
977-3 resin, 3% binder	Tg = 204	81
Increasing residual binder concentrations doesn’t change the DOC or Tg until 3% concentration is reached.		

2.1.2 Residual Binder Mechanical Tests

The residual binder mechanical testing was done to determine if there was an effect on the mechanical properties at two different levels of binder, production level; 1% by weight, and elevated level; 4% by weight. Table 2 shows the test matrix and Table 3 shows the results. The conclusion was that within the standard deviation, the warp compression specimens tested wet at elevated temperature (ETW) were the only ones that showed a significant difference in mechanical properties. This is also borne out from the chemical testing where the degree of cure was a bit lower for the elevated binder level fabric.

Table 2: Test matrix for residual binder investigation.

Test Matrix: Residual Binder Screening			Number of Specimens at each Binder Level			
Panel	Property	Orientation	*CTD	*RT	*ETD	*ETW
1	Warp Tension	$[0]_8$	3	3	3	0
2	Fill Tension	$[90]_8$	0	3	0	0
3	Warp Compression	$[0]_8$	0	3	3	3
4	In Plane Shear	$[+45,-45]_{2S}$	3	3	3	3
5	Laminate Short Beam Shear	$[45,0,45,0]_S$	3	3	3	3
6	Filled Hole Tension	$[45,0,45,0]_S$	3	3	0	0
7	Open Hole Compression	$[45,0,45,0]_S$	0	3	0	0

*CTD Cold Temperature Dry (-53.88℃)
*RT Room Temperature in the testing lab
*ETD Elevated Temperature Dry (93.33℃)
*ETW Elevated Temperature Wet (93.33℃/100% Relative Humidity)

Table 3 displays the results of the residual binder test results. The portion of the table that does not have values is where the tests were not completed. The values listed are the percentages of the higher residual binder level material properties to the production level material properties. It shows that with the exception of the warp compression properties, there is virtually no difference between the properties.

Table 3: Results of residual binder tests.

Test	CT	RT	ETD	ETW
Warp Tension Strength/Modulus/Strain	.99/1.03	1.03/.98	1.05/1.02	
Fill Tension Strength/Modulus		1.00		
Warp Compression Strength/Modulus/Strain		1.07/1.01	-	.86/.86
In Plane Shear Strength/Modulus	.96/.98	.98/.99	.95/.92	.97/.87
Inter-laminar Shear Strength	.95	1.00	.97	.86
Filled Hole Tension Strength/Modulus	1.0/1.0	1.04/.95	.98	
Open Hole Compression		.95		.82

To further exemplify the effects of residual binder on DiscoTex®, Figure 3 below is typical property behavior for the high and low levels of residual binder. Figure 4 illustrates the results of the warp compression testing.

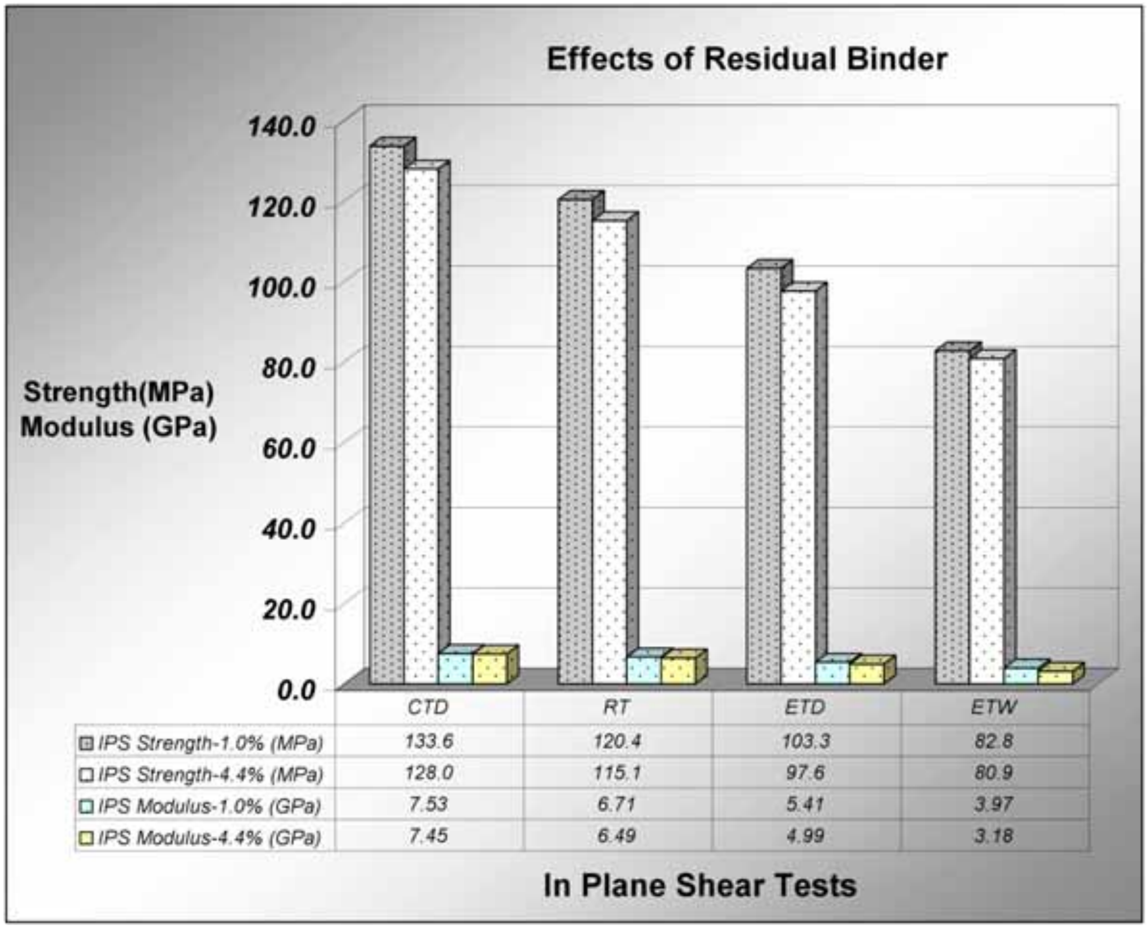

Figure 3: Typical effects of residual binder on DiscoTex® fabric.

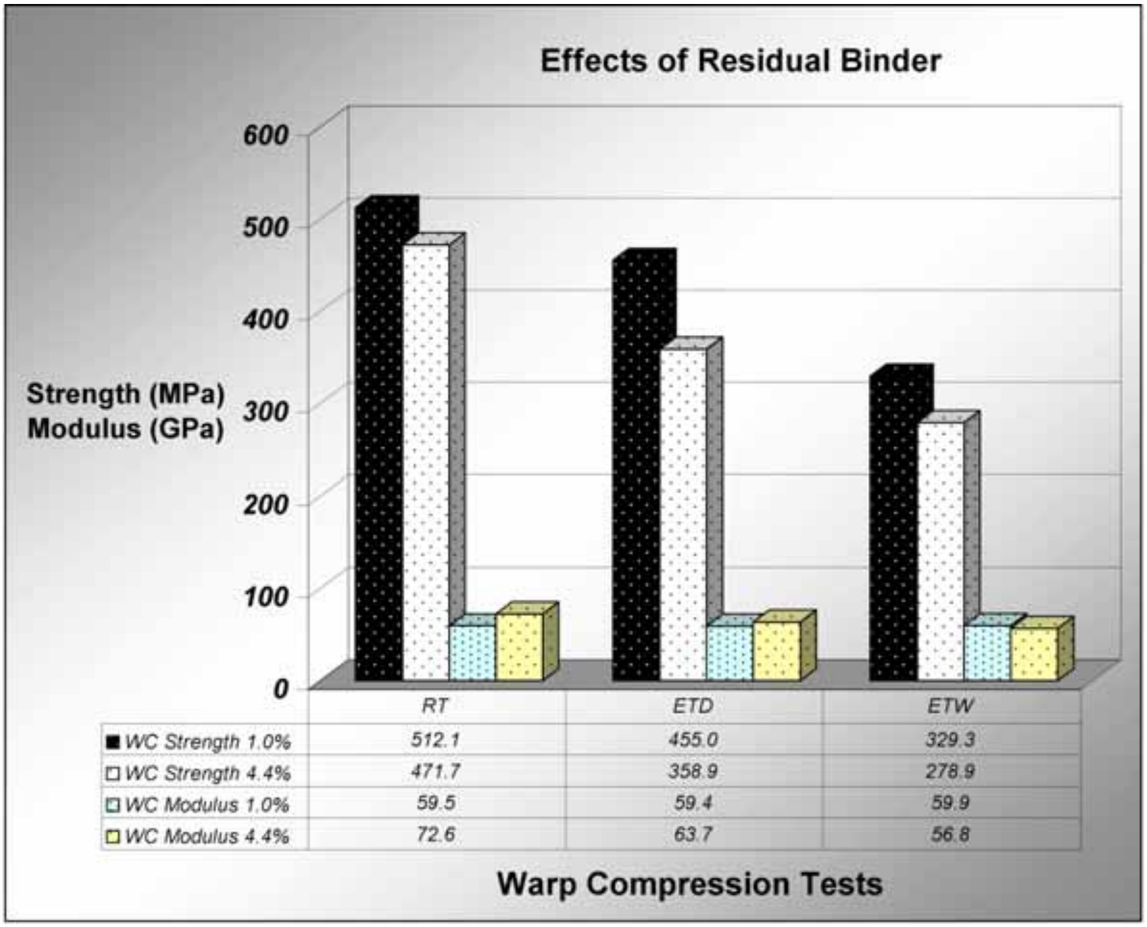

Figure 4: Effect of Residual Binder on Warp Compression Specimens

2.2 Stretching screening

The stretching screening test program validated mechanical properties at various percentages of stretch, 10%, 20%, 30% and determined the effect of stretching on the systems' mechanical behavior. By evaluating these different levels of stretch, we were able to determine what percentage of stretch the material could be qualified to.

2.2.1 Test panel fabrication

The screening test panels were stretched using a tensile test machine. Pepin Associates, Inc. used a uni-axial stretching method, in which the lay-ups were sandwiched between textured rubber sheets, vacuum-bagged, heated, and stretched to the desired percent—once in the warp (0°) direction and once in the (90°) fill direction. These stretched lay-ups were used to fabricate the panels used for this program. This method was ultimately not repeatable enough for the qualification test panels.

2.2.2 Non-Destructive Evaluation

After stretching, the panels were sent to Boeing, St. Louis for ultrasonic evaluation (C-Scan) and to the National Institute for Aviation Research (NIAR) at Wichita State University for photomicrographs. C-Scans show the density of the panel and may reveal any localized stretching occurring in the composite. Photomicrographs reveal a cross section of the laminate, which can be evaluated for porosity, resin pooling, and uniformity. The panel is sectioned and polished to create a photographable surface. Below are examples of each type of non-destructive evaluation.

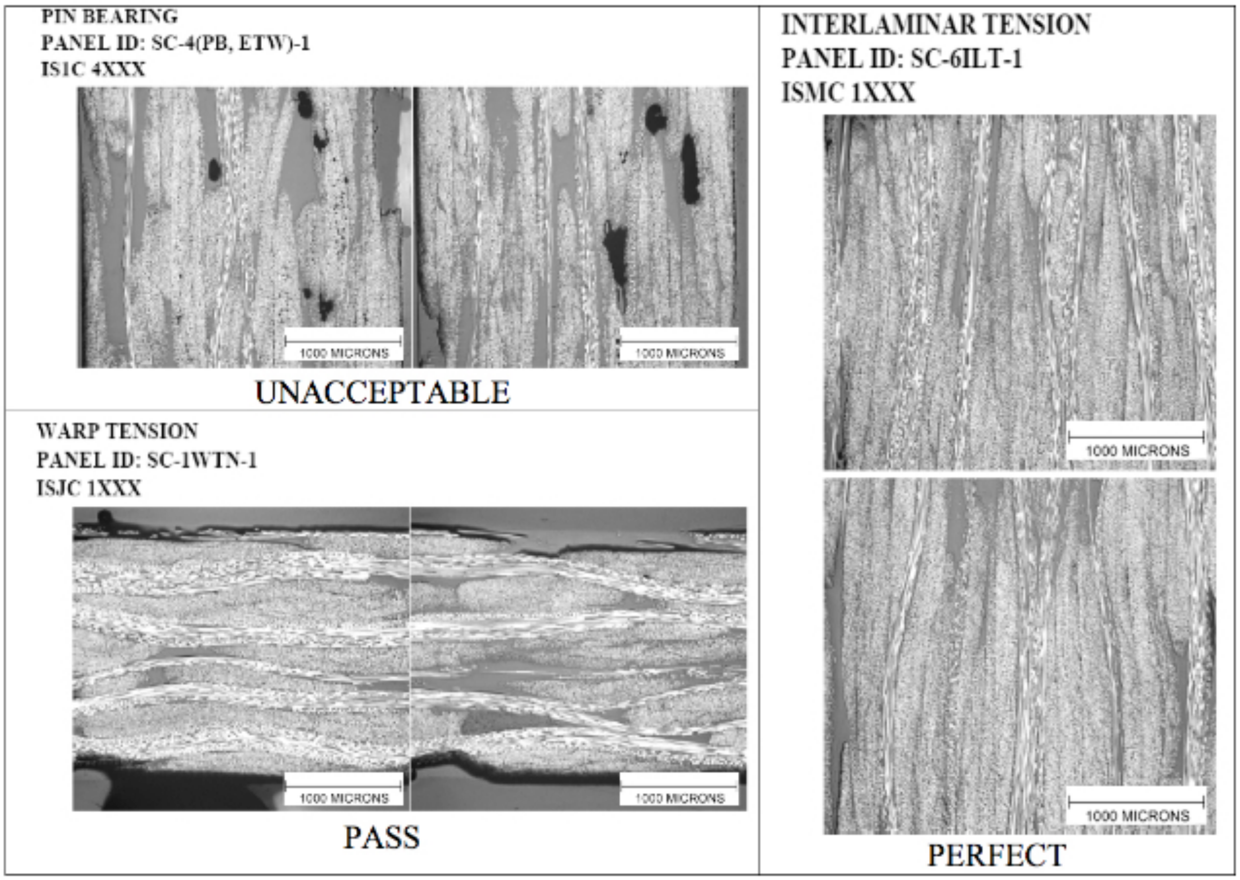

Figure 5: Photomicrographs showing varying examples of Pepin panels.

The photomicrograph above on the top left is one of the panels Pepin Associates, Inc. remade due to the black spots, which are air pockets and the gray identifies some fairly large pools of resin. The bottom left image is showing us surface porosity, which is acceptable, but gives the laminate a rougher surface. The photomicrograph on the right is an example of a perfect laminate.

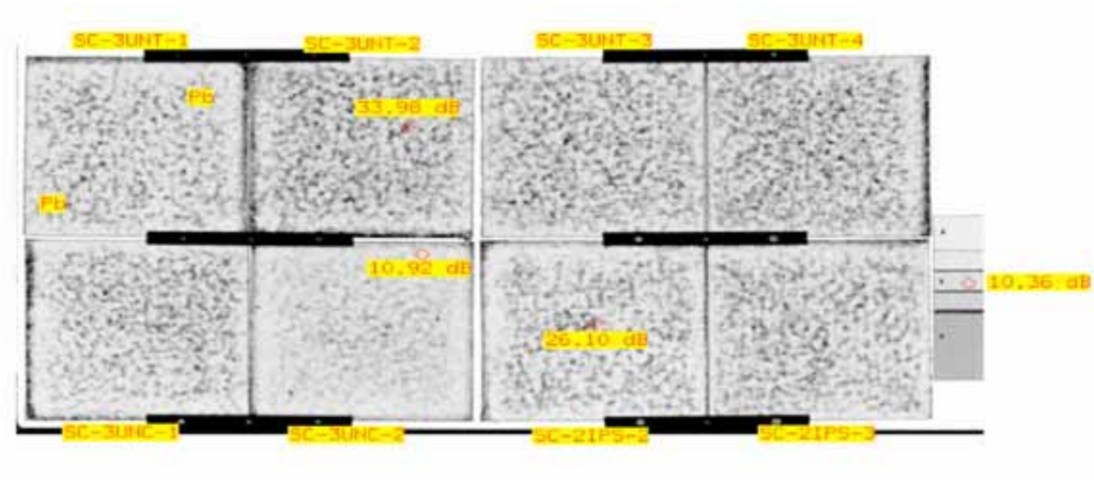

Figure 6: C-scans showing low-density areas within the panel. These panels were remade.

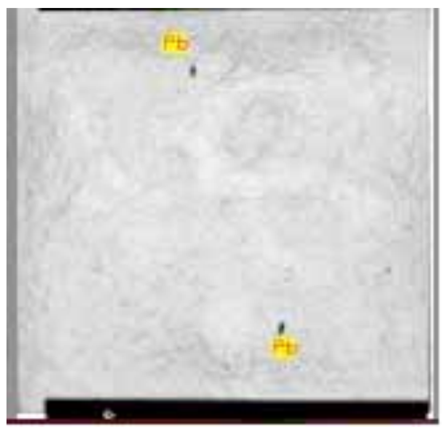

Figure 7: A clear C-scan showing an acceptable panel.

The NDE proved most valuable in the screening lots of DiscoTex® panels. The single panel shown above is an example of an acceptable panel; it has clear, consistent coloring, while the 8 panels shown above that appear to have a marbled texture. This tells us that the panel density is not uniform. Some of the cured panels appeared to be acceptable but were, in fact, locally stretched in many areas. When one area of a composite stretches more than the others, the thickness is not uniform throughout. One of the stretching screening lots was repeated due to local stretching discovered by C-scan.

2.2.3 Mechanical Testing

The stretching screening test matrix examined three specimens at room temperature (RT) for each property and each level of stretch. Listed below are the specific mechanical property tests. The National Institute of Aviation Research (NIAR) Laboratory performed all mechanical tests and initial data reduction.

Table 3: Screening test matrix to determine which level of stretch would be selected for qualification.

Test Matrix: Stretching Screening				**Number of Specimens**		
Panel	Property	Orientation	Test Temp.	10%	20%	30%
1	Warp Tension	$[0]_8$	RT	3	3	3
2	Fill Tension	$[90]_8$	RT	3	3	3
3	Warp Compression	$[0]_8$	RT	3	3	3
4	In Plane Shear	$[+45,-45]_{2S}$	RT	3	3	3
5	Laminate Short Beam Shear	$[45,0,45,0]_S$	RT	3	3	3
6	Filled Hole Tension	$[45,0,45,0]_S$	RT	3	3	3
7	Open Hole Compression	$[45,0,45,0]_S$	RT	3	3	3

2.3 Stretching Screening Mechanical Tests

Test results of the stretching screening lot showed consistent mechanical property data in stretched DiscoTex® above 30% and a significant decrease in mechanical properties at 40%. The 40% stretched panels were visually unacceptable and unrepeatable. Therefore, the qualification portion of the program compared un-stretched DiscoTex® to DiscoTex® that had been stretched 30%.

2.4 Qualification

2.4.1 Panel Fabrication

Pepin Associates, Inc. used patented CD-Tow machines to make enough CD-Tow for 3 lots of carbon DiscoTex® fabric. This fabric is a 6 warp x 6 pick per centimeter, 5 harness satin woven on a Dornier Rapier loom on premises. Each lot was sized to support the creation of both un-stretched and stretched test panels. CYTEC prepregged each fabric lot with 977-3 resin. Pepin Associates, Inc. then laid up un-stretched and stretched panels as required to perform the qualification test matrix.

Figure 8: Carbon DiscoTex® fabric with discontinuous glass tracers rolling off the loom at Pepin Associates, Inc.

The stretching of the qualification panels needed to be reliable and repeatable. After several trials Pepin Associates, Inc. developed a unique stretching fixture for this application. This fixture can be described as a double-diaphragm stretching chamber, which biaxially stretches two single plies of prepreg to the desired 30 percent; one on each side of the chamber. The plies are encapsulated in a vacuum bag on either side of the chamber, heated and stretched. The vacuum bag is transparent which allows the technician to measure a grid on the prepreg to precisely see when the panel has reached 30 percent. Once 30 percent is reached the evacuation of the chamber is stopped and the plies are cooled in the stretched form. Once cool, the plies are removed, trimmed to size, and ready to be laid up into test panels.

As described in the test matrix, 28 panels of various lay-ups were created for each mechanical property database.

Figure 9: One ply of DiscoTex® prepreg reaches 30% stretch in stretching chamber.

Pepin Associates, Inc. created an approved method for panel fabrication. Test panels are 33.02 cm. x 33.02 cm. in size and are various thicknesses and lay-ups according to the requirements of the test matrix. To fabricate a panel, plies were laid up according to the design lay-up for a particular set of specimens. The prepreg panels were then placed on flat aluminum tooling plates, vacuum bagged and autoclave cured. The lay-up of stretched and un-stretched prepreg plies was done in the same fashion. Ultimately, 304 plies of prepreg per lot were stretched and laid up during this program. Once the panels are cured, they were demolded and sent to Boeing for NDE. Panel fabrication steps are shown in Figure 10.

Cutting prepreg for panels. Lay-up ready for vacuum bag. Panels ready for autoclave.

Figure 10: Panel fabrication and lay-up at Pepin Associates, Inc. laboratory.

2.5 Qualification Mechanical Tests

The qualification test matrix was established by Boeing and is shown in Table 4 below. Three different lots of material were fabricated. Within each lot, a set of un-stretched panels and a set of stretched panels were tested using the qualification test matrix. Twenty-eight panels were required for each of the six data sets. The National Institute of Aviation Research (NIAR) Laboratory performed all mechanical tests and initial data reduction.

Table 4: Qualification Test Matrix

Qualification Test Matrix			Number of Coupons			
Property	**Test Method**	**Lay-up**	**CTD**	**RT**	**ETD**	**ETW**
Warp Tension	ASTM D 3039	$[0]_8$	6	6	6	0
Fill Tension	ASTM D 3039	$[90]_8$	6	6	6	0
Warp Compression	SACMA SRM1	$[0]_8$	0	6	6	6
Fill Compression	SACMA SRM1	$[90]_8$	0	6	6	6
In-Plane Shear	ASTM D 3518	$[\pm45]_{2S}$	6	6	6	6
Unnotched Tension	ASTM D 3039	$[45,0,-45,90]_S$	6	6	6	0
Unnotched Compression	ASTM D 6641	$[45,0,-45,90]_S$	0	6	6	6
Laminate ILS	ASTM D 2344	$[45,0,-45,90]_S$	6	6	6	6
Open Hole Tension	ASTM D 5766	$[45,0,-45,90]_S$	6	6	0	6
Filled Hole Tension	ASTM D 6742	U* $[45,0,-45,90,45,0]_S$ S* $[45,0,-45,90,45,0,-45,90]_S$	6	6	0	0
Open Hole Compression	ASTM D 6484	$[45,0,-45,90]_S$	0	6	0	6
Filled Hole Compression	ASTM D 6484	U* $[45,0,-45,90,45,0]_S$ S* $[45,0,-45,90,45,0,-45,90]_S$	0	6	0	6
Pin Bearing	WSU Method (Same as 5215 Qualification)	$[45,0,-45,90,45,0]_S$	6	6	6	6
Interlaminar Tension	ASTM D 6415	U* $[45,0,-45,90,45,0]_S$ S* $[45,0,-45,90,45,0,-45,90]_S$	0	6	6	6
Compression Strength after Impact	SACMA SRM 2	$[45,0,-45,90,45,0]_S$	0	6	0	0
Interlaminar Fracture Toughness	BSS 7273	$[0]_{20}$ Warp/Fill	0	6	0	0
Interlaminar Fracture Toughness	BMS 8-276J	$[0]_{20}$ Warp/Fill	0	6	0	0

*U - Un-stretched Lay-up
*S - Stretched lay-up includes extra plies to achieve equivalent cured laminate thickness as cured un-stretched laminate.

3. RESULTS

The Challenge Program provided Pepin Associates, Inc. with the resources to transition the DiscoTex® aligned, discontinuous composite reinforcement material to a commercially viable formable composite alternative. The Boeing Company has approved DiscoTex® for a Boeing Material Specification which means that this product can be used in the fabrication of Boeing products and components.

The Challenge program also resulted in an extensive set of material properties and forming capabilities, which can be used by designers in developing new designs with complex shapes and curvatures.

Results from the mechanical tests showed an expected knockdown in matrix-dominated properties such as compression and tension, but unexpectedly showed data comparable to similar continuous systems in pin bearing, inter-laminar shear, inter-laminar tension, and in-plane shear strengths.

Although the test results are not yet complete, the preliminary mechanical data trends toward very little knockdown between un-stretched and stretched DiscoTex®, which is certainly welcome news for designers and fabricators of complex parts. Due to the direct comparison of un-stretched DiscoTex® to DiscoTex® that has been stretched 30%, an engineer or a designer can consider both sets of data when designing a new component.

4. CONCLUSIONS

Based on the extensive testing and process development gained under the Challenge Program, Pepin Associate's aligned discontinuous composite reinforcement, DiscoTex®, is now part of Boeing's Material Specification Database. It is clear that the production level of residual binder has no effect on the mechanical and chemical properties of this system and that composites containing stretched DiscoTex® are a substantial alternative to traditional continuous composite reinforcement materials. The material can be formed as a wet lay-up, prepreg or VARTM infused preform. Manufacturing engineers and technicians will select the most appropriate method for a specific application. Lastly, DiscoTex® is not Carbon specific—it can be made from glass, quartz, ceramic, or even a hybrid of these materials.

5. ACKNOWLEDGEMENTS

Pepin Associates, Inc. would like to thank the Air Force Research Laboratory and the Defense Acquisition Challenge Program for their support of this program. We would also like to acknowledge the contribution of Boeing, St. Louis for drafting the Boeing Material Specification for DiscoTex® prepreg and the National Institute for Aviation Research for performing all mechanical tests and initial data reduction.

6. REFERENCES

1. Moody, A. E., Neal, A., Engelbart, R., Chute, A., Townsley, J. *Proceedings of the 52nd International SAMPE Technical Conference*, 2007

7. APPENDIX 1 – DATA SUMMARY TABLES:

Mechanical properties of AS4 discontinuous carbon fabric prepregged with 977-3 resin.

UNSTRETCHED

Property	Test Condition	Average
Warp Tensile Strength (MPa)	CT	550.56
	RT	572.83
	ET	599.04
	ETW	
Warp Tensile Modulus (GPa)	CT	65.03
	RT	64.86
	ET	64.79
	ETW	
Fill Tensile Strength (MPa)	CT	527.32
	RT	548.35
	ET	573.55
	ETW	
Fill Tensile Modulus (GPa)	CT	62.84
	RT	62.50
	ET	61.95
	ETW	
Warp Compression Strength (MPa)	CT	
	RT	633.12
	ET	549.19
	ETW	437.49
Warp Compression Modulus (GPa)	CT	
	RT	61.60
	ET	62.18
	ETW	61.74
Fill Compression Strength (MPa)	CT	
	RT	610.53
	ET	529.48
	ETW	445.42
Fill Compression Modulus (GPa)	CT	
	RT	58.21
	ET	59.72
	ETW	59.82
In-Plane Shear Strength (MPa)	CT	137.18
	RT	124.95
	ET	107.11
	ETW	88.76
In-Plane Shear Modulus (GPa)	CT	7.14
	RT	6.05
	ET	5.37
	ETW	4.49

STRETCHED

Property	Test Condition	Average
Warp Tensile Strength (MPa)	CT	497.05
	RT	535.37
	ET	540.37
	ETW	
Warp Tensile Modulus (GPa)	CT	63.68
	RT	63.23
	ET	62.62
	ETW	
Fill Tensile Strength (MPa)	CT	473.04
	RT	514.27
	ET	527.42
	ETW	
Fill Tensile Modulus (GPa)	CT	61.34
	RT	60.67
	ET	61.24
	ETW	
Warp Compression Strength (MPa)	CT	
	RT	583.11
	ET	478.85
	ETW	
Warp Compression Modulus (GPa)	CT	
	RT	60.65
	ET	67.38
	ETW	
Fill Compression Strength (MPa)	CT	
	RT	565.17
	ET	469.62
	ETW	
Fill Compression Modulus (GPa)	CT	
	RT	55.69
	ET	63.95
	ETW	
In-Plane Shear Strength (MPa)	CT	138.80
	RT	127.22
	ET	108.55
	ETW	96.77
In-Plane Shear Modulus (GPa)	CT	7.35
	RT	6.21
	ET	5.34
	ETW	5.22

UNSTRETCHED

Property	Test Condition	Average
Unnotched Tensile Strength (MPa)	CT	437.75
	RT	453.36
	ET	454.53
	ETW	
Unnotched Tensile Modulus (GPa)	CT	47.59
	RT	46.47
	ET	45.81
	ETW	
Unnotched Compression Strength (MPa)	CT	
	RT	466.27
	ET	409.25
	ETW	342.01
Unnotched Compression Modulus (GPa)	CT	
	RT	43.40
	ET	42.82
	ETW	44.51
Laminate ILS Properties Strength (MPa)	CT	77.22
	RT	68.39
	ET	60.41
	ETW	49.17
Open Hole Tension Strength (MPa)	CT	296.26
	RT	315.07
	ET	
	ETW	316.52
Open Hole Tension Modulus (GPa)	CT	45.98
	RT	46.08
	ET	
	ETW	43.79
Filled Hole Tensile Strength (MPa)	CT	286.31
	RT	304.85
	ET	
	ETW	
Filled Hole Tensile Modulus (GPa)	CT	45.64
	RT	45.60
	ET	
	ETW	
Open Hole Compression Strength (MPa)	CT	
	RT	294.63
	ET	
	ETW	228.50
Open Hole Compression Modulus (GPa)	CT	
	RT	45.67
	ET	
	ETW	46.13

STRETCHED

Property	Test Condition	Average
Unnotched Tensile Strength (MPa)	CT	401.91
	RT	415.58
	ET	421.80
	ETW	
Unnotched Tensile Modulus (GPa)	CT	47.03
	RT	45.40
	ET	44.81
	ETW	
Unnotched Compression Strength (MPa)	CT	
	RT	414.59
	ET	350.42
	ETW	
Unnotched Compression Modulus (GPa)	CT	
	RT	44.30
	ET	44.66
	ETW	
Laminate ILS Properties Strength (MPa)	CT	78.62
	RT	67.71
	ET	61.13
	ETW	
Open Hole Tension Strength (MPa)	CT	273.02
	RT	289.75
	ET	
	ETW	
Open Hole Tension Modulus (GPa)	CT	43.82
	RT	44.01
	ET	
	ETW	
Filled Hole Tensile Strength (MPa)	CT	272.61
	RT	290.33
	ET	
	ETW	
Filled Hole Tensile Modulus (GPa)	CT	44.44
	RT	43.54
	ET	
	ETW	
Open Hole Compression Strength (MPa)	CT	
	RT	279.01
	ET	
	ETW	
Open Hole Compression Modulus (GPa)	CT	
	RT	41.14
	ET	
	ETW	

UNSTRETCHED

Property	Test Condition	Average
Filled Hole Compression Strength (MPa)	CT	
	RT	414.74
	ET	
	ETW	317.45
Filled Hole Compression Modulus (GPa)	CT	
	RT	42.67
	ET	
	ETW	42.94
Pin Bearing Properties Strength (MPa)	CT	905.71
	RT	833.71
	ET	788.59
	ETW	763.97
Interlaminar Tension Strength (MPa)	CT	
	RT	45.18
	ET	
	ETW	
Compression Strength afte Impact (MPa)	CT	
	RT	217.14
	ET	
	ETW	
Compression After Impact Modulus (GPa)	CT	
	RT	44.36
	ET	
	ETW	
Fracture Toughness - GIC (MPa)	CT	
	RT	12.06
	ET	
	ETW	
Fracture Toughness - GIC (MPa)	CT	
	RT	13.62
	ET	
	ETW	
Fracture Toughness - GIIC (MPa)	CT	
	RT	95.15
	ET	
	ETW	
Fracture Toughness - GIIC (MPa)	CT	
	RT	94.54
	ET	
	ETW	

STRETCHED

Property	Test Condition	Average
Filled Hole Compression Strength (MPa)	CT	
	RT	386.33
	ET	
	ETW	287.53
Filled Hole Compression Modulus (GPa)	CT	
	RT	41.37
	ET	
	ETW	42.47
Pin Bearing Properties Strength (MPa)	CT	970.37
	RT	852.42
	ET	818.55
	ETW	766.32
Interlaminar Tension Strength (MPa)	CT	
	RT	39.78
	ET	
	ETW	
Compression Strength afte Impact (MPa)	CT	
	RT	185.47
	ET	
	ETW	
Compression After Impact Modulus (GPa)	CT	
	RT	44.00
	ET	
	ETW	
Fracture Toughness - GIC (MPa)	CT	
	RT	10.36
	ET	
	ETW	
Fracture Toughness - GIC (MPa)	CT	
	RT	10.53
	ET	
	ETW	
Fracture Toughness - GIIC (MPa)	CT	
	RT	74.72
	ET	
	ETW	
Fracture Toughness - GIIC (MPa)	CT	
	RT	68.02
	ET	
	ETW	

Data shown represent averages of three lots. Blue shaded fields indicate an average based on two lo
the third lot testing is still in progress.