Mechanical Property Translation in Oriented, Discontinuous Carbon Fiber Composites

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ABSTRACT

Oriented, discontinuous fiber composites offer the potential for cost effective, lightweight aerospace structures if the orientation of the discontinuous fibers provides adequate translation of mechanical properties when compared to traditional continuous fiber composites. A composite preform technology called the Programmable Powdered Preform Process for Aerospace (P-4A) was investigated under a United States Air Force research program to produce carbon fiber preforms using oriented, discontinuous fibers. At the start of the effort, historical data was collected to understand the mechanical property capabilities of oriented, discontinuous composites. Carbon and glass preforms were fabricated using the P-4A process, infused with resin and tested for strength and stiffness. The results were compared to continuous fiber composite properties to evaluate mechanical property translation. The oriented discontinuous fiber composites have high stiffness retentions that exceed 90%. Lamina strength properties are lower than continuous fiber strengths. However, the laminate strength properties are comparable to continuous fiber laminate strengths. Since laminate strengths and stiffnesses are typically the critical design properties, P-4A oriented discontinuous fiber composites are viable candidates for most aerospace structures.

KEYWORDS: Fibers, Discontinuous, Mechanical Properties

1. 1. INTRODUCTION

Discontinuous fiber composites offer processing and cost advantages over continuous fiber composites. This form of composite is used in much of the fiber reinforced composite market where the higher performance of continuous fiber composites is not needed or is not cost effective. Discontinuous fiber composites have traditionally been used as reinforcements in low cost manufacturing processes such as injection molding and compression molding. Most of the discontinuous fiber orientations are random; resulting in lower performance composites when compared to the highly oriented, continuous fiber composites. In the random material, longer fibers improve the performance of the material, but manufacturing processes are more costly. The continuous fiber composites provide excellent performance, but the attendant higher manufacturing costs have often limited the applications to high end products such as aerospace components and sporting goods. There has been much development over the past fifteen years to attain an optimal combination of the forms: oriented discontinuous fiber composite. An oriented discontinuous fiber composite material would provide the higher performance of continuous fiber composites with the cost effective processing of random, discontinuous fiber composites. In addition, more complex structural shapes that cannot be fabricated using continuous fibers could be produced while retaining higher performance.

To obtain this cost effective combination of processing and performance, one of the key objectives is to obtain mechanical properties that approach those of continuous fiber composites. As the discontinuous fiber processes are developed, the mechanical property translation must be monitored. The property translation provides one metric of the success of an oriented discontinuous composite. It also provides information for guiding the development of the orientation process.

2. MATERIALS AND PROCESSES

Higher performance in discontinuous fiber reinforced composites depends on fiber alignment, uniform distribution, fiber length and good adhesion between the fibers and the matrix (Reference 1). A variety of methods have been developed to align discontinuous fibers. These include liquid dispersion, centrifugal, electrical, magnetic and stretching continuous fibers. All of these processes have yet to provide commercial materials due to disadvantages and costs associated with additional material fabrication steps and/or lower than desired performance.

In the continuing effort to develop cost effective composite technology, Owens Corning developed a highly automated process to spray up discontinuous fiber preforms (Reference 2). This Programmable Powdered Preform Process (P4) uses a computer-controlled chopper head mounted on a robotic arm to chop glass roving and deposit the fibers on a shaped screen to create a preform. The preform can then be transferred to a liquid molding tool for resin infusion to yield a finished composite part. The process offers cost effective production of discontinuous composites because the material creation and preform fabrication take place simultaneously; whereas other discontinuous fiber composites generally require the creation of the material followed by a separate forming step. The potential of this process led the Automotive Composites Consortium to make the technology a focal project of their composite development efforts (References 3, 4).

One of the interesting capabilities of the P4 process is the ability to orient the discontinuous fibers as they are sprayed onto the screen. This provides for efficient structural laminates since the fibers are oriented and enables higher fiber volumes to be attained. Random fibers cannot be tightly packed together so there is an upper limit on fiber volume of 35 to 40%. The oriented fiber composites can obtain the 55 to 60% fiber volumes typically found in high performance continuous fiber composites. The process potential led the US Air Force Research Laboratory to initiate a program to demonstrate the feasibility of adapting the P4 technology for the cost effective fabrication of aerospace composite structures. The two major challenges in the P4-A (i.e. P4 for Aerospace) program are to convert the process from glass fibers to carbon and to obtain high mechanical property performance with the oriented discontinuous fibers.

The mechanical property translation of oriented discontinuous fibers have been generally quoted as being able to attain 90% of the stiffness and 50% of the strength of continuous fiber composites (Reference 1). However, to better understand the mechanical property translation of discontinuous fiber preforms and laminates, data from previous industry efforts was collected. An extensive literature search of the P-4A team member libraries and databases was conducted to find chopped fiber data. From the potential data sources, over 50 publications and data packages were thoroughly reviewed and relevant mechanical properties were excerpted. The open literature papers were also compared with team member data to eliminate overlap. A historical database was developed using an Excel® spreadsheet and standard format to enable a quick and intuitive review of the collected data. Not all data sources provided every mechanical property; most provided three or four. Whenever reported, critical data pedigree such as fiber and resin type, length of fiber, fiber volume, degree of fiber alignment, orientation process, infusion/cure process, test coupon size, and composite lay-up were included in the database. In addition, a premium was placed on those data sources reporting both continuous and discontinuous properties, so direct comparisons could be made and preliminary design-to properties estimated.

Some of the first oriented discontinuous composite investigations were performed using glass (Reference 5). These showed strength retentions of 25 to 42% and stiffness retentions of 81 to 86%. Oriented discontinuous carbon fiber data reported strength retentions of 37 to 90% and stiffness retentions of 77 to 94% (References 6, 7, 8, 9). Based on the papers and data, average mechanical property translations were developed for the following properties: tension strength and modulus, compression strength and modulus, flexural strength and modulus, and interlaminar shear. A graphical summary of the historical mechanical property translations is shown in Figure 1. The average strength retentions vary from 63% to 92%, depending on failure mode. The average stiffness retentions vary from 77% to 94%. This database reports translations for chopped fiber forms. It does not include data for fiber forms that are not chopped. An example of an excluded form is the DuPont LDF® (Long Discontinuous Fiber) product which, again, is not a chopped fiber, but a stretch-broken fiber (Reference 10). The fiber lengths are much longer than those of chopped fibers and its strength retentions are greater than chopped fiber strength retentions.

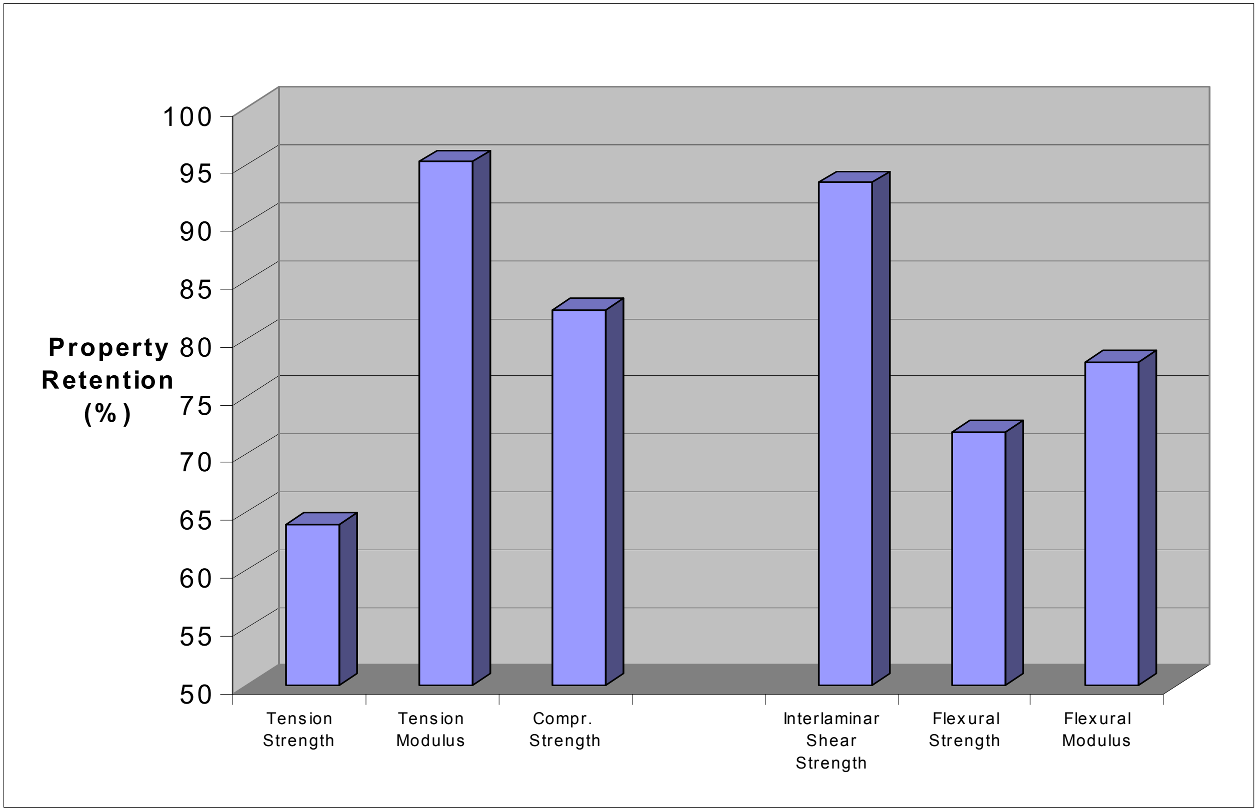

Figure 1. Mechanical Property Translations from the Historical Database

3. EXPERIMENTAL

Mechanical property testing was preformed for a sequence of preforms. This sequence followed the development of the P-4A process described in Reference 11. A key part of the development was the evolution of fiber orientation devices for the P-4A machine. The first preforms started with glass since this was the material used with the parent P4 process, however most of the subsequent preforms were carbon. The mechanical property data was an important discriminator in evaluating the orientation devices and many other P-4A processing parameters.

3.1 Mechanical Property Testing of Oriented Glass Preforms. Since the basis for development of this oriented, discontinous carbon fiber process was the P4 glass process, the first preforms were oriented discontinuous glass preforms. These were fabricated on the Owens Corning P4 machine in Battice, Belgium (Reference 2). Unidirectional (0°) preforms of chopped E-glass were created. To establish the mechanical property translation, stitched continuous unidirectional E-glass from Brunswick Technologies was laid up by hand to be the baseline preforms. Three program team members were each given an oriented discontinuous preform and a continuous preform to infuse with resin. One set was infused with Shell's Epon® 862 epoxy using the matched tool resin transfer molding process (RTM). The second set was infused with Cytec's Cycom® 823 epoxy using one-side tooling and the vacuum assisted resin transfer molding process (VARTM).

The third set was infused with Shell's 2704 epoxy using the VARTM process. Straight-sided tension specimens were machined in 0° direction from each of the six cured panels. The specimens were tested to failure per ASTM D3039 under room temperature ambient conditions.

3.2 Mechanical Property Testing of Simulated P-4A Preforms. Prior to delivery and installation of the prototype P-4A preform machine, discontinuous carbon preforms were fabricated by alternate methods to simulate P-4A carbon preforms. The simulated panels were to assist in understanding some of the parameters involved in oriented discontinuous carbon composites. Various simulation methods were used. A pre-prototype chopper head and orientation device was set up at the University of Dayton Research Institute (UDRI). At Northrop Grumman, prepreg tows were cut into chopped fiber length and laid up to simulate P-4A panels. An orientation device consisting of a chopping wheel and belt delivery head was also evaluated at Northrop Grumman as an alternate method to the P-4A air delivery device. Some continuous carbon panels using prepreg were fabricated as baseline panels.

Preforms were fabricated using AS4, G30-500, G30-700 and T700SC carbon fibers. These are all standard modulus carbon fibers. Nominal orientation was 0° unidirectional. The preforms were infused with various epoxy resins using both the RTM and VARTM infusion processes. Straight-sided tension specimens were machined in 0° direction from the panels. The specimens were tested to failure per ASTM D3039 under room temperature ambient conditions.

3.3 Mechanical Property Testing of Interim P-4A Preforms. After the P-4A machine began operation, there was an evolution of orientation devices which mounted on the chopper head. This process development effort was aimed at providing an optimum combination of manufacturing feasibility, preform quality and mechanical performance. Three interim orientation devices were used: first ramp & roller, large ramp & roller, and an "elephant trunk". To evaluate the effect of fiber length on property translation, fiber lengths of 50.8, 76.2, 101.6 and 127 mm were evaluated.

All of these preforms were fabricated using G30-500 3K carbon fibers and PT500® binder for consolidation. Small fiber tow size was used to maximize mechanical property translation for this process which is discontinuous on the tow level, not the filament level. The effect of tow size on tension strength was evaluated by isolating the pertinent results from the prototype tests as discussed in Reference 12. Most of the panels were infused with Epon 862 epoxy and curing agent W using RTM infusion. A few panels were infused with Cycom 823 and Ciba 8610 epoxies using the VARTM process. Both unidirectional (0°) and quasi-isotropic laminates were fabricated. Unidirectional tension specimens were machined from the panels and tested per ASTM D3039. Unnotched tension specimens were machined from the quasi-isotropic laminates and tested per ASTM D3039. Open hole tension specimens were machined from the quasi-isotropic laminates and tested per CMC Method P6-5. All specimens were statically test to failure under room temperature ambient conditions.

3.4 Mechanical Property Testing of First Generation P-4A Preforms. After evaluating the processing capabilities of the different orientation devices, a new orientation device was developed to provide the best current combination of manufacturing operation and preform quality. Recognizing that additional improvements would need to be made in the future before this emerging technology was production ready, the current configuration was called the "first generation" P-4A machine. A mechanical and physical property test matrix to characterize the P-4A preforms was developed. A summary of the test properties and parameters is shown in Table 1. The test matrix evaluated oriented P-4A preforms, random P-4A preforms and a few continuous fiber baseline panels. The tests included lamina and laminate tests. All laminates were quasi-isotropic layups. Most tests were at room temperature ambient conditions with a few checks at –65°F dry and 220°F wet environments. The test data is considered 'first generation' properties that provides a performance measure for assessing P-4A feasibility.

Table 1. Test Plan for First Generation P-4A Carbon Fiber Preforms

Mechanical Property	Layup	Test Environment		
		-54°C (–65°F) ambient	Room Temp ambient	104°C (220°F) wet
Lamina				
0° Tension	0°	x	x	
0° Compression Modulus	0°		x	x
0° Compression Strength	0°/90°		x	
In-Plane Shear (±45° Tension)	0°/90°		x	x
Laminate				
Unnotched Tension	Quasi		x	
	Random		x	
Unnotched Compression	Quasi		x	
Open Hole Tension	Quasi	x	x	x
	Random		x	
Open Hole Compression	Quasi		x	x
Bearing	Quasi		x	x
Compression After Impact	Quasi		x	

All P-4A laminates were discontinuous G30-500 (3K) fiber preforms infused with Epon 862 epoxy using resin transfer molding (RTM). The continuous fiber panels were fabricated using dry wound continuous G30-500-3K fiber preforms that were infused with Epon 862 epoxy. These provided a baseline for direct comparison of properties. Each preform panel was ultrasonically inspected and physical properties (e.g. fiber volume, resin content) were measured for the panels. The most recent versions of ASTM, SACMA and CMC test methods were used for the test procedures.

4. RESULTS AND DISCUSSION

Review of the data provided information on the strength and stiffness retentions that could be expected from the P-4A process and the effect of some process parameters on stiffness and strength. The data results from the preforms also provided inputs for orientation device development.

4.1 Mechanical Property Translation in Oriented Glass Preforms. The oriented discontinuous glass preforms results were compared to the continuous glass test results for each resin case to determine the 0° Tension property retentions shown in Table 2. All data was normalized to 55% fiber volume prior to comparisons and retention calculations. As should be the case, the various combinations of resins and infusion processes yield very similar 0° Tension properties for the baseline stitched continuous unidirectional glass. The oriented, discontinuous Battice P4 preform strengths were consistent for each resin combination, but there was more scatter in the stiffnesses. As discussed previously, the historical glass data showed strength retentions of 25 to 42% and stiffness retentions of 81 to 86%.

Table 2. 0° Tension Property Retention for Oriented, Discontinous Glass Preforms

Resin/Process	Strength Retention (%)	Stiffness Retention (%)
Epon 862 RTM	46	72
Cycom 823 VARTM	50	79
Epon 2704 VARTM	52	85
Average	49	79

4.2 Mechanical Property Translation in Simulated P-4A Preforms. The simulated P-4A preforms were fabricated using a number of fibers and techniques for simulating the discontinuous preform. Since these preforms were for general trend investigation, only a few continuous fiber baseline panels were fabricated. There was a little baseline data for the G30-700, G30-500 and T700SC fibers. Therefore, 0° Tension properties were taken from supplier data for these fibers: G30-700 and T700SC with F= 335 ksi, E = 20.8 msi; and G30-500 with F= 291 ksi, E = 20.3 msi.

Property retentions for 0° Tension are shown in Table 3. Results are grouped by the orientation device used to create the preforms. The multiple retention values in each category represent the retentions for different fibers. Data was normalized to 55% fiber volume prior to comparisons and retention calculations. All strength retentions were less than 44%. The stiffness translation was similar for the two mechanical chopping devices. The Northrop Grumman (e.g., NG) simulated panels had very good alignment since they were laid up by hand, and consequently had stiffnesses equivalent to continuous fiber stiffness.

Table 3. 0° Tension Property Retention for Simulated P-4A Carbon Preforms

Head type	Strength Retention (%)	Stiffness Retention (%)
UDRI pre-prototype	23, 25, 29, 34, 40	76, 80, 81
NG Simulated panels	29, 43, 44	103, 116, 118
NG Belt head	36	76

The UDRI pre-prototype panels also provided an evaluation of processing parameters. Fiber overlap of 0.75 inch and 1.5 inch (50% overlap on 3 inch fibers) did not make a difference on mechanical properties. Moving the chopper head in a traditional up & back lay down motion was slightly better than a sinewave lay down. An effect of fiber tow size was seen as documented in 12. For G30-500, the 3K fiber tows showed a 37% strength improvement and a 2% stiffness improvement over the 6K fiber tows for 0° Tension.

4.3 Mechanical Property Translation in Interim P-4A Preforms. During development of the P-4A process, there was an evolution of orientation devices which mounted on the chopper head. Three interim orientation devices were used: first ramp & roller, large ramp & roller, and an "elephant trunk". The test results are categorized according to the orientation device. Other pertinent process parameters such as fiber length are also listed. All preforms used G30-500 3K fibers. Where possible, the mechanical properties were compared to continuous fiber baselines. A summary of the 0° Tension property translation is shown in Table 4.

Table 4. 0° Tension Property Retention for Interim P-4A Carbon Preforms

Head type	Strength Retention (%)	Stiffness Retention (%)
First Ramp & Roller	36	74
Large Ramp & Roller 4 inch fiber	50	93
Large Ramp & Roller 5 inch fiber	43	94
Elephant Trunk 2 inch fiber	44	91
Elephant Trunk 3 inch fiber	46	94

The interim test results provided insight into the effects the P-4A process parameters on mechanical properties. The results show a general improvement in strength retention with the interim fiber delivery systems as compared to the first P-4A orientation device and the pre-P-4A prototypes. At best, strength retention for the highly loaded unidirectional tension is 50%. Within the scatter of the data, stiffness retentions are not affected by the process parameters evaluated and remain consistently above 90%.

Since structures are laminates, these properties have a more important effect on design than the 0° Tension strength. The comparison of open hole tension property translations are shown in Table 5. There are some general trends, but all of the retentions are in the same range. Accounting for material and test scatter, as well as the test quantities, the properties are not affected by fiber length or by the interim orientation systems. Some random spray preforms were generated. The random panels theoretically have fibers in all directions and should have similar properties to quasi-isotropic laminates. The random spray is lower cost than oriented spraying. The random preforms that used machine passes in the four quasi directions (0, +45, -45, 90) resulted in better retentions than the back and forth spray pattern. After normalizing to a 55% fiber volume, the random preforms were comparable to the oriented preforms. However, orientation of discontinuous fiber results in higher fiber volumes than random spray due to fiber packing. In actual application, there is an upper limit on the properties of random preforms.

Table 5. Open Hole Tension Property Translation for Interim P-4A Carbon Preforms

Preform Parameters	Strength Retention (%)
Elephant Trunk Oriented quasi layup (2 inch) fiber	69
Elephant Trunk Oriented quasi layup 3 inch fiber	67
Large Ramp & Roller Oriented quasi layup 4 inch fiber	75
Random Back & Forth Spray, 50.8 mm (2 inch) fiber Tested in x-direction	71
Random Back & Forth Spray, 50.8 mm (2 inch) fiber Tested in y-direction	70
Random Quasi Spray, 50.8 mm (2 inch) fiber Tested in x-direction	78
Random Quasi Spray, 50.8 mm (2 inch) fiber Tested in y-direction	82

4.4 Mechanical Property Translation in First Generation P-4A Preforms. The First Generation P-4A properties were generated for the tests shown previously in Table 1. A property retention comparison is shown in Table 6 for some of the properties where exactly comparable baseline continuous data was generated. This baseline data comes from panels using the same fiber, resin and infusion process. Since it is very difficult to obtain exactly comparable data because of the material/processing flexibility of composites, the first generation P-4A properties are also compared against similar continuous fiber carbon composites in Table 7. Similar composites is defined as standard modulus, standard strength carbon fibers in 350°F cured epoxies. The continuous fiber data come from public domain references using the same or similar test methods. Fiber dominated properties were normalized to 55% fiber volume.

Table 6. Property Translation for P-4A First Generation Properties

Property	Strength Retention, %	Stiffness Retention, %
0° Tension	51	98
In-Plane Shear	158	157

Table 7. P-4A First Generation Properties Compared to Properties of Other Continuous Carbon Fiber Materials

Table 7(a) Lamina Property Comparison

Property	Material			
	P-4A First Generation G30-500-3K /Epon 862	G30-500-3K /Epon 862 Continuous Fiber Uni Tape	AS4/3501-6 Continuous Fiber Uni Tape	T300 15k/976 Continuous Fiber Uni Tape
Stiffness				
E11t, MPa (msi)	116.7 (16.92)	118.8 (17.23)	124.1 (18.00)	124.1 (18.00)
E11c, MPa (msi)	94.3 (13.67)		112.5 (16.32)	118.1 (17.14)
G12, MPa (msi)	6.1 (0.88)	3.9 (0.56)	5.4 (0.78)	6.3 (0.91)
Strength				
F11t, GPa (ksi)	1124 (163)	2186 (317)	2841 (267)	1331 (193)
F11c, Gpa (ksi) <4>	1220 (177)		1330 (193)	1186 (172)
F12, GPa (ksi)	110 (16.0)	70 (10.1)	79 (11.5)	77 (11.1)

Table 7(b) Laminate Property Comparison

Property	Material			
	P-4A First Generation G30-500-3K /Epon 862	AS4/PR500 Continuous Fiber 5HS Fabric	AS4/3501-6 Continuous Fiber Uni Tape	T300 3K/977-2 Continuous Fiber 8HS Fabric
Unnotched Tension				
Strength, GPa (ksi)	443 (64.2)		605 (87.8)	
Stiffness, Mpa(msi)	41.8 (6.06)		45.6 (6.62)	
Open Hole Tension				
Strength, Gpa(ksi)	335 (48.6)	316 (45.8)	392 (56.8)	265 (38.4)
Stiffness,MPa(msi)	49.6 (7.19)	45.6 (6.62)		48.1 (6.98)

Open Hole Compression				
Strength GPa (ksi)	272 (39.4)	301 (43.7)		306 (44.4)
Stiffness,Mpa (msi)	41.7 (6.05)	44.4 (6.44)		44.5 (6.45)
Compression After Impact				
Strength, GPa (ksi)	250 (36.3)	263 (38.1)		
References		13	14, 15	16

Notes: 1. All properties are for room temperature, ambient environment.
2. All properties were normalized to 55% fiber volume except In-plane Shear.
3. Laminate data is for quasi-isotropic layups.
4. 0° Compression strength was backed out from 0°/90° data.

4.5 Assessment of P-4A Mechanical Property Translation. Review of the P-4A mechanical properties shows that the stiffness retention target of 90% was attained. The strength retention target of 80% was attained for the notched laminate properties that are design drivers. Strength retention for an ultimate fiber strength property such as 0° Tension was approximately 50%.

Table 8 provides a summary of the 0° Tension property translation for historical data and the various data sets developed in the P-4A program. As seen in this table, the oriented P-4A properties improved as the process development progressed toward the first generation preforms. Given the high load that must be abruptly transferred at the ends of the tows (3000 to 12000 fibers) through resin, discontinuous carbon fiber composites will not approach the lamina tension strength. Additional mechanics of material studies can assist in understanding the most important parameters so the preforming process can possibly be refined to improve the tension strength translation.

Table 8. Summary of Property Retentions for 0° Tension

	Strength Retention, %	Stiffness Retention, %
Historical Glass	34	85
P-4A Oriented Glass	49	79
Historical Carbon	64	95
Simulated P-4A	34	91
Interim P-4A	46	93
First Generation P-4A	51	98

As shown in Tables 6 and 7(a), the in-plane shear properties of the discontinuous composite are much better than continuous composites. Not all of the oriented discontinuous fibers are perfectly aligned at the desired orientation. These “angle ply” fibers increase the shear properties just as continuous fiber angle plies increase the shear properties of a laminate over lamina. As fiber orientation of the process improves, this property gain will drop. However, there will always be some scatter in the alignment of the discontinuous fibers, so P-4A preforms should always give slightly better in-plane shear properties.

As seen in Table 7(b), the P-4A laminate properties compare very favorably with continuous fiber properties. The compression after impact (CAI) strengths were very good. This may be due to some fiber tows not laying down planar during the preforming process. They may be providing some through the thickness reinforcement that damage resistance and damage tolerance. The mechanics of oriented, discontinuous fibers needs to be more fully understood as there are detrimental effects for some properties and beneficial effects for other properties. It is important to reiterate that the properties generated are not design data, rather they are still only preliminary values.

5. CONCLUSIONS

The mechanical property testing conducted during the P-4A program demonstrated that oriented discontinuous carbon fiber composites have sufficient property translation compared to continuous fiber composites to be used for certain erospace structures. The oriented discontinuous fiber composites have high stiffness translation that exceeds 90%. Lamina strength properties are lower than continuous fiber strengths, however the laminate strength properties approach 70 – 80% of continuous fiber laminate strengths. Since laminate strengths and stiffnesses are typically the critical design properties, P-4A oriented discontinuous fiber composites are viable candidates for most aerospace structures. Combining sufficient performance with the substantial cost savings that can be attained with this automated process, P-4A preforms have the potential to be a preferred manufacturing process for many aerospace structures.

There are a number of additional issues that should be addressed in a future process development program. Tradeoffs between oriented and random discontinuous fibers should be considered. Early process evaluation showed similar mechanical properties for random and oriented discontinuous fibers. The process and orientation device available at the end of the program demonstrated a benefit of orientation. Orientation allows increased fiber volumes and higher fiber-dominated properties to be attained. The effects of tow size, fiber length, load transfer parameters, binder, and sizing needs be systematically investigated. Mechanical property testing needs to demonstrate that there is no negative environmental interaction between environment and the discontinuous fiber/resin interface. Uniform density and controlled ply thickness is important for design functionality, structural integrity and assembly. An important advantage of continuous carbon fiber composites is that they are insensitive to fatigue; this needs to be demonstrated for P-4A discontinuous carbon fiber laminates.

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7. BIOGRAPHIES

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