THE EFFECT OF TOWS AND FILAMENT GROUPS ON THE PROPERTIES OF DISCONTINUOUS FIBER COMPOSITES

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ABSTRACT

Traditionally, discontinuous fiber composites have been discontinuous on a filament level. A composite preform technology entitled the Programmable Powder Preform Process for Aerospace (P4-A) produces discontinuous fiber preforms by chopping fiber bundles such as carbon tows and glass rovings. The discontinuous fibers can be random or oriented. The fiber discontinuity at this macro level results in different property translations than found in composites that are discontinuous at the filament level. The effects of tow size were investigated analytically and experimentally. Tow sizes of 1000, 3000, 6000 and 12000 filaments were investigated. The tow size affects the strength translation from continuous fibers to discontinuous fibers, the critical fiber length needed to attain maximum fiber strength, and correct failure mode.

KEYWORDS: Fibers, Discontinuous, Critical Length

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. As shown in Figure 1, the low cost, low performance end of fiber reinforced composites consists of short, milled fibers in resin which can be used with rapid, highly automated manufacturing processes. 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: aligned 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.

Figure 1. Oriented Discontinuous Fiber Composites Potentially Offer a Cost-Effective Combination of Processing and Performance

2. 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. The liquid dispersion methods uniformly distribute discontinuous fibers in liquid suspension. The liquid is drained through a filter to leave a consolidated mat of aligned fibers. The liquid medium is also utilized in the centrifugal alignment methods also make use of a liquid medium. A promising electrical method drops discontinuous fibers through an orientation chamber where electric fields align the fibers in the same direction. The aligned fibers are subsequently deposited onto a moving belt to produce a mat (Reference 2). All of these processes have yet to provide commercial materials due to disadvantages associated with additional material fabrication steps and/or lower than desired performance. A long discontinuous fiber (LDF) product was developed by DuPont (Reference 3) by stretching continuous prepreg such that the highly aligned fibers beneficially broke into randomly distributed discontinuous fibers. On the down side, the LDF material form had to start with more costly prepreg material and had limitations on the structural forms where it could be used. On a commercial basis, aligned discontinuous fiber composites have yet to deliver significant reductions in product fabrication costs.

In the continuing effort to develop cost effective composite technology, Owens Corning developed a highly automated process to spray up discontinuous fiber preforms (Reference 4). 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 5, 6).

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.

Historically, the mechanical properties of oriented discontinuous short fibers in composites have been able to reach 90% of the stiffness and 50% of the strength of continuous fiber composites (Reference 1). The property retention is very dependent on the combinations of alignment, fiber length, fiber/matrix adhesion and fiber packing. Some of the first aligned discontinuous composite investigations were performed with glass using a liquid slurry process in Reference 7. The stiffness retention was 81 to 86% and the strength retention was 25 to 42% of continuous glass fiber composites. Aligned discontinuous carbon fiber data has

been reported with stiffness retention of 90% and strength retentions of 37 to 90% (References 8, 9, 10, 11). The LDF material showed stiffness retention of above 90% and strength retention of 80 to 95%. However, this is not a typical form of aligned discontinuous fiber composite since the starting material is highly aligned, continuous fiber prepreg.

3. 3. EXPERIMENTAL

In support of the P4-A mechanical property development effort, this investigation focused on fiber tow size. A secondary parameter was fiber length since critical length is needed to develop maximum strength retention in discontinuous fiber composites.

The P4-A process uses fiber tows as the starting material form. As the tows go through the chopper head, the tow bundles are chopped by a rotating blade perpendicular to the fiber axis. The length of the chopped fiber bundle can be varied. The fibers in the tows are coated with an epoxy sizing. Sizings are used with many carbon fibers to promote matrix adhesion and protect the fiber during handling. In carbon chopping and pressure spraying, the sizing prevents the small diameter carbon fibers from scattering into the air.

Since the objective of using discontinuous fiber processes is to obtain low cost composite fabrication, the use of lower cost, high filament count tows is preferred. Traditionally, the carbon composite industry has used tows of 12,000 (12k) filaments. This tow size has worked well for the production of high quality prepreg. As affordable cost has become a more important factor in carbon composites and as more non-prepreg fabrication process have been developed, the industry has pushed to make use of lower cost, high filament count tows. Figure 2 shows the general cost trend for carbon tow sizes.

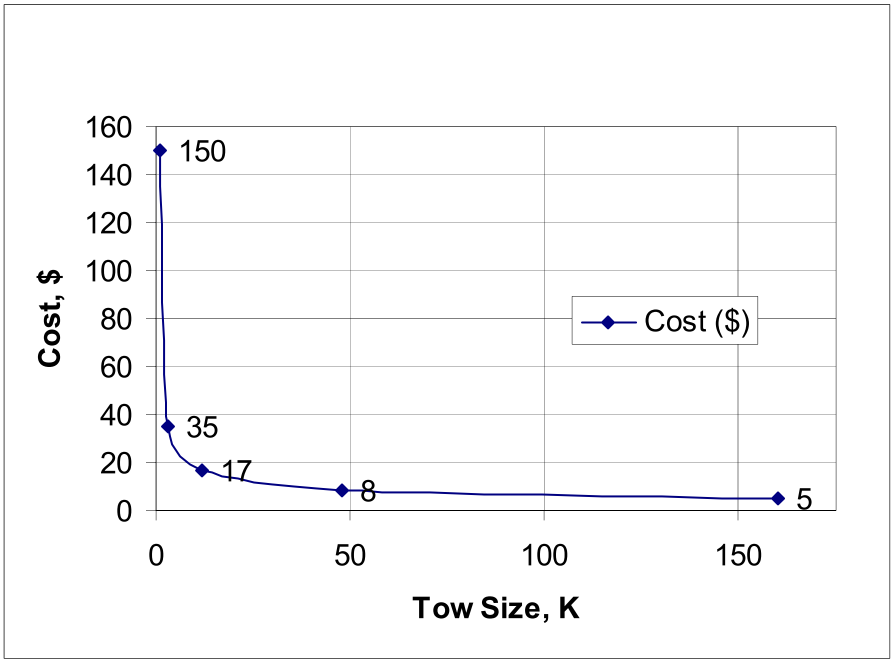

Figure 2. General Cost Trend for Carbon Fiber Tow Sizes

Initially, 48k tows were considered. However, these large bundles did not work well in the process so 12k tows were substituted and worked well in the process. Therefore, this investigation concentrated on carbon tow sizes of 3000, 6000 and 12000 filaments to create oriented, discontinuous carbon preforms. Two carbon fibers from Toho Carbon Fibers were used: G30-700 and G30-500. Properties for the fibers from Reference 12 are shown in Table 1. Initial work focused on the 12k tows using the G30-700 fiber. After test results showed less than the desired strength retention, the smaller tow sizes were investigated. G30-500 fiber was selected due to availability.

Property	**G30-500**	**G30-700**
Tension Strength, GPa, (ksi)	**3792 (550)**	**4826 (700)**
Tension Stiffness, MPa, (msi)	**234 (34.0)**	**241 (35.0)**
Elongation (%)	**1.60**	**2.00**
Size Level (%)	**1.3**	**1.3**
Density (g/cc)	**1.78**	**1.81**

Table 1. Properties of G30-500 and G30-700 Carbon Fibers

Fiber lengths of 50.8mm, 76.2mm, 101.6mm and 127mm (2, 3, 4 and 5 inches) were evaluated under this effort. These fiber lengths work well in the fiber delivery system to produce satisfactory preforms. Table 2 shows the key fiber parameters in the test panels. All preforms had all fibers oriented in the 0° direction yielding a unidirectional preform.

Panel Number	Fiber	Tow Size	Fiber Length, mm (in)
Effect of Tow Size			
1	G30-700	12k	76.2 (3)
2	G30-500	6k	76.2 (3)
3	G30-500	3k	76.2 (3)
Effect of Fiber Length			
4	G30-500	3k	50.8 (2)
5	G30-500	3k	76.2 (3)
6	G30-500	3k	101.6 (4)
7	G30-500	3k	127 (5)

Table 2. Tow Size and Fiber Length Parameters

Some of the discontinuous fiber preforms were infused using resin transfer molding (RTM) with Shell Epon 862 epoxy and curing agent W. Final cure was at 177°C (350°F) for two hours. Other preforms were infused using vacuum assisted resin transfer molding (VARTM) with Ciba 8611 epoxy cured at 250°F followed by a 350°F postcure. For trend observation, the different resin systems were deemed to be comparable and not an issue in this effort.

To evaluate the oriented discontinuous preforms, 0° Tension tests were conducted per ASTM D3039. Environmental conditions were room temperature and ambient moisture content. Ultimate strength and stiffness were measured.

4. 4. RESULTS AND DISCUSSION

4.1 Effect of Discontinuous Fiber Tow Sizes on Tension Strength **The unidirectional tension test results of the fiber tow size comparison are shown in Table 3. Since there was a significant variation in measured fiber volume, the strength and stiffness values were normalized to 55% fiber volume to allow for an accurate comparison.**

Panel	**1**	**2**	**3**
Fiber	**G30-700**	**G30-500**	**G30-500**
Tow Size	**12k**	**6k**	**3k**
Measured Fiber Volume (%)	**48.6**	**66.0**	**51.6**
Measured Strength, Mpa (ksi)	**737.0 (106.9)**	**702.6 (101.9)**	**752.2 (109.1)**
Measured Stiffness, Gpa (msi)	**93.56 (13.57)**	**133.90 (19.42)**	**106.32 (15.42)**
Normalized Fiber Volume (%)	**55**	**55**	**55**
Normalized Strength, Mpa (ksi)	**834.3 (121.0)**	**585.4 (84.9)**	**802.5 (116.4)**
Normalized Stiffness, Gpa (msi)	**106.97 (15.37)**	**111.63 (16.19)**	**113.42 (16.45)**

Table 3. Effect of Fiber Tow Size on 0° Tension Properties

The normalized strengths and stiffness show the effects of tow size on tensile properties. The first panel tested was the 12k preform using the G30-700 fiber. Comparing the properties from this preform to continuous unidirectional prepreg properties for G30-700 fiber showed 36% strength retention and 74% stiffness retention. These property retentions are lower than those reported for other oriented discontinuous carbon composites. This led to the consideration of smaller tow sizes. Switching to the G30-500 fiber in smaller tow sizes, the 3k tow preform showed a significant increase in strength over the 6k tow preform. The property retentions compared to continuous unidirectional prepreg properties are shown in Table 4 for all three laminates.

Panel	**1**	**2**	**3**
Fiber	**G30-700**	**G30-500**	**G30-500**
Tow Size	**12k**	**6k**	**3k**
Strength Retention (%)	**36%**	**29%**	**40%**
Stiffness Retention (%)	**74%**	**80%**	**81%**

Table 4. Effect of Fiber Tow Size on 0° Tension Property Retention

It is important to note failure modes when reviewing composite material data. The 0° tension tests with the 12k tows did not exhibit the classic catastrophic unidirectional tension failure mode where fiber bundles split longitudinally and are severed transversely. These tensile specimens had intralaminar resin cracking at the ends of the discontinuous tows that led to interlaminar splitting along ply interfaces. Besides being premature, the specimen failure was gradual and not catastrophic.

4.2 Fiber Critical Length **When tows are chopped in the P4A process, the resulting fiber form are bundles or 'logs of fibers' instead of discrete filaments. The sizing which aids in the chopping and orientation of the carbon fibers also prevents the fibers from spreading out. Most discontinuous fiber composites have been discontinuous on a filament level. Fiber filaments were not grouped together and fiber ends were distributed throughout the composite matrix. In random discontinuous composites, the randomness led to an well distributed dispersion of fiber ends. In other aligned discontinuous composites, fiber bundle dispersion depended on material fabrication process. The slurry process led to well distributed fiber ends. The electrostatic process led to various amounts of dispersion (Reference 2). When fibers end, the relatively high load carried axially in the fiber must shear in the resin for transfer to adjacent fibers. When filaments end, the resin and fiber/resin interface can adequately transfer the fiber load. However, when large numbers of fibers end simultaneously, the fiber loads exceed the resin and interface capabilities and fail. This large stress concentration at the end of the 12k tows caused a failure in the resin and/or interface. The crack in the resin then spread between ply interfaces.**

The tension specimens from the 6k and 3k discontinuous composites exhibited the correct failure mode. The stress concentrations at these fiber tow ends are reduced to a level that the load can be adequately transferred by the resin and fiber/resin interface.

The incorrect failure mode of the 12k tow material and the low strength retention of all three tow size materials led to concern about critical fiber length. It is well-documented in the literature that discontinuous fiber-reinforced composites require some critical (or minimum) length of fiber in order to assure complete shear load transfer from the matrix to the fiber. Unfortunately, it is also documented in the literature that not everyone can agree on what that critical length should be. Critical fiber length , L_c, is the minimum fiber length needed to achieve the

$$L_c = \frac{\sigma_f \, d}{2 \, \tau_c}$$

maximum fiber strength (Reference 1).

where L_c is the critical length
d is the diameter of the fiber bundle
τ_c is the shear strength at the fiber-matrix interphase
σ_f is the ultimate strength of the fiber

The prediction of the critical length from various models collectively known as shear lag models is well-known and generally agreed upon. Typically, the model is based on the following assumptions: 1) perfect bonding between fiber and resin, 2) both the fiber and resin behave elastically, and 3) the fiber exhibits transversely isotropic behavior and the resin exhibits isotropic behavior.

In Reference 13, Skourlis took these typical models and hypothesized that the interphase (the matrix-like material right at the fiber surface in a composite) might also make a difference in the critical length. This hypothesis was based on observations that mechanical (and physical) properties of the interphase are often significantly different from the bulk matrix. Consequently, the stress translation from the matrix to the fiber may be impacted by the properties of the interphase and therefore may affect the critical length. Skourlis arrived at an equation to predict the critical aspect ratio (i.e., critical length divided by fiber diameter). This equation takes into account both the elastic and shear moduli for the fiber, the shear modulus for the interphase and the bulk matrix, the radius of the interphase (i.e., how far does it extend from the fiber surface), and Poisson's ratio for the fiber. For a typical carbon/epoxy composite, he demonstrated that if the shear modulus of the interphase is greater than or equal to the shear modulus of the bulk matrix, then the critical aspect ratio of the fiber will always be approximately 30, regardless of the interphase radius. However, as the shear modulus of the interphase drops below that of the bulk matrix, the critical aspect ratio can increase to a maximum approaching 140 and is very dependent on the depth of the interphase (the interphase radius).

4.3 P4-A Tow Critical Length **Since all critical fiber length research is aimed at single round fibers, the current research is somewhat complicated by the desire to predict the critical length of the fiber tows (logs) of many thousand individual fibers.**

The first step to predicting the critical length is to determine the fiber diameter. While this is straightforward for a single fiber, it is far more complicated for a tow. The packing of the fibers in a tow and the final tow geometry must be considered. Three types of tow geometries were considered during this effort: hexagonal, circular, and rectangular as illustrated in Figure 3. In the case of the rectangular geometry, both the width and the thickness must be considered as viable diameter measurements.

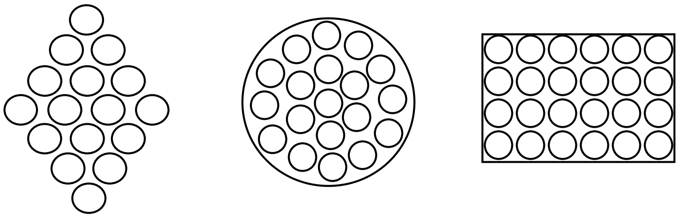

Figure 3. Idealized Fiber Tow Geometries

The assumption of "tow" diameter or effective diameter of the "logs" can make a significant impact on the critical length. Using the packing factors, fiber filament diameters and typical ply thicknesses, effective tow diameters were calculated for the idealized geometries. An idealized rectangle for 1k tow was not calculated because no actual thickness and width measurements were available. Using the

Skourlis "best case" and "worst case" critical aspect ratios of 30 and 140 respectively, critical fiber (tow) lengths were calculated for the idealized geometries and effective diameters. The results from the critical fiber (tow) length calculations are shown in Tables 5 and 6.

Tow Size	Effective Diameter (microns)			
	Hexagon	Circle	Rectangle (thickness)	Rectangle (width)
1000	369	286	N/A No data for 1K tow	N/A No data for 1K tow
3000	639	495	84	2540
6000	904	700	109	4318
12000	1278	990	112	7620

Table 5. Effective Diameters for Idealized Tow Geometries

Tow Size	Assumed Critical Aspect Ratio	Critical Fiber Length (mm)			
		Hexagon	Circle	Rectangle (thickness)	Rectangle (width)
1000	30	11.1	8.6	N/a	N/a
	140	51.7	40.0	N/a	N/a
3000	30	19.2	14.9	2.5	76.2
	140	89.5	69.3	11.8	355.6
6000	30	27.1	21.0	3.3	129.5
	140	126.5	98.0	15.3	604.5
12000	30	38.3	29.7	3.4	228.6
	140	178.9	138.6	15. 7	1066.8

Table 6. Predicted Critical Lengths for 1k, 3k, 6k, and 12k Tows

As Table 6 clearly demonstrates, the effective diameter of the tow is the driving variable in determining the critical length. This single value can change a critical length from less than three-quarters of an inch to more than three feet. The wide variation in critical length values points to the importance of tow geometry definition in the modeling of the fiber "logs". The packing factor used in the circular and hexagonal calculations also needs to be fully defined to reach an accurate solution. From the initial investigations, it does seem clear that 1k and 3k tows have much smaller critical lengths and are more attractive from a potential strength standpoint, regardless of geometry. The range of interphase best and worst case results in a five fold effect on critical length.

Based on the economics of carbon fiber tow sizes shown previously in Figure 2, the 1k fiber tows are not a viable choice. For the 3k tows, the critical lengths calculated for a majority of the interphase and effective diameter parameters all fall within the capability of the P4-A equipment and process. Therefore, the 3k tows were selected for further investigation. Using the 3k tows, unidirectional preforms of oriented

discontinuous fibers were sprayed up, infused and cured to experimentally investigate fiber length effects. Results for the 0° tensile tests are shown in Table 7.

Panel	4	5	6	7
Fiber Length, mm	50.8 (2)	76.2 (3)	101.6 (4)	127 (5)
Measured Fiber Volume (%)	54.6	53.8	50.5	49.3
Measured Strength, MPa (ksi)	954.1 (138.4)	989.3 (143.5)	999.04 (144.9)	843.22 (122.3)
Measured Stiffness, GPa (msi)	107.1 (15.53)	109.5 (15.89)	101.70 (14.75)	100.53 (14.58)
Normalized Fiber Volume (%)	55	55	55	55
Normalized Strength, MPa (ksi)	961.0 (139.4)	1010.7 (146.6)	1087.29 (157.7)	941.13 (136.5)
Normalized Stiffness, GPa (msi)	107.8 (15.64)	111.9 (16.23)	110.66 (16.05)	112.11 (16.26)

Note: All panels used G3-500 fiber in 3k tow size.

Table 7. Effect of Fiber Length on 0° Tension Properties

5. 5. CONCLUSIONS

The tow size of carbon fibers used to produce oriented discontinuous fiber composites has a significant effect on the mechanical properties of the composite. The grouping of fiber filaments results in stress concentrations at the end of filament groups or tows. This greatly reduces the strength of the composite laminate, slightly reduces the stiffness and can change the failure mode of the composite. Test trends showed that smaller diameter carbon fiber tows provided better translation of tensile strength. When the filaments stay together in the final laminate, the tow itself acts as a large diameter fiber and may need to be longer to attain critical fiber length. The critical length is the minimum length necessary to attain maximum tensile strength of the fiber. Calculation of the critical fiber length is highly dependent on two parameters: interphase shear strength and fiber diameter. When the discontinuous fibers stay grouped, the effective diameter of the tow becomes an overriding factor that makes it difficult to accurately predict critical length for the tow. In contrast, random discontinuous fiber composites have well dispersed chopped fibers and do not have high concentrations of fiber ends resulting in high stresses. The matrix material can adequately transfer the fiber load to adjacent fibers. Random processes can use delivery systems and sizing parameters that allow the fiber tows and rovings to be dispersed to the filament level. The goal of orientation can result in the oriented discontinuous fibers remaining in filament groups. Tow or filament group size need to be considered in discontinuous fiber composites, especially when oriented fibers and high mechanical properties are desired.

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7. 7. BIOGRAPHIES

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