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QUANTIFICATION OF PROCESSING PARAMETERS FOR WIND TURBINE BLADES

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ABSTRACT

All materials have an influence from the processing parameters for structural performance, but composite materials have a much more intimate materials/ processing/structural performance connection due to their macroscopic inhomogeneities. In this paper, a link is provided between processing parameters, material architecture, and mechanical performance for various material architectures. In particular, a simple formula is provided to understand the fiber volume of a given part. This fiber volume is then linked with the fatigue performance. These data are indicative of the influence of processing pressures on laminate fiber volumes, independent of processing techniques and can be useful to wind turbine blade manufacturers to prepare processing conditions, a priori, to minimize expensive trial and error manufacturing development.

INTRODUCTION

Previous works have indicated the critical importance of fiber content to mechanical properties [e.g. 1-3]. This is a consequence of the typical material architectures that are used in wind turbine blades. Figure 1 is an illustration of typical materials utilized in wind turbine blades. The D155, A130, and DB120 materials are from Owens Corning Fabrics and are stitched in some form to provide better handling characteristics for large volume manufacturing [4]. The UC1018V material is from Collins Craft, and has unidirectional fibers bonded to a veil scrim on the backside [5].

These all have the same basic fiber material, but they have profoundly different macroscopic architectures. The intent of these architectures is to improve the handling characteristic in a dry material form compared to spools of fiber. This in turn influences the processing characteristics and resulting mechanical properties. It can be difficult in practice to achieve the desired fiber content in a composite part. Fiber volume is a controlling factor for durability and damage tolerance of structures made of composite materials. A high fiber volume may be advantageous for increasing static stiffness and fracture properties, but may be very deleterious to fatigue performance as illustrated in Figure 2. Figure 2 is a semi-log plot of fatigue life of D155 strands, and was fit according to:

$$S/S_0 = 1 - b \log N \qquad 1)$$

Where S is the maximum cyclic stress, S_0 is the static strength, b is the fatigue coefficient, and N is the cycles to failure.

The curve fits for other fiber volumes are shown in Table 1 for the D155 material [6,7]. The 10^7 cycles to failure was arbitrarily chosen to represent fatigue lifetimes of wind turbines. This is in contrast to the 10^6 cycles to failure often chosen for other machine endurance limits.

Table 1. Fatigue Life of D155 Material at Various Fiber Volume Fractions

Fiber Volume, V_F, %	Fatigue Coefficient, b, (Equation 1)	Strain to failure at 10^7 cycles, %, R = 0.1
50	0.103	1.19
56	0.108	1.07
61	0.112	1.05
66	0.123	0.93

The point is, there is a complicated interaction between fiber volume and fatigue life of structures made from candidate materials such as those illustrated in Figure 1. This interaction must be understood to determine the

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fatigue life of the wind turbine blade, especially as we venture into large (1+ megawatt) utility grade wind turbines.

This is a brief summary of a study relating ply thickness, fiber content and molding pressure for candidate material architectures. The purpose is to quantify manufacturing procedures so that target fiber contents can be readily achieved, and the fiber content can be accurately determined from the thickness. Complete data are available in the DOE/MSU materials database [6-8].

EXPERIMENTAL METHODS

Flat composite plates, approximately 20 by 35 cm in dimensions, were manufactured using hand layup procedures on a flat, level aluminum plate. The fabric was impregnated with isothalic polyester resin, and, well before the resin had started to cure, steel weights (14 total, each with a fabric contact area of 6.25 cm^2) were placed on the uncured composite surface to generate different through-thickness pressures between 0.84 and 71.4 kPa. The different pressures were generated by square steel bars of different heights. A top view of the experimental setup is shown in Figure 3. A Teflon sheet (0.1 mm thick) was placed between the steel weights and the fabric to ensure separation after curing. The steel weights were placed on the fabric after it had been wet out to avoid dry friction problems (and poor wet-out areas) in the fabric. Composite plates were manufactured with one, two and three plies, utilizing the same fabric and fabric orientation, which allowed for different ply strand nesting (consolidation) geometries. After curing, the plate was sectioned and the thicknesses of the individual areas were measured by averaging measurements of each side. Some minor thickness variations on the coupons were found as a consequence of irregularity of the pressure distribution. This was due to the fabric and surface stitching (hard versus soft contacts). There was no influence of the individual steel blocks on the adjacent blocks due to the Teflon film or the fabric.

For the test coupons with two or three plies, the thickness of the test coupon was divided by the number of plies to obtain the average ply thickness. There is some error in this method at low (less than 25 percent) fiber volume fractions, as the matrix rich regions between the plies is included in this thickness. Different fiber stacking (and nesting) possibilities in some unidirectional laminates are shown in Figure 4. The nesting variations shown at constant fiber content are typical variations observed when different parts of a laminate are sectioned, using fabric D155. The right side of the figure shows the effects of increasing fiber content for a fabric with widely-spaced strands, D092.

At higher fiber contents, where fiber nesting occurs, the average ply thickness may be less than it would be without nesting, especially with fabrics having large spaces between strands. Thus, in a laminate with adjacent plies of other orientations, nesting will not occur, and the ply thickness may be greater than obtained here. However, given a part thickness, a very good relationship exists between the part fiber volume and the thickness.

The theoretical prediction for ply thickness versus fiber volume fraction can be predicted via:

$$t = \frac{A}{V_F} \qquad 2)$$

where t is the ply thickness and A is the volume of solid glass.

The value of A can be estimated a priori with manufacturers areal weight data and fiber density or via simple weight measurements of the fabric. Also, the tests described above are relatively simple, and can be conducted prior to making a large (expensive) wind turbine blade. It is noted that Equation 2 works equally well for carbon fiber based laminates [6].

Figure 5 is a comparison of the data for D155 fabric with this relationship, showing excellent agreement. The ply thickness versus fiber volume percent graphs are all similar, with regards to one, two or three plies in the composite. Other architectures as shown in Figure 1 yield similar close agreement. The maximum margin of error on these relationships was estimated at ± 5 percent and is dependant upon uniformity of the fibers across the ply; voids between fiber bundles will tend to cause fiber nesting if adjacent plies are available to fill the voids.

Figure 5 is an illustration that this relationship holds independent of the number of plies. However, the through thickness processing pressure has a significant influence on the fiber volume for a given number of plies. The effect of number of plies is shown in Figure 6.

Fiber nesting causes through-thickness pressure increase (spikes) to occur at higher fiber contents in composites with two and three plies. The single ply data are in indication of the uniformity of the fiber distribution, and any hard contact points present in the basic reinforcement geometry. Low fiber contents at the same pressure indicate that the fabric architecture has large voids which must be filled by adjacent plies (if available), or that excessive pressure is necessary to flow the fabric strands sideways to fill the voids. Either way, these voids hinder the achievement of higher average fiber contents. Hard contact points, generated by stitching threads or fiber intersections in woven fabrics, cause a large increase in the through - thickness pressures as the contacts interact with adjacent plies or mold surfaces. This is most noticeable in the A130 type fabrics illustrated in Figure 1at fiber contents above 43 percent, when the thermoplastic weft weaving thread penetrates the composite surface, causing raised bumps on the surface. (Further details may be found in Reference 6.) The D155 fabric (Figure 6) has an abrupt pressure change (termed a pressure transition) at approximately 38 percent, which is almost vertical, and is caused by the stitching contacting the mold surface; this locally compresses the D155 strands under the stitch. These compression points are shown to reduce fatigue performance [6,7]. With multiple layers, this effect can be somewhat reduced due to fiber and stitching nesting. Identification of these phenomena is available in Reference 6.

The influence of stitching on processing is seen in Figure 7. The top of the figure is an illustration of how the stitching creates “hard points” through the stacking. Further down in the figure, another laminate was made with the weft stitching removed. (For reference, the fibers are approximately 15 μm in diameter.) Notice the ability of the fibers to move laterally and pack in a more continuous manner, like laminates made with unidirectional fibers with no stitching. This inhomogeneity, with the locally high fiber volume has a profound influence on the fatigue life of the structure as was illustrated in Figure 2. Hence, while these stitched materials have attractive handling characteristics in a dry form, care must be taken to manufacture structures with adequate fatigue life. This is a major challenge for wind turbine blades compared to other fiberglass reinforced plastics such as boat hulls, holding tanks, and pressure tanks because of the higher number of fatigue cycles.

A comparison between prepreg and the D155 material is provided in Figure 8. Both are E-glass fibers. The prepreg is 3M-SP250 [9].The D155 material has an average fiber volume of 40% while the prepreg has an average fiber volume of 56%. Notice the level of inhomogeneity in the D155 compared to the prepreg. With increasing magnification in the fiber region, this inhomgeneity lessens and the D155 material has approximately the same local fiber volume as the prepreg. The implication is that those materials with less inhomogeneity such as prepregs can have a higher number of fibers, with no loss of fatigue performance, compared to those with locally high, but lower average fiber volumes. Higher fiber volumes result in higher absolute stiffness and strength of the structure.

The through-thickness pressure versus fiber volume relationship for the DB120 fabric architecture of Figure 1 is shown in Figure 9. The same sensitivity to number of plies exists, but it is slightly less dramatic than the D155 material as a result of better nesting properties.

MULTIDIRECTIONAL LAMINATES

When plies of different fabrics are stacked together, the actual fiber content in each ply may differ from the overall average. This different ply fiber content effect is shown in Figure 10 for the material sequence having the configuration $(0/\pm45/0)_S$. These multidirectional laminates have the designation DD5. The 0^0 plies are the D155 material of Figure 1, and the ±45 plies are the DB120 plies of Figure 1. In Figure 10, following the 20 kPa pressure line, the fiber content in the DB120 fabric is about 33 percent, the fiber content in the D155 ply is about 42 percent, while the overall laminate is about 37 percent. The individual ply thicknesses (0 and ±45) in these graphs, when added together, may not equal the composite thickness due to matrix rich regions between the plies, or to fiber nesting. The separate plies were measured from the test coupons under the microscope. Additional weights were used to generate higher pressures (Figure 11), and these high pressures were part of the problem encountered in molding the high fiber content multidirectional materials. The high molding pressures used to manufacture these composites also introduce a question as to whether fiber damage occurs. The multidirectional laminates with a fiber content above 60 percent did have a slightly reduced ultimate tensile strength/fiber volume ratio. This could be due to fiber damage or a significant change in the ply architecture as a result of the higher processing pressures. This raises the question between hard versus soft tooling for manufacturing wind turbine blade structures with these types of stitched materials. However, the main concern with high fiber contents is the tensile fatigue performance, as was illustrated in Figure 2.

The current database contains data for all materials tested in terms of fiber content, thickness, and variations and tolerances for these parameters [6,8]. Also included is a table giving the fiber content where the pressure starts to transition, about 20 kPa, and the tensile properties may decline for glass fiber materials.

CONCLUSIONS

The relationship provided by Equation 2 allows convenient determination of the fiber content for each fabric, knowing the molding pressure. The relationships also allow for quick verification of the values listed in the fatigue database [6,8], and where discrepancies were found, additional matrix burn off tests were performed to confirm the accuracy of the database values. Some fiber content corrections were made in the current version of the database.

If a composite is manufactured with the same fabric for all the plies, the fiber volume fraction will be the same in each ply. This is also the case for most prepregs. Prepregs would be expected to have the intraply homogeneity of the bottom of Figure 7 where the stitching has been removed. However, when combinations of different fabrics are used, the local fiber content may be different in different plies, and corrections in the ply properties must be performed to accurately predict the material behavior. This point has been identified for the DD series of laminates in the DOE/MSU database [6,8], and the reason for this influence is illustrated in Figure 7.

DESIGN RECOMMENDATION

The data can be used to obtain the expected laminate thickness and individual ply fiber contents for a particular molding pressure. For multidirectional composites the common factor is the through-thickness pressure, which must be the same throughout the preform (neglecting fabric weight). The fabric thickness for each ply can be determined from the graphs or tables at the same through-thickness pressure and added to obtain the total composite thickness. The corresponding ply fiber volume fraction can be used to obtain the ply properties. This approach is developed further in Reference 10. For design data, some simple cross-sectional photo-micrographs can yield information concerning local variations in fiber content. It is the local fiber volume, not the average fiber volume that controls durability and damage tolerance. This is an area of great interest as we continue to explore the materials/manufacturing/structural performance link for low cost materials suitable for wind turbine blades.

REFERENCES

[1] Mandell, J.F., Samborsky, D.D., and Cairns, D.S., "Advanced Wind Turbine Blade Structure Development at Montana State University," *Wind Energy 1997*, ASME/AIAA 189-196 (1997).

[2] Cairns, D.S. and Skramstad, J. "Evaluation of Hand Lay-up and Resin Transfer Molding in Composite Wind Turbine Blade Manufacturing," Report SAND00-1425, Sandia National Laboratories, Albuquerque, NM (2000), www.coe.Montana.edu/composites

[3] Mandell, J.F., Samborsky, D.D., and Sutherland, H.J., "Effects of Materials Parameters and Design Details on the Fatigue of Composite Materials for Wind Turbine Blades," 1999 European Wind Energy Conference, 1-5 March 1999, Nice France, pp. 628-633, www.sandia.gov/Renewable_Energy/wind_energy/other/EWEC99-1.pdf

[4] Owens Corning Fabrics (Knytex), New Braunfels, Texas, www.owenscorning.com

[5] CollinsCraft Composites Group Inc., Walhalla, SC, www.cofab.com

[6] Mandell, J.F., Samborsky, D.D., and Cairns, D.S. "Fatigue of Composite Materials and Substructures for Wind Turbine Blades" Contractor Report SAND 2002-0771, Sandia National Laboratories, Albuquerque, NM (March 2002), www.coe.Montana.edu/composites

[7] Samborsky, Daniel, D., "Fatigue of E-glass Fiber Reinforced Composite Materials and Structures," M.S. Thesis, Department of Civil Engineering, Montana State University, 1999.

[8] Mandell, J.F. and Samborsky, D.D. "DOE/MSU Composite Material Fatigue Database: Test Methods, Materials, and Analysis," Contractor Report SAND97-3002, Sandia National Laboratories, Albuquerque, NM (1997) [www.coe.Montana.edu/composites]

[9] Sundsrud, Jerry, Davis, J. W., "Fatigue Data on a Variety of Non-Woven Glass Composites for Helicopter Rotor Blades," Composite Materials: Testing and Design (Fifth Volume), ASTM STP 674, S.W. Tsai, Ed., 1979, pp. 137-148.

[10] Rossell, Scott, "Fluid Flow Modeling of Resin Transfer Molding for Composite Material Wind Turbine Blade Substructures," M.S. Thesis, Department of Chemical Engineering, Montana State University, 2000.

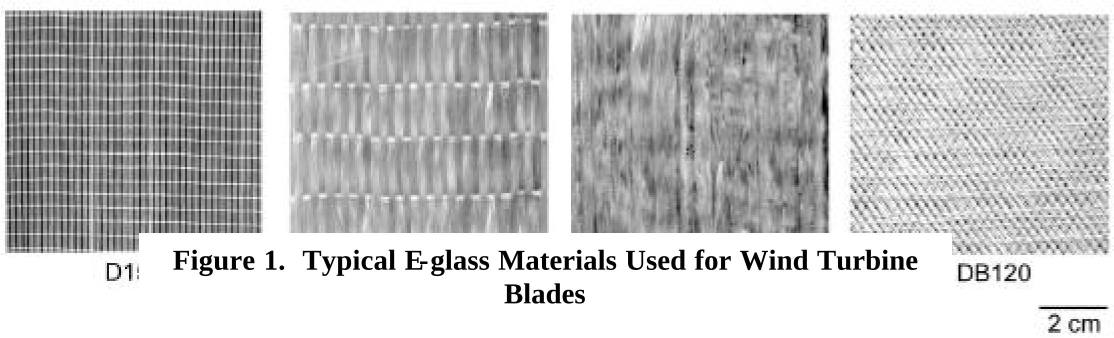


Figure 1. Typical E-glass Materials Used for Wind Turbine Blades

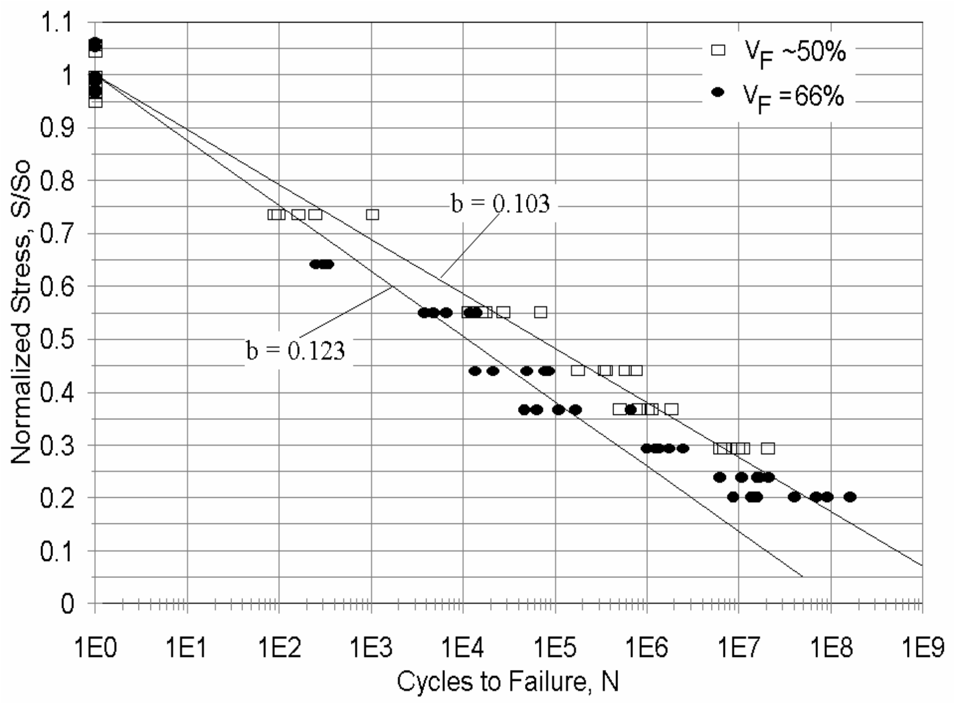


Figure 2. Fatigue Performance of D155 (R= 0.1) Unidirectional Laminates at Two Fiber Volumes

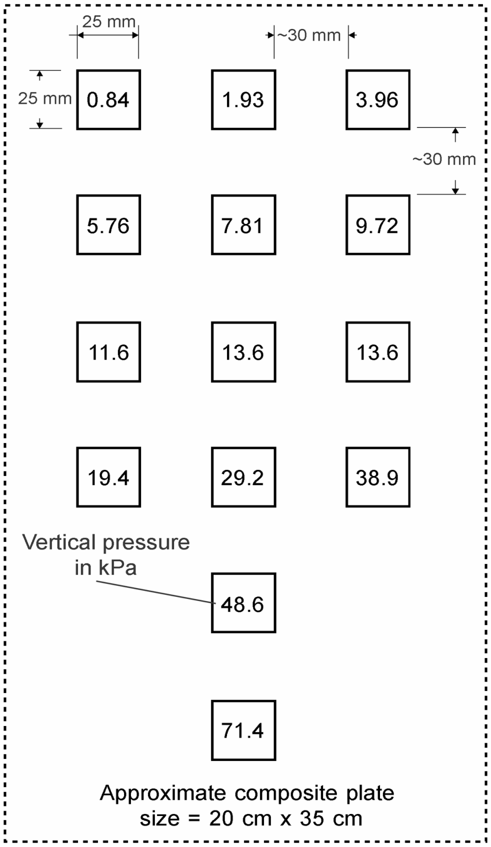


Figure 3. Pressure Study Experimental Setup

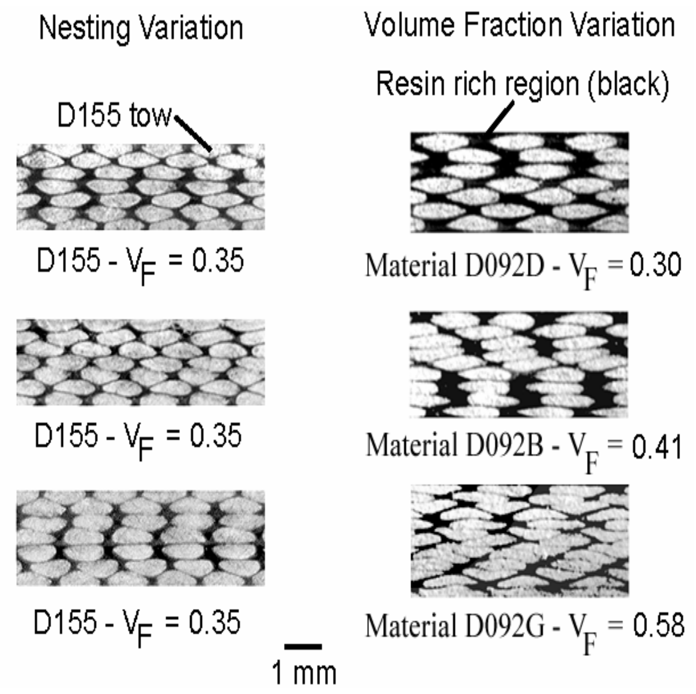


Figure 4. Nesting and Volume Fraction Variation from Molding Process

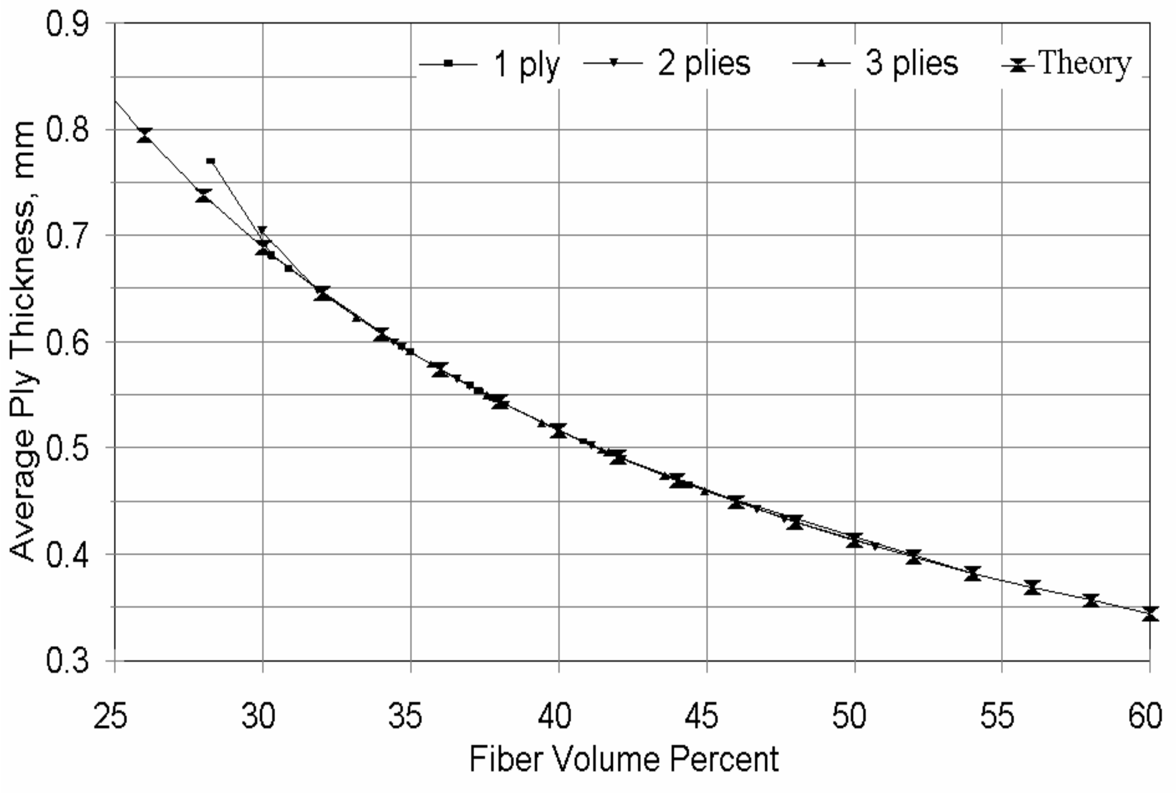


Figure 5. Average Ply Thickness versus Fiber Volume Percent for D155 (experiment vs. theory)

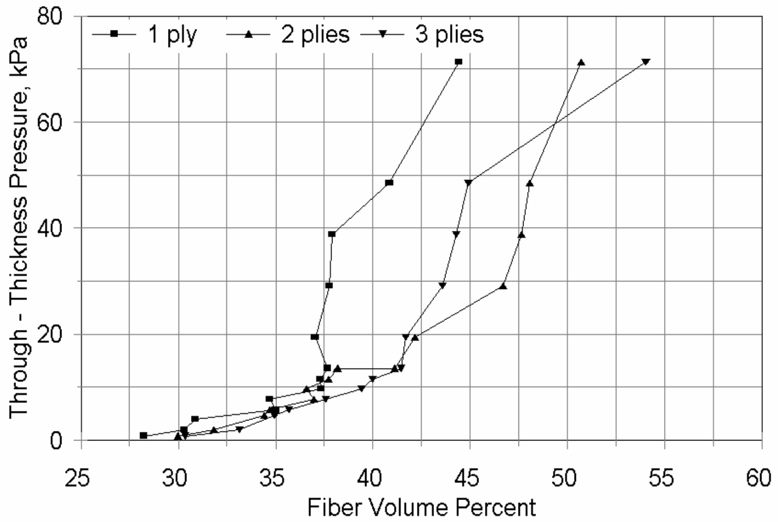


Figure 6. Through-Thickness Pressure versus Fiber Volume Percent for Fabric D155

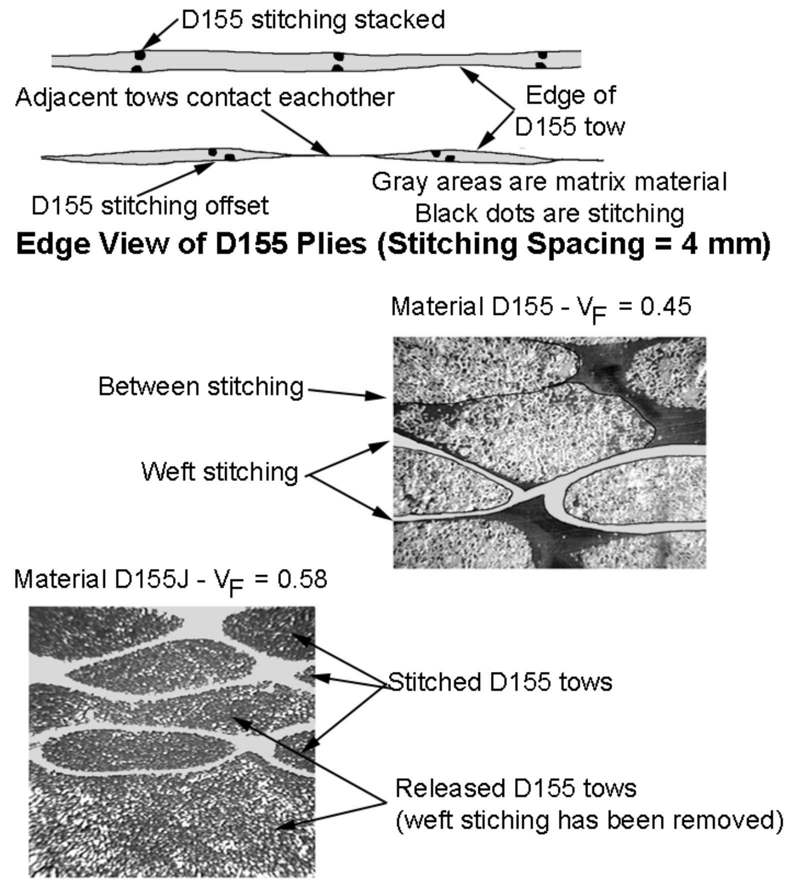
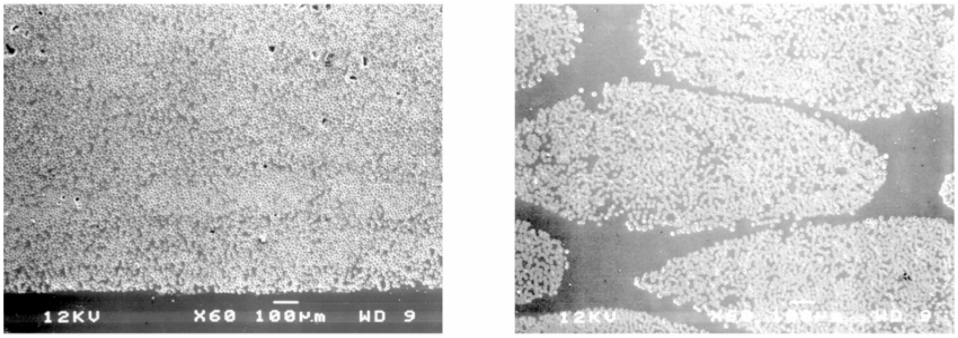
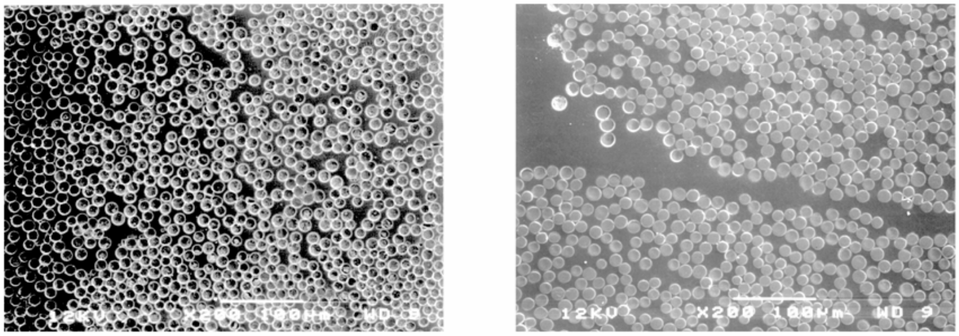


Figure 7. Fabric Stitching Interaction with Adjacent Ply stitching and the Effects of Removing the Stitching (for reference, diameter of fibers is approximately 15 mm)



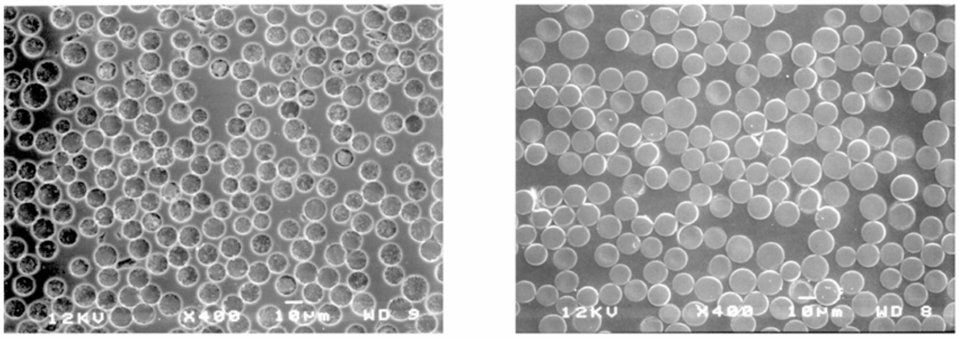
Prepreg (60X magnification)

D155 (60X magnification)



Prepreg (200X)

D155 (200X)



Prepreg (400X)

D155 (400X)

Figure 8. Comparison of Prepreg versus D155 material,
D155 is 40% average fiber volume, Prepreg is 56% average fiber volume

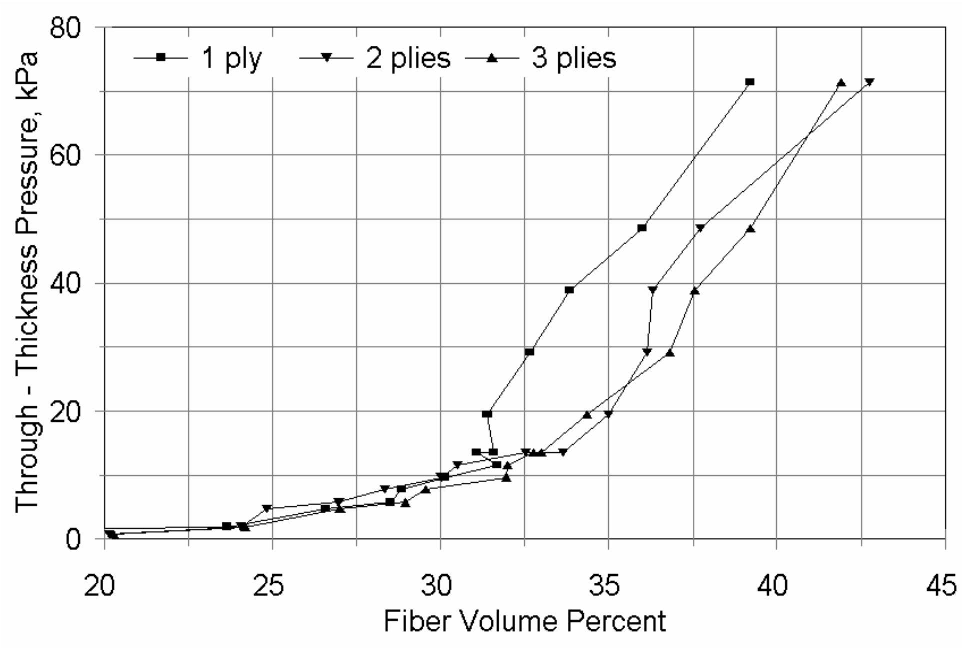


Figure 9. Through-Thickness Pressure versus Fiber Volume Percent for Fabric DB120.

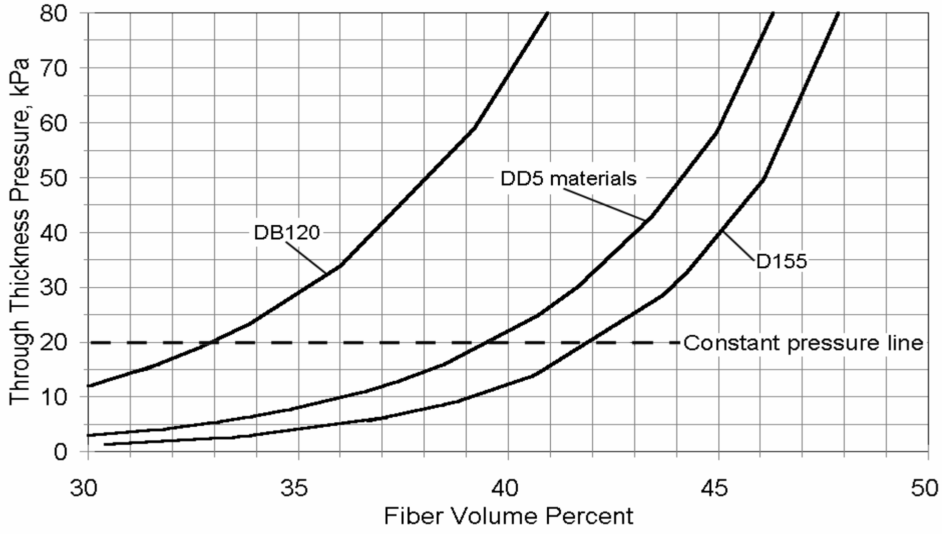


Figure 10. Through-Thickness Pressure versus Fiber Content for DD5 $(0/\pm45/0)_S$ laminates, 0^0 plies are D155 materials , and the ±45 plies are DB120 materials

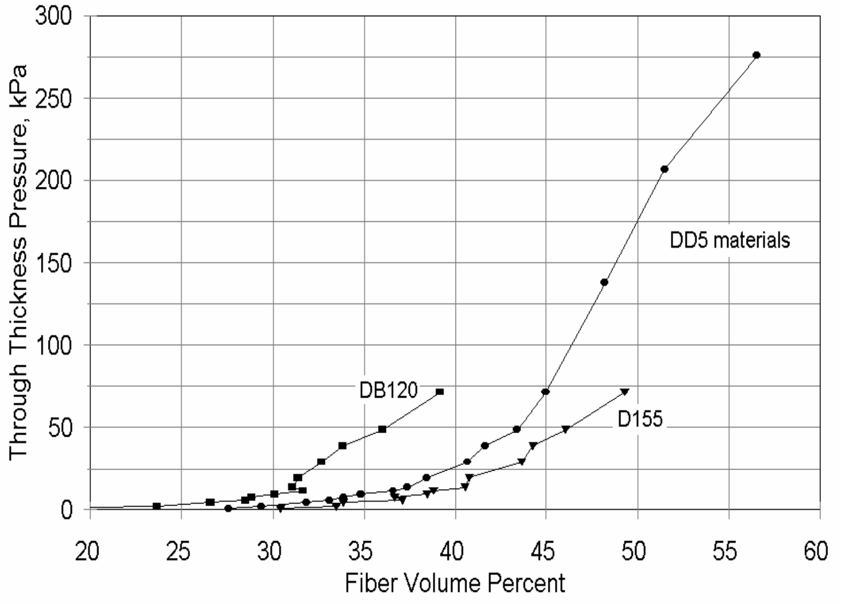


Figure 11. Higher Through-Thickness Pressure versus Fiber Content for DD5 (0/±45/0)$_S$ laminates, 0^0 plies are D155 materials , and the ±45 plies are DB120 materials