AUTOMATED WIND BLADE PRODUCTION

In this article, valuable material benefits that arise from wind blade automation are highlighted by the experts at PPG Industries.

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NOVEL MATERIAL AND PROCESS technologies for wind blade design and production are critical to increasing the competitiveness of wind power generation. As part of a Department of Energy (DOE)-funded project conducted by PPG Industries (PPG) and MAG Industrial Automation Systems (MAG), the potential of producing fiber glass composite blades using automated manufacturing was evaluated. This paper focuses on the material evaluation and corresponding impact on blade performance as part of the funded study.

During the first stage of the project, a comprehensive review of the DOE composite material database was performed. The results of this review were combined with data from PPG and publicly available information and analyzed for performance characteristics based upon material type[1].

The outcome of this analysis identified state of the art composite material technology and performance characteristics used by wind blade designers. These properties (Table I) were the benchmark for the work performed in the remainder of this study. Some of the key conclusions of the comprehensive database evaluation included:

- Unidirectional, prepreg-based laminates made with E-Glass and epoxy resin have better tensile modulus compared to equivalent infused laminates;

- Tensile modulus values of 47 and 48 GPa have been reported for unidirectional laminates made with E-Glass prepreg and correspond to the highest tensile modulus reported for any E-Glass composites;
- Laminates fabricated with PPG's HYBON® 2026 roving and epoxy resin resulted in higher fatigue performance when compared to laminates produced with other roving inputs.

During the second stage of the project an experiment was conducted to evaluate the effects of fiber diameter, linear density (TEX), and fabric areal weight on material properties. The samples were produced in two distinct reinforcement formats: weft insertion fabrics with 90+ percent of the reinforcement in one direction, and by dry filament winding to mimic the reinforcement packing of a unidirectional prepreg. The glass fiber sizing chemistry and the sizing content was kept constant: PPG's HYBON 2026 multi-compatible roving. The experiment revealed that the roving based factors considered did not have a significant effect on the mechanical properties of the laminates. However, the study showed that the fabric style/architecture and fiber volume fraction achieved using a particular reinforcement had a significant effect on the composite mechanical properties (fig. 1). Furthermore, the elimination of crimp and improvements in fiber alignment as found in resin pre-impregnated rovings can increase overall mechanical performance. A detailed description of these results was reported at a SAMPE Technical Conference in May 2011[2].

Using these findings, the next step was the experimental determination of mechanical properties of currently used non-crimp fabrics. As concluded from the database analysis, a set of composite laminates (uniaxial, biaxial and tri-axial) was produced and tested using the HYBON 2026 roving in commercially available non-crimp fabrics (same fiber orientation within a ply). These results were used as the lower limit considered acceptable for any new material. All laminates were produced with a standard epoxy resin (Momentive Epikote™ MGS L135/Epikure™ MGS RIM H1366) via vacuum assisted resin transfer molding (VARTM).

The evaluation conducted on unidirectional laminates used a dry filament winding process. While not viable for the production of wind blade components, this process was used as an upper boundary for composite laminate performance because it allowed for higher fiber volume fractions[2] than those achieved with today's non-crimp fabric technology. The performance result was expected to be representative of a composite laminate produced through automation.

Four independent epoxy prepreg producers were selected to manufacture the materials. After fabrication according to the laminate schedules, the laminates were laid on a flat tool using either an automated tape laying machine or a fiber placement machine (depending upon the material format requested by MAG) and were molded under vacuum at the recommended temperature defined by the prepreg producers (fig. 2). Table II summarizes the unidirectional (UD) material forms and laminate processes used in the study. Tensile, compressive and fatigue properties were determined for these materials.

The tensile strength of the materials was segmented into three groups. The highest perform-

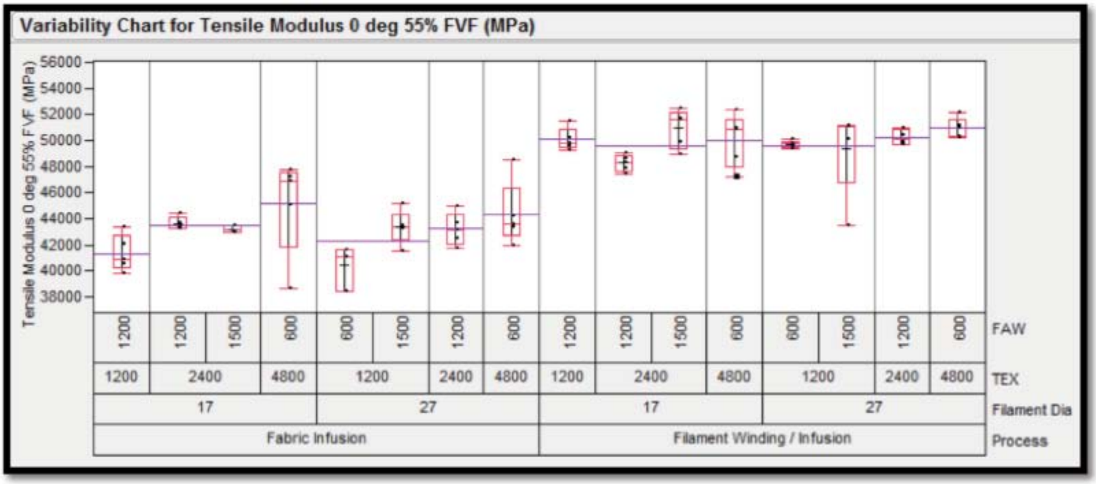

Fig. 1: Tensile Modulus for UD composite laminates produced with weft insertion fabrics and dry filament winding (with varying filament diameter, linear density, and fabric areal weight).

Property	Standard
Tensile strength and tensile modulus in the fiber direction	ISO 527
Tensile strength (perpendicular to the fiber direction)	ISO 527
Tension-tension fatigue performance of composite laminates	ISO 13003
Compressive strength and modulus in the fiber direction	ISO 14126
Fiber volume fraction	ISO 1172
Specific gravity	ISO 1172

Table 1: Identified critical material properties for wind blade composites.

ing material was the dry wound laminate and was considered a "benchmark" because it is not a feasible wind blade manufacturing solution. The second group consisted of one UD towpreg, the UD slit tape, and the UD wide tape laminates. The third group, and lowest performers, consisted of the standard non-crimp fabric widely used for blade production and one UD towpreg material. The statistical comparison of the tensile strength by material form (fig. 3) indicated that modest improvements (0-13 percent, depending on specific material format) in tensile strength can be achieved with the prepreg/automation materials when compared to the standard non-crimp materials commonly used.

The tensile modulus for the diverse material forms is shown in fig. 4. This analysis confirmed that the effect of laminate glass content, driven by the reinforcement format and manufacturing process, has a significant impact on the stiffness of the laminates. All of the UD prepreg/automation material inputs performed significantly better than the non-crimp fabric baseline and were statistically equivalent to the upper bound dry wound infusion laminates. This is a promising finding as it proves that by using automation techniques for laminate production and the state of the art reinforcements, significantly higher stiffness—up to 20 percent, in some cases—can be achieved. Therefore, longer blade lengths and improved energy generation capacity could be realized.

The compressive properties of a composite material greatly depend on the compressive performance of the resin system and fiber alignment. The compressive properties measured in most prepreg/automation materials were statistically equivalent to the standard fabric-based materials utilized in the industry. Similar trends to those observed in the UD laminates were observed with double bias laminates and do not merit additional discussion. The glass transition temperatures for the epoxy resin systems were found to be significantly higher than the infusion epoxy resin Tg.

Fig. 2: Unidirectional towpreg processing in a flat tool via automated fiber placement machine (photo courtesy of MAG).

Representative laminates of all material variants were subjected to tension-tension fatigue to determine the S-N fatigue curve using a servo hydraulic testing machine. The specimens were subjected to various levels of cyclic loading at a rate of 5 Hz with an R value of 0.1 until failure. Figure 5 shows the fatigue performance of the different materials compared to the current non-crimp technology (UD

NCF infusion). While the performance of the dry wound infused laminates was not achieved, it was encouraging to note that both the Towpreg 1 laminate and slit tape laminate performed significantly better than the industry standard.

PREDICTIVE MODELING

To evaluate the impact of the composite laminates on wind blade performance, a full scale finite element blade model was developed. The model used a 33.25m long blade geometry imported from Nu-

Material Form	Laminate Process	Description
UD non-crimp fabric (standard control – lower bound)	Infusionva	Infusion
UD dry wound roving (upper bound)	Infusion	Infusion
UD towpreg 1/prepreg	Fiber Placement/Automation	A single end of 2400 TEX roving is impregnated with B staged epoxy resin; the material is chilled and is helically wound on a 3" cardboard spool.
UD towpreg 2/prepreg	Fiber Placement/Automation	A single end of 2400 TEX roving is impregnated with B staged epoxy resin; the material is chilled and is helically wound on a 3" cardboard spool.
UD wide tape/prepreg	Tape Layup/Automation	Several ends of 2400 TEX roving are brought together in parallel and are impregnated with B staged epoxy resin to produce a 12" wide tape. Interleave PE/siliconized paper film is used to prevent material from adhering to each other and allow for subsequent unwinding in automatic manufacturing.
UD slit tape/prepreg	Fiber Placement/Automation	Several ends of 2400 TEX roving are brought together in parallel and are impregnated with B staged epoxy resin to produce a 4" wide tape. The material is slit and helically wound into 16 - 1/4" slit tape spools in a secondary process. Interleave PE film is used to prevent material from adhering to each other and allow for subsequent unwinding in automatic manufacturing.

Table 2: Material forms and processes evaluated for technical feasibility assessment.

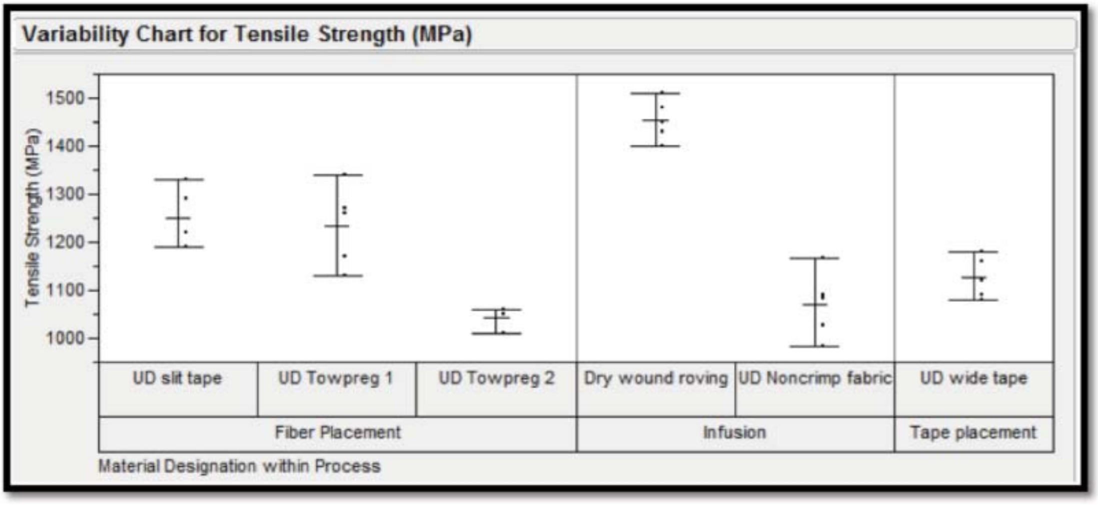

Fig. 3: Tensile strength (MPa) vs. material designation for UD laminates.

Rotor Radius (R)	35m
Blade Length (L)	33.25m
Max. Chord	2.8m
Max. Chord Location (% of R)	25
Twist	10.5^0
Weight of the Blade	4733 Kg
Number of Airfoil Stations	6
Airfoil Sections Type	Circle, S818,S825,S826

Table 3: Blade model specifications[3].

Layer #	Material	Thickness
1	Gel coat	0.51 mm
2	Random mat	0.38 mm
3	Tri-axial fabric	0.89 mm
4 0%-15% c 15%-50% c 50%-85% c	 Balsa Spar Cap Mixture Balsa	 0.5% c Specified % t/c 1.0 % c
5	Tri-axial Fabric	0.89 mm

Table 4: Blade structural shell material definition[3].

merical Manufacturing and Design (NuMAD) software, which was originally developed by Sandia National Laboratories into an finite element analysis (FEA) platform using ANSYS® software. The model included detailed laminate and material information based on a composite shell element formulation for the prediction of stresses and deformations. The blade model specifications are outlined in Table III and IV and are documented in detail in the National Renewable Energy Laboratory (NREL) report (NREL/SR-500-29492)[3] and correspond to a three-blade wind turbine with rotor radius of 35m and tip speed ratio of 7 for a generation capacity of 1.5MW.

All pre-processing of the 3D FEA, model geometry creation (fig. 6), material designation (Table IV and V), meshing, and boundary condition definition was done using NuMAD software. The blade model wire frame geometry is shown in fig. 7.

For the model, the spar cap consisted of alternating layers of tri-axial (CDB340) and unidirectional fabrics (A260). The tri-axial fabric was composed of 50 percent $\pm 45^0$ and 50 percent 0^0 fibers. The spar cap mixture laminate had 70 percent unidirectional and 3 percent tri-axial fabrics by weight. Although changes were implemented to the spar cap, no changes were performed on the root or shear web sections from the NREL design. The material models described in Tables IV and V were assigned to the blade 3D model in NuMAD. The 3D model generated in NuMAD was analyzed in ANSYS using a composite shell element (SHELL281, fig. 8). SHELL281 is an eight-node structural shell with 6 degrees of freedom at each node (translations and rotations in X, Y, and Z axes).

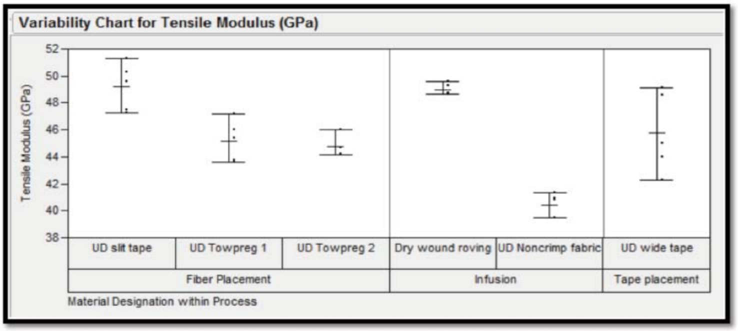

Fig. 4: Tensile modulus (GPa) vs. material designation (UD laminates).

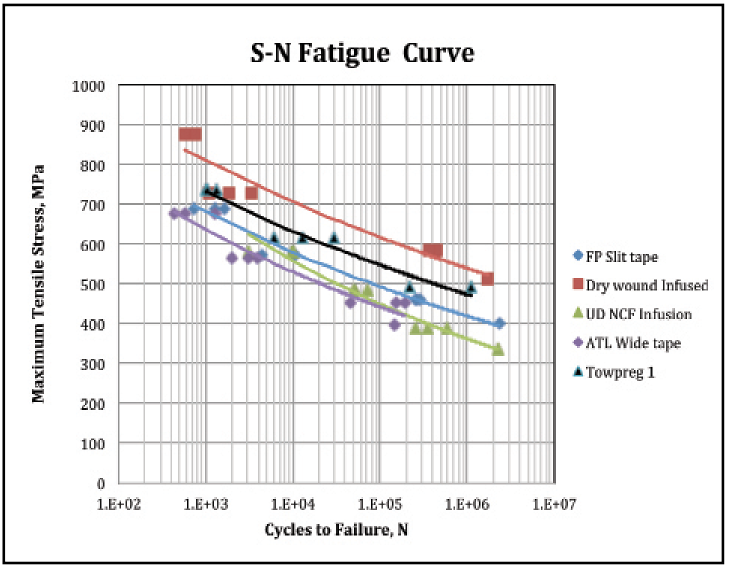

Fig. 5: Fatigue performance of automation materials and non-crimp fabric based laminates..

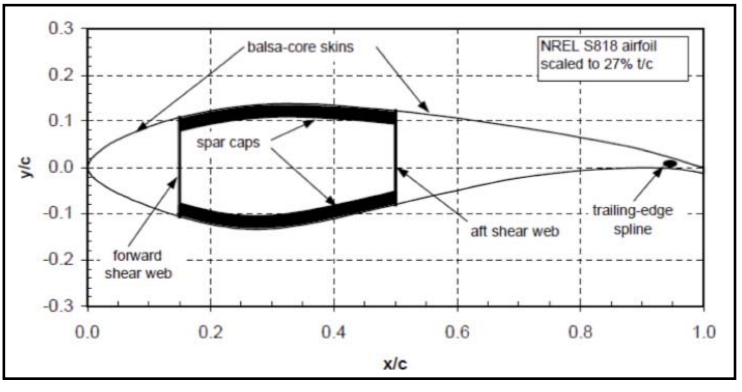

Fig. 6: Blade geometry cross section[3].

Using the ANSYS GUI environment, a master node was defined at the tip of the blade and coupled to the blade tip edge nodes. A static load of 1,000 kg was applied at the master node, acting vertically downwards along the Y-axis of the model coordinate system, inducing flap-wise deformation to the blade. A dummy load was selected to characterize the stiffness of the blade and had no relation to the actual aero-elastic loads expected to be endured during blade service. The model was also used to calculate the weight of the different sections of the blade.

Using the baseline model, the material properties of the blade were replaced with state of the art properties from the UD prepreg using HYBON 2026 roving input and other E-glass offerings from PPG. The maximum displacement occurred at the blade tip in the flap wise direction. The weight of the new blade was calculated as 5237 kg, due to the increased fiber weight fraction of the unidirectional composite.

The focus of the modeling efforts shifted to the impact of the mechanical properties of the evaluated materials on blade weight and energy generation capacity. For this purpose, the blade model was scaled to generate a 40m, 3MW blade. The experimentally determined mechanical properties from the analysis were used to design equivalent stiffness blades, using the highest performing automation materials. The total calculated blade weights from the FEA model and the blade lengths are summarized as follows:

Case 1: The spar cap of the blade is produced with UD prepreg while keeping the remaining blade materials constant. The blade can be made 4 percent lighter while maintaining the stiffness of the baseline 40m blade.

Case 2: The complete blade is made by prepreg/automation using automated fiber placement.

Property	A260 UD	CDB340 Tri-axial	Spar Cap Mixture (70% UD and 30% tri-axial)	Random Mat	Balsa	Gel Coat	Fill Epoxy
Ex (GPa)	31	24.2	27.1	9.65	2.07	3.44	2.76
Ey (GPa)	7.59	8.97	8.35	9.65	2.07	3.44	2.76
Gxy (GPa)	3.52	4.97	4.7	3.86	0.14	1.38	1.1
Vxy	0.31	0.39	0.37	0.3	0.22	0.3	0.3
Vf	0.4	0.4	0.4	-	N/A	N/A	N/A
wf	0.61	0.61	0.61	-	N/A	N/A	N/A
Density (g/cm^3)	1.70	1.70	1.70	1.67	0.144	1.23	1.15

Table 5: Preliminary blade material properties[1].

The blade has a 5 percent weight savings compared to the baseline due to the increased stiffness provided by the pre-impregnated materials.

Case 3: The blade is produced with pre-impregnated rovings using automated fiber placement but the blade length is increased without increasing tip deflection. The resulting blade is heavier, but energy generation capacity was increased by approximately 6 percent.

Case 4: The spar cap is made using automation but the blade length was increased to match the stiffness of the baseline. The blade length increased to 40.8m and resulted in an energy generation capacity increase of approximately 4 percent.

CONCLUSION

Materials suitable for automation were evaluated and composite laminates made using those materials demonstrated significant improvements in laminate strength, stiffness and fatigue life as compared to existing materials.

The automated fiber placement process was found to be a technically feasible alternative to resin infusion to produce equivalent or higher performing composites. The potential for higher strength, stiffness and durability compared to current materials used for the production of blades was shown.

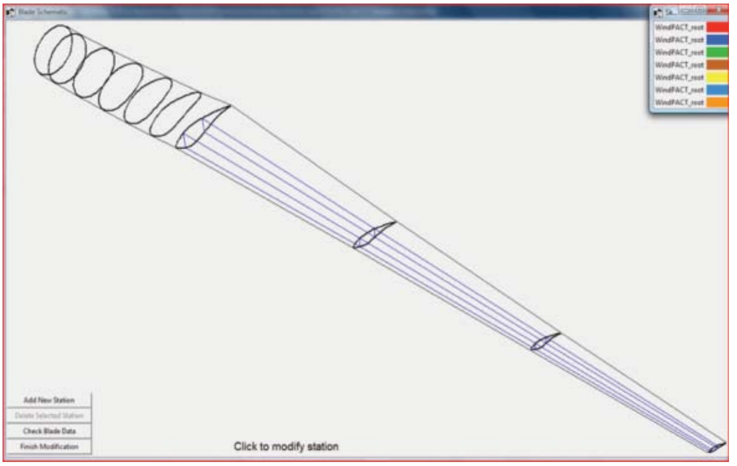

Fig. 7: Blade wire frame geometry in NUMAD.

The materials designated as Towpreg 1 and slit tape processed via automated fiber placement resulted in increased performance and are recommended as technology capable or that requiring minor development for further evaluation. A manufacturing trial on a scaled wind blade component is recommended at this point as these materials have proven capable of increased mechanical properties against the benchmark materials and were found to be amenable to automated processing.

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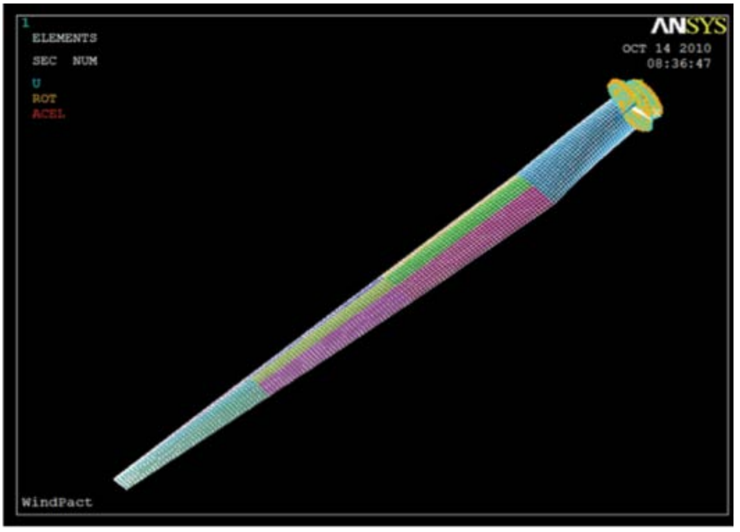

Fig. 8: Blade finite element model boundary conditions

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REFERENCES:

1) Watson, J.C., and J.C. Serrano. “Composite Materials for Wind Blades.” Wind Systems. September 2010: 46-51.
2) Serrano, J. C., J. Watson, S. Vennam. “Performance Drivers on Glass Fiber Composites for Wind Blades.” International SAMPE Technical Conference (2011) p. 14.
3) WindPACT Turbine Design Scaling Studies Technical Area 1. Composite Blades for 80- to 120-Meter Rotor, NREL/SR-500-29492, April 2002.