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LIST OF ACRONYMS

ATL - Automated Tape Layup
BIAX – Biaxial [0/90] Laminate
COE – Cost of Energy
DOE – Department of Energy
FW – Filament Winding
FP – Fiber Placement
FVF - Fiber Volume Fraction (%)
GUI – Guide User Interface
HM – High Modulus
ISO – International Standards Organization
IRR – Internal Rate of Return
MSU – Montana State University
NCF – Non Crimp Fabric
NPV – Net Present Value
NUMAD – Numerical Manufacturing and Design Tool
OOA – Out of Autoclave
PE – Polyethylene
ROA – Return on Assets
ROCE – Return of Capital Employed
TRIAX – Triaxial Laminate
UD – Unidirectional [0] Laminate
VARTM – Vacuum Assisted Resin Transfer Molding
WACC – Weighted Average Cost of Capital

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Executive Summary

New and novel material and process technologies applied in wind blade designs and production are critical to increasing the competitiveness of wind power generation against traditional sources of energy. In this project, through collaboration between PPG Industries and MAG Industrial Automation Systems, the potential of using automated manufacturing for the production of fiber glass composite wind blades was evaluated from both technical and economic points of view. Further, it was demonstrated that by modifying the standard blade raw material forms through the use of cost effective pre-impregnated rovings coupled with using an automated fiber placement machine to lay up the parts, it is possible to produce state of the art composite laminates with significantly improved mechanical performance and with higher processing rates than standard blade production technology allows for today, thereby lowering the cost of energy over turbine blades made using traditional processes and materials.

Comparison with Program Goals

In conformity with the scope of work of the submitted proposal, the project team completed each task and documented and reported its findings on the appropriate quarterly report submitted to the DOE project team. The activities and this report are divided into 5 subtasks:

- Material Investigation – Reviews traditional materials and key specifications and testing methods.
- Manufacturing and Automation – Identifies new candidate material forms and automated layup processes.
- Process Development – Performs trials of candidate materials and processes.
- Predictive Analysis – Assesses impact of new material forms and automated processes on a model blade design.
- Feasibility Assessment – Compares traditional manufacturing processes and materials to new candidate material forms and automated processes.

Task 1 – Materials Investigation

1.1. Database Review

A comprehensive review of the MSU/DOE composite material database was performed. Internal PPG test data as well as publicly available mechanical property data from other material suppliers were entered into a broader material property database compiled using Microsoft® Access. The database was used to determine the state of the art in composite material technology and the material performance characteristics (see Table 1 below) used as selection criteria by wind blade designers. These parameters were used as a benchmark for the material investigations and testing performed through the remainder of the program.

Table 1 Identified Critical Material Properties for Wind Blade Composites

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

From the database review the following conclusions were drawn:

1. From the static test data reviewed it can be inferred that for unidirectional laminates made with E-glass and epoxy resin, prepreg based laminates have better tensile modulus compared to equivalent infused laminates.
2. Tensile modulus values of 47 GPa and 48 GPa were reported in the MSU database for unidirectional laminates made with Scotchply™ SP250E glass prepreg manufactured by 3M and GURIT, respectively, on Sparpreg™ UD glass prepreg. These correspond to the highest tensile modulus reported with E-glass based composites.
3. R-glass fiber based UD laminates reported higher tensile strength and tensile modulus compared to E-glass fiber based UD laminates, but the same trends were not evident in complex (alternating ply) laminates. This finding highlighted the importance of material form optimization in achieving improved mechanical properties in a composite laminate.
4. Fatigue performance of R-glass epoxy based laminates was observed to be superior to E-glass epoxy based laminates.
5. Laminates fabricated with PPG HYBON 2026 roving and epoxy resin were shown to result in higher fatigue performance (even at high fiber volume fractions) when compared to laminates produced with other roving inputs.

1.2. Material Selection

Fiber glass reinforcements and polymer resins used in wind blades can be found commercially in a wide variety of formats. For the case of the fiber reinforcements in particular, there is a broad range of fiber diameters, fabric areal weight and fabric architecture, sizing chemistry etc. that are routinely used by the different blade makers and wind OEMs depending on their manufacturing process and specific mechanical requirements. As part of this project, a parametric experiment was designed to evaluate the effects of three parameters (fiber diameter, linear density (TEX) and areal weight of the fabric) on the material properties. Two levels for the fiber diameter (17 and 27 microns), and three levels each for linear density (1200TEX, 2400TEX, 4800TEX) and areal weight (600gsm, 1200gsm, 1500gsm) were considered. The test plan consisted of 8 experimental samples produced with the objective to identify the interactions between the linear density (TEX) and areal weight of the fabric while minimizing the number of experiments. The glass fiber sizing chemistry and the sizing content (LOI) was kept constant in all cases (PPG HYBON 2026 – Multi compatible roving). A total of 8 weft-inserted unidirectional fabrics with the trial rovings were produced for the subsequent molding of composite plates. Table 2 illustrates the corresponding description of the fabrics produced.

Table 2 Fabric architecture produced with combinations of fiber diameter, linear density and fabric areal weight

Fabric Designation	Fiber Diameter (Microns)	Fiber Linear Density (TEX)	Fabric Areal Weight (g/m ²)
1	17	1200	1200
2	17	2400	1200
3	17	2400	1500
4	17	4800	600
5	27	1200	1500
6	27	1200	600
7	27	2400	1200
8	27	4800	600

Once the laminates were manufactured from the developed fabrics and were tested for their static and dynamic mechanical properties, a statistical analysis revealed that none of the reinforcement driven factors considered i.e. filament diameter, linear density and fabric areal weight, appeared to have a significant effect on the static tensile strength and tensile modulus performance of both the fabric based and the dry filament wound based laminates. A detailed summary of the mechanical data and the statistical analysis completed can be found on the published conference paper titled “Performance Drivers on Glass Fiber Composites for Wind Blades” presented at the SAMPE technical conference in Long Beach, CA in May of 2012. The major conclusions from the materials selection task are included below:

1. The weft inserted fabric based laminates showed inferior performance compared to the dry wound infused laminates. This suggests that the fabric architecture seems to be the influencing factor as it determines the resulting fiber volume fractions. Furthermore, the fabric architecture is indirectly being affected by the linear density of the fiber. The

lower the linear density and higher the fabric areal weight, the more tightly packed are the fibers in the fabric which leads to excessive waviness (higher crimp). This reduces the static tensile and fatigue performance of the laminates. While this effect is not as pronounced in traditional stitch bonded fabrics used in the wind industry, the resulting performance of the dry wound UD laminates suggests considerable potential performance benefits for UD prepreg-based laminates that are not prone to misalignment, or crimp and do not include any weft reinforcements.

2. The tension-tension fatigue performance for UD filament wound laminates produced with direct draw roving inputs with lower level filament diameter fibers (17 μm) appeared to be statistically higher than equivalent laminates produced with (27 μm) fibers for the produced test laminates.

1.3 Laminate Production and testing:

Several unidirectional, biaxial and triaxial laminates were produced throughout the program using the corresponding fabric constructions and ply schedules with a standard wind energy epoxy resin (Hexion RIM L135/RIM 1366) via vacuum assisted resin transfer molding (VARTM). The mechanical properties (static and dynamic) of the different plates produced were then measured using the corresponding ISO standards identified in 1.1 (see Table 3 and Figure 1).

As a representative sample of current wind energy composite materials technology and in support of the database analysis and the materials selection task, a set of composite laminates (uniaxial, biaxial and triaxial) was produced and tested with PPG's HYBON 2026 (state of the art wind energy E-glass roving) on commercially available stitch-bonded fabrics. The test results from the stitch-bonded fabric based laminates were used as the baseline performance considered acceptable for any new material to conform to industry standards.

Additionally, the same set of experiments and tests was conducted on unidirectional laminates manufactured using a dry fiber winding/infusion process. This process, while not commercially viable for the production of wind blade components, can be used as an upper bound level for composite laminate performance as it allows for significantly larger fiber volume fractions than those reached with standard non-crimp fabric technology used in the industry today. As such, its performance was expected to be more in line with that of a composite laminate produced through automation.

Table 3 Mechanical test data for UD, biaxial, double bias and complex laminates produced via resin infusion

Process			Dry Fiber Winding/Infusion*	Stitch bonded fabric – Vacuum Infusion			
Benchmark			HIGH	LOW			
Property	Units	Standard	UD	UD	Biax 0/90	Double Bias +/-45	Quad [+45/0/90/-45]
Tensile Strength 0 (Avg)	MPa	ISO-527	1450	1060	394	85	236
Tensile Strength - 0 deg (COV)	%		3.0	5.1	6.8	2.1	10.62
Tensile Modulus 0 (Avg)	MPa	ISO-527	48990	41100	21360	12100	15470
Tensile Modulus - 0 (COV)	%		1.7	3.0	8.2	2.5	9.27
Tensile Strength -90 (Avg)	MPa	ISO-527	64.6	41.7	315	85	241
Tensile Strength - 90 degree (COV)	%		4.9	3.2	10.5	2.1	4.66
Tensile Modulus - 90 (Avg)	MPa	ISO-527	15800	11000	19830	12100	15670
Tensile Modulus - 90 (COV)	%		1.6	6.3	4.8	2.5	5.29
Compression Strength 0 (Avg)	MPa	ISO-14126	850	640	280	130	230
Compression Strength - 0 (COV)	%		5.7	3.3	5.1	1.0	11.1
Compression Modulus 0 (Avg)	MPa	ISO-14126	43460	42400	16200	12900	12140
Compression Modulus - 0 (COV)	%		6.3	4.3	26.94	11.6	28.7
Specific Gravity	g/cc	ASTM D792	2.05	1.9	1.81	1.8	1.8
% Glass Content (Avg)	%	ASTM D2584	79	72	64.8	72	64.5
% Resin Content (Avg)	%	ASTM D2584	21	28	35.2	28	35.4

*Dry fiber winding/infusion was used as a benchmark and is not yet a feasible process for wind blade automation.

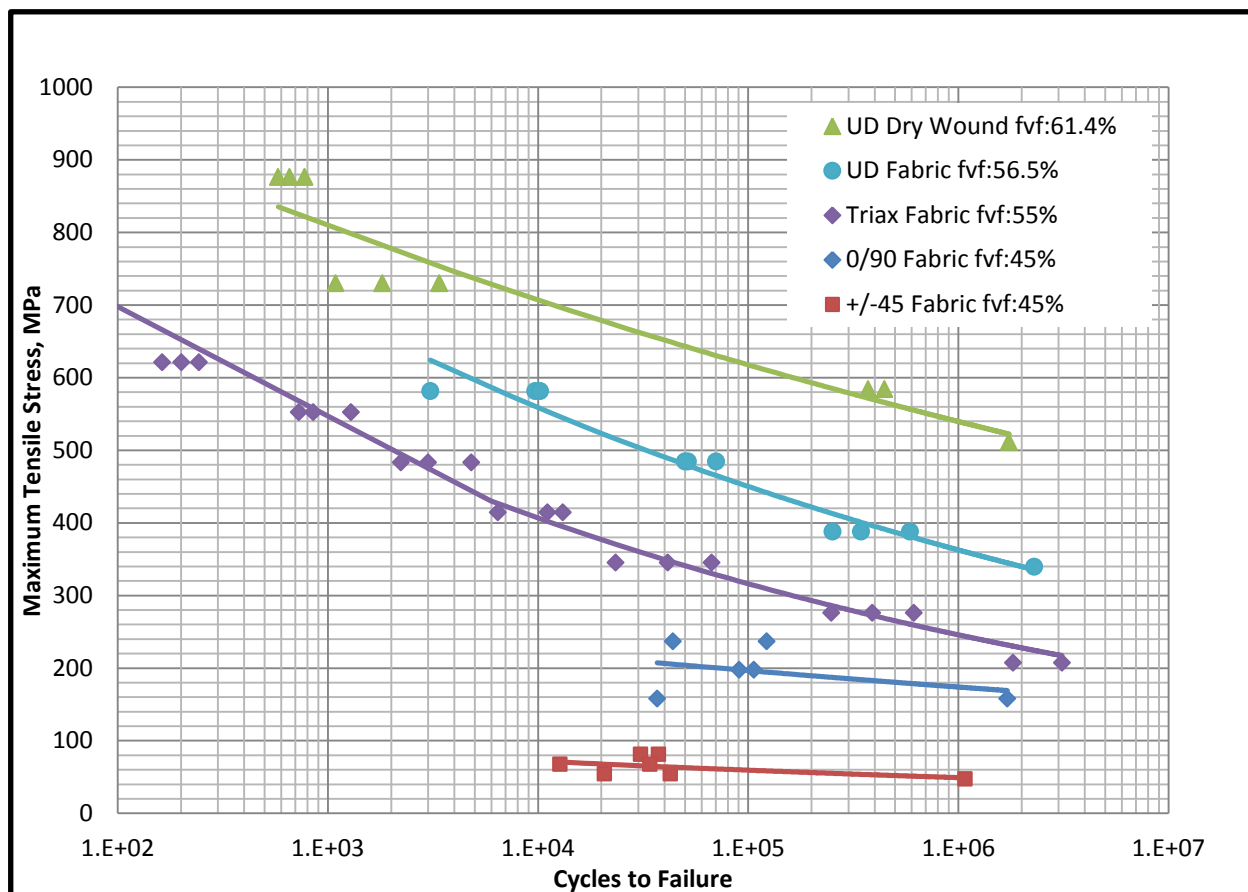


Figure 1 Fatigue performance of infusion-based composites. (Note: UD dry fiber wound/infusion used as benchmark only but is not a feasible wind blade manufacturing process)

Task 2 - Manufacturing and Automation

2.1 Process Benchmarking

This task included a comprehensive study of blade fabrication methodologies common in the wind industry. From this analysis, three main blade design/production methodologies were identified and were classified as *Type 1*, *Type 2* and *Type 3* blades (Fig 2).

Type 1 blades include a central “box beam” spar made through the use of unidirectional prepreg and subsequently overwrapped with glass fiber prepreg around a rotating mandrel. The cured spar is then adhesively bonded to separately molded blade shells which can be produced either via vacuum infusion or through vacuum molded prepregs. The complete assembly is then cured in a closed mold at the respective temperature dictated by the corresponding resin system.

Type 2 blades consist of a bottom and top blade shell made through vacuum infusion in which a premolded spar cap section (unidirectional fabric based) is integrated into the shell structure prior to infusion. The two shells are bonded together by closing together hinged tooling along with the introduction of two vertical shear webs (made primarily with double bias reinforcements and core materials). All other subsections including the root section are premolded via vacuum infusion on non-crimp fabrics and are cured separately prior to bonding.

Type 3 blades are made through a 1-shot vacuum infusion process and integrate a joint-free blade construction that typically features a single main spar. The reinforcements are placed in the proper orientations according to the structural purpose of the section in a similar manner as in type 1 and type 2 blades.

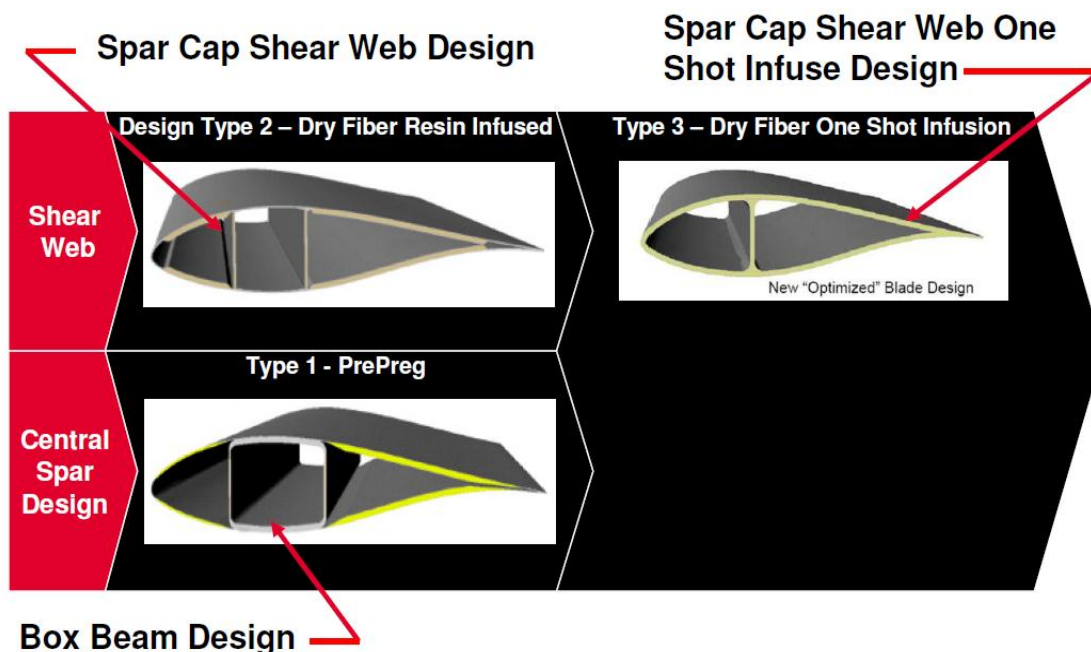


Figure 2 Typical blade designs used today in the wind industry

2.2 Manufacturing /Automation Concept Development

Automated layup of composite materials provides many benefits over manual hand layup methods. Primary benefits of automated layup over hand layup include:

- More accurate material placement for more repeatable and consistent molded parts.
- Elimination of wrinkles in laid up materials, resulting in higher strength laminates.
- Higher material utilization which lowers overall material requirements and scrap generation.
- Ability to optimize design by leveraging automation advantages.
- Higher throughput of parts in less floor space, thereby lowering overall indirect costs.

Outside of the scope of this project, MAG already embarked on the development of an automated fiber placement gantry machine called the VIPER[®] 7000, which is capable of producing up to 60 m blades. This machine represents a natural iteration and refinement of 30 years of MAG's supply of fiber placement systems used in the production of structural aerospace components. The machine is a 6-axis configuration that consists of a gantry bridge structure guided on low floor rails that can straddle a single skin mould lay-up tool or two spar cap lay-up tools. The machine is easily configurable for longer blades by simply adding sections of floor rail to the machine. If required, the floor rails can be below floor level to provide open floor access for easy mould tool shuttle. The machine can place prepreg in a half shell skin mould that has 2.5 m minimum root diameter and is up to 60 m in length. The machine

configuration is a medium sized high speed gantry with uprights supporting a horizontal cross-rail. The cross-saddle which is cantilever mounted to the cross-rail provides 4.0 m of cross travel motion of the vertical slide. The vertical slide provides 1.5 m vertical travel of the 3- axis wrist and FP (fiber placement) head.

The machine can have as many as 64 material spools (32 in each creel house) including an automatic spool changing system to enable continuous operation. Each creel house will be attached to one of the machine gantry uprights near factory floor level. Each creel house can deliver 16 lanes into the fiber delivery system that feeds the vertically oriented head operating in the center of the system. Each creel house can also hold 2 spools per lane (32 spools total feeding 16 lanes) and is enabled with auto splice of the waiting spool when the first one is depleted.

As part of this project, a virtual process simulation was produced using the VIPER[®] 7000 machine on MAG's ACES Offline Programming and Simulation software to determine manufacturing efficiency, material lay down rates, process timing, interference issues, etc. A snapshot of a skin manufacturing simulation is shown in Figure 3 and a rendering of MAG's VIPER[®] 7000 machine is shown in Figure 4.

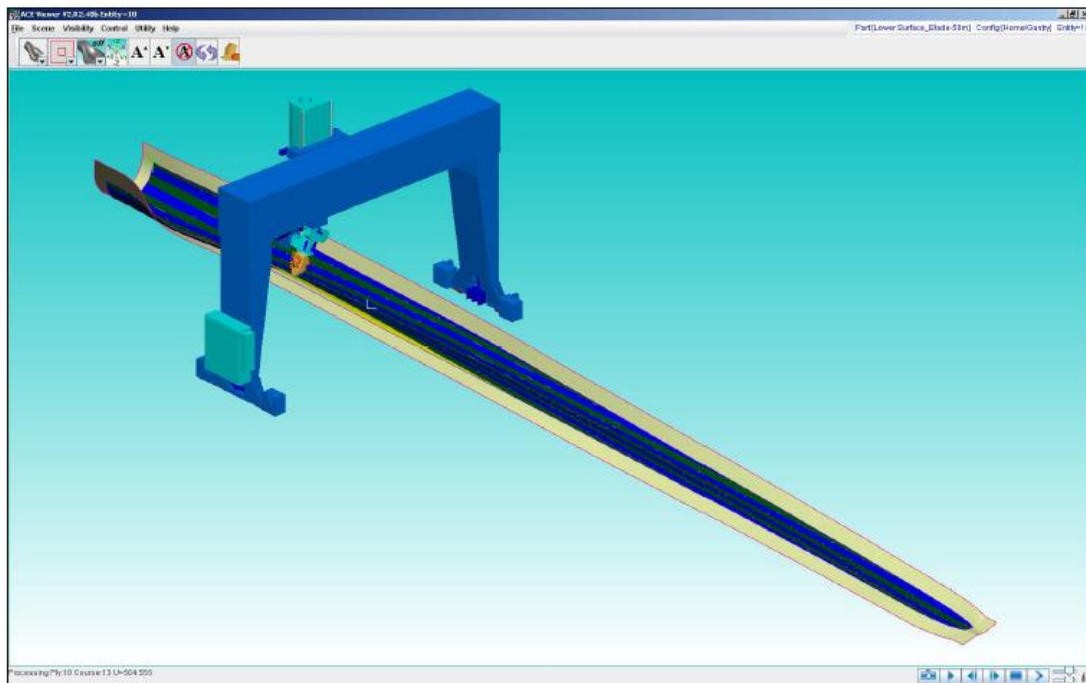


Figure 3 Automated Manufacturing simulation on VIPER 7000 developed by MAG for production of blade skins and spar caps

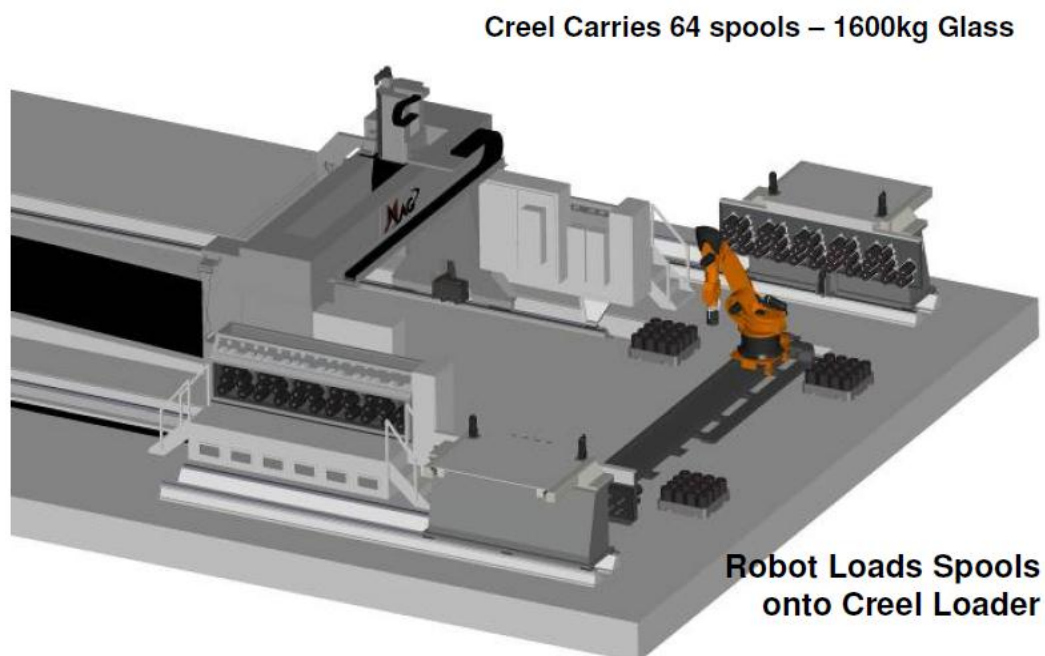


Figure 4 MAG VIPER 7000 Automated Material Loading Concept

Task 3 - Process Development

Existing “automation ready” carbon fiber prepreg materials used widely in aerospace applications exhibit excellent process and mechanical performance. However, these materials are cost prohibitive for the wind industry and are not a feasible alternative. Thus, it was the intention of this part of the project to produce and evaluate cost competitive alternatives to aerospace grade materials for use in existing automated equipment. For this purpose, four independent epoxy prepreg producers, each with unique proprietary prepreg technology were approached to support the intermediate material production suitable for automation.

3.1 Material Process Characteristics and Prepreg Production

Prepreg material input for the automation trials was produced in a variety of product formats. The table below shows a breakdown of the intermediate material forms produced and the corresponding production and evaluation schedule.

Table 4 Material production and evaluation schedule

Material Designation	Format	Fiber Orientation	Production	Process Evaluation	Laminate Production	Testing
NCF DB	ATL	45/-45	Q3 2010	Q4 2010	Q4 2010	Q4 2010
NCF	ATL	0/90	Q3 2010	Q4 2010	Q4 2010	Q4 2010
Wide tape	ATL	0	Q4 2010	Q1 2011	Q1 2011	Q1 2011
Towpreg 1	FP	0	Q4 2010	Q4 2010	Q4 2010	Q1 2011
Towpreg 2	FP	0	Q4 2010	Q4 2010	Q4 2010	Q1 2011
Slit tape	FP	0	Q1 2011	Q1 2011	Q1 2011	Q1 2011

NCF – Non crimp fabric
ATL – Automated Tape Layup
FP – Fiber placement
DB – Double bias

3.2 Surrogate Process Trials

Once the intermediate materials were produced, automated lamination trials were performed at MAG for both ATL (Automated Tape Layup) grade materials and FP (Fiber Placement) grade materials as per the Table 4 schedule. ATL material is traditionally 3" (75mm), 6" (150mm) or 12" (300mm) wide. The ATL machine dispenses a single roll of material during each pass of the machine. Fiber placement machine dispenses up to 32 lanes of material simultaneously. The lanes are typically .125" (3mm), .25" (6mm) or .5" (12mm) wide each and the material is wound on spools similar to thread. In both cases, the material is uni-directional with fibers running the length of the spool or roll. However, some fabric type materials can be dispensed on tape laying equipment and the following trials include such material.

The standard process evaluation procedure included the layup of UD, biaxial and triaxial laminates for subsequent vacuum oven molding and mechanical testing. For successful processing in automated equipment, certain material traits are required, including:

- Low amount of fuzz being generated while processing through the machine,
- Consistent unwinding properties, including consistent unwinding tension and minimal stringer formations caused by fibers on the different spool layers adhering to one another,
- Consistent width and thickness control (for processing through the machine and final laminate qualities),
- Minimum resin accumulation on machine components as the material is being processed by the machine,
- Adequate resin saturation throughout the material,
- Appropriate tack level that allows processing, without sticking to machine components.

For each material layup trial, the process engineer documented the processing characteristics mentioned above. A compilation of comments on the materials produced is included below:

Non crimp fabric based epoxy prepreg. ATL grade.

The material was delivered wound on 3" (7.5 cm) diameter cardboard cores and subsequently re-wound in small batches to fit on the tape laying machine. This fabric based prepreg appeared to have adequate resin impregnation and did not show any evidence of fabric distortion. Material packaging, slip sheet and appearance were deemed adequate. Tack level was low to the touch, but the material adhered to itself sufficiently under light compaction pressure. The prepreg tape was made with normal release paper on one side and polyethylene (PE) film on the back surface. The material cutters worked well to trim the tape, but showed some signs of resin accumulation after the trials. No fuzz was generated through the process.

Fiber glass 12" (0.3 m) wide tape. ATL grade.

Tape appearance and packaging was adequate, and the roll was re-wound with paper on the inside of the tape as required by the specific machine. Future machines could be designed to process material without backing paper. The material ran through the tape laying machine without problems, and fiber wet out appeared adequate. Adhesion and tack was sufficient to hold on to the paper and it released without any problems when placed on the tool. The

automated cutter cut with only a slight amount of resin accumulation on the blade through the trials.

Towpreg 1. FP grade.

This .25" (6mm) wide material was processed directly from roving and placed by the manufacturer on standard cardboard cores with no backing film. The towpreg was initially too tacky for processing, but after a week of aging, tack levels had decreased and it could be processed through the machine. The cutters and guides had considerable resin residue after the trials. The material visually seemed to have adequate wet-out. The material width control needed improvement as the variation caused large gaps to form between dispensed tows, which resulted in laminates with high surface undulations and resin rich areas. The material supplier expressed confidence in being able to improve tack levels and width control on future production runs of material. Considering the history of pre-impregnated tow material, it is expected that all of these variables can be brought into a consistent operating window which provides optimum performance through the machine and in the laminate.

Towpreg 2. FP grade.

As received material was ¼" (6mm) wide, but it was thicker than other materials previously tested, which was found to be the cause of several process challenges. However, the machine can easily be modified to process thicker materials. This material was also slightly high on tack, but processed adequately through the machine and on the tool. Width variation was also observed with this sample material and thus corresponding laminates exhibited surface undulations similar to those observed on Towpreg 1. Again generally all variables that can be optimized for maximum performance through the machine and in the laminate by the material suppliers.

Fiber glass ¼" (6mm) slit tape. FP grade.

This material was processed from ¼" (6mm) wide slit prepreg tape, which represents the most expensive prepegging process and is typically reflected in material cost. Standard fiber placement PE backing film was used for the slit tape to enable relatively easy unwinding. The slit tape had acceptable width control and separated without any major problems from the PE backing. The slit tape was evaluated in three different areal densities (200, 400 and 600 gsm). Tack levels were on the higher side for all areal densities, though two laminates each were produced from the 400 and the 600 gsm tape. The 400 gsm tape was found to provide the best processing performance. Moderate resin accumulation in the cutters was observed and no fuzz accumulation was evident during any of the trials. As expected, this material was found to provide the best overall processing performance from the tested variants.

Selected illustrations of the different materials being processed in tape placement and fiber placement machines are shown on in Figure 5:

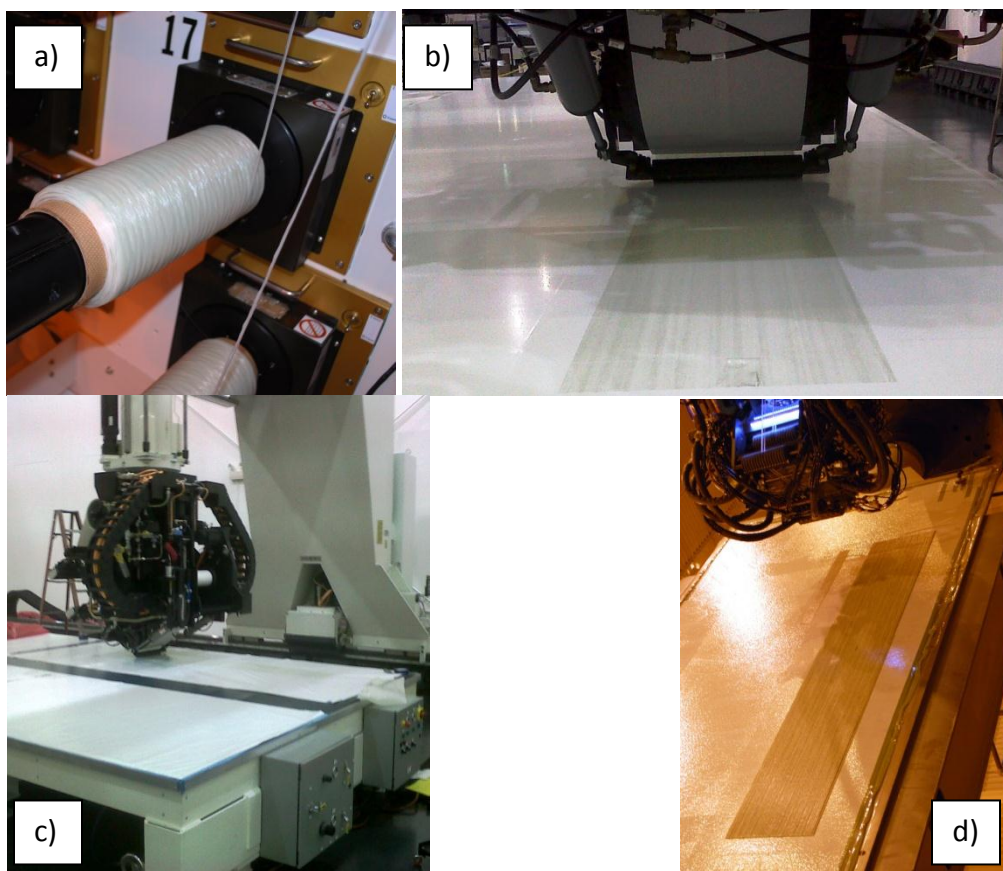


Figure 5 Different fiber glass pre impregnated materials being processed on ATL and FP machines

- a) Towpreg 1 on spools in machine
- b) Wide prepreg tape on tape laying head
- c) NCF prepreg on tape laying machine
- d) Towpreg 2 being processed by fiber placement head

3.3 Laminate Production and Testing

All composite laminates were molded under vacuum at the recommended temperature as defined by the particular requirements of the prepreg suppliers listed in Table 5. The composite laminates were then conditioned to standard laboratory conditions and tested according to the previously mentioned standards (Table 1) at PPG's ISO 17025-accredited Science and Technology Laboratory in Shelby, NC. Data analysis is included in the technical feasibility assessment - Task 5.1.2.

Table 5 Cure schedules for different prepreg systems

Material Designation	Cure temp	Cure time	Post cure
	°C	Hours	
NCF Prepreg	80	5	
UD Wide tape Prepreg	100	5	
UD Slit tape	100	5	
UD Towpreg 1	93	0.5	2H@120°C
UD Towpreg 2	80	2	1H@120°C

Task 4 - Predictive Analysis

Using the capabilities acquired through the project (software and hardware), the development and implementation of a full scale finite element blade model was completed. The model uses a 33.25 m long (1.5 MW) blade geometry imported from Sandia NUMAD into Ansys[®] FEA platform and includes detailed laminate and material information based on a composite shell element formulation for the prediction of stresses and deformations.

4.1 Motivation and Objective

The primary objective of this predictive analysis was to study the effect of blade material properties on wind turbine blade stiffness and weight and thus evaluate the impact of different material formats and processing on the resulting cost of energy (COE). This study was performed by developing a wind turbine blade 3D numerical model and analyzing it by using a commercial finite element code. The results of the finite element analysis were then incorporated into a cost of energy model developed by University of Maine.

4.2 Blade Model

The blade design utilized throughout this document is documented in detail in the NREL report (NREL/SR-500-29492)¹. It corresponds to a 3 blade wind turbine with a rotor radius of 33.25m and a tip speed ratio of 7 for a generation capacity of 1.5MW. Additional design information not included in this report can be obtained from WP_NUMAD report² and NREL FAST code³.

4.3 Blade Geometry and Structural Modeling

The general specifications of the blade model used in this study are listed in Table 6. Figure 6 shows the blade plan form. The blade is initially divided into 6 stations in the span-wise direction with stations located at 5, 7, 25, 50, 75 and 100% span (r/R). The root section is circular from 5 to 7% r/R and then transitions to an airfoil shape (S818 airfoil) located at 25% r/R, which is also the maximum chord location. The blade design then tapers linearly from maximum chord to the tip. Additional stations were added to the blade design in between 7 and 25% r/R with airfoils by linear interpolation from a circle and the S818 airfoil. Table 7 describes the station design and definition information.

Table 6 Blade model specifications¹

Rotor Radius (R)	33.25m
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
Primary Structural Member	Box Spar

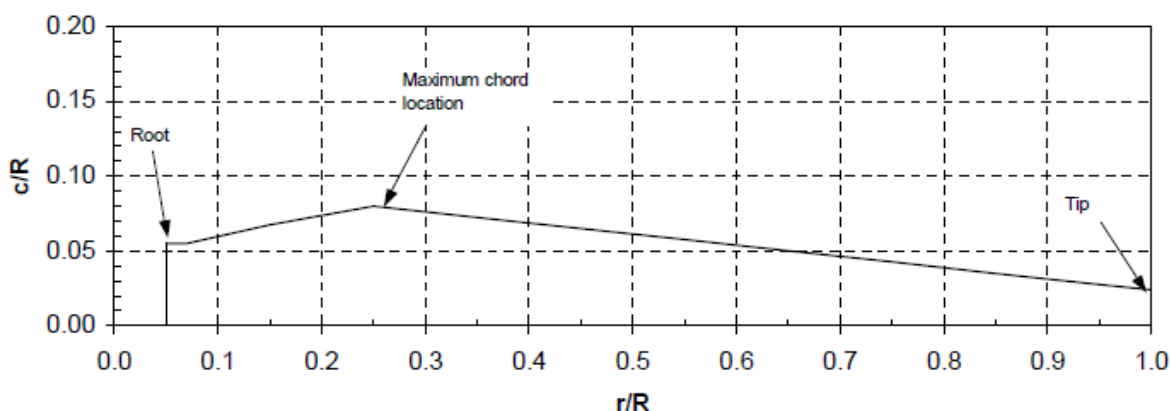


Figure 6 Blade plan form¹

Table 7 Station design and blade definition information²

	%r/R	Distance from Root (m)	Airfoil	Airfoil thickness %t/C	Chord, C	Twist (deg)	X-offset
Root	5	0	Circular	N/A	1.89	10.5	50
	7	0.7	Circular	N/A	1.89	10.5	50
	9	1.96	S818_20P	-	2.072	10.5	46
	10	3.22	S818_40P	-	2.254	10.5	42
	14	4.48	S818_60P	-	2.436	10.5	38
	21	5.74	S818_80P	-	2.618	10.5	34
Max Chord	25	7	S818	30	2.8	10.5	30
	50	15.75	S825	21	2.158333	2.5	30
	75	24.5	S825	21	1.516667	0	30
Tip	100	33.25	S826	16	0.875	-0.6	30

The primary load-carrying member in this model is designed as a box spar, with shear webs located at 15% and 50% of the chord. Figure 7 shows the blade geometry cross section at the maximum chord region. The outer skin and shear webs are designed as sandwich structures with balsa core sandwiched between tri-axial fabric laminates. The outer skin extends from 0 to 15% of the chord forming the leading edge panel and from 50 to 100% of the chord forming the trailing edge panel. The spar cap extends from 25% of the span with maximum thickness and for simplicity it is assumed to taper off to zero at the tip of the blade. The trailing edge is designed as a sharp edge without finite thickness for ease of mathematical modeling and to allow for a smaller number of elements.

4.4 Blade 3D Finite Element Modeling

All the pre-processing of the 3D finite element analysis, i.e. model geometry creation, material assignment, meshing, and boundary condition definition was done using NuMAD software. NuMAD (Numerical Manufacturing and Design) was originally developed by Sandia National Laboratories as a graphic user interface based pre processing software for ANSYS. The blade model wire frame geometry was generated with the features described in section 2.1 and is shown in Figure 8.

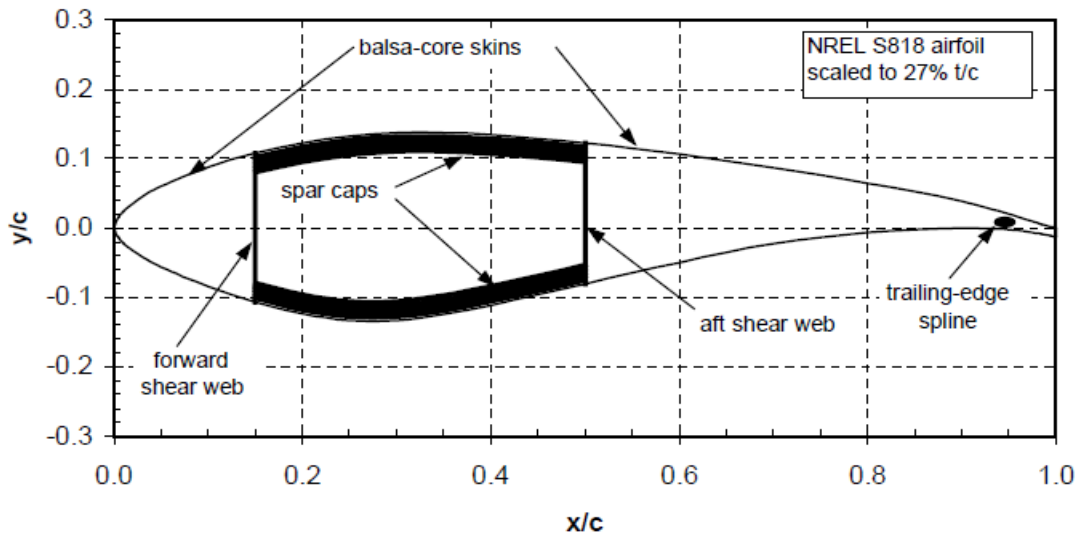


Figure 7 Blade geometry cross section¹

Table 8 Blade structural shell material definition¹

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

The blade structural shell material definition used in reference [1] was also used in the present study and is shown in Table 8 for reference. Reference [1] contains an in-depth analysis of the material properties of each layer for the different blade sections.

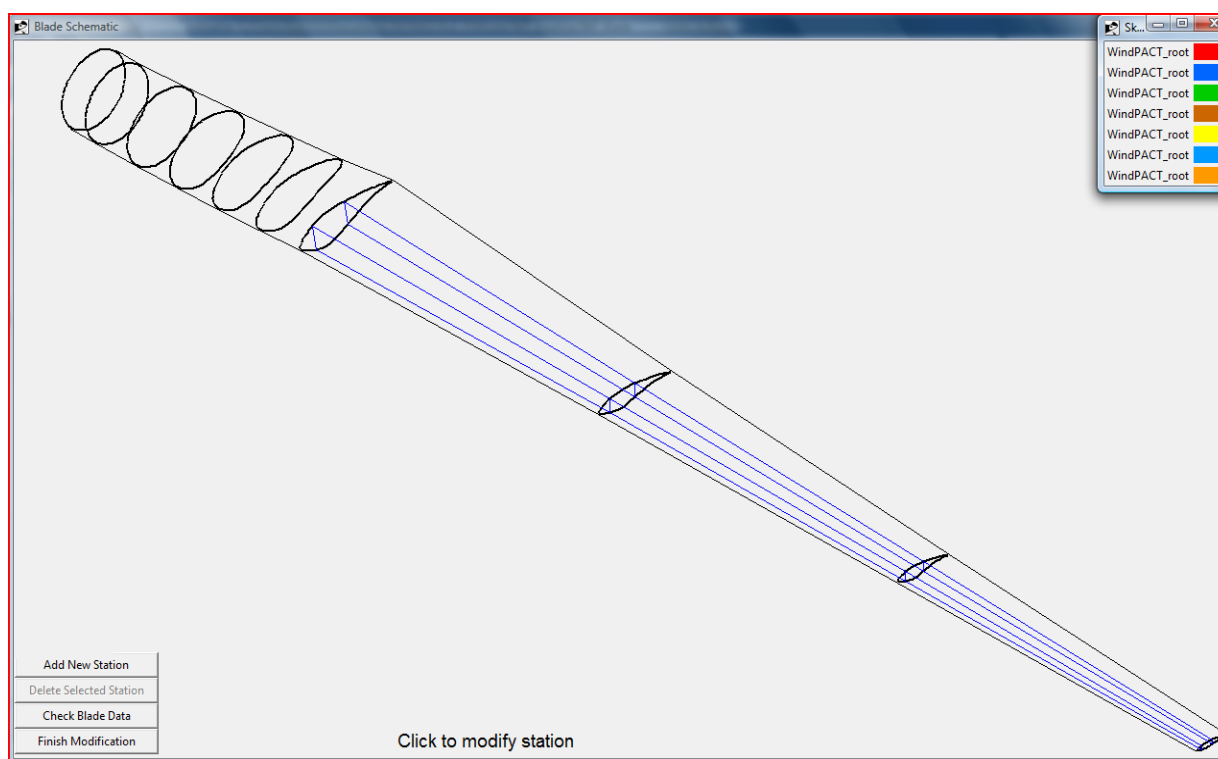


Figure 8 Blade wire frame geometry in NUMAD

Table 9 Preliminary Blade Material Properties¹

Property	A260 UD	CDB340 Tri-axial	Spar Cap Mixture (70% UD and 30% triax)	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/cm³)	1.70	1.70	1.70	1.67	0.144	1.23	1.15

The model described in the NREL report had the laminate material properties listed in Table 9. The spar cap was composed of alternating layers of tri-axial (CDB340) and unidirectional fabrics (A260). The tri-axial fabric was composed of 50% $\pm 45^\circ$ and 50% 0° fibers. The resulting spar cap mixture laminate had 70% unidirectional and 30% tri-axial fabrics by weight. No changes were performed on the root or shear web sections from the NREL design and the root section was modeled without the blade hub connecting hardware. The material models described in Tables 6-9 were assigned to the blade 3D model in NuMAD.

Figure 9 shows the 3D blade model with the material models assigned. Each material model for a particular section is identified by a different color.

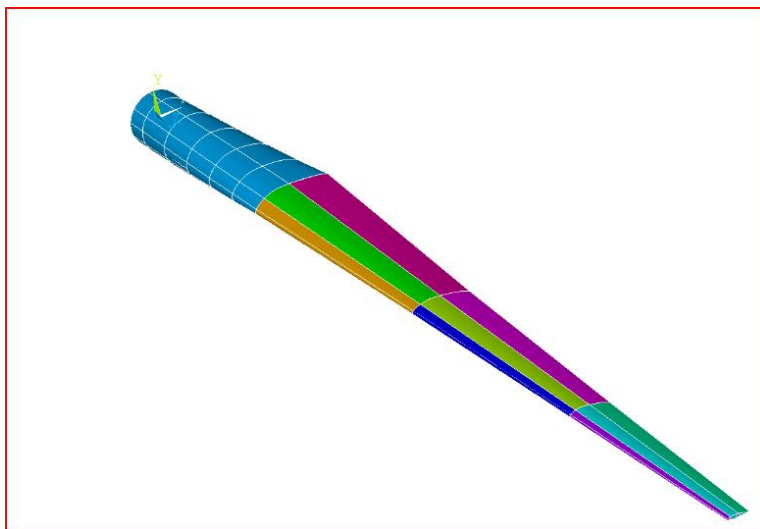


Figure 9 Blade shell model with material assignment

The 3D model generated with the material properties listed above was meshed in NuMAD, using ANSYS composite shell element (SHELL281). SHELL281 is an 8 node structural shell, with 6 degrees of freedom at each node (translations and rotations in x, y, and z axes) and can be used for layered applications for modeling composite laminates and sandwich structures. The structural behavior of SHELL 281 is governed by first order shear deformation theory. When used in layered shell applications the thickness data provided in the section definition is used in the solution (input from NuMAD) and any real constant data defined is ignored.

The initial iteration of the model was meshed with 7211 elements, with a designated element size of 0.2m. Fixed-Fixed boundary conditions were applied to the blade root edge (Figure 10), to replicate the constraint from the standard bolted connection. Once the model was meshed and boundary conditions were applied, input file for ANSYS was generated as an output file from NuMAD.

The input file was then loaded into ANSYS. Using the ANSYS GUI environment a master node was defined at the tip of the blade and coupled to the blade tip edge nodes as shown in Figure 11. A static load of 1000 kg was applied at the master node, acting vertically downwards along the y axis of the model coordinate system (i.e. inducing flap-wise deformation to the blade). The dummy load was selected to characterize the stiffness of the blade and has no relation to the actual aero-elastic loads expected to be endured during blade service.

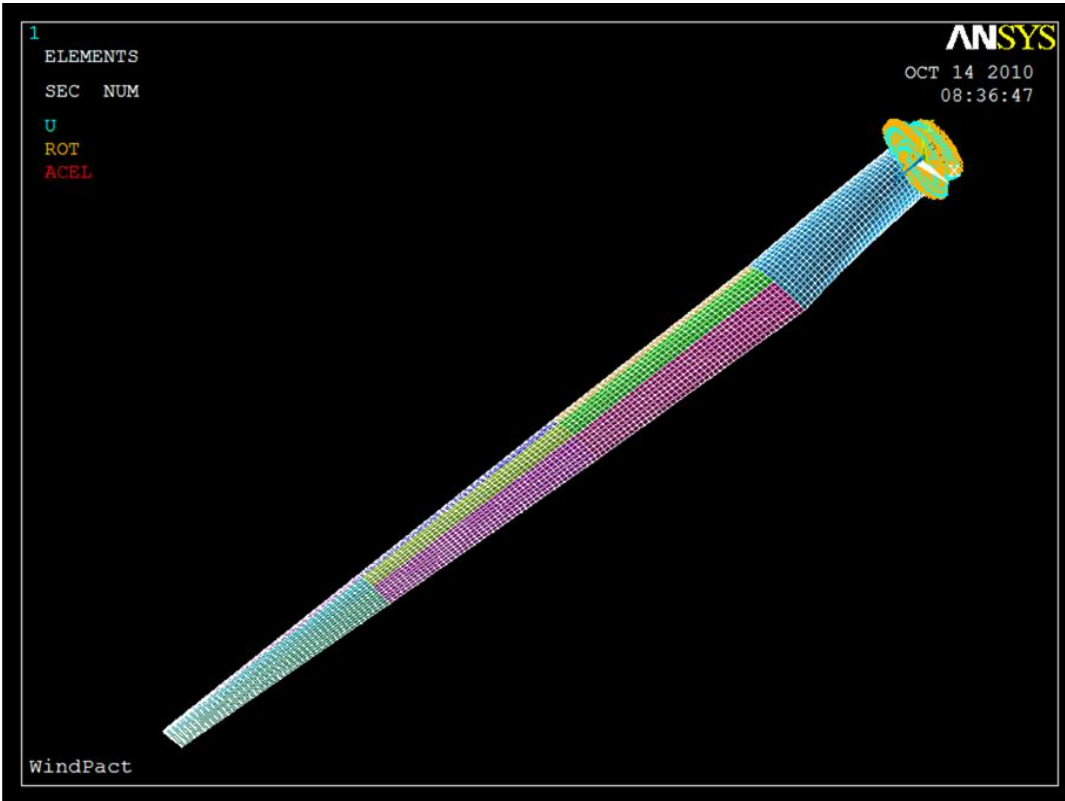


Figure 10 Blade finite element model boundary conditions

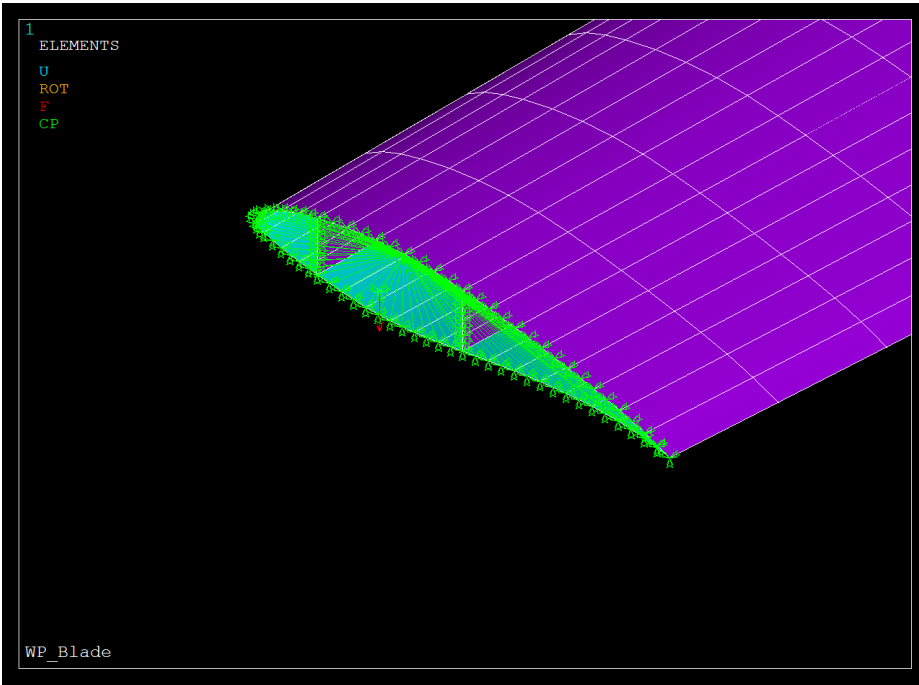


Figure 11 Blade finite element model coupled master node with load

Table 10 Blade solid model weight by components

Blade Component	Weight (kg)
Spar Cap (Low Pressure Surface)	1437
Spar Cap (High Pressure Surface)	1457
Shear Web (Forward)	53
Shear Web (Aft)	55
Skin (Low Pressure Surface)	242
Skin (High Pressure Surface)	238
Root	1251
Total Blade (33.25m 1.5 MW)	4733

4.5 Preliminary Model Results

The first iteration of the ANSYS finite element model with a mesh density of 7211 elements was solved for displacement using a linear elastic solution. Figure 12 shows the displacement results of the baseline blade model. As expected, the maximum displacement is shown to occur at the tip of the blade, with a value of 0.0675 m in the flap-wise direction. The total weight of the first iteration preliminary finite element blade model was 4733 Kg. Table 10 shows the distribution of the weight of the total blade and its individual components.

Once the baseline model was completed, the material properties of the blade model were replaced with state of the art properties from PPG E-glass offerings (PPG HYBON 2026 NCF/epoxy) obtained through experimentation in task 1 (Table 11). The model was solved with the same boundary and load conditions as in the preliminary blade model. Figure 13 shows the displacement results of the new blade model. The maximum displacement is shown to occur at the tip of the blade again, with a value of 0.0475 m in the flap wise direction. The weight of the new blade model is now 5237 kg due to the increased fiber weight fraction of the UD composite.

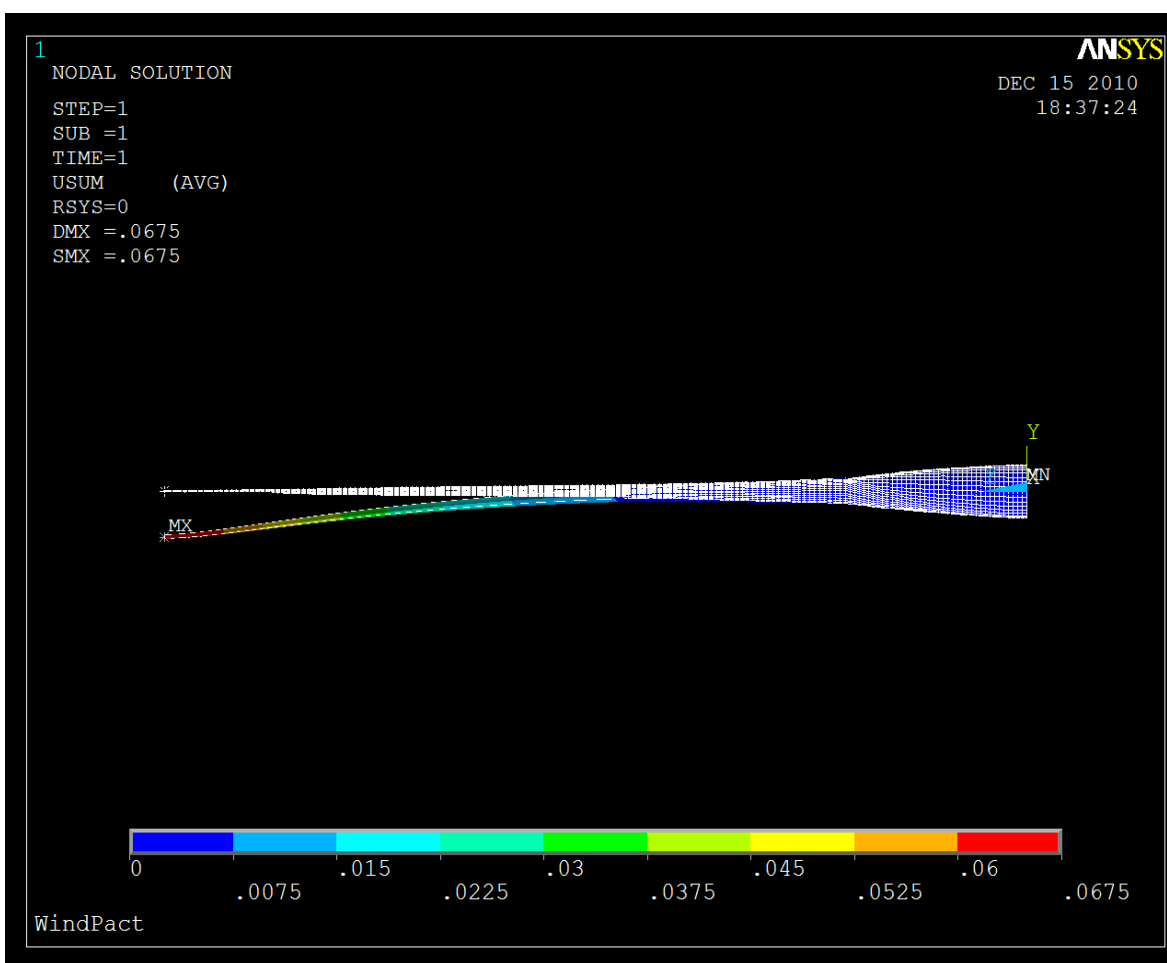


Figure 12 Displacement result of first iteration preliminary blade model

Table 11 Blade material properties (PPG HYBON 2026 NCF/Epoxy model)

Property	PPG UD NCF	PPG Triaxial	Spar Cap Mixture (80% UD and 20% triax)	Random Mat	Balsa	Gel Coat	Fill Epoxy
Ex (GPa)	42.8	29.2	40.08	9.65	2.07	3.44	2.76
Ey (GPa)	6.8	13.03	8.04	9.65	2.07	3.44	2.76
Gxy (GPa)	3.5	6.7	4.14	3.86	0.14	1.38	1.1
Vxy	0.3	0.39	0.31	0.3	0.22	0.3	0.3
FVF %	53	53	53	-	N/A	N/A	N/A
Density (g/cm ³)	1.93	1.93	1.93	1.67	0.144	1.23	1.15

A convergence study was performed on the new blade model to evaluate the stability of the deformation results. This was achieved by increasing the mesh density by a suitable discrete interval. The solution is considered to have converged once the tip deflection value is stabilized and no further significant change is observed with the increase in mesh density. Six solution iterations with different mesh densities were evaluated. Figure 14 shows the results of convergence study.

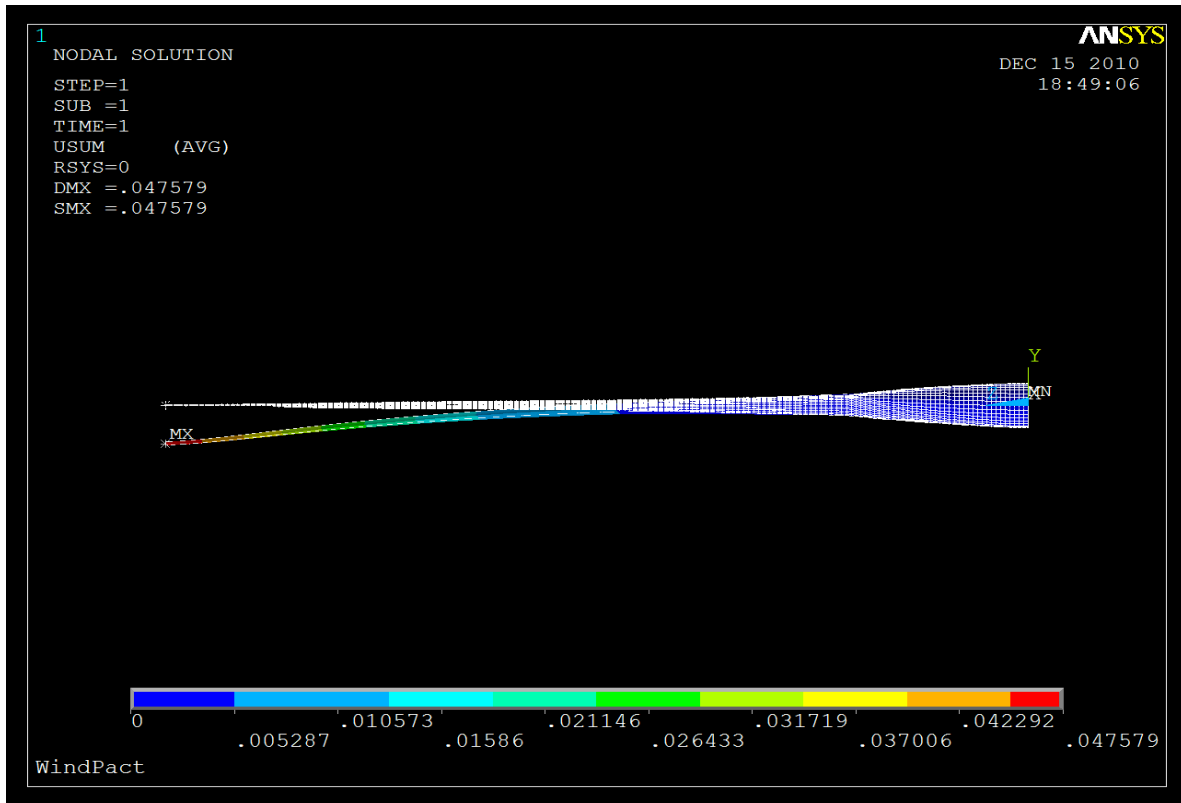


Figure 13 Displacement result of PPG E-glass blade model

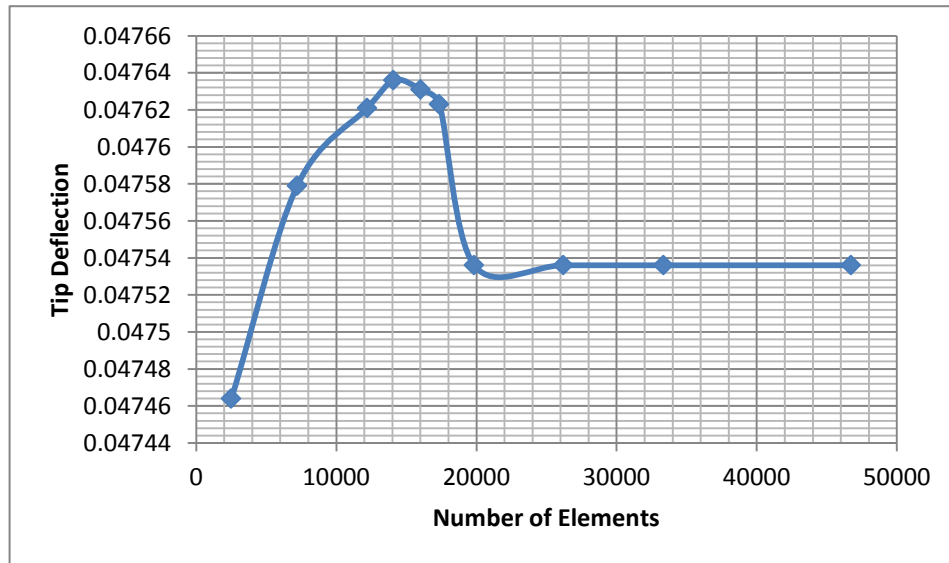


Figure 14 Convergence based on blade tip deflection

The model with the optimum mesh density resulting in a converged solution was thus considered as the final baseline model for comparison in our subsequent parametric study. The model had a mesh density of 26,208 elements and resulted in a tip deflection value of 0.0475 m under the same loading and boundary conditions as listed before.

4.6 Parametric Study Description

The main objective of this parametric study was to evaluate the effect of the fiber properties and the blade manufacturing process on the weight and stiffness of the 33.25m (1.5 MW) blade and in turn their direct effect on cost of energy.

The following cases were considered for the parametric study:

Case 1: Implemented to obtain the same deflection as in the baseline 33.25m 1.5 MW model, it provides the potential increase in blade length that can be achieved by replacing the E-glass fabric based spar cap with a high performance glass fiber-based spar cap, manufactured using the automatic fiber placement process. The additional length will enable an increase in energy production as the swept area of the blade increases without a deflection penalty.

Case 2: Implemented to obtain the same length and deflection as in the baseline model, it provides a corresponding decrease in thickness and in weight. This can be achieved by replacing the E-glass fabric based spar cap with a thinner high performance glass fiber based spar cap manufactured using the automatic fiber placement process.

4.7 Parametric Study Results

Case 1: The spar cap material properties of the baseline model were replaced with the hypothetical values expected for the high performance fiber based composite. The material properties of all other sections of the blade were maintained the same as in the baseline (PPG HYBON 2026 NCF/epoxy) model. The same meshing procedure, boundary, and load conditions as in the baseline model were applied to the new model and solved for deflection using a linear analysis. Several finite element solving iterations were performed by scaling the new model along the span direction only until the resulting tip deflection value matched that of the baseline blade model (equivalent flap wise stiffness design). The new blade length achieved by replacing the E-glass fabric based spar cap with a high performance fiber based spar cap, manufactured using the automatic fiber placement process, was found to be 34.5 m, which is 3.6% longer compared to base line model. The new weight of the scaled blade model was calculated to be 5,421 kg.

Case 2: The spar cap and root material properties of the baseline model were replaced with those discussed in Case 1. The blade length and material properties of all other sections of the blade were maintained the same as in the baseline model. The same meshing procedure, boundary, and load conditions as in the baseline model were applied to the new model solved for deflection. The weight of the new blade with a high performance glass fiber based spar cap, manufactured using the automatic fiber placement process, and standard E-glass on the root section was found to be 5,219 kg. which corresponds to a marginal weight reduction of less than 1% compared to the E-glass only baseline model.

4.8 Cost of Energy

In collaboration with University of Maine, a cost of energy analysis was performed using the results obtained from the parametric study. The cost of energy (COE) model incorporates the impact of capital costs, debt, operating expenses and energy generation as illustrated in the equation:

$$\text{COE} = (\text{ICC} \times \text{FCR} + \text{AOE}) / \text{AEP}$$

Where, COE is the cost of energy, AEP is the annual energy production, AOE is the annual operating expenses (which includes operating environment, local taxes, Insurance, etc.), and FCR is fixed charge rate which includes debt and equity cost. Table 12 lists the assumptions for the cost energy study in the present document and Figure 15 shows the analysis methodology used for incorporating the material improvements into the cost estimation.

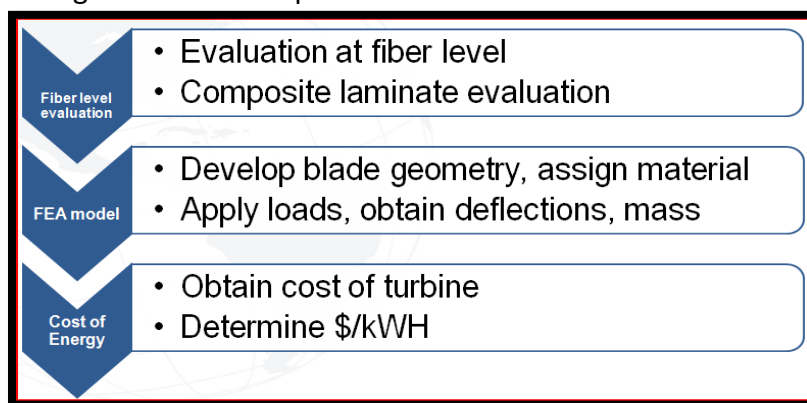


Figure 15 Analysis methodology for determination of cost of energy

Table 12 Cost of energy model assumptions

Variable	Value
Project size	60 MW
Wind speed range	13-17mph (Class 4)
Turbine size	1.5 MW, 33-meter long blade
Net capacity factor	30%
Benchmark capital Cost	\$2.2M per installed MW ⁴
Fixed charged rate	10%
Annual operating costs	\$15/MWh ⁴
Production tax credit	\$0.015 / kWh

Once the results from the parametric study were incorporated into the cost of energy model, the model predicted a potential decrease in COE of 3.5% for case 1 (which was obtained by replacing the E-glass based spar cap with the high modulus spar cap fabricated via automated fiber placement process). Additional information for case 1 results is summarized below in Table 13.

For case 2, although the weight of the blade was marginally reduced by the introduction of a thinner spar cap, no significant benefits were observed from the COE model against the standard infusion blade.

Table 13 Potential improvements based on 1.5 MW turbine blade obtained by using high performance fiber glass materials in spar caps (case 1).

% Increase in blade length	% Increase in weight	% Increase in produced energy output	% Decrease in COE
3.76%	3.5%	7.7%	3.57%

Task 5 - Feasibility Assessment

5.1. Technical Feasibility

5.1.1 Automated Processing Summary and Opinion

Through the surrogate process trials (task 3.2), it was possible to analyze a number of different cost-competitive material inputs in actual fiber placement and automated tape lay up machines for the production of multidirectional flat composite laminates. Material-specific parameters for automated processing including tack, fuzz generation, material width control, flatness, ease of release from backing materials, and potential lay down rates have been evaluated for a suite of different pre-impregnated fiber products. While there are still variables to be optimized at this point of the development in order to optimize these material forms for automation, it was proven that the fiber placement processing technology is a feasible approach for the production of wind blades and is capable of producing higher FVF composites in a consistent manner.

5.1.2 Performance evaluation of composites produced via automated processes and comparison against traditional vacuum infusion

Uniaxial and biaxial composite laminates were made with the material forms previously described in Table 3 and were evaluated for their static and dynamic properties.

Static Properties - Unidirectional Laminates

Unidirectional composite laminates were produced and evaluated with the following material forms listed in Table 14.

Table 14 Material forms and processes evaluated for technical feasibility assessment

Material Form	Process
UD non-crimp fabric (standard control – lower bound)	Infusion
UD dry wound roving (upper bound)	Infusion
UD towpreg 1 (fiber placement)	Fiber Placement
UD towpreg 2 (fiber placement)	Fiber Placement
UD wide tape (Automated Tape Layup)	Automated Tape Layup
UD slit tape (Fiber placement)	Fiber Placement

The tensile strength performance of the material forms evaluated could be segmented into three groups (see Figure 16 below and Appendix A). The highest performing material was found to be the dry-wound/infused laminate; this material should be considered as a “virtual benchmark”, as it is not a feasible manufacturing solution for a turbine blade but is commonly used as a roving evaluation technique. The second identified performance group consisted of two of the fiber placement prepreg materials (UD slit tape and UD towpreg 1) as well as the 12” (0.3m) wide tape placement laminate. The third group of lowest performers with respect to tensile strength consisted of the standard non-crimp fabric that is used widely for blade production today and UD towpreg 2.

The statistical comparison of the tensile strength by material input shown in Figure 16 indicates that marginal improvements in tensile strength were achieved with the prepreg/automation materials when compared against the standard materials used today.

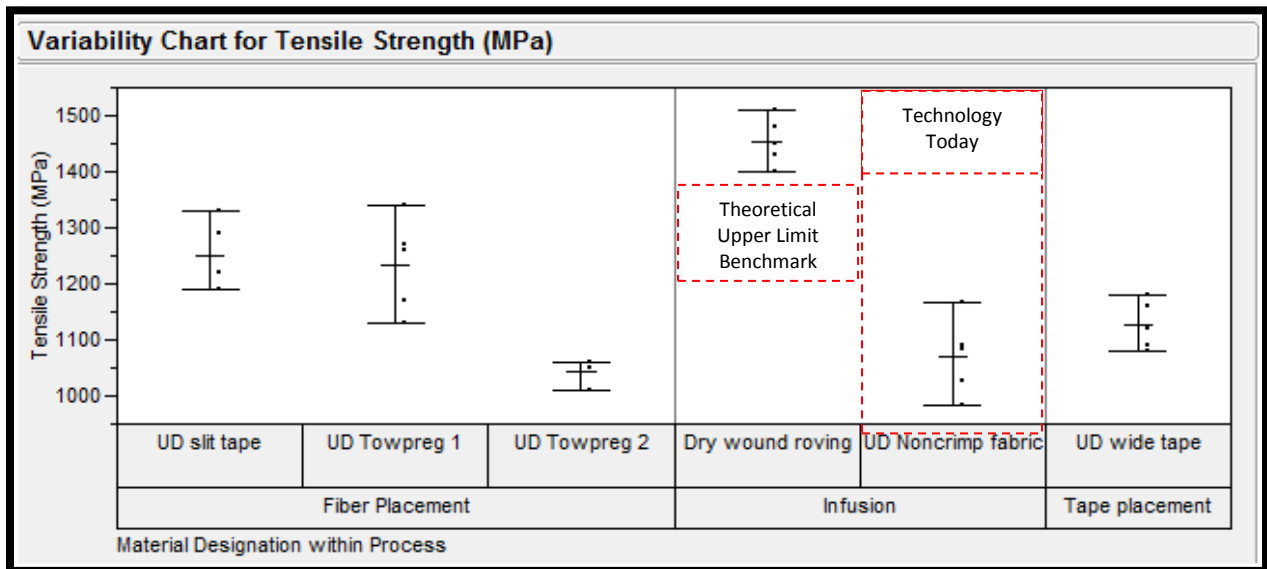


Figure 16 Tensile strength (MPa) vs. material designation for UD laminates

The tensile modulus was also compared among the different candidate materials. These results are presented in Figure 17 and Appendix 1. It was found that the effect of glass content of the laminates (which is largely driven by the manufacturing process) does have a significant impact on the stiffness of the laminates. In this case, all of the UD prepreg/automation material inputs performed significantly better than the non-crimp fabric baseline and were found to be 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, significantly higher stiffness can be achieved with positive implications on blade length and generation capacity.

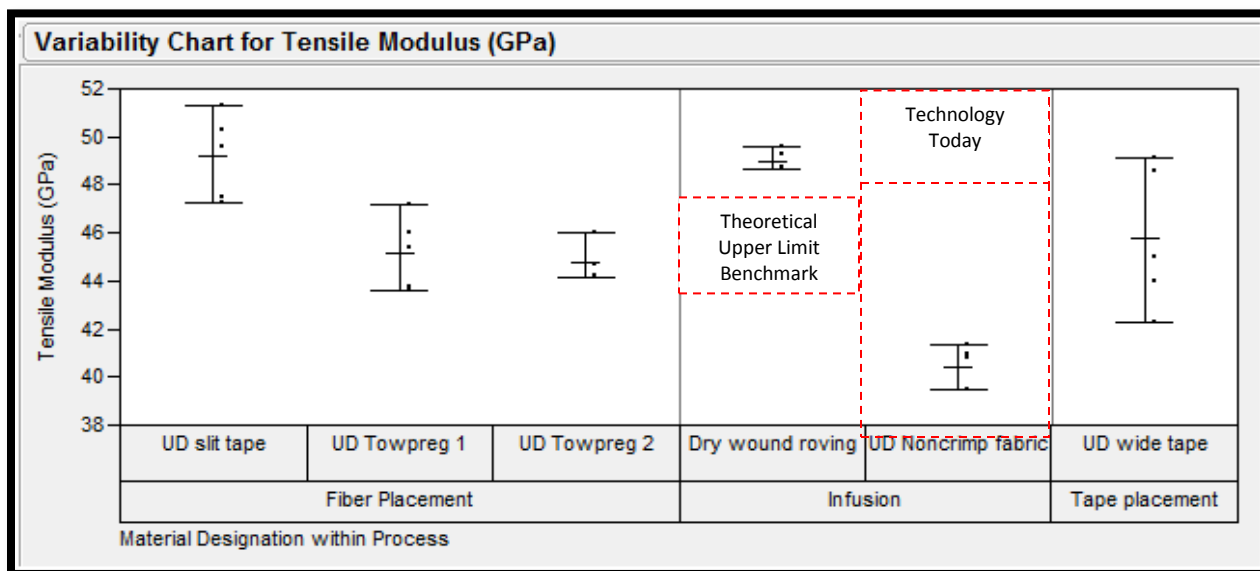


Figure 17 Tensile modulus vs. material designation (UD laminates)

The compressive properties of a composite material depend greatly on the compressive performance of the specific resin system and the fiber alignment. The compressive properties measured in most prepreg/automation materials were found to be statistically equivalent to the standard fabric-based materials utilized in the industry today. Compressive modulus and strength as a function of the different material inputs is plotted below in Figure 18.

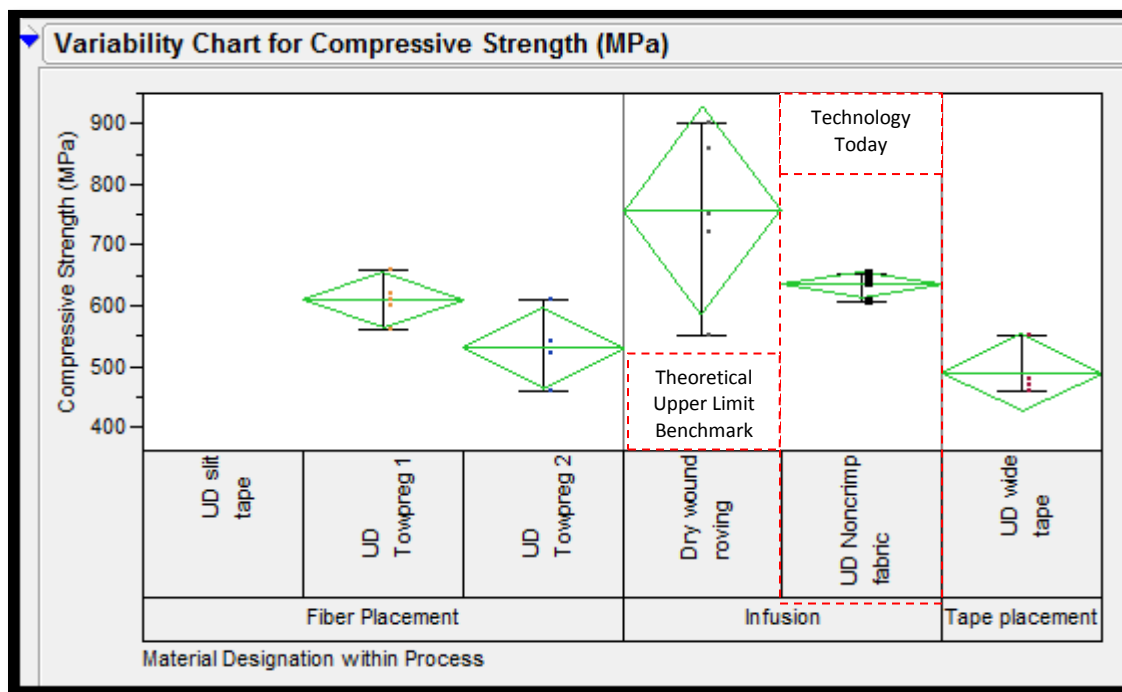


Figure 18 Tensile modulus vs. material input for different material forms (UD laminates)

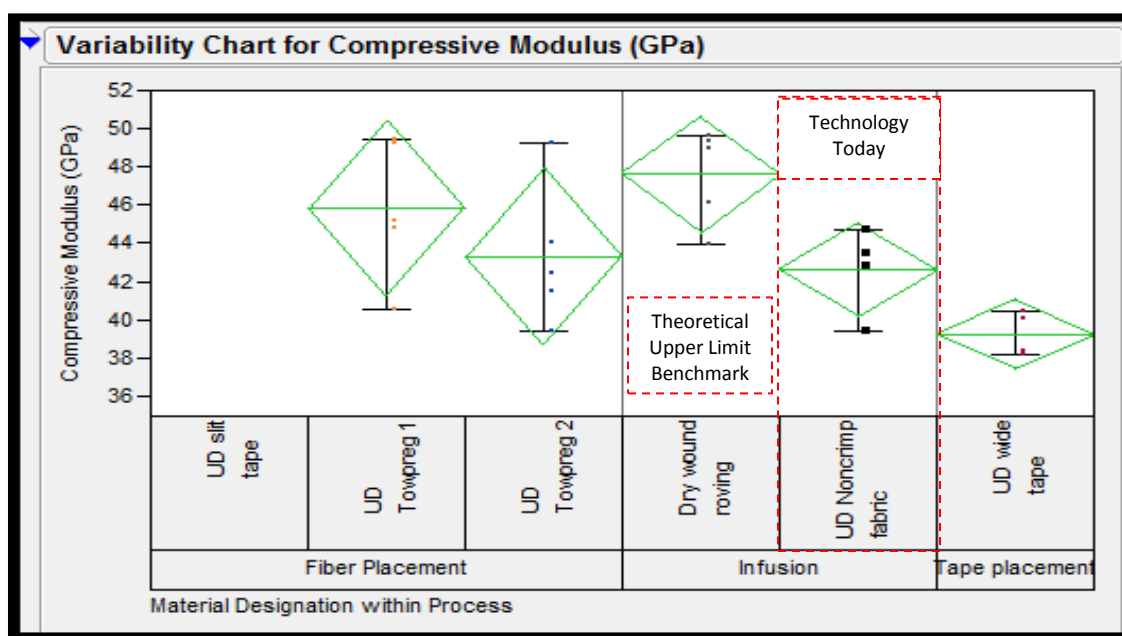


Figure 19 Compressive properties vs. material input and process technology

Biaxial and Complex laminate testing

Similar positive trends to those observed in the UD laminates were observed with biaxial (Table 15) and double bias (Table 16) laminates. In most instances (with the exception of compressive properties of double bias laminates), the automation-based materials, regardless of the format and specific resin system, performed at a level equivalent to or above that of the non-crimp fabric based laminates produced by resin infusion. Additionally, the transition temperature for the epoxy resin systems utilized was found to be significantly higher than the standard infusion resin glass transition temperature (T_g).

Table 15 Biaxial laminate static test data

Material Designation	NCF	Towpreg 1	Slit tape	NCF
Format		PREPREG		FABRIC
Process	ATL	FP	FP	INFUSION
Lay up	[0/90]3	[0/90]6	[0/90/90/0]	[0/90]
Tensile Strength (MPa)	438	588	612	394
Tensile Modulus (GPa)	20.62	26.32	27.86	21.36
Compressive Strength (MPa)	312	384	N/A	275
Compressive Modulus (GPa)	22.49	25.27	N/A	17.84
Glass Content (%)	65.02	75.6	73.46	65

Table 16 Double Bias laminate static test data

Material Designation	Non crimp fabric	Towpreg 1	Slit tape	Non crimp fabric
Format	EPOXY PREPREG			FABRIC
Process	ATL	FP	FP	INFUSION
Lay up	[45/-45]3	[45/-45]	[45/-45]	[45/-45]
Tensile Strength (MPa)	107	96	130	84
Tensile Modulus (GPa)	12.05	12.37	12.09	12.19
Compressive Strength (MPa)	103	105	N/A	129
Compressive Modulus (GPa)	10.64	7.36	N/A	12.98
Glass Content (%)	64.7	75.89	76.93	72.3
DMTA Tg C	93	115	144	80

Dynamic (Fatigue) Testing

Representative laminates of all the material variants were subjected to tension-tension fatigue to determine the S-N curve using a servo hydraulic tensile tester. Using the static tensile strength data as a baseline, the specimens were subjected to various levels of cyclic loading at a rate of 5 Hz with and an R (Maximum stress/Minimum stress) value of 0.1 until failure. Figure 20 below shows the characteristic fatigue performance of the different materials considered against the current wind energy technology (UD NCF infusion). While the performance of the dry wound infused laminates was not achieved, it is encouraging to note that both the Towpreg 1 based laminate and the slit tape material (both processed through fiber placement) performed better than the industry standard (the non-crimp fabric-based composite made by infusion).

Conclusion

The automated fiber placement process was found to be a technically feasible alternative to resin infusion to produce equivalent/higher performing composites with the potential for higher strength, stiffness and durability compared to the technology used today for the production of blade components and assemblies. Furthermore it was proved that significant COE reductions (up to 3.5%) can be achieved by using this technology with newly developed glass fibers.

The materials designated as Towpreg 1 and ¼" (6mm) slit tape processed via automated fiber placement are recommended as Technology Capable (TCD) with minor development for additional screening and perhaps a subsequent manufacturing trial on a scaled wind blade component. These materials were able to provide increased mechanical properties against the benchmark materials and were amenable to automated process. A representative material specification for these materials is included as reference in Table 17.

Table 17 Material specification for automated fiber placement of turbine blade components

Fiber Glass Roving		PPG HYBON 2026
Sizing chemistry	Epoxy compatible roving	
Fiber diameter	17um	+/- 3um
LOI	0.7%	+/- 0.2
Linear Density	2400TEX	+/- 200
Resin system	OOA grade epoxy	
cure temp	80-120 C	
cure time	5H	
Prepreg Resin Content	40%	+/- 1%

Class A		Preimpregnated slit tape
Manufacturing Process	Automated Fiber Placement – Slit tape	
Tack Level	Medium Tack - self adhesion to tooling surface, adequate release from separation media	
Separation media	Siliconized paper, PE or equivalent.	
width	12mm	+/- 0.7 mm
Thickness	0.35mm	+/- 0.05 mm

Class B		Unidirectional Towpreg
Manufacturing Process	Automated Fiber Placement – Towpreg	
Tack Level	Medium Tack - self adhesion to tooling surface, adequate release from separation media	
Separation media	No separation media required if appropriate tack is achieved	
width	12mm	+/- 0.5 mm
Thickness	0.35mm	+/- 0.07 mm

Packaging Requirements (applicable to class A and B materials)

Roll diameter	76.2mm
Material build up diameter of core	101.6 mm OD or greater on 76mm core
Package Length	25.4 cm long centered on core, helically wound

Minimum Performance Requirements			
Tensile Strength - X	1350 MPa	min	ISO 527-5
Tensile Modulus - X	48000 MPa	min	ISO 527-5
Fiber Weight Fraction	76.5%	+/- 1%	ISO 1172
Tensile Strength - Y	50MPa	min	ISO 527-4
Fiber Volume Fraction	59%	+/- 1%	ISO 1172
Fatigue Performance	per S-N plot below - (Tension-Tension R=0.1 F- 5 Hz) 2 mm thick laminates (slit tape and Towpreg 1)		

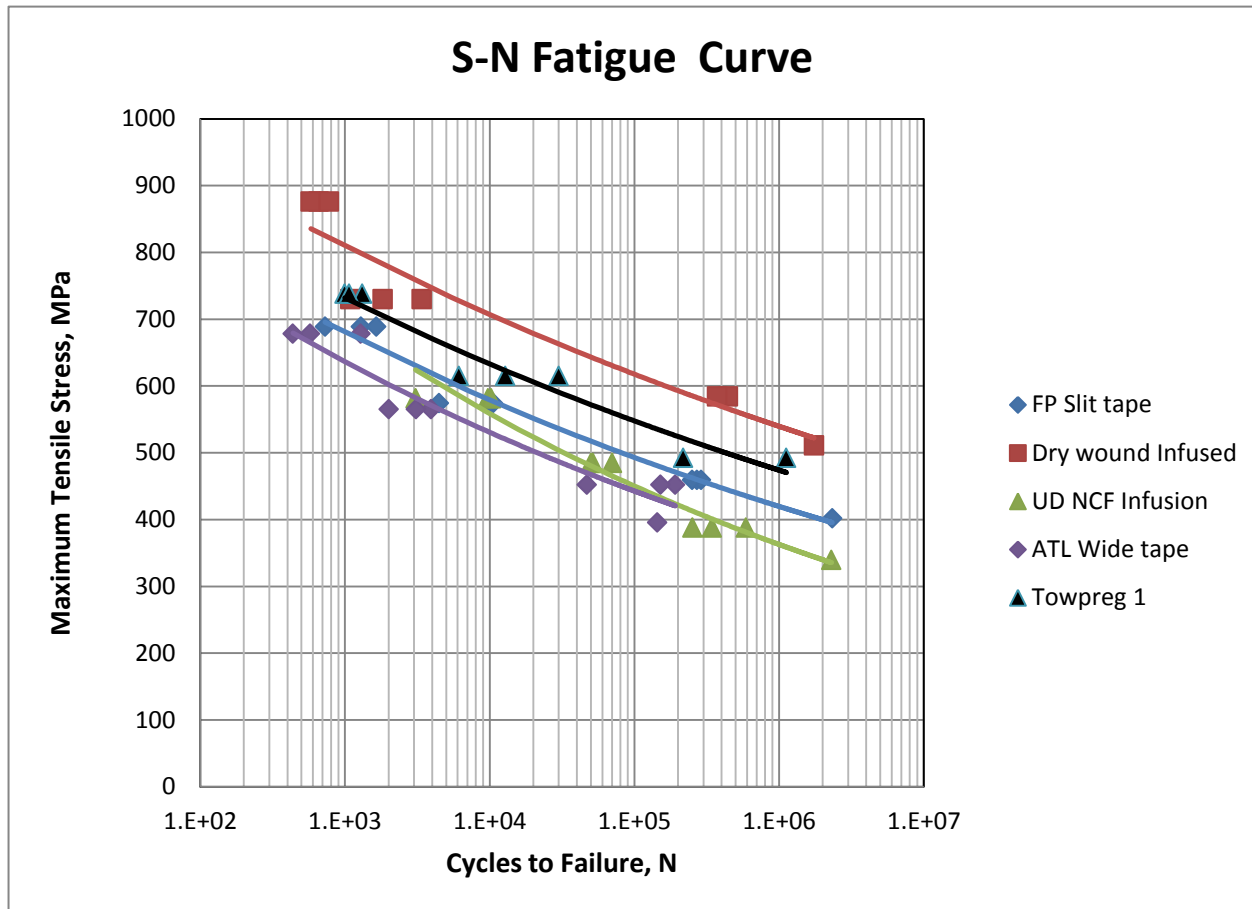


Figure 20 Results from Dynamic Fatigue Testing.

5.2. Economic Feasibility

Methodology:

An economic model for blade manufacturing was developed in collaboration with the University of Maine to enable the comparison of different manufacturing methods. Three manufacturing alternatives were considered in this analysis:

- 1) Method 1: Manual infusion
- 2) Method 2: Manual infusion combined with automated spar cap manufacturing
- 3) Method 3: Fully automated production cell

This economic model presents a financial analysis of blade manufacturing and does not consider full life cycle cost benefits of automation nor its additional impact on cost of energy. However it is reasonable to expect similar laminate performance improvements as realized in the aerospace industry over the past 30+ years using the automated fiber placement process with industry grade materials. It is especially important to consider the reduction of laminate defects, part-to-part manufacturing consistency, and laminate strength which would lead to optimized blade designs targeted for automation. All of these factors should be considered in future studies to fully quantify the impact of automation and prepreg materials on blade life cycle cost and performance.

Method 1	Method 2	Method 3
<ul style="list-style-type: none"> • Shell: <ul style="list-style-type: none"> • Vacuum Infusion • Spar cap: <ul style="list-style-type: none"> • Vacuum Infusion • Root: <ul style="list-style-type: none"> • Wet layup/Infusion 	<ul style="list-style-type: none"> • Shell: <ul style="list-style-type: none"> • Vacuum Infusion • Spar cap: <ul style="list-style-type: none"> • Automation • Root: <ul style="list-style-type: none"> • Wet layup/Infusion 	<ul style="list-style-type: none"> • Shell: <ul style="list-style-type: none"> • Automation • Spar cap: <ul style="list-style-type: none"> • Automation • Root: <ul style="list-style-type: none"> • Automation

Figure 21 Manufacturing alternatives considered in economic analysis

The economic analysis was conducted using ply schedules and geometry typical from a 40-meter blade for a 3.1 MW turbine for class IV wind as a benchmark. The following steps were taken to determine the economic feasibility of the different alternatives:

- 1) Determine the bill of materials (BOM) of the blade from the FEA model
- 2) Determine total man-hours per blade
- 3) Determine the production time per blade
- 4) Determine the list of capital equipment and the corresponding manufacturing plant
- 5) Determine the capital expenditures
- 6) Define the rate of depreciation for equipment and building

Bill of Materials Analysis:

The bill of materials (BOM) for each manufacturing method was developed using finite element analysis (FEA) on the 40-meter blade model by changing the material properties for each manufacturing alternative. It was assumed that 1/2" unidirectional prepreg tapes (such as the one described in Table 17) were used in all automated manufacturing processes and that stitched bonded glass fabric (NCF) was used in all manual operations. A summary of the BOM for all cases is shown in Table 18 and a detailed bill of materials with estimated material prices for the three alternatives is included as a reference in Appendix 2. As would be expected, the BOM for the automation case has a higher cost than that for the manual methods due to the additional expenses incurred in intermediate processing of the narrow tape materials. Material scrap was calculated and included in the calculations for the three alternatives. Our economic model predicts an increased level of scrap material generated by methods 1 and 2. Fiber placement process typically yields 2-5% scrap. Scrap from hand layup can vary up to 50% on some parts.

Table 18 Bill of materials summary for considered manufacturing alternatives

	Fabric Infusion Method 1	Automated Spar Cap Method 2	Fully Automated Production Method 3
BOM (USD \$)	\$53,836	\$60,838	\$69,421

Total man-hours / production time per blade

A detailed manufacturing process analysis was developed for each manufacturing method to calculate the total man-hours and production time per blade (see appendix 3 for sample calculation). Total labor cost was estimated using a flat rate of \$40 per hour, including overhead. The automation process data was determined from comprehensive process modeling simulations developed by MAG for the different blade components.

A summary of the total man-hours and production time per blade for the three alternatives is shown in Table 19. As it would be expected, the automation alternative resulted in considerable direct labor savings as fewer operators are needed to lay down material into the molds. The considerable time savings in blade production from 29 to 12 hours highlight the benefits of automated production at fast lay down rates.

Table 19 Estimated man-hours and production time per blade.

	Fabric Infusion Method 1	Automated Spar Cap Method 2	Fully Automated Production Method 3
Production time per blade (hrs)	29	29	12
Total man-hours per blade	770	658	331
Total direct labor cost per blade (\$)	\$30,800	\$26,320	\$13,240

A detailed breakdown of the total man-hours required to manufacture a blade by each alternative is shown in Figure 21.

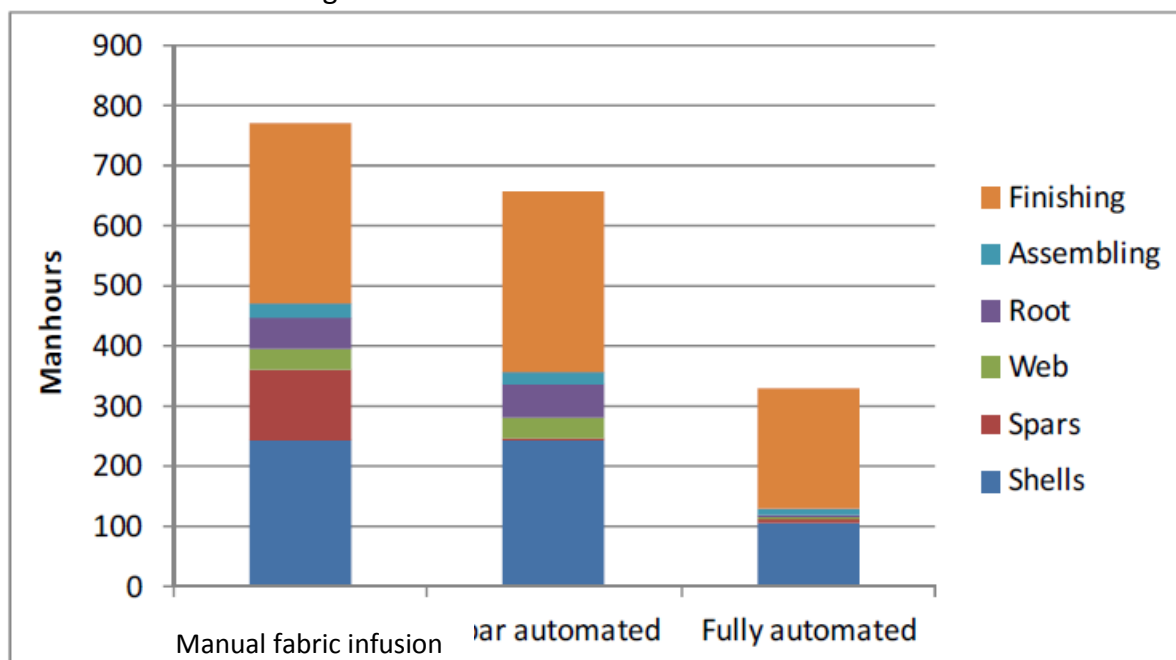


Figure 22 Man-hour distribution for different production tasks for all methods

Manufacturing Facilities:

The manufacturing plant design depends on the desired annual blade output. As part of this effort, a conceptual design of the manufacturing facility was developed for each manufacturing method based on an annual production rate of approximately 1000 blades per year, as shown in Table 20. As might be expected, the operational schedule was optimized to take full advantage of the automation methods and the production efficiency reflects the consistency and repeatability of automation. The study assumes an operational schedule ranging from 250 to 287 production days per year and the manufacturing efficiencies of 85% to 92% efficiency. This step was essential for many reasons; a) to determine the size of the facility and to calculate the annual cost of labor, overhead costs (utility and fixed labor cost), and capital expenditures; b) to minimize the CapEx spend while optimizing overall plant throughput; c) maximize equipment utilization and d) to accurately evaluate the methods against appropriate standards.

The manual infusion (Method 1) plant was designed for 6 assembly lines, each producing one blade every 29 hours leading to an annual production rate of 1055 blades per year (250 operational days). The manual infusion plant using automated spar caps (Method 2) was designed for 6 assembly lines, each producing one blade every 29 hours leading to an annual production rate of 1068 blades per year (250 operational days). The fully automated (Method 3) plant was designed for 2 assembly lines, each producing a blade every 12 hours, and leading to an annual production rate of 1033 blades per year (287 operational days).

Table 20. Determination of facility requirements for different manufacturing alternatives

Column1	Fabric Infusion Method 1	Automated Spar Cap Method 2	Fully Automated Production Method 3
Shell mold cycle time (hrs)	29	29	12
Operational days/annum	250	250	287
Operational efficiency	85%	86%	90%
Number of shell mold tool sets across total number of production lines	6	6	2
Total number of blades per year	1,055	1,068	1,033
Facility size (sq ft)	310,000	310,000	152,741

Capital Expenditures:

Capital expenditures were divided into two categories: 1) Equipment and tooling; and 2) Building infrastructure.

Equipment and Tooling

Using the annual production rate and the plant conceptual designs, the tooling and equipment requirements were calculated. A summary of the list of capital equipment and costs is shown in Table 21. A summary of total capital equipment cost for all three cases is shown at the bottom of the table.

Table 21 Tooling and equipment breakdown for three manufacturing alternatives

Manual Fabric Infusion (Method 1)			
Item description	No	Item Cost (\$)	Total (\$)
Shell mold set which includes LP and HP	6	\$800,000	\$4,800,000
Spar mold set which includes LP and HP	6	\$400,000	\$2,400,000
Web mold	6	\$150,000	\$900,000
Root mold	6	\$145,000	\$870,000
Shell plug	1	\$400,000	\$400,000
Spar plug	1	\$250,000	\$250,000
Total		\$2,145,000	\$9,620,000

Automated Spar Cap (Method 2)			
Column1	No	Item Cost (\$)	Total (\$)
Shell mold set which includes LP and HP	6	\$800,000	\$4,800,000
Spar mold set which includes LP and HP	4	\$400,000	\$1,600,000
Web mold	6	\$150,000	\$900,000
Root mold	6	\$145,000	\$870,000
Shell plug	1	\$400,000	\$400,000
Spar plug	1	\$250,000	\$250,000
Automation equipment for spar caps	1	\$3,400,000	\$3,400,000
Total		\$5,545,000	\$12,220,000

Full Automation (Method 3)			
Column1	No	Item Cost (\$)	Total (\$)
Shell mold set which includes LP and HP	4	\$800,000	\$3,200,000
Spar mold set which includes LP and HP	4	\$400,000	\$1,600,000
Web mold	4	\$150,000	\$600,000
Root mold	2	\$290,000	\$580,000
Automation equipment for shell	2	\$4,000,000	\$8,000,000
Automation equipment for spar caps	1	\$3,400,000	\$3,400,000
Automation equipment for root	1	\$4,500,000	\$4,500,000
Automation equipment for web	1	\$3,400,000	\$3,400,000
Automation equipment for finishing	1	\$2,700,000	\$2,700,000
Shell plug	1	\$400,000	\$400,000
Spar plug	1	\$250,000	\$250,000
Total		\$20,290,000	\$28,630,000

	Fabric Infusion Method 1	Automated Spar Cap Method 2	Fully Automated Production Method 3
Total tooling and equipment cost (\$)	\$9,620,000	\$12,220,000	\$28,630,000

Building Infrastructure

Land and building costs of a manufacturing plant for each manufacturing method were calculated using a nominal cost of \$120 per square feet (sq ft). A summary of the building cost and size is shown in Table 22. It can be seen that the fully automated manufacturing method (Method 3) will require a smaller plant footprint compared to methods 1 and 2, due to its higher production rate.

Table 22 Building cost details based on calculated plant footprint

Item description	Fabric Infusion Method 1	Automated Spar Cap Method 2	Fully Automated Production Method 3
Building size (sq ft)	310,000	300,000	152,741
Building cost @ \$120/sq ft	\$37,200,000	\$36,000,000	\$18,328,920

TOTAL CAPEX:

Total CAPEX (capital expenditure) is the sum of the tooling, equipment cost and building cost. Table 23 summarizes total CAPEX for all three manufacturing methods.

Table 23 Total CAPEX for three manufacturing alternatives

	Fabric Infusion Method 1	Automated Spar Cap Method 2	Fully Automated Production Method 3
Total CAPEX	\$46,820,000	\$48,220,000	\$46,958,920

Indirect Costs:

Depreciation

The CAPEX was depreciated over 5 years for tooling and plugs. The automation equipment was depreciated over 10 years, and the building was depreciated over 20 years. Table 24 provides a summary of the annual depreciation costs for the three manufacturing methods.

Table 24. Depreciation per annum for manufacturing alternatives

	Depreciation (\$/annum)		
Shell mold set which includes LP and HP	\$960,000	\$960,000	\$640,000
Spar mold set which includes LP and HP	\$480,000	\$320,000	\$320,000
Web mold	\$180,000	\$180,000	\$120,000
Root mold	\$174,000	\$174,000	\$116,000
Shell plug	\$80,000	\$80,000	\$80,000
Spar plug	\$50,000	\$50,000	\$50,000
Automation equipment	\$0	\$340,000	\$2,200,000
Building/Facilities	\$1,860,000	\$1,800,000	\$916,446
Total	\$3,784,000	\$3,904,000	\$4,442,446

Plant Overhead

The annual cost to operate the manufacturing facilities was calculated using a fixed rate of \$10/sq ft. A summary of the annual indirect cost for all three cases is shown in Table 25. Again, lower operating costs are achieved from the fully automated alternative as footprint is reduced in comparison to manual alternatives.

Table 25 Plant overhead for manufacturing alternatives

Column1	Fabric Infusion Method 1	Automated Spar Cap Method 2	Fully Automated Production Method 3
Building size (sq ft)	310,000	300,000	152,741
Overhead cost per year @ \$10/sq ft	\$3,100,000	\$3,000,000	\$1,753,467 *

*Overhead on method 3 was adjusted to account 14% increase in workdays per year

Financial Analysis:

The cost of manufacturing one blade was calculated for all three cases by adding the BOM, direct labor cost, indirect cost per blade, and depreciation cost per blade. A cost breakdown is shown in Table 26 for all three manufacturing methods. The information is also presented in graphic form in Figure 23 and is compared against an assumed \$110,000 per blade sale price.

Table 26 Blade Cost breakdown

Cost per blade	Fabric Infusion Method 1	Automated Spar Cap Method 2	Fully Automated Production Method 3
BOM	\$53,836	\$60,838	\$69,421
Total direct labor cost per blade	\$30,800	\$26,320	\$13,240
Indirect cost per blade	\$2,938	\$2,810	\$1,697
Depreciation per blade	\$3,586	\$3,657	\$4,300
Total Blade Cost	\$91,160	\$93,625	\$88,657

Based on the resulting numbers it is apparent that blade production costs are lower for the automated option given the savings in direct labor, the reduction in plant footprint and the faster material lay down rates.

Once the manufacturing parameters and the cost for the considered options were determined, the financial viability of the automation project was calculated by NPV, IRR and financial ratios. This analysis determined the net present value of the future cash flows expected with each alternative.

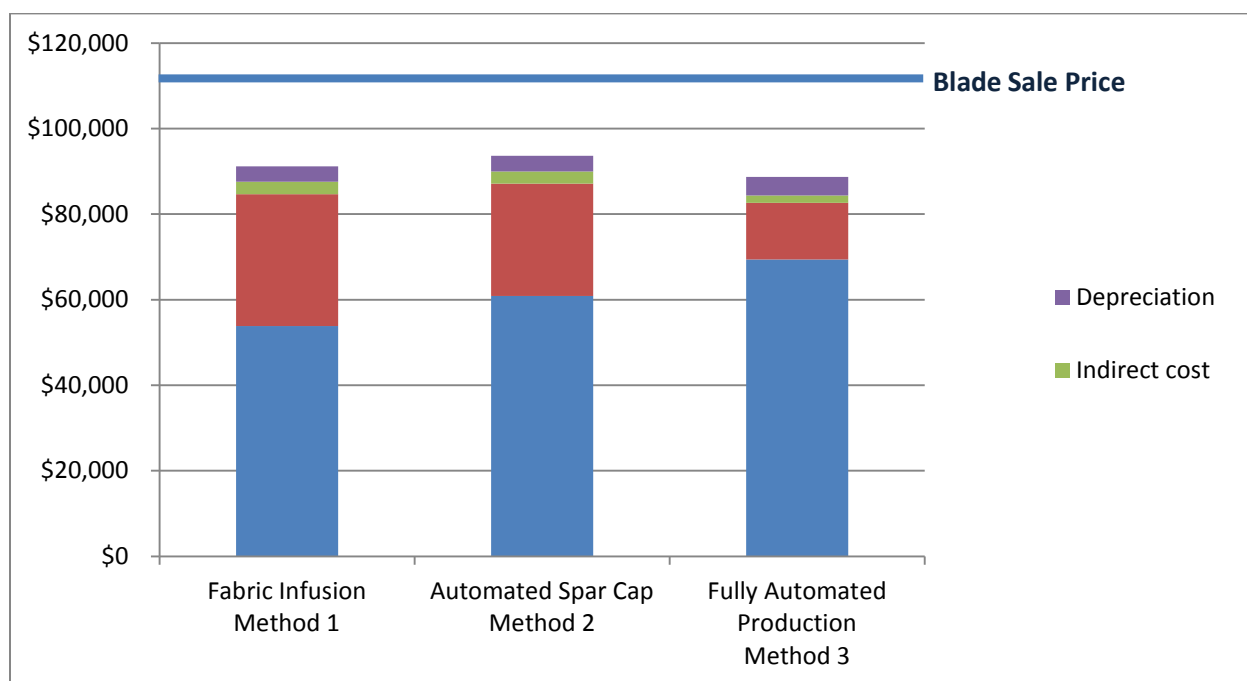


Figure 23 Blade cost breakdown for manufacturing alternatives

A financial analysis was conducted for each manufacturing method to compare profitability and return on investment for all three manufacturing methods and select the most attractive alternative from a financial point of view. A theoretical income statement for each case was developed and used to determine the corresponding cash flows for the duration of the project. This data was also used to calculate profit margin, return on assets (ROA), internal rate of return (IRR), return on capital employed (ROCE) and Net Present Value (NPV). A weighted average cost of capital (WACC) of 12% was used for a project period of 10 years on the NPV calculations. A summary of the projected income statement and the financial metrics is shown in Table 27.

From the analysis it can be inferred that all alternatives are attractive from an investment point of view as all NPV are positive and all internal rates of return calculated are higher than the discount rate. The full automation alternative (method 3) allows for a higher profit margin than the manual methods due to lower direct and indirect costs, and given the proposed manufacturing layout, could result in a slightly higher return on assets (47% for automation vs. 42% for manual). It can further be noted that the infusion process (method 1) came out ahead of method 2 (automated spar cap) in terms of return on capital, however automating a section of the blade could be a feasible alternative for a make vs. buy case in which the blade OEM can find it attractive to purchase higher performance pre-made spar sections from a dedicated automated molder with lower fixed costs than the blade OEM. As the technology matures, it can be expected that automation will become even more attractive for blade producers as lower cost manufacturing solutions become available in the market place.

Table 27 Projected income statement and financial ratios

	Fabric Infusion Method 1	Automated Spar Cap Method 2	Fully Automated Production Method 3
Income Statement			
Theoretical blades per year	1,055	1,068	1,033
Gross Sales	\$116,068,966	\$117,434,483	\$113,652,000
Material Costs	\$56,806,599	\$64,949,780	\$71,725,392
Direct Labor Costs	\$32,499,310	\$28,098,869	\$13,679,568
Indirect Costs	3,100,000	3,000,000	1,753,467
Depreciation	\$3,784,000	\$3,904,000	\$4,442,446
EBIT	\$19,879,056	\$17,481,834	\$22,051,127
Profit Margin	17%	15%	19%
Profit Margin (with depreciation)	20.4%	18.2%	23.3%
Taxes	\$6,957,670	\$6,118,642	\$7,717,894
Net Income	\$12,921,386	\$11,363,192	\$14,333,233
Financial Ratios and Analysis Metrics			
Asset turnover (GS/CAPEX)	2.48	2.44	2.42
Return on Assets	42%	36%	47%
ROA (with depreciation)	51%	44%	56%
Return on Capital	27.6%	23.6%	30.5%
NPV @ 12%WACC	\$53,020,024	\$43,008,629	\$67,627,336
IRR	35%	16%	25%

SUMMARY OF ACCOMPLISHMENTS

From the extensive body of work performed in this project, the following summary of key accomplishments was drawn:

- **A wind blade material property database was developed by using internal PPG test data and input from the MSU database.** Through evaluation of the database it was possible to identify the key performance metrics for wind blade composite materials utilized today.
- The performance of a **state of the art fiber glass roving and resin system in different product formats utilized in wind (mainly prepreg and stitch bonded fabrics)** has been thoroughly characterized and documented for its static and dynamic properties.
- **A stand alone gantry type automation machine offered by MAG for the production of wind blade components of up to 60m in length was found to be a technically viable solution for wind turbine blade production.** Several layup and process simulations have been performed with the machine model to determine the respective material lay down rates and calculate machine efficiency and resulting component production times.
- **Several finite element models have been developed with the purpose of measuring basic characteristics of wind blades (stiffness, weight).** Furthermore, the models were

used to determine the corresponding bill of materials for blades produced via automation and traditional infusion processes.

- Various low cost intermediate material forms suitable for automation were evaluated with existing fiber placement equipment for their process characteristics through standard automation routines. **Composite laminates made with the candidate materials were also tested for static and dynamic performance and demonstrated significant potential improvements in laminate strength, stiffness and fatigue life in comparison to existing materials.**
- **From the technical evaluation it was determined that delivery of pre-impregnated glass fiber materials to the work piece via automation is a technically viable manufacturing alternative for the production of wind blade components.** As a first step towards commercial implementation of this technology, a detailed material specification has been developed based on the selected materials for a first generation wind automation material form that incorporates processing advantages through automated processes and provides excellent mechanical properties.
- **Through the use of automation and innovative fiber glass materials it was deemed possible to further reduce the cost of energy generation for the development of larger and stiffer blades.** Experimental verification of the calculations performed here is expected in subsequent stages of this project.
- **A detailed economic analysis of blade production by automation has been developed and has been compared to existing manufacturing processes.** The economic results show the full automation method with a slight Return on Investment (ROI) performance advantage over the manual infusion method. The full automation method allows wind blade producers to obtain higher profit margins, and reduced direct and indirect expenses in a streamlined production facility with smaller plant footprint than a traditional infusion manufacturing setting. **The automation method NPV is 27.5% higher than the manual infusion method which indicates higher positive cash flows with the automation approach.** It should be noted that the material cost is the single biggest variable driving the automation IRR (25%) below manual infusion (35%). However, both IRR's are positive and above 20%, which indicates strong growth rate for both approaches. It should also be noted that a 15% improvement in prepreg material cost would bring automation into the 35% IRR range with a corresponding NPV over 100% higher than that of manual infusion.

CONCLUSIONS

This project has proven that the combination of pre-impregnated fiberglass based materials deposited onto wind turbine blades using automated fiber placement machines represents a technical and economically viable improvement over current blade manufacturing technology. In addition, this project demonstrated that laminates constructed of the newly developed preimpregnated glass fiber based materials can meet or exceed the mechanical properties and overall performance of currently used vacuum infused laminates. The combination of the demonstrated technical performance and economic modeling results strongly supports further development of wind blade materials and automated manufacturing processes. Further work

in the following areas will solidify the economic benefits of improved glass fiber materials and automation processes:

- Evaluate the further potential benefits that can be achieved in cost of energy reduction through the use of novel high performance fiber glass materials
- Improve/optimize prepreg production processes to lower the cost of material;
- Develop new resins to reduce the cure times and increase productivity;
- Further optimize turbine blade designs to take advantage of precision fiber placement.

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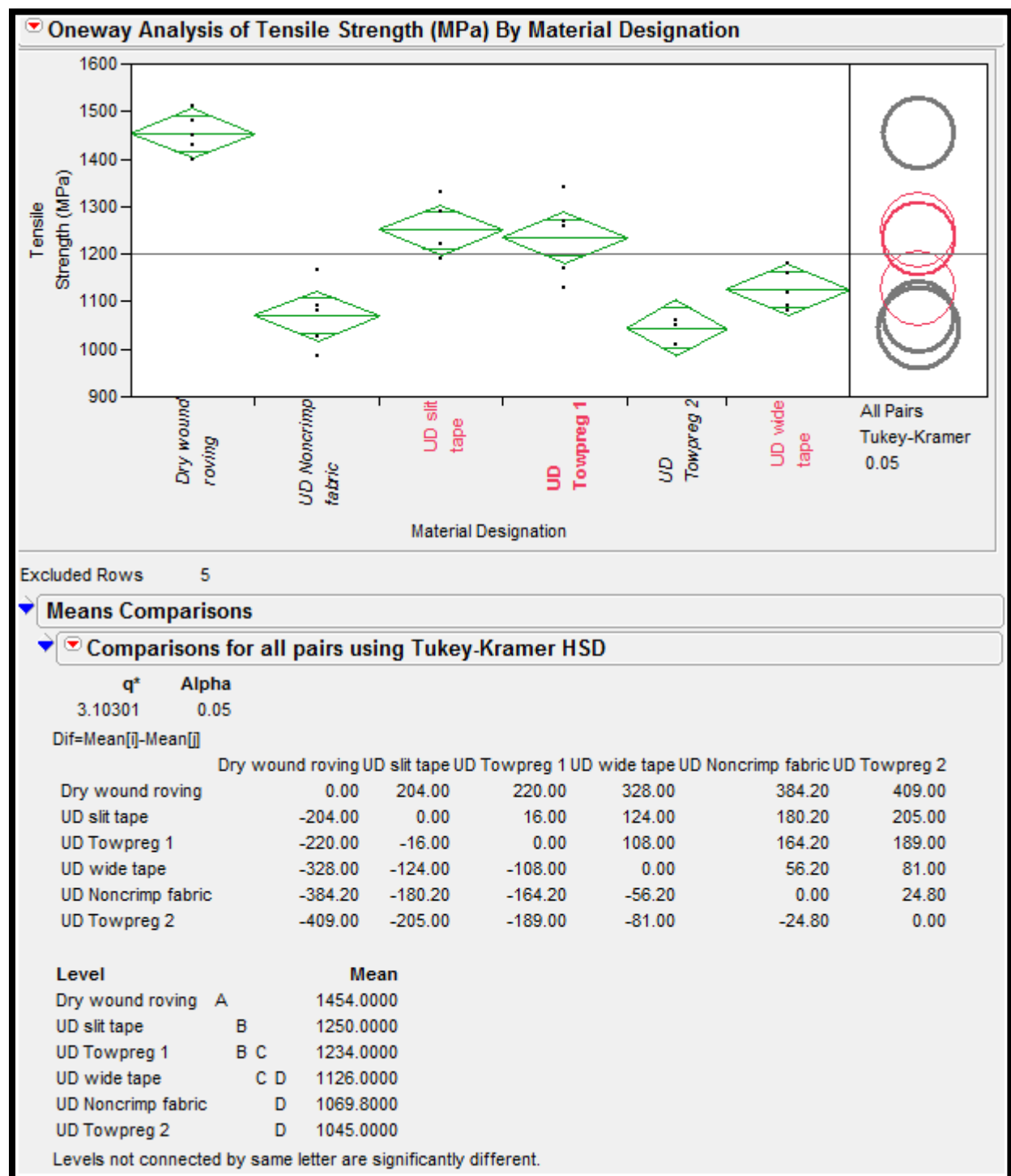
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APPENDIX 1 STATISTICAL ANALYSIS SUMMARY OF TEST DATA FOR UD LAMINATES



APPENDIX 2 BILL OF MATERIALS FOR EQUIVALENT STIFFNESS BLADES PRODUCED THROUGH DIFFERENT MANUFACTURING PROCESSES

Table 28 Bill of Materials. Method 1 (Infusion)

	kg	%	\$/kg	Total
Glass Fabric	6,807	51%	\$ 2.9	\$ 19,740
Glass Scrap	1,702	25%		\$ 4,935
Resin	2,917	22%	\$ 4.3	\$ 12,544
Resin Scrap	729	25%		\$ 3,136
Core	497	4%	\$ 20.0	\$ 9,935
Core Scrap	75	15%		\$ 1,490
Adhesive	307	2%	\$ 4.3	\$ 1,318
Adhesive Scrap	77	25%		\$ 330
Studs	204	2%	\$ 2.0	\$ 409
Total	13,314	kg		\$ 53,836

Table 29 Bill of Materials. Method 2 (Sparcap automation)

	kg	%	\$/kg	Total
Glass prepreg	4,773	41%	\$ 5.8	\$ 27,682.24
Prepreg Scrap	239	5%		\$ 1,384
Glass Fabric	3,257	28%	\$ 2.9	\$ 9,446.54
Fabric Scrap	814	25%		\$ 2,362
Infusion Resin	1,311	11%	\$ 4.3	\$ 5,636.44
Resin Scrap	197	15%		\$ 845
Core	497	4%	\$ 20.0	\$ 9,934.58
Core Scrap	75	15%		\$ 1,490
Adhesive	307	3%	\$ 4.3	\$ 1,318.38
Adhesive Scrap	77	25%		\$ 330
Studs	204	2%	\$ 2.0	\$ 408.80
Total	11,750	kg		\$ 60,837.97

Table 30 Bill of Materials. Method 3 (Full automation)

			\$/kg	Total
Glass prepreg	9,185	78%	\$ 5.8	\$ 53,275.32
Scrap	459	5%		\$ 2,664
Glass Fabric	0	0%	\$ 2.9	\$ -
Scrap	0	25%		\$ -
Infusion Resin	0	0%	\$ 4.3	\$ -
Scrap	0	25%		\$ -
Core	497	4%	\$ 20.0	\$ 9,934.58
Scrap	75	15%		\$ 1,490
Adhesive	307	3%	\$ 4.3	\$ 1,318.38
Scrap	77	25%		\$ 330
Studs	204	2%	\$ 2.0	\$ 408.80
Total	10,804	kg		\$ 69,420.63

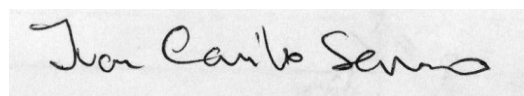
APPENDIX 3 SAMPLE OF PROCESS TIME DATA SHEET FOR MANUAL INFUSION (METHOD 1)

One Shell			
	hour	labor	man-hour
Mould prep/ Gel coat	2	10	20
Fabric layup/Root inserts/core applicatic	5	10	50
Vacuum Bag Application	2	6	12
Infusion	2.5	10	25
Cure	10	1	10
Consumable Removal	0.5	8	4
TOTAL	22		121
Assembling			
	hour	labor	man-hour
Adhesive Application	1	8	8
Adhesive Cure	5	1	5
Demould	1	10	9
Total Mould Time	7		22
Finishing			
	hour	labor	man-hour
Finishing	15	20	300
Total Mould Time	29		770

One Spar			
	hour	labor	man-hour
Mould Preparation	0.5	8	4
Fabric/Prepreg Lay-up	3	10	30
Vacuum Bag Applicati	0.5	8	4
Infusion	1.5	6	9
Cure	10	1	10
Consumable Remova	0.5	4	2
TOTAL	16		59
Root manufacturing			
	hour	labor	man-hour
Mould Preparation	0.75	2	1.5
Fabric/Prepreg Lay-up	2	4	8
Vacuum Bag Applicati	0.5	2	1
Vacuum drop test	0.5	1	0.5
Infusion	1.5	2	3
Cure	10	1	10
Consumable removal	1.25	2	2.5
TOTAL	16.5		26.5

Web			
	hour	labor	man-hour
Fabric layup/core	3	4	12
Vacuum Bag Application	0.5	4	2
Infusion	1.5	6	9
Cure	10	1	10
Consumable Removal	0.5	4	2
TOTAL	15.5		35

Total manhours = 2x shell time + 2x spar + 2x root +Web+ assembling + finishing



Juan Camilo Serrano
Fiber Glass Science and Technology