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TX-100 Manufacturing Final Project Report

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Abstract

This report details the work completed under the TX-100 blade manufacturing portion of the Carbon-Hybrid Blade Developments: Standard and Twist-Coupled Prototype project. The TX-100 blade is a 9 meter prototype blade designed with bend-twist coupling to augment the mitigation of peak loads during normal turbine operation. This structural coupling was achieved by locating off axis carbon fiber in the outboard portion of the blade skins. The report will present the tooling selection, blade production, blade instrumentation, blade shipping and adapter plate design and fabrication. The baseline blade used for this project was the ERS-100 (Revision D) wind turbine blade. The molds used for the production of the TX-100 were originally built for the production of the CX-100 blade. The same high pressure and low pressure skin molds were used to manufacture the TX-100 skins. In order to compensate for the difference in skin thickness between the CX-100 and the TX-100, however, a new TX-100 shear web plug and mold were required. Both the blade assembly fixture and the root stud insertion fixture used for the CX-100 blades could be utilized for the TX-100 blades. A production run of seven TX-100 prototype blades was undertaken at TPI Composites during the month of October, 2004. Of those seven blades, four were instrumented with strain gauges before final assembly. After production at the TPI Composites facility in Rhode Island, the blades were shipped to various test sites: two blades to the National Wind Technology Center at the National Renewable Energy Laboratory in Boulder, Colorado, two blades to Sandia National Laboratory in Albuquerque, New Mexico and three blades to the United States Department of Agriculture turbine field test facility in Bushland, Texas. An adapter plate was designed to allow the TX-100 blades to be installed on existing Micon 65/13M turbines at the USDA site. The conclusion of this program is the kick-off of the TX-100 blade testing at the three testing facilities.

Acknowledgements

This project was supported by Sandia National Laboratories under Contract 72852 – Revision 3. The technical manager was Thomas Ashwill. The author would like to thank Thomas Ashwill, Paul Veers, Mark Rumsey, Dale Berg, Jose Zayas and Daniel Laird at Sandia National Laboratories for their guidance. The author would also like to thank Dayton Griffin at Global Energy Concepts, Mike Zuteck at MDZ Consulting and Stephen Nolet at TPI Composites for their help in completing this project.

Table of Contents

List of Figures

Summary

This report details the work completed under the TX-100 blade manufacturing portion of the Carbon-Hybrid Blade Developments: Standard and Twist-Coupled Prototype project. The TX-100 blade is a 9 meter prototype blade designed with bend-twist coupling to augment the mitigation of peak loads during normal turbine operation. This structural coupling was achieved by locating off axis carbon fiber in the outboard portion of the blade skins. The report will present the tooling selection, blade production, blade instrumentation, blade shipping and adapter plate design and fabrication. The baseline blade used for this project was the ERS-100 (Revision D) wind turbine blade [1]. The molds used for the production of the TX-100 were originally built for the production of the CX-100 blade [2]. The same high pressure and low pressure skin molds were used to manufacture the TX-100 skins. In order to compensate for the difference in skin thickness between the CX-100 and the TX-100, however, a new TX-100 shear web plug and mold were required. Both the blade assembly fixture and the root stud insertion fixture used for the CX-100 blades could be utilized for the TX-100 blades. A production run of seven TX-100 prototype blades was undertaken at TPI Composites during the month of October, 2004. Of those seven blades, four were instrumented with strain gauges before final assembly. After production at the TPI Composites facility in Rhode Island, the blades were shipped to various test sites: two blades to the National Wind Technology Center at the National Renewable Energy Laboratory in Boulder, Colorado, two blades to Sandia National Laboratory in Albuquerque, New Mexico and three blades to the United States Department of Agriculture turbine field test facility in Bushland, Texas. An adapter plate was designed to allow the TX-100 blades to be installed on existing Micon 65/13M turbines at the USDA site. The conclusion of this program is the kick-off of the TX-100 blade testing at the three testing facilities.

1.0 TX-100 Design

1.1 9 Meter Blade Design Background

The TX-100 blade continued to build upon many years of nine meter wind blade development efforts. The original blade design, the ERS-100, was a product of the Blade Manufacturing Initiative (BMI) contract between Sandia National Laboratories and TPI Composites [1]. Revision A of the ERS-100 blade was nine meters in length, utilized NREL high lift airfoils and included 10 bolts in the root connection on a bolt circle diameter of 251.5mm – to match up with the existing pattern of the Kenetech 56-100 turbine. The original ERS-100 station sections (root sections and outboard airfoil sections) are shown in Figure 1. The ERS-100 root pattern is shown in Figure 2. After several iterations, the Revision D version of the ERS-100 was 8.8 meters in length and still included 10 bolts in the root. During the detailed design phase of the CX-100 and TX-100 project, the design team decided to modify the existing ERS-100 Revision D plugs to become skin plugs for the CX-100 and TX-100 blades.

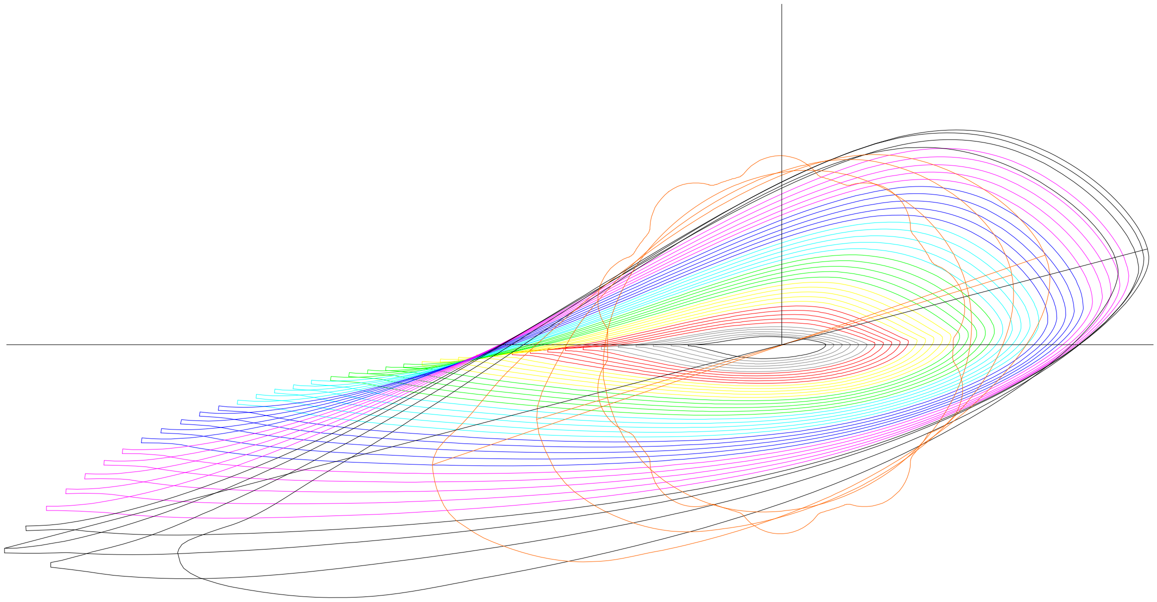


Figure 1 Original ERS-100 Station Sections

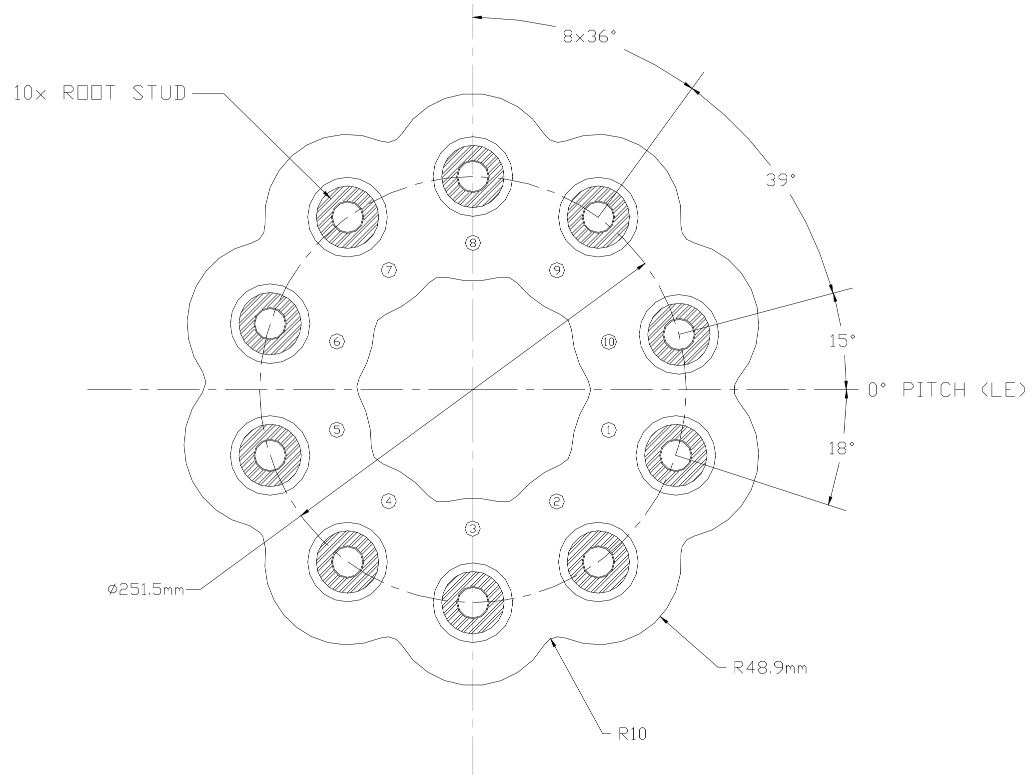


Figure 2 Original ERS-100 Root Pattern

1.2 TX-100 Geometry

When gathered at the CX-100 Detailed Design Review Meeting at SNL in December of 2003, the team decided to set the length of the CX-100 and the TX-100 at nine meters. The decision was also made to change the root connection configuration. As mentioned above, the last revision of the ERS-100 blade had a bolt circle diameter of 251.5mm and a bolt count of ten. This original root connection design was dictated by the need to connect the ERS-100 blade to existing turbines. Going forward, however, the team had the freedom to redesign the root in order to reduce the loads in that area of the blade. All agreed that we should increase the number of bolts and increase the diameter of the bolt circle. No matter what configuration we chose, both the CX-100 and TX-100 would need an adapter plate to fit onto the Micon test turbine in Bushland, TX – the chosen location for field testing. When considering the options for the enlarged root, a configuration that had been used on an earlier blade design, the NPS-100, made good sense. The NPS-100 blade had been an offshoot of the ERS-100 design. It was developed in conjunction with Northern Power Systems for a 100 kilowatt, upwind, three-bladed, stall-controlled turbine that they produced for remote environments [3]. TPI Composites already had some manufacturing experience with the NPS root configuration. The NPS root design had also fared extremely well in both static and fatigue testing of full scale blades at the National Wind Technology Center (NWTC) – a part of the National Renewable Energy Laboratory (NREL) [4]. The team decided to use the NPS-100 root configuration in the CX-100 and TX-100 blades. This configuration is shown in Figure 3. It includes 12 bolts on a bolt circle diameter of 300mm.

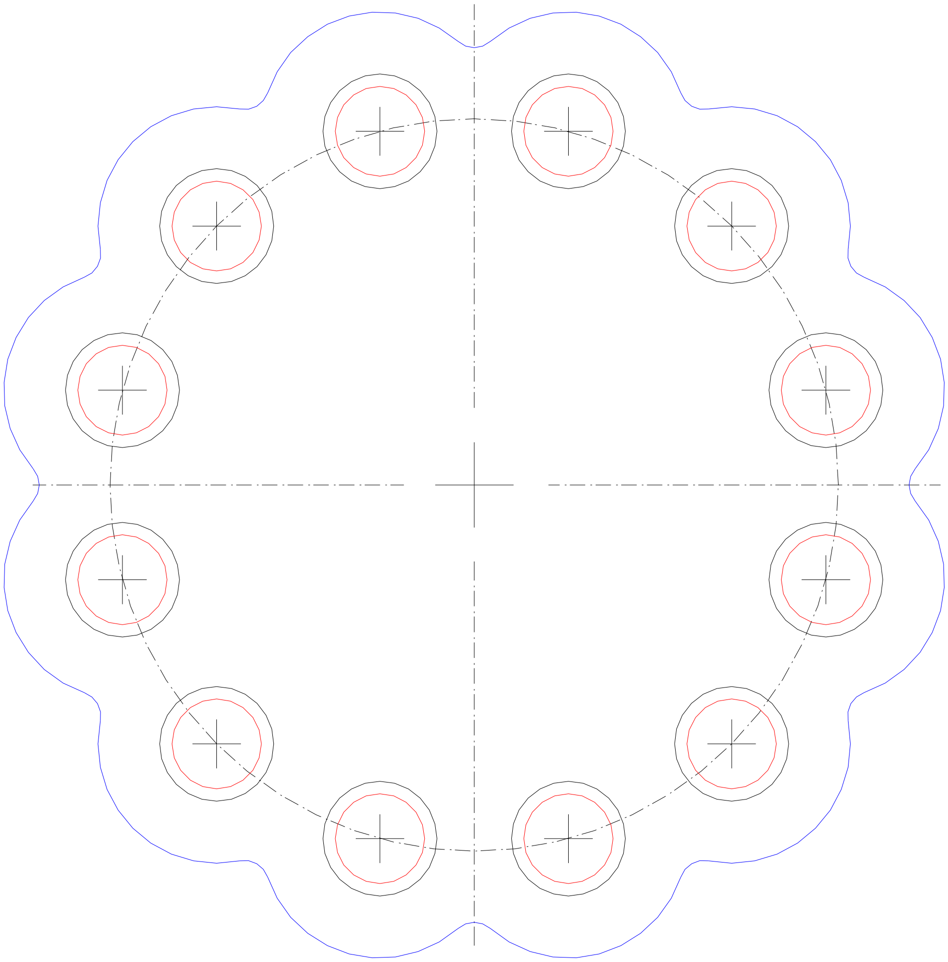


Figure 3 NPS-100 Root Configuration

Both the ERS-100 and the NPS-100 roots had shaped outer skins that conformed with the circular shapes of the root stud cavities within the blade root laminate. This can be seen on the outer surface of the NPS root shown in Figure 3. These shapes have become known as scallops. The purpose of the scallops was to force the fiberglass in the root area to form tightly around the root stud cavities – thus eliminating the need for inefficient filler fiberglass between the cavities. Although we believed this to be the best theoretical design of the root, the manufacturing reality was somewhat different. While not impossible, fabricating blade roots with the scalloped design was more difficult on the shop floor. It was much more consistent and repeatable to produce the blade root in the shape of a simple cylinder. Therefore, the team decided to design the new root with a cylinder for the outer shape. As shown in Figure 4, the resulting TX-100 root configuration still utilized 12 bolts on a bolt circle diameter of 300mm – but also maintained a simple outer shell.

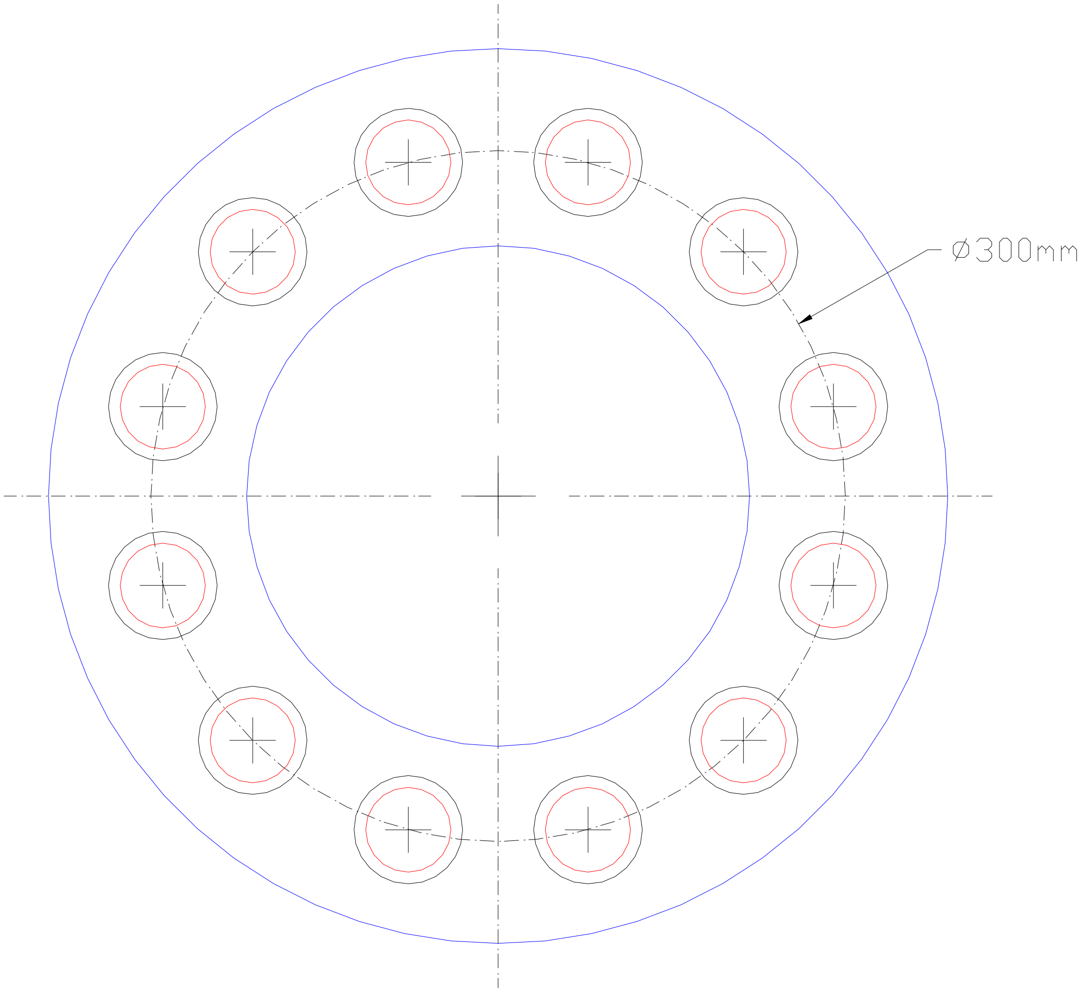


Figure 4 TX-100 Root Configuration

As mentioned above, the CX-100 design team also decided to set the length of the new blade at 9 meters. Because the existing ERS-100 Revision D plug was 8.8 meters long, TPI Composites had to rework the skin plugs to increase their lengths by 200 mm. Due to the fact that we were already planning on modifying the root section of the plugs for the CX-100 project, the team decided to add the required 200 mm in that section. The result is that the remaining outboard section of the plugs would remain untouched [2]. This remained true for the TX-100 blades because they used the same skin molds from the CX-100 project.

2.0 TX-100 Shear Web Mold

In preparing for this manufacturing project, the team determined that one additional mold would have to be fabricated in order to build the TX-100 blades. Because the relative high pressure and low pressure skin thickness of the TX-100 blade would be different from those of the CX-100 blade, new shear web geometry was required. The definition of the new geometry was best defined by using the first set of TX-100 skins that were produced. The process described below, therefore, had to be completed just after the beginning of the TX-100 manufacturing process.

The TPI Composites prototype department adjusted the geometry of an existing CX-100 shear web to mock up the shape of a TX-100 shear web inside blade #1. After determining the new shape, we then used that piece as a plug to develop a TX-100 shear web mold. The mold was built using this new plug – and then prepared for shear web production. Figure 5 shows the new TX-100 shear web mold.

Figure 5 TX-100 Shear Web Mold

3.0 TX-100 Manufacturing Preparation

3.1 TX-100 Blade Design

The first step in the production of the TX-100 blade was undertaking the design of the structure. This task was accomplished under the first phase of the contract. The details of this work, including design objectives, constraints, material selection, internal structure design and final blade design can be found in the reports documenting the original phase of this contract [5]. The final result of the design effort for the TX-100 was a structural design package that would serve as the entry point into blade manufacturing at TPI Composites. This design package was presented at a detailed design review meeting at Sandia National Laboratories on 26 February, 2004. The geometry of the blade included two structural skins – the high pressure skin and the low pressure skin. Each skin contained a spar cap of unidirectional fiberglass material situated along the spanwise axis of the blade. Furthermore, each skin incorporated carbon fiber in the outboard half of the blade. This carbon fiber was oriented at 20° offset from the blade axis to augment bend-twist coupling. The blade skins were connected together at the leading edge and the trailing edge, as well as by a shear web in the center of the blade. As preparation to enter the manufacturing phase of this project, the TX-100 team agreed on several detail design points at the design review meeting. These points are summarized as follows:

- The team had chosen a design with five layers of C520 unidirectional fiberglass spar cap. All five layers would be the same length and the same shape.

- In order to reduce the torsional stiffness of the blade (to enhance the twist capability), the DBM-1208 fiberglass spar cap covers would be removed from the design of the blade.

- For the forward (leading edge) and aft (trailing edge) panels of the blade, 3/8" balsa would be used as a core material from the outboard end of the root build-up to the joint between the glass and the carbon in the skin. This joint traversed the blade skins at a 20° diagonal, starting at the trailing edge at 15% span and ending at the leading edge at 39% span. Outboard of this joint, ¼" balsa would be used as a panel stiffener.

- The ¼" balsa would be filleted along the leading edge and trailing edge of the blade to allow the carbon to make a smoother transition off of the face of the balsa to the edge of the laminate where no balsa exists. This laminate detail would allow for gentler curvature of the carbon fibers, which would reduce stress concentrations during blade loading.

- In order to prevent the carbon fiber from having to make the sharp transition onto a flange, all of the locations where the carbon fabric meets a flange would include an additional strip of DBM-1708 fiberglass. Similar to the balsa fillet situation discussed above, forcing the carbon to traverse a sharp corner could result in stress concentrations during loading. The fiberglass strip would overlap the carbon by a few inches, round the transition onto the return flange and fill out the rest of the width of the flange.

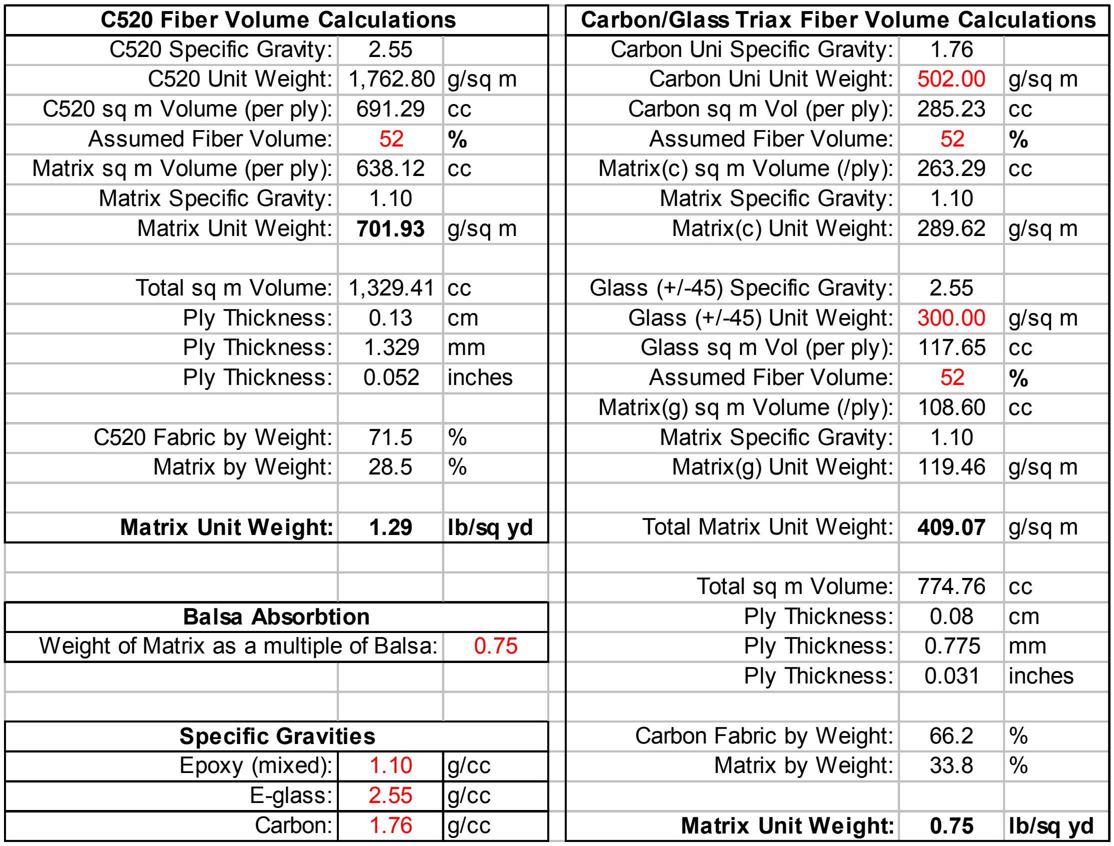
- The five fiberglass spar cap layers would be transitioned into the blade root laminate before any of the root build-up layers were added. Furthermore, unlike the CX-100 blade, the root build-up layers would be placed into the mold from the longest layer to the shortest layer.

3.2 TX-100 Bill of Material

The TX-100 Bill of Material (BOM), like the blade design discussed in the previous section, was completed during the first phase of the contract. This Excel spreadsheet served as a final laminate design tool, a material usage estimator, a material cost estimator and a blade (and component) weight estimator. There were several categories of inputs required in the BOM in order to accurately estimate the production run material usage amounts and cost estimates. The first input, partially shown in Figure 6, consisted of a list of the material to be used in the construction of the blades. In the expanded version of this page, each entry was also assigned a unit weight (or part weight, if applicable), a mix ratio (if applicable) and a unit cost. The next set of inputs was the infusion assumptions. These values, shown for a few items in Figure 7, set the value of fiber volume for each material. This was in turn used to calculate the weights and volumes of the fiberglass, carbon and epoxy in the blade. The final set of inputs, some of which is shown in Figure 8, consisted of different specifications for various parts of the blade. These included root fasteners, bonding details, laminate pattern areas and manufacturing scrap factors. All of the inputs, combined with line by line laminate calculations contained in different areas of the spreadsheet, were used to estimate overall material usage. TPI Composites used these estimates for ordering material and planning the production of the TX-100 blades. The BOM for this blade was completed in the first phase of this contract.

Material	Description	TPI Part Number	UOM
3/4oz Mat	3/4 oz per square foot mat (x60")	46051	lb
DBM-1208	+/-45 (12 oz) / 3/4oz Mat (6.75 oz) (x50")	46250	lb
DBM-1708	+/-45 (17 oz) / 3/4oz Mat (6.75 oz) (x50")	46262	lb
C260	(or A260) 26oz Unidirectional	85200	lb
C520	52oz Unidirectional	46510	lb
Hy-Tri (500gsmC)	Saertex V95351 (150gsm(-45)g/502gsm(0)c/150gsm(+45)g/6gsmstch)	TBD	lb
Balsa, 3/8"	10 lb per cubic foot	47057	sf
Balsa, 1/4"	10 lb per cubic foot	46015	sf
Huntsman LY1564	Epoxy Resin [9.55 lbs/gal - 1.14 g/cc (sg)] [Mixed: 9.2 lbs/gal - 1.10 g/cc (sg)]	TBD	lb
Huntsman XP3486	Epoxy Hardener - Slow [8 lbs/gal - 0.96 g/cc (sg)]	TBD	lb
Gelcoat	Gelcoat - White Sport - 953-WA411	46508	lb
At-Prime	At-Prime Adhesion (Part A and Part B) [11 lbs per gallon]	46110	lb
Plexus 550 Part A	[7.75 lbs/gal - 0.93 g/cc (sg)] [Mixed: 8.35 lbs/gal - 1.00 g/cc (sg)]	29238	ga
Plexus 550 Part B	[14.3 lbs/gal - 1.72 g/cc (sg)]	29239	ga
Root Stud, 3/4-16		85006	ea
West System 105	West System 105 [52.03 gal/drum][appr. $3.75/lb]	29068	ga
West System 206	Hardener, 206E West Slow	29117	ga
404 Filler	Filler, High Density, 404-45B	46393	lb
Aerosil	Filler, Thix, R200 Aerosil	46028	lb

Figure 6 BOM Material Inputs



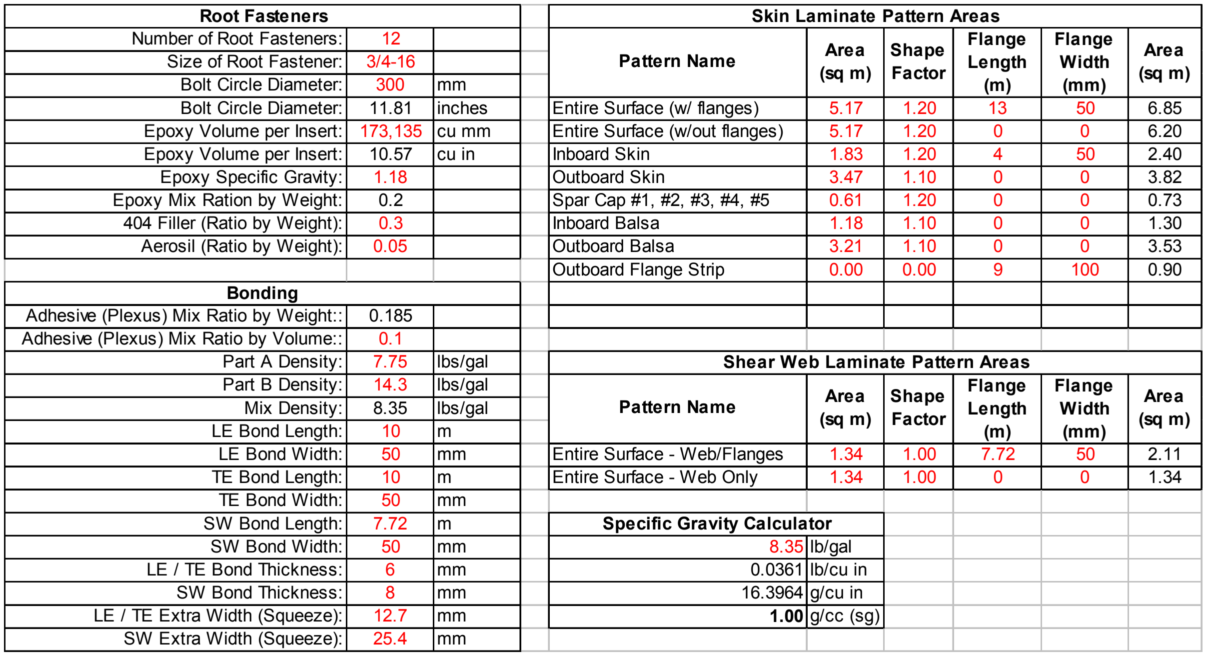
C520 Fiber Volume Calculations		
C520 Specific Gravity:	2.55	
C520 Unit Weight:	1,762.80	g/sq m
C520 sq m Volume (per ply):	691.29	cc
Assumed Fiber Volume:	52	%
Matrix sq m Volume (per ply):	638.12	cc
Matrix Specific Gravity:	1.10	
Matrix Unit Weight:	**701.93**	g/sq m
Total sq m Volume:	1,329.41	cc
Ply Thickness:	0.13	cm
Ply Thickness:	1.329	mm
Ply Thickness:	0.052	inches
C520 Fabric by Weight:	71.5	%
Matrix by Weight:	28.5	%
Matrix Unit Weight:	**1.29**	**lb/sq yd**

Balsa Absorbtion	
Weight of Matrix as a multiple of Balsa:	0.75

Specific Gravities		
Epoxy (mixed):	1.10	g/cc
E-glass:	2.55	g/cc
Carbon:	1.76	g/cc

Carbon/Glass Triax Fiber Volume Calculations		
Carbon Uni Specific Gravity:	1.76	
Carbon Uni Unit Weight:	502.00	g/sq m
Carbon sq m Vol (per ply):	285.23	cc
Assumed Fiber Volume:	52	%
Matrix(c) sq m Volume (/ply):	263.29	cc
Matrix Specific Gravity:	1.10	
Matrix(c) Unit Weight:	289.62	g/sq m
Glass (+/-45) Specific Gravity:	2.55	
Glass (+/-45) Unit Weight:	300.00	g/sq m
Glass sq m Vol (per ply):	117.65	cc
Assumed Fiber Volume:	52	%
Matrix(g) sq m Volume (/ply):	108.60	cc
Matrix Specific Gravity:	1.10	
Matrix(g) Unit Weight:	119.46	g/sq m
Total Matrix Unit Weight:	**409.07**	g/sq m
Total sq m Volume:	774.76	cc
Ply Thickness:	0.08	cm
Ply Thickness:	0.775	mm
Ply Thickness:	0.031	inches
Carbon Fabric by Weight:	66.2	%
Matrix by Weight:	33.8	%
Matrix Unit Weight:	**0.75**	**lb/sq yd**

Figure 7 BOM Infusion Assumptions



Root Fasteners		
Number of Root Fasteners:	12	
Size of Root Fastener:	3/4-16	
Bolt Circle Diameter:	300	mm
Bolt Circle Diameter:	11.81	inches
Epoxy Volume per Insert:	173,135	cu mm
Epoxy Volume per Insert:	10.57	cu in
Epoxy Specific Gravity:	1.18	
Epoxy Mix Ration by Weight:	0.2	
404 Filler (Ratio by Weight):	0.3	
Aerosil (Ratio by Weight):	0.05	

Bonding		
Adhesive (Plexus) Mix Ratio by Weight::	0.185	
Adhesive (Plexus) Mix Ratio by Volume::	0.1	
Part A Density:	7.75	lbs/gal
Part B Density:	14.3	lbs/gal
Mix Density:	8.35	lbs/gal
LE Bond Length:	10	m
LE Bond Width:	50	mm
TE Bond Length:	10	m
TE Bond Width:	50	mm
SW Bond Length:	7.72	m
SW Bond Width:	50	mm
LE / TE Bond Thickness:	6	mm
SW Bond Thickness:	8	mm
LE / TE Extra Width (Squeeze):	12.7	mm
SW Extra Width (Squeeze):	25.4	mm

Skin Laminate Pattern Areas

Pattern Name	Area (sq m)	Shape Factor	Flange Length (m)	Flange Width (mm)	Area (sq m)
Entire Surface (w/ flanges)	5.17	1.20	13	50	6.85
Entire Surface (w/out flanges)	5.17	1.20	0	0	6.20
Inboard Skin	1.83	1.20	4	50	2.40
Outboard Skin	3.47	1.10	0	0	3.82
Spar Cap #1, #2, #3, #4, #5	0.61	1.20	0	0	0.73
Inboard Balsa	1.18	1.10	0	0	1.30
Outboard Balsa	3.21	1.10	0	0	3.53
Outboard Flange Strip	0.00	0.00	9	100	0.90

Shear Web Laminate Pattern Areas

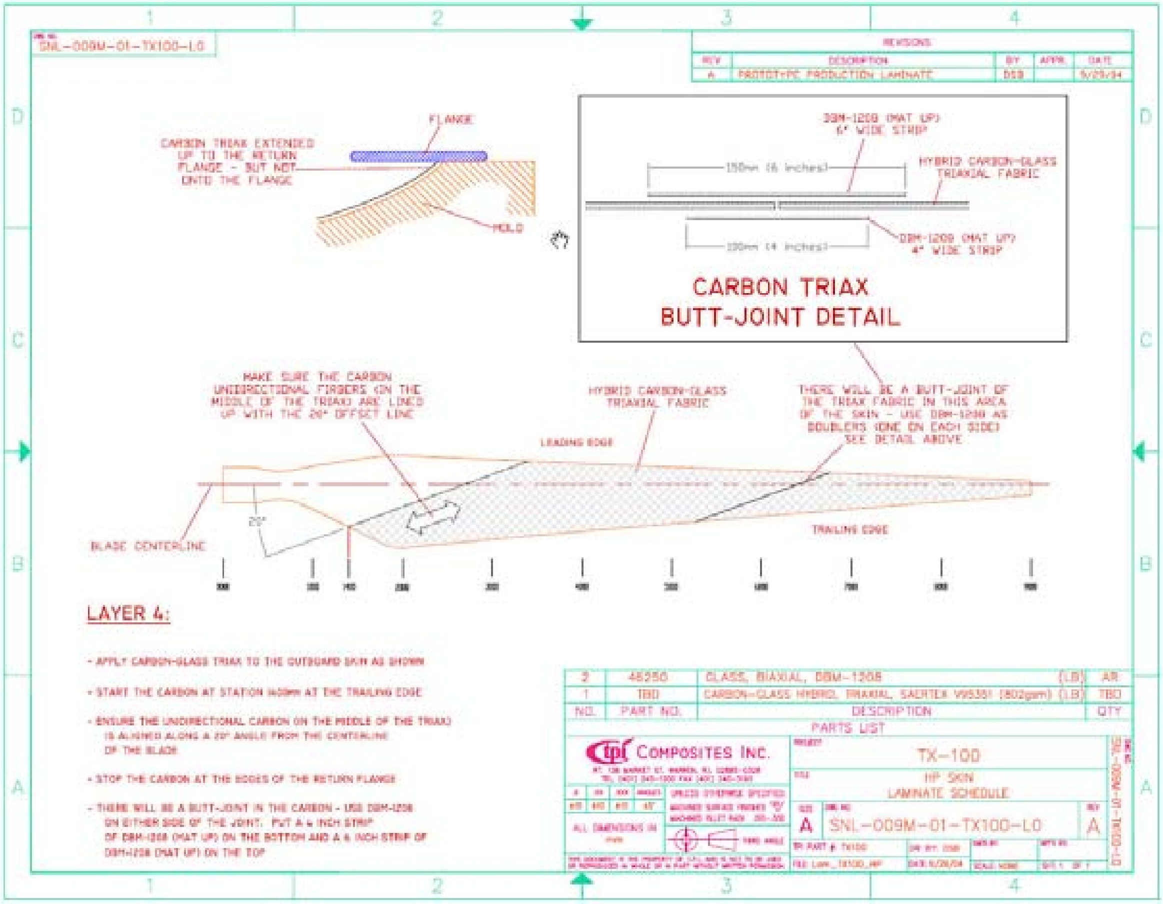
Pattern Name	Area (sq m)	Shape Factor	Flange Length (m)	Flange Width (mm)	Area (sq m)
Entire Surface - Web/Flanges	1.34	1.00	7.72	50	2.11
Entire Surface - Web Only	1.34	1.00	0	0	1.34

Specific Gravity Calculator	
8.35	lb/gal
0.0361	lb/cu in
16.3964	g/cu in
1.00	g/cc (sg)

Figure 8 BOM Specifications

3.3 TX-100 Laminate Schedules / Work Instructions

Before producing blades on the shop floor, a set of laminate schedules and work instructions had to be developed. As with the blade design and the BOM, the laminate schedules and work instructions were developed and presented for the TX-100 during the first phase of this contract. To serve as an example of the type of instructions presented in the shop floor laminate schedule, a page of the TX-100 High Pressure Skin Laminate Schedule is shown in Figure 9. The page layout and instruction approach shown here – in this case for the skin carbon triax layer – were also utilized throughout the shop documents for each layer of the laminate.



LAYER 4:

- APPLY CARBON-GLASS TRIAX TO THE OUTBOARD SKIN AS SHOWN
- START THE CARBON AT STATION 1400mm AT THE TRAILING EDGE
- ENSURE THE UNIDIRECTIONAL CARBON (IN THE MIDDLE OF THE TRIAX) IS ALIGNED ALONG A 20° ANGLE FROM THE CENTERLINE OF THE BLADE
- STOP THE CARBON AT THE EDGES OF THE RETURN FLANGE
- THERE WILL BE A BUTT-JOINT IN THE CARBON - USE DBM-1208 ON EITHER SIDE OF THE JOINT. PUT A 4 INCH STRIP OF DBM-1208 (MAT UP) ON THE BOTTOM AND A 6 INCH STRIP OF DBM-1208 (MAT UP) ON THE TOP

NO.	PART NO.	DESCRIPTION	QTY
2	46250	GLASS, BIAXIAL, DBM-1208 (LB)	AR
1	TBD	CARBON-GLASS HYBRID, TRIAXIAL, SAERTEX V95351 (802gsm) (LB)	TBD

PARTS LIST

TPI COMPOSITES INC.

Figure 9 TX-100 HP Carbon Triax Skin Laminate Schedule

Included with the work instructions was a package of manufacturing quality documentation. Each blade produced had a distinct packet of quality sign-off sheets that were evaluated and approved for each step of the manufacturing process. Actions governed included such processes as mold preparation, laminate placement, epoxy measurement, epoxy mixing, infusion, assemble and finishing. Some of the critical steps included authorization from a supervisor. Upon completion of the production of any given blade, the package of quality documents was filed in the quality assurance office to be kept on hand in case any issues arise with that blade.

4.0 TX-100 Blade Manufacturing

4.1 TX-100 Pattern Cutting

Upon commencing manufacturing, the first step was to cut patterns for the entire production run. In the case of the TX-100, this included seven blades. The pattern shapes could be developed in two different ways. The first involved drawing patterns using a computer drafting program. If a three dimensional model of the blade was available, all of the material patterns could be extracted using the proper software. However, even with very accurate three dimensional representations of layer shapes, some hand trimming would have to be completed in the mold during ply insertion. Without the benefit of a three dimensional computer model of the blade, only some layers could be accurately drawn using a computer drafting program. Other layers would have to be defined using paper patterns in the mold.

The first pattern to be defined was the five layers of the spar cap in each skin. These layers used the C520 fiberglass fabric for the material. This pattern, which is displayed in Figure 10, was drawn using the information provided by the TX-100 blade design. The main parameters involved were layer length and layer width at certain spanwise stations.

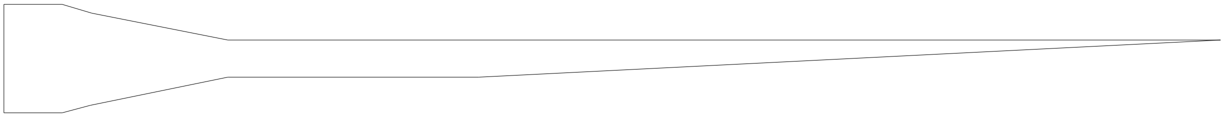


Figure 10 TX-100 Spar Cap Pattern

Another example of patterns drawn using computer drafting programs were the root build up layers. These shapes, some of which are shown in Figure 11, were cut using several materials, including C520, C260 and DBM-1208.

Figure 11 TX-100 C520 Root Patterns

Because the above patterns were defined digitally, the manufacturer had the option of producing these layers on an automated material cutting machine. In the case of the TX-100, however, all patterns were cut by hand.

Other types of patterns were defined using the mold as a template. These patterns, such as the full skin layers, were detailed by laying paper in the three dimensional mold to define the shape of the two dimensional pattern. Once the shape was defined, a more permanent template was produced using a material such as thin wood or cardboard. In order to cut these patterns using an automated cutting machine, these shapes would have to be digitized and turned into computer drawings. As mentioned above, the exception to this is the case where a three dimensional computer model was available – when all pattern shapes could be defined directly from computer data and thus cut on an automated machine without having to digitize hand patterns. The hand made patterns of the TX-100 were not digitized because all patterns were cut by hand.

The final patterns created were for the core in the aft and forward panels of the skin. These patterns, defined in the mold during the first lay-up of the skin, were then transferred to a more durable construction of thin wood. All of the material shapes were cut – 57 separate layers for each skin – and placed in order on a rolling manufacturing cart. These carts, called kits, were stationed next to the mold during the lay-up of the skins.

4.2 TX-100 Material Lay-Up

After cutting the material patterns, the next step in the blade manufacturing process was to place the materials into the mold. All molds had to be prepared for demolding using a mold release agent. This step is known as Mold Prep. With newer, more efficient mold release agents, this application does not have to occur before each lay-up. The mold does, however, have to be cleaned before each lay-up.

The first layer to go down into the mold was the gelcoat. This became the outer layer of the blade, providing a clean finish to the blade as well as protecting the composite materials of the blade from the harmful effects of UV degradation. The gelcoat – colored white in the case of the TX-100 – was sprayed onto the mold surface to a specified thickness. After the gelcoat was allowed to dry – or ‘tack’ – the rest of the laminate would then be placed into the mold. Figure 12 and Figure 13 show gelcoat after it has been sprayed into the skin mold.

Figure 12 TX-100 Gelcoat (1)

Figure 13 TX-100 Gelcoat (2)

After attaching the metal return flanges to the molds – which provide a bonding surface for the two skins, skin layers number 2 through number 64 were placed into the molds utilizing the instruction of the floor laminate schedules. The layers included such materials as ¾ oz Mat (¾ oz per square foot random strand fiberglass mat), DBM-1708 (17 oz per square yard double-bias 45° fiberglass), DBM-1208 (12 oz per square yard double-bias 45° fiberglass), C520 (52 oz per square yard unidirectional fiberglass), C260 (26 oz per square yard unidirectional fiberglass) and balsa core. Also included in the middle of the lay-up were cavity molds – to form chambers for subsequent root stud bonding – and fiberglass filler pieces (using scraps of C520 unidirectional fiberglass) between the cavity molds. Several of these layers are illustrated in Figures 14 through 22.

Figure 14 TX-100 Lay-Up (1)

Figure 15 TX-100 Lay-Up (2)

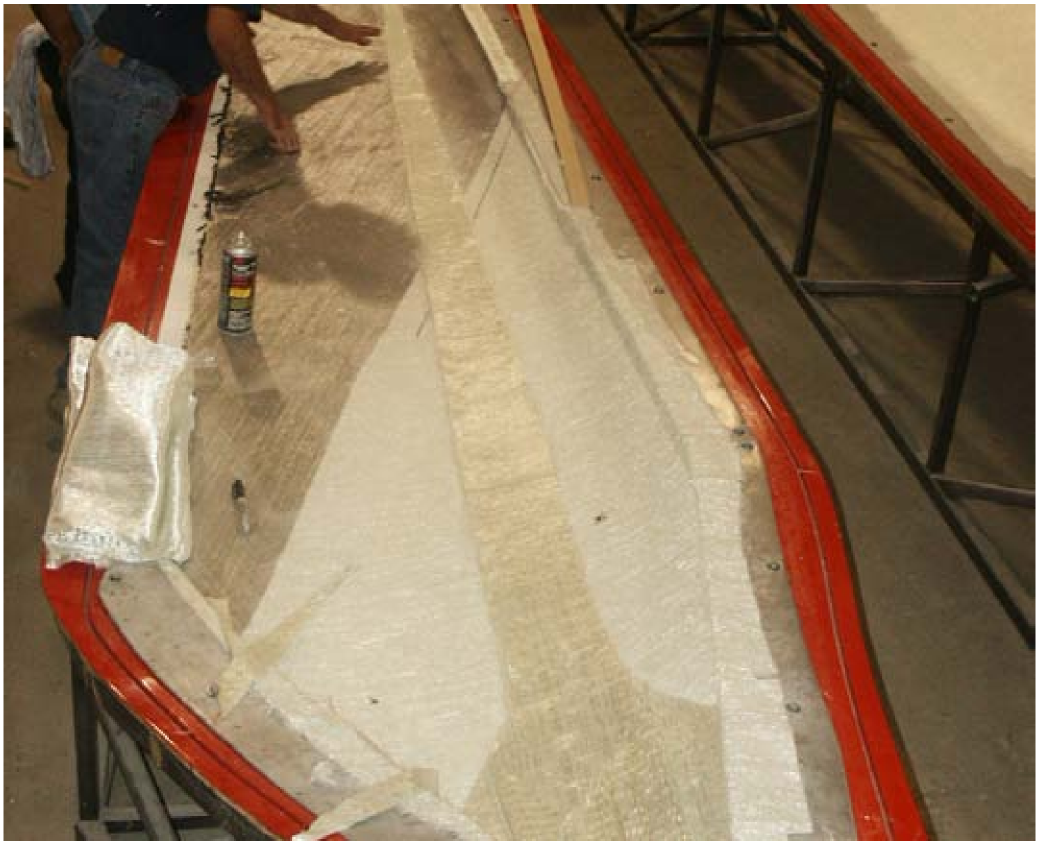


Figure 16 TX-100 Lay-Up (3)

Figure 17 TX-100 Lay-Up (4)

Figure 18 TX-100 Lay-Up (5)

Figure 19 TX-100 Lay-Up (6)

Figure 20 TX-100 Lay-Up (7)

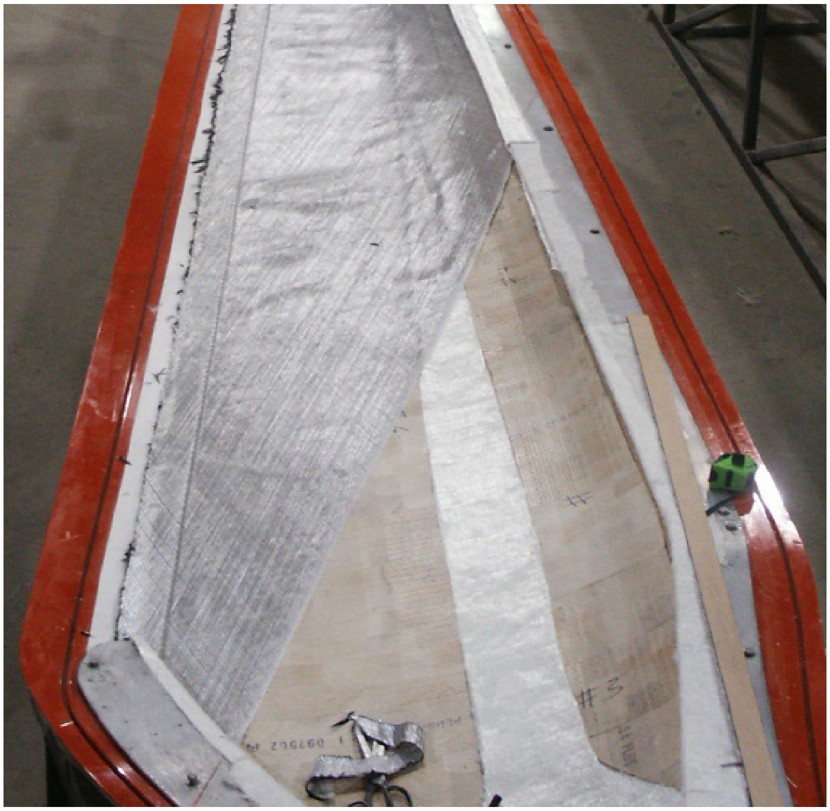


Figure 21 TX-100 Lay-Up (8)

Figure 22 TX-100 Lay-Up (9)

4.3 TX-100 Infusion

The manufacturing steps following material lay-up included vacuum bagging, infusion, post curing and demolding. The first step, vacuum bagging, occurred directly after all of the layers were placed into the mold. In the absence of a silicone bag, the blade was bagged using consumable materials. The main component was the nylon film vacuum bag. This covered the entire part and was sealed at the edges of the mold. This bag formed the barrier with which to evacuate the air from the blade laminate. Also included in the process of vacuum bagging were laying down all of the resin feed lines and the vacuum lines. These features, along with peel ply and infusion flow medium, augmented the infusion of resin (or in this case, epoxy) into the dry blade laminate. Figures 23 through 25 demonstrate the process of vacuum bagging.

Figure 23 TX-100 Vacuum Bagging (1)

Figure 24 TX-100 Vacuum Bagging (2)

Figure 25 TX-100 Vacuum Bagging (3)

The next step was the infusion and post curing of the blade components. The TX-100 blades were infused with a Huntsman Epoxy (LY1564). All of the bagged molds were placed into an oven to be used during post cure. The epoxy was pulled into the part using the vacuum created during the bagging process. Strategically placed on the blade skins, the resin feed lines evenly distributed the epoxy during infusion. Once the entire part was filled and the epoxy began to cure, the vacuum was turned down to a lower level and the temperature around the molds was elevated from room temperature to about 180 degrees Fahrenheit. The infusion process is shown in Figures 26 through 28.

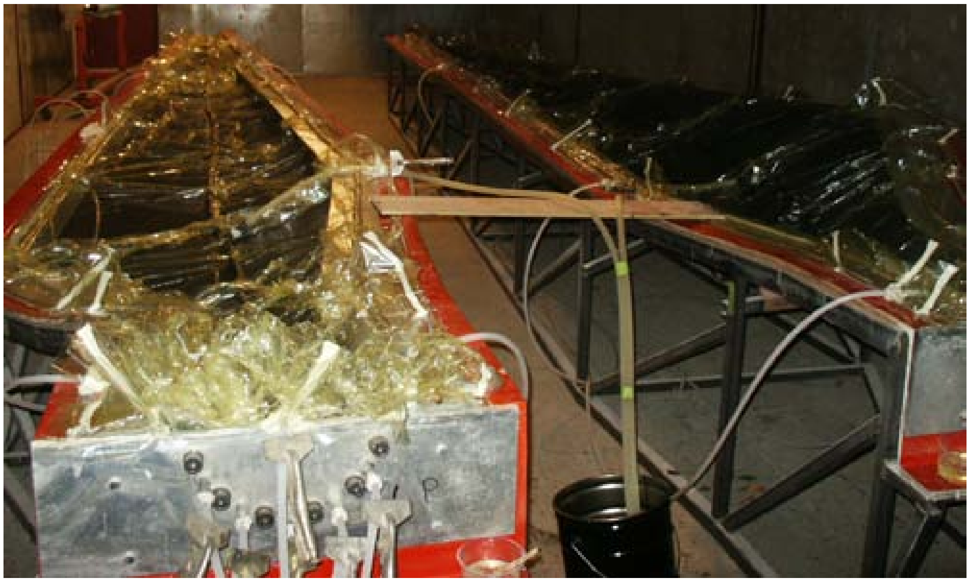


Figure 26 TX-100 Infusion (1)

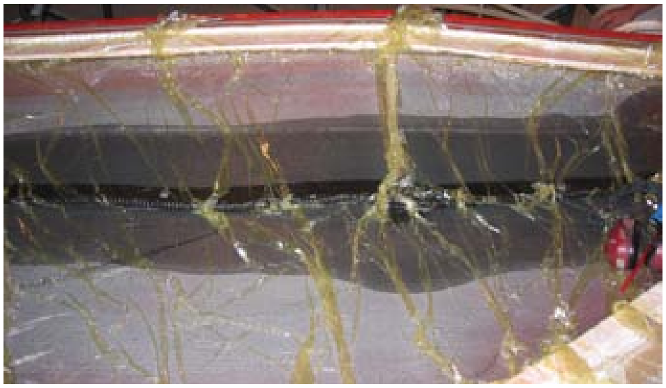


Figure 27 TX-100 Infusion (2)

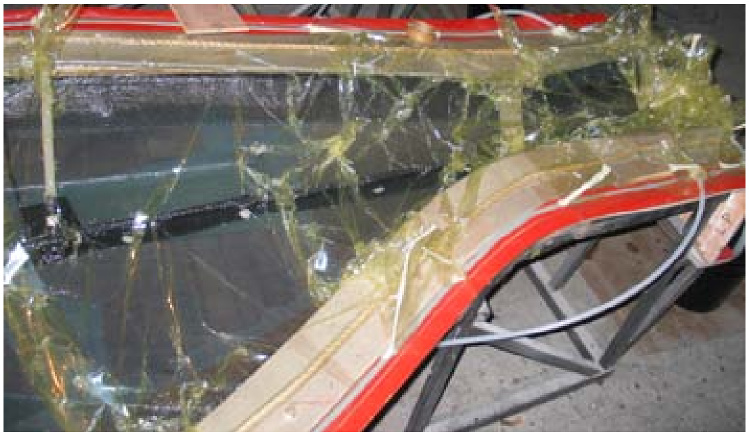


Figure 28 TX-100 Infusion (3)

The final step before assembly was demolding. This was the process of taking the composite part out of the mold. This is illustrated in Figure 29.

Figure 29 TX-100 Demolding

4.4 TX-100 Assembly

After demolding the TX-100 components – the low pressure skin, the high pressure skin and the shear web – the blade had to be assembled. The assembly of the TX-100 blade included two major steps: blade bonding and root stud insertion.

Blade bonding occurred in the blade assembly fixture. The low pressure skin was vacuumed into place in the lower fixed portion of the fixture. The high pressure skin was vacuumed into place in the over-swinging component of the assembly fixture. Using Plexus 550, the shear web was bonded into its proper location in the low pressure skin. This process was guided by locating arms referenced off of the structure of the assembly fixture. Once the lower shear web bond had cured, the high pressure skin was bonded to the upper flange of the shear web and the leading and trailing edges of the low pressure skin. Plexus 550 was used for this bond also. This procedure was accomplished by applying adhesive to the surfaces of the low pressure skin and the shear web and then swinging the high pressure skin over onto the top of the assembly. The upper skin was held down with weights and straps – assuring a complete bond to the lower surfaces. The Plexus 550 was allowed to cure overnight while the blade was in the assembly fixture.

After removing the bonded blade from the assembly fixture, it was placed into the root stud insertion fixture. The purpose of the root stud insertion fixture was to align and bond the 12 threaded inserts into the root of the TX-100 blade. These inserts will be used to attach the blade to the turbine (with an adapter plate as an interface). The bonded blade was strapped into the root stud insertion fixture to ensure proper location of the root stud cavities. Twelve threaded inserts were attached to a sliding locator plate inboard of the blade root. Once all of the parts were secured in place, the adhesive used to bond the root studs into the blade root was mixed. The adhesive used in this process was West System 105/206 epoxy. The epoxy was thickened with high density 404-45B Filler and R200 Aerosil. All of the root stud cavities were back-filled with this thickened epoxy. The root studs themselves were also coated with the epoxy. At this point, the 12 inserts were slid into the blade root – displacing some of the epoxy located in the cavities. Once entirely into position, the sliding plate was locked and the assembly was left to cure overnight. Figures 30 through 33 show various stages of the TX-100 blade in the fixtures.

Figure 30 TX-100 Assembly (1)

Figure 31 TX-100 Assembly (2)

Figure 32 TX-100 Assembly (3)

Figure 33 TX-100 Assembly (4)

5.0 TX-100 Instrumentation

During the assembly process, several of the TX-100 blades were instrumented with strain gauges. A significant part of the TX-100 project included a flight test program to interrogate the bend-twist performance of the blade. In an effort to support the test program and obtain useful data TPI Composites and Sandia National Laboratories agreed to instrument four of the seven blades.

Blades #004 and #005 were fully instrumented with gages at approximately 75%, 50% and 25% of blade span to measure flapwise bending strains. These two blades also received rosette gauges – measuring strains at a 45° angle from the blade pitch axis – at the three locations. Additionally, blades #004, #005, #006 and #007 were instrumented with strain gages at the root to measure both flapwise and edgewise bending strains.

Figure 34 shows the full instrumentation applied to blades #004 and #005. Each pair of gages made up a temperature compensated half arm of a full bridge. Combining maximum and minimum bending strains (high pressure and low pressure skins) provided high bridge output for accurate strain measurement.

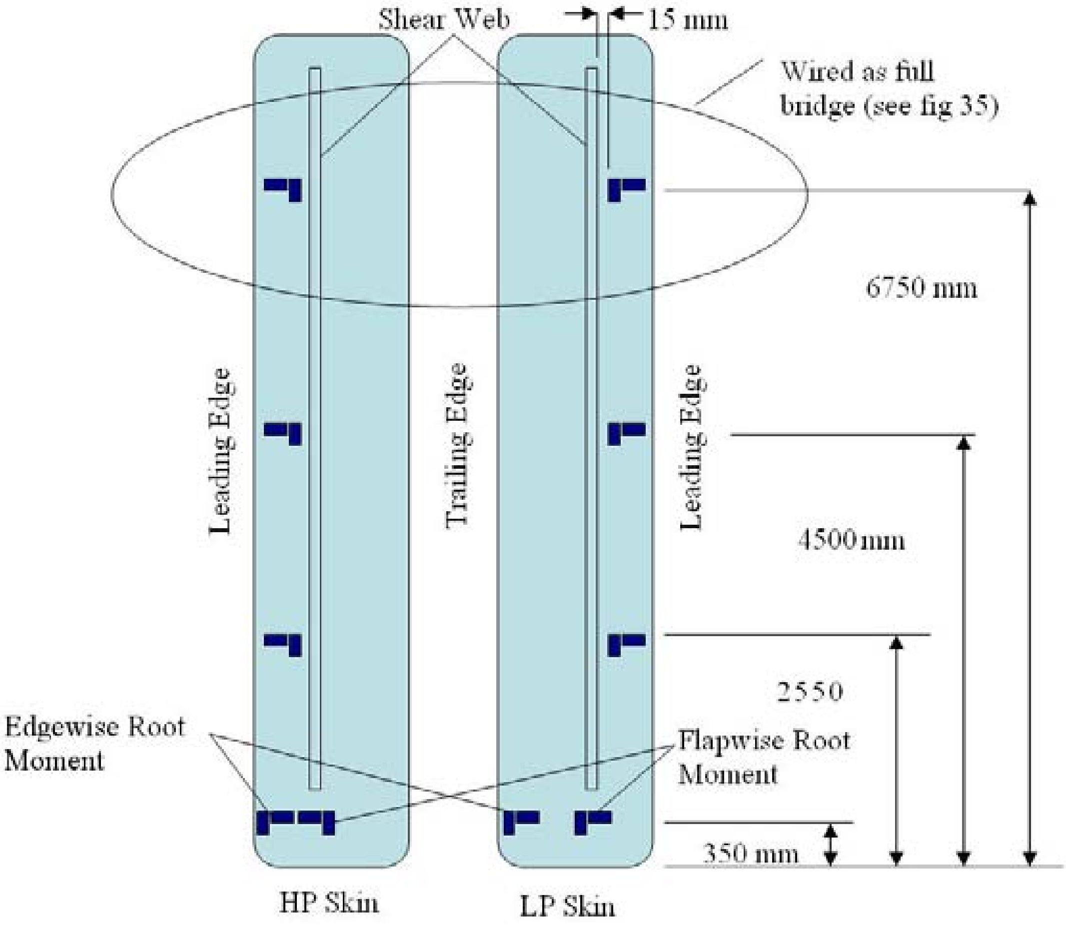


Figure 34 TX-100 Gauge Placement

Figure 35 is a diagram of the wiring of a complete Wheatstone bridge circuit. Axial gages made up the active component of the bridge while transverse gages provided temperature compensation. The axial gage on high pressure skin was wired to indicate a positive strain equaled tension.

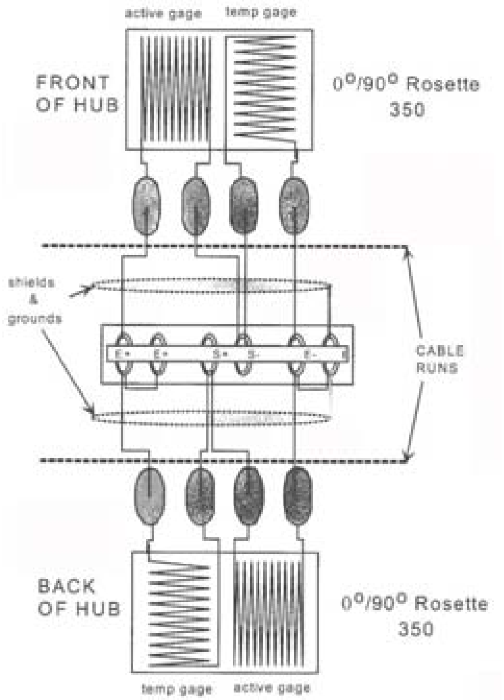


Figure 35 Wheatstone Bridge Diagram

Figures 36 through 39 show various views of the gauges installed in the TX-100 blades during assembly.

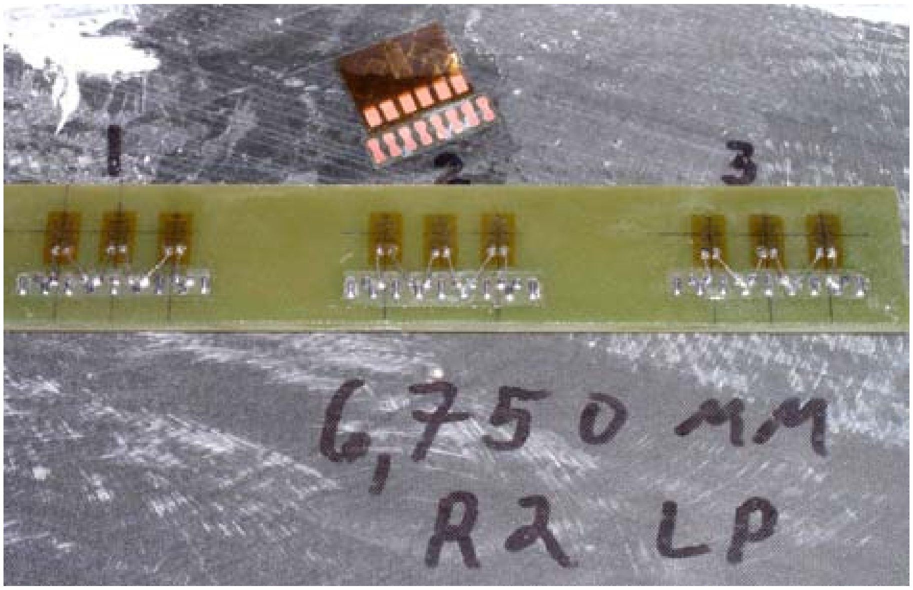


Figure 36 TX-100 Instrumentation (1)

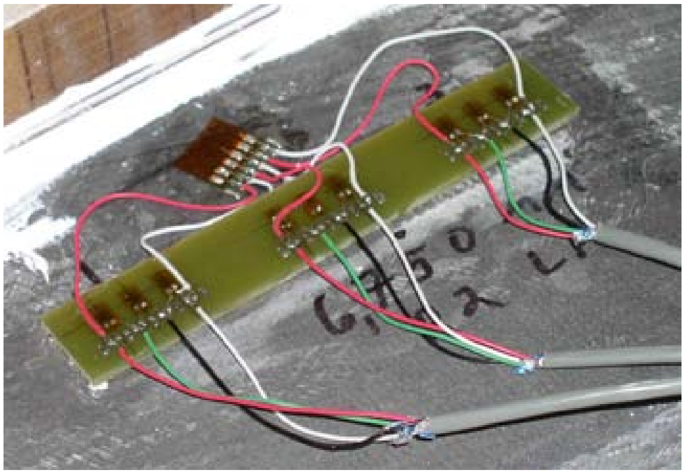


Figure 37 TX-100 Instrumentation (2)

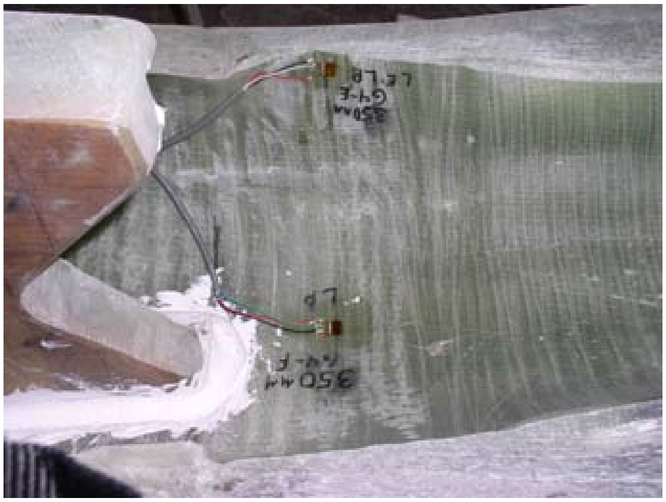


Figure 38 TX-100 Instrumentation (3)

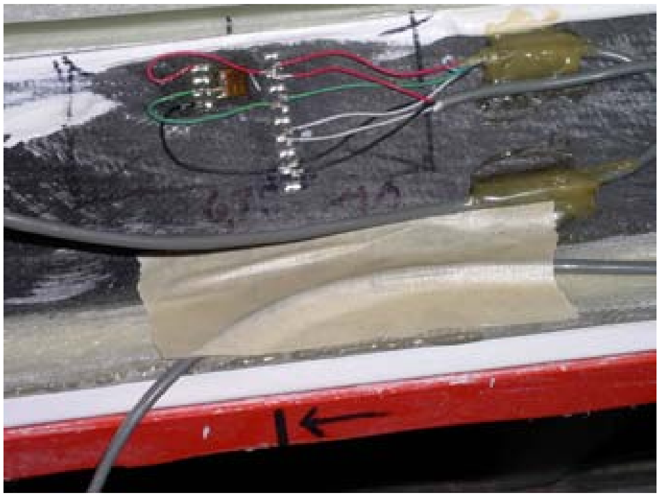


Figure 39 TX-100 Instrumentation (4)

6.0 TX-100 Shipping

6.1 TX-100 Weights and Balance

Before shipping the TX-100 blades to their final destinations, TPI Composites weighed each blade and determined the spanwise center of gravity for each blade. Using this information, the static balance of each blade was calculated. The static balance determined which blades are suitable to be flown with each other on the test turbine in Bushland, Texas. Figure 40 is a schematic of the method used to weigh and balance each blade. Figure 41 is a table of the results of this process.

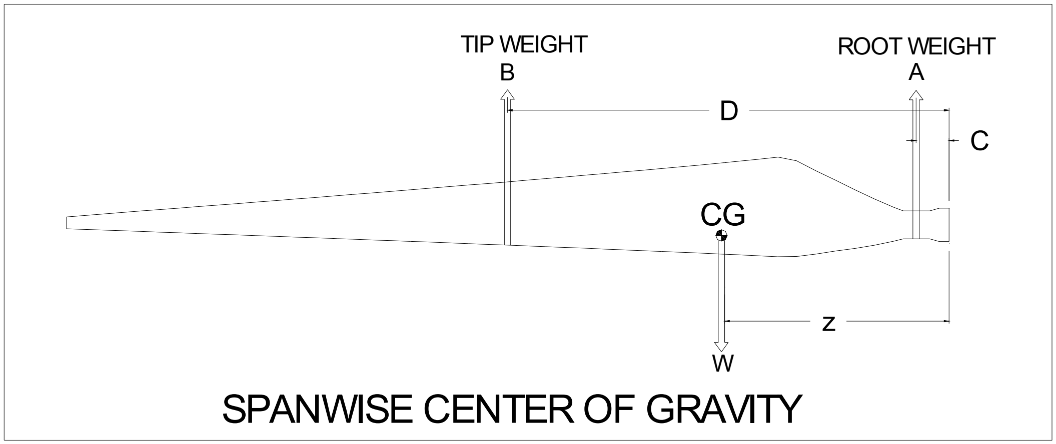


Figure 40 TX-100 Weight and Balance Schematic

TX-100 Blade Weights and CGs (Standard Units)

	Blade #	Test Location	A (lbs)	B (lbs)	C (inches)	D (inches)	Blade Length (inches)	Blade Weight (lbs)	Spanwise CG (inches)	Static Balance (in-lbs)	Instrumentation
4 February, 2005	001	SNL	140.0	224.5	20.375	138.375	354.33	364.5	93.1	33,918	
	002	NWTC	151.5	202.5	25.875	142.750	354.31	354.0	92.7	32,827	
	003	SNL	163.5	198.0	22.625	149.875	354.38	361.5	92.3	33,374	
	004	NWTC	133.5	237.0	19.625	134.625	354.36	370.5	93.2	34,526	Full Span Instrumentation
	005	USDA	171.0	192.5	22.625	153.250	354.39	363.5	91.8	33,370	Full Span Instrumentation
	006	USDA	144.0	210.5	17.000	140.750	354.28	354.5	90.5	32,076	Root Instrumentation
	007	NWTC/USDA	173.0	184.5	21.375	156.125	354.32	357.5	90.9	32,503	Root Instrumentation
								360.9	**92.1**	**33,228**	

TX-100 Blade Weights and CGs (Metric Units)

	Blade #	Test Location	A (kgs)	B (kgs)	C (mm)	D (mm)	Blade Length (mm)	Blade Weight (kgs)	Spanwise CG (mm)	Static Balance (m-kgs)	Instrumentation
4 February, 2005	001	SNL	63.5	101.8	518	3,515	9,000	165.3	2,363.5	390.7	
	002	NWTC	68.7	91.8	657	3,626	8,999	160.5	2,355.4	378.1	
	003	SNL	74.1	89.8	575	3,807	9,001	163.9	2,345.0	384.4	
	004	NWTC	60.5	107.5	498	3,419	9,001	168.0	2,367.0	397.7	Full Span Instrumentation
	005	USDA	77.6	87.3	575	3,893	9,002	164.9	2,331.7	384.4	Full Span Instrumentation
	006	USDA	65.3	95.5	432	3,575	8,999	160.8	2,298.2	369.5	Root Instrumentation
	007	NWTC/USDA	78.5	83.7	543	3,966	9,000	162.1	2,309.3	374.4	Root Instrumentation
								163.7	**2,339**	**382.8**	

Figure 41 TX-100 Weight and Balance Table

6.2 TX-100 Shipping

The seven TX-100 blades were loaded onto a flatbed truck to be shipped to three locations. Figure 42 is a table of the blade destinations.

Blade Number	**Shipped to**	**End Use**
Blade TX-100-001	Sandia	Mass Properties, Modal and Blade Slicing
Blade TX-100-002	NREL/NWTC	Static Test (or Fatigue Test)
Blade TX-100-003	Sandia	Mass Properties, Modal and Blade Slicing
Blade TX-100-004	NREL/NWTC	Fatigue Test (or Static Test)
Blade TX-100-005	USDA/Bushland	Performance Test
Blade TX-100-006	USDA/Bushland	Performance Test
Blade TX-100-007	NREL/NWTC (USDA/Bushland)	Proof Static Test at NREL – then shipped to USDA for Performance Test

Figure 42 TX-100 Shipping Table

7.0 TX-100 Adapter Plates

7.1 TX-100 Adapter Plate Design and Manufacturing

As was the case with the CX-100 blades, the TX-100 blades also required an adapter plate to fit onto the Micon turbine in Bushland, Texas. The root pattern of the TX-100 included 12 bolts on a bolt circle diameter of 11.811 inches. The hub of the Micon had a pattern of 24 holes on a bolt circle diameter of 19.843 inches. But in addition to simply providing an interface between the two root sizes, a request was made by Sandia National Laboratories to manufacture an adapter plate with a wedge to provide additional blade coning on the test turbine. Sandia National Laboratories, in conjunction with Dayton Griffin at Global Energy Concepts, determined that without any additional coning, the flexibility of the TX-100 blade would possibly pose a risk of tower strike during operation. An angle of 3.8° was determined to be sufficient to mitigate the risk of tower strike. TPI Composites designed, analyzed and created manufacturing drawings for the TX-100 adapter plates. The plates were manufactured and delivered to the test turbine site at Bushland, Texas. Figures 43 and 44 show the geometry of the computer solid model created for the structural analysis of the adapter plates.

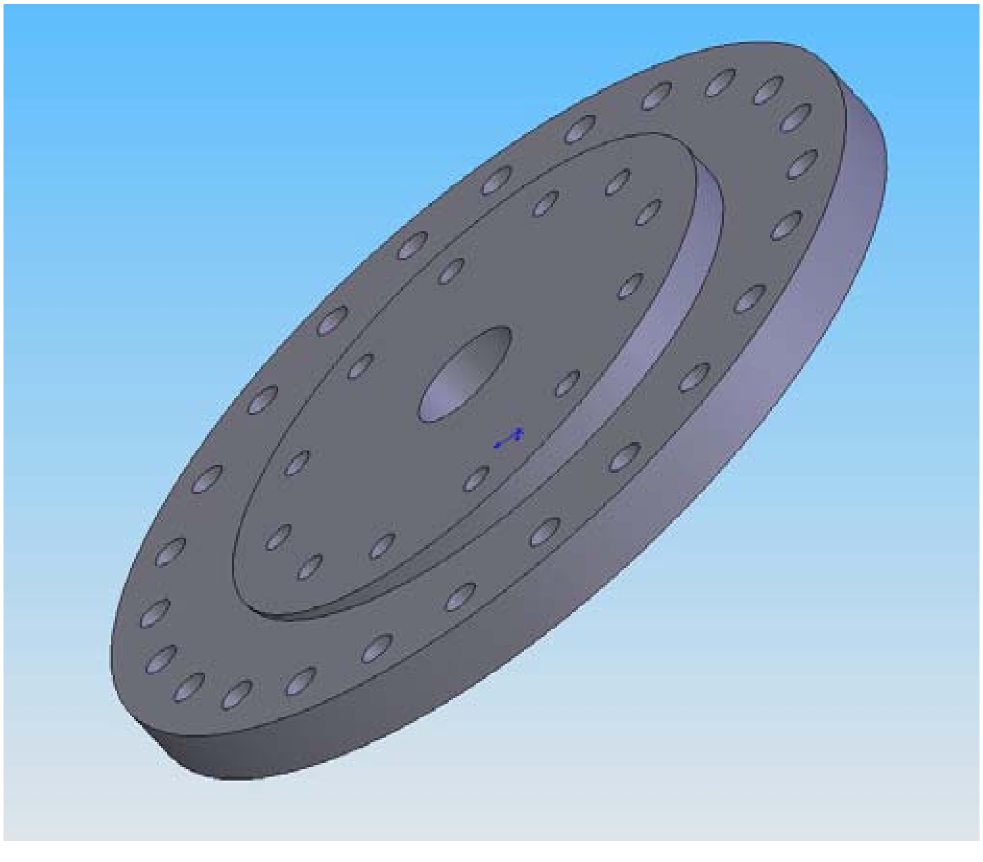


Figure 43 TX-100 Adapter Plate Solid Model (1)

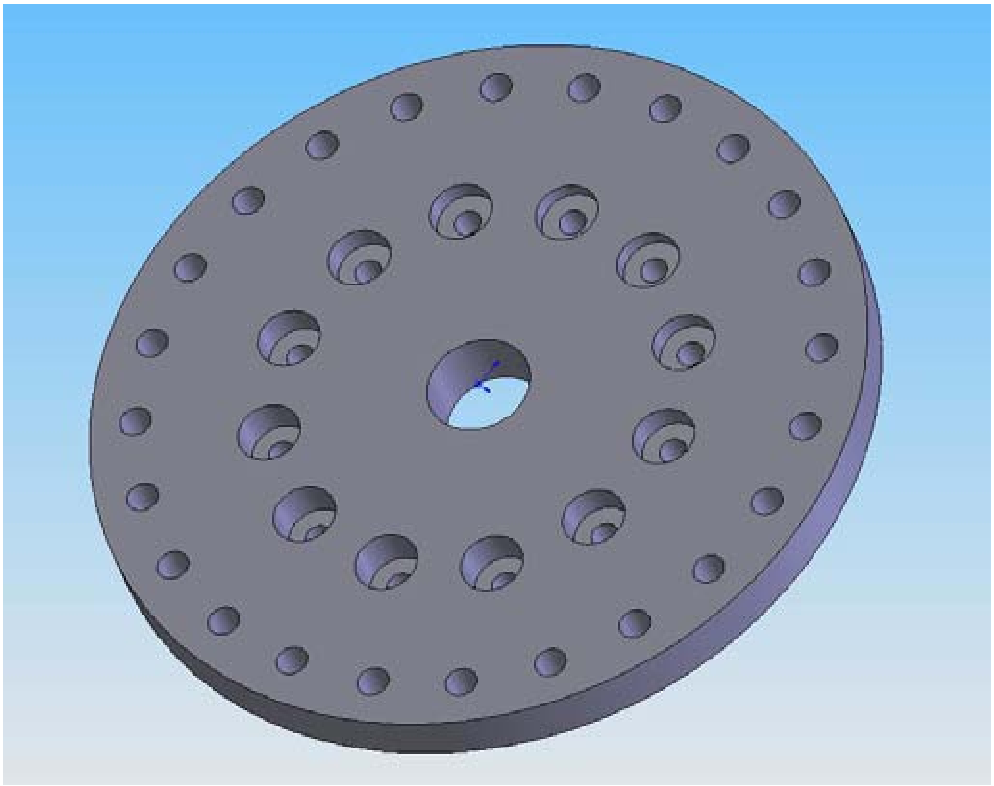


Figure 44 TX-100 Adapter Plate Solid Model (2)

After creating the three dimensional computer solid model, TPI Composites used finite element analysis to predict the deflections, strains and stresses on the adapter plate during turbine operation. The results of this analysis are presented in Figures 45 through 48. Figure 45 is a visual representation of the relative deformation of the plate during peak blade loading. Because the actual deformation would not be noticeable in normal view, the scale of the deformation is magnified by about 1,000 times. Figure 46 shows the same deformation, but adds a color gradient to represent actual deflections of the plate. The area of the plate in red is the location of the maximum deflection – about 0.002 inches. Figure 47 displays the stress distribution over the entire plate during peak loading. As can be seen in the figure, the plate experiences a maximum stress level of about 17,500 pounds per square inch. Figure 48 shows a plot of the safety factor for the plate. In this case, a safety factor of 3 was chosen as the division between the two colors – blue and red. This meant that all sections of the plate shaded blue had a safety factor greater than 3, while the red areas had a safety factor less than three. Because the steel used to manufacture the plates had a minimum yield strength of 50,000 pounds per square inch, and our maximum stress was 17,500 pounds per square inch, even the highest stressed areas of the plate in red had a minimum safety factor of 2.86. Figures 49 and 50 show the manufacturing drawings used to fabricate the adapter plates.

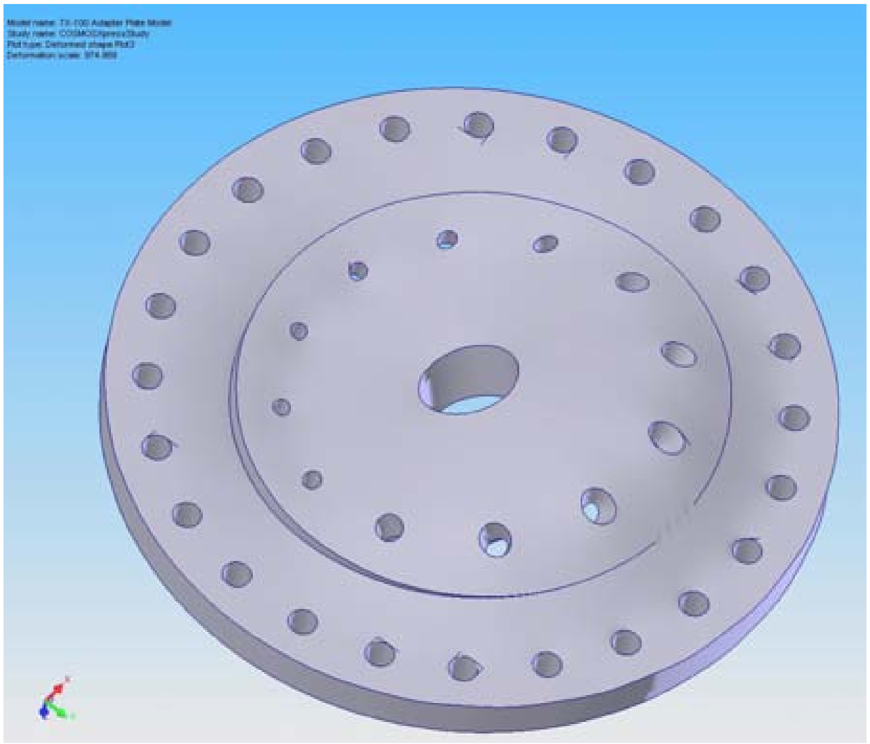


Figure 45 TX-100 Adapter Plate FEA - Deformation

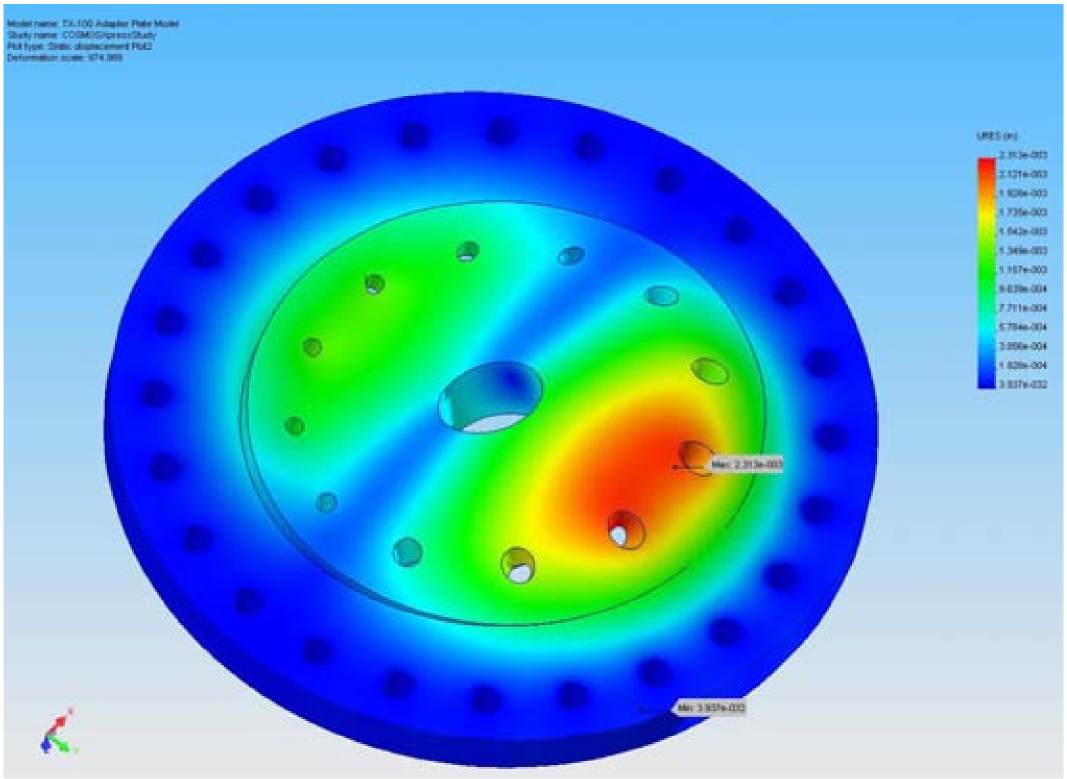


Figure 46 TX-100 Adapter Plate FEA - Displacement

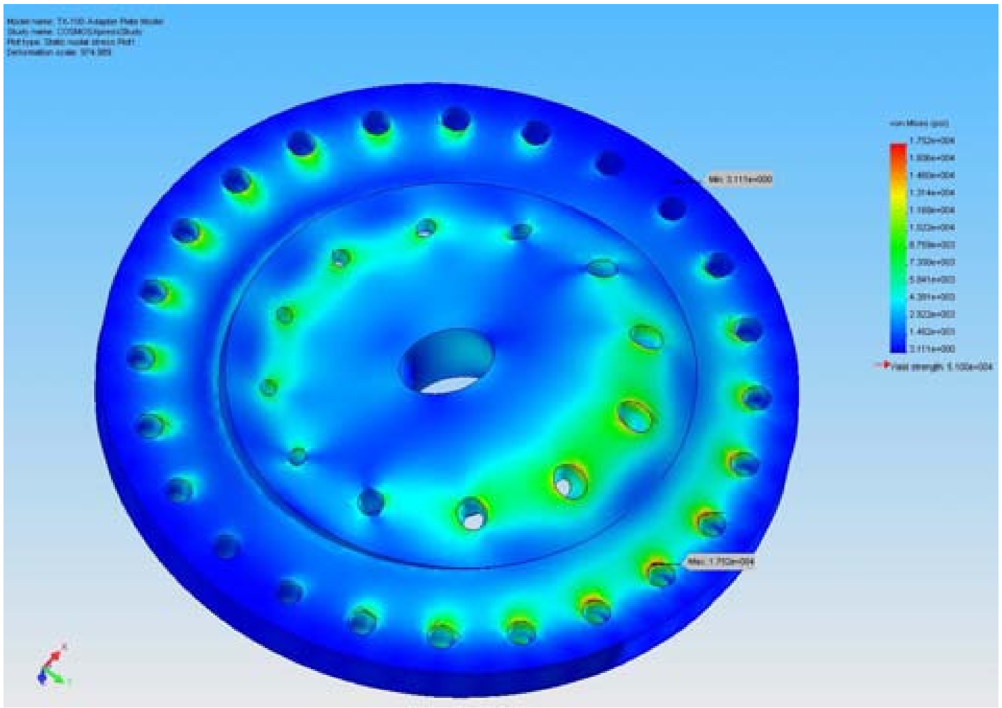


Figure 47 TX-100 Adapter Plate FEA – Stress Analysis

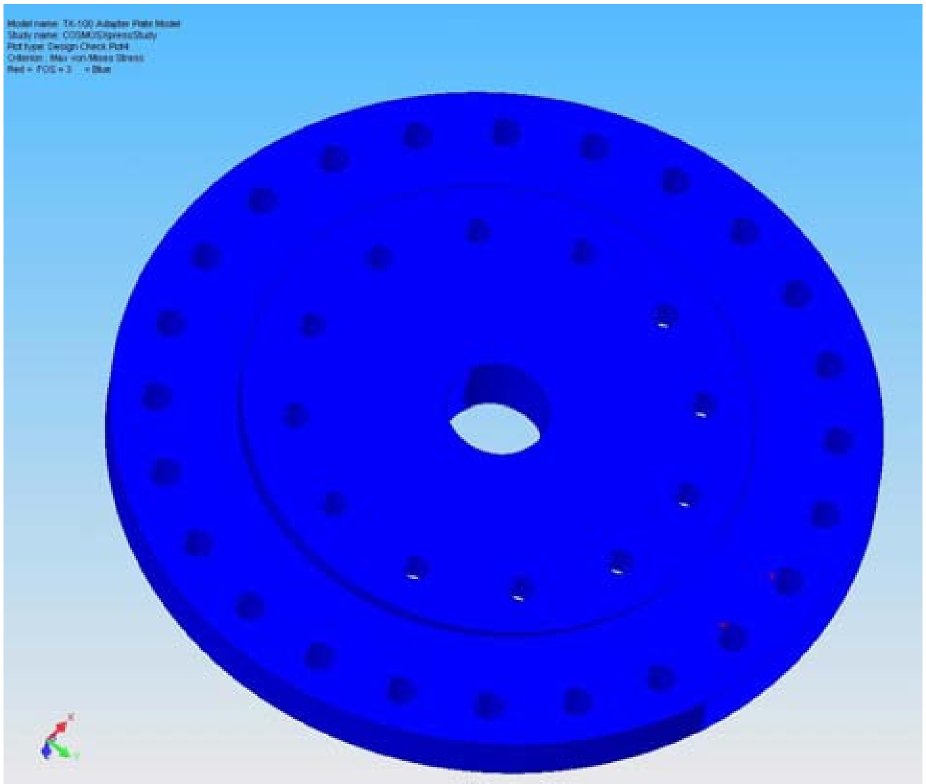
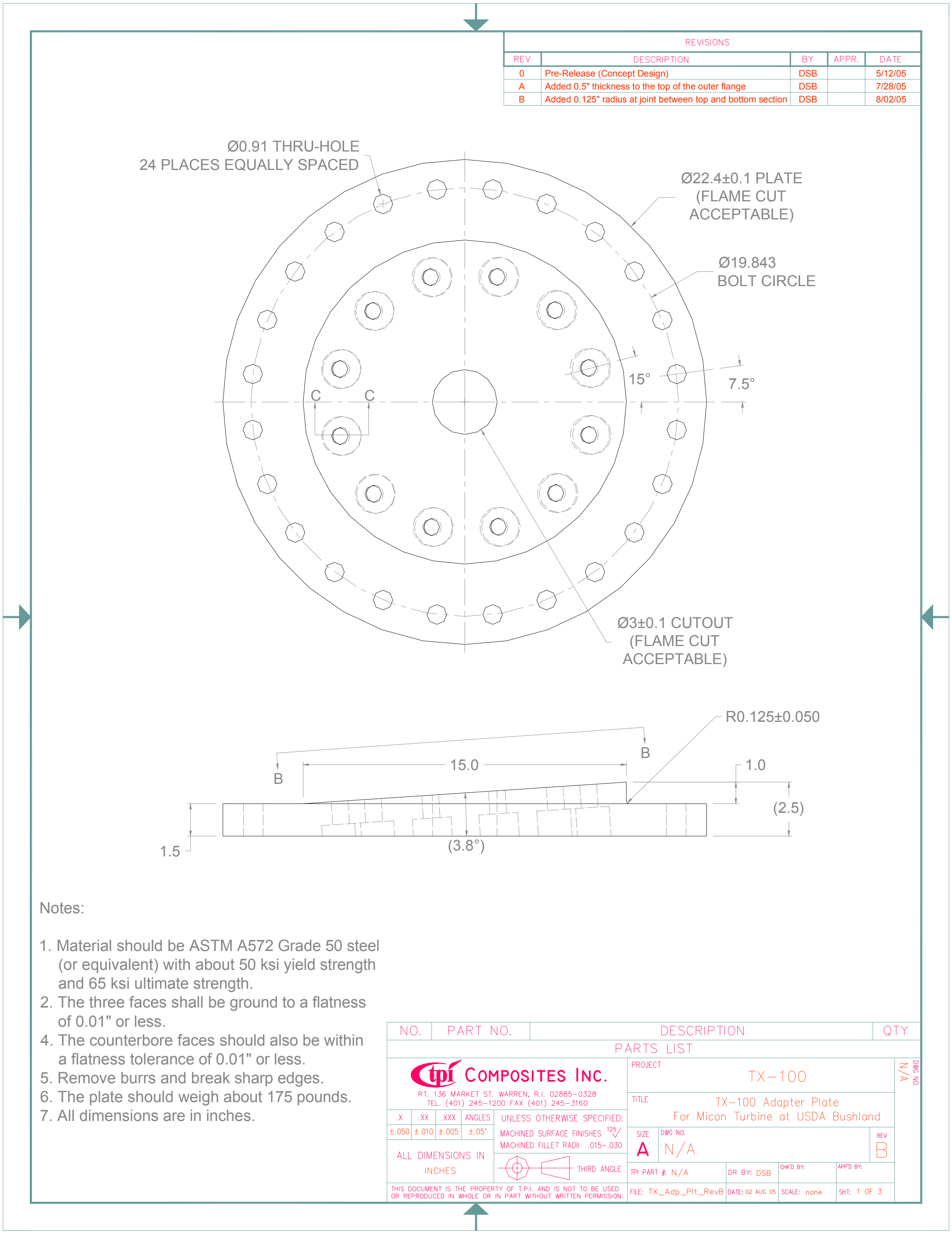


Figure 48 TX-100 Adapter Plate FEA – Safety Factor



REVISIONS

REV	DESCRIPTION	BY	APPR.	DATE
0	Pre-Release (Concept Design)	DSB		5/12/05
A	Added 0.5" thickness to the top of the outer flange	DSB		7/28/05
B	Added 0.125" radius at joint between top and bottom section	DSB		8/02/05

Notes:

1. Material should be ASTM A572 Grade 50 steel (or equivalent) with about 50 ksi yield strength and 65 ksi ultimate strength.
2. The three faces shall be ground to a flatness of 0.01" or less.
4. The counterbore faces should also be within a flatness tolerance of 0.01" or less.
5. Remove burrs and break sharp edges.
6. The plate should weigh about 175 pounds.
7. All dimensions are in inches.

NO.	PART NO.	DESCRIPTION	QTY

PARTS LIST

tpi COMPOSITES INC.
RT. 136 MARKET ST. WARREN, R.I. 02885-0328
TEL. (401) 245-1200 FAX (401) 245-3160

.X	.XX	.XXX	ANGLES
±.050	±.010	±.005	±.05°

ALL DIMENSIONS IN INCHES

UNLESS OTHERWISE SPECIFIED:
MACHINED SURFACE FINISHES 125√
MACHINED FILLET RADII .015-.030
THIRD ANGLE

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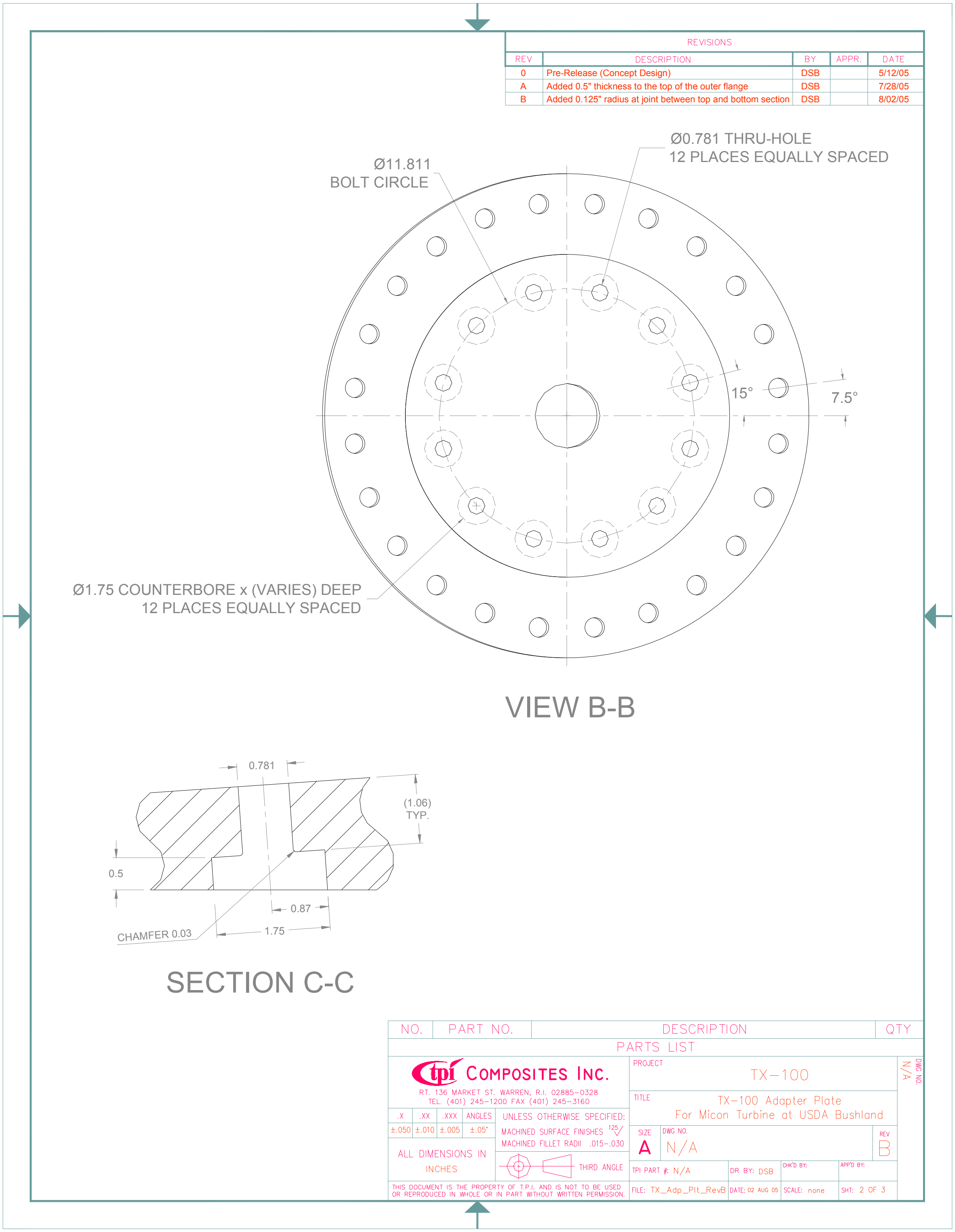
PROJECT TX-100
TITLE TX-100 Adapter Plate
For Micon Turbine at USDA Bushland
SIZE A
DWG NO. N/A
REV B
TPI PART #: N/A
DR BY: DSB
CHK'D BY:
APP'D BY:
FILE: TX_Adp_Plt_RevB
DATE: 02 AUG 05
SCALE: none
SHT: 1 OF 3
DWG NO. N/A

Figure 49 TX-100 Adapter Plate – Manufacturing Drawing (1)



REVISIONS

REV	DESCRIPTION	BY	APPR.	DATE
0	Pre-Release (Concept Design)	DSB		5/12/05
A	Added 0.5" thickness to the top of the outer flange	DSB		7/28/05
B	Added 0.125" radius at joint between top and bottom section	DSB		8/02/05

NO.	PART NO.	DESCRIPTION	QTY

PARTS LIST

COMPOSITES INC.
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TEL. (401) 245-1200 FAX (401) 245-3160

.X	.XX	.XXX	ANGLES
±.050	±.010	±.005	±.05°

ALL DIMENSIONS IN INCHES

UNLESS OTHERWISE SPECIFIED:
MACHINED SURFACE FINISHES 125
MACHINED FILLET RADII .015-.030

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PROJECT TX-100

TITLE TX-100 Adapter Plate
For Micon Turbine at USDA Bushland

SIZE A

DWG NO. N/A

REV B

DWG NO. N/A

TPI PART #: N/A

DR BY: DSB

CHK'D BY:

APP'D BY:

FILE: TX_Adp_Plt_RevB

DATE: 02 AUG 05

SCALE: none

SHT: 2 OF 3

Figure 50 TX-100 Adapter Plate – Manufacturing Drawing (2)

8.0 Conclusion

The TX-100 manufacturing project successfully demonstrated the design and manufacturing of a full scale bend-twist wind turbine blade. The coupling of bend and twist was achieved through the use of off-axis carbon fiber in the outboard section of the blade skins. This coupling could lead to the mitigation of blade loads during turbine operation. At the same time that the carbon fiber provided coupling, it also augmented the strength and stiffness of the entire blade structure. This reduced the requirement of composite materials in other areas of the blade – for example, fiberglass in the spar cap – thus reducing the overall weight of the blade compared to a traditional fiberglass 9-meter blade. The design and manufacturing team gained valuable experience in the process of laminating and infusing carbon fiber in a wind turbine blade.

Although the 9 meter TX-100 blade demonstrated the possible reduction of blade loads during turbine operation through adaptive technology, greater benefits should be realized as this attribute is deployed on larger wind turbine blades. As the design phase of the 9 meter project demonstrated, the intended targets for this innovation are blades with a span of approximately 40 meters or longer. This project provides a solid foundation on which to build.

9.0 References

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4. Musial, W., Hughes, S., “Final Report for the NPS NW-100 Blade Fatigue Test,” Test Number NWTC-ST-NPS-FAT-01-1202, National Renewable Energy Laboratory, Golden, CO, November, 2003.

5. TPI Composites, “Design of 9-Meter Carbon-Fiberglass Prototype Blades: CX-100 and TX-100 Final Project Report,” SAND2007-0201, Sandia National Laboratories, Albuquerque, NM, September 2007.

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