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CX-100 Manufacturing Final Project Report

Derek S. Berry
TPI Composites, Inc.
373 Market Street
Warren, RI 02885

Sandia Technical Manager: Tom Ashwill

Abstract

This report details the work completed under the CX-100 blade manufacturing project. It presents the tooling design and manufacturing, blade production, blade instrumentation, blade shipping and adapter plate design and fabrication. The CX-100 blade was designed to demonstrate the efficient use of carbon fiber in the spar cap of a wind turbine blade. The baseline blade used for this project was the ERS-100 (Revision D) wind turbine blade. ERS-100 master plugs – for both the high pressure and low pressure skins – were modified to create plugs for the CX-100. Using the new CX-100 master skin plugs, high pressure and low pressure molds were fabricated. Similar modifications were also completed on the shear web plug/mold, the blade assembly fixture and the root stud insertion fixture. Once all of the tooling modifications were complete, a production run of seven CX-100 prototype blades was undertaken. Of those seven blades, four were instrumented with strain gauges before final assembly. After production at the TPI facility in Rhode Island, the blades were shipped to various test sites: two blades to the NWTC at NREL, two blades to Sandia National Laboratory and three blades to the USDA-ARS turbine field test facility located in Bushland, Texas. An adapter plate was designed to allow the CX-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 blade testing at the three testing facilities.

Acknowledgements

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Summary

This report details the work completed under the CX-100 blade manufacturing project. It will present the tooling design and manufacturing, blade production, blade instrumentation, blade shipping and adapter plate design and fabrication. The CX-100 blade was designed to demonstrate the efficient use of carbon fiber in the spar cap of a wind turbine blade. The baseline blade used for this project was the ERS-100 (Revision D) wind turbine blade. ERS-100 master plugs – for both the high pressure and low pressure skins – were modified to create plugs for the CX-100. Using the new CX-100 master skin plugs, high pressure and low pressure molds were fabricated. Similar modifications were also completed on the shear web plug/mold, the blade assembly fixture and the root stud insertion fixture. Once all of the tooling modifications were complete, a production run of seven CX-100 prototype blades was undertaken. Of those seven blades, four were instrumented with strain gauges before final assembly. After production at the TPI facility in Rhode Island, the blades were shipped to various test sites: two blades to the NWTC at NREL, two blades to Sandia National Laboratory and three blades to the USDA-ARS turbine field test facility located in Bushland, Texas. An adapter plate was designed to allow the CX-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 blade testing at the three testing facilities.

1.0 CX-100 Skin plugs

1.1 Baseline: ERS-100 Revision D

The CX-100 blade builds 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 Laboratory (SNL) and TPI Composites, Inc. (TPI) [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 project, a decision was made by the team to modify the existing ERS-100 Revision D plugs to become skin plugs for the CX-100 blade.

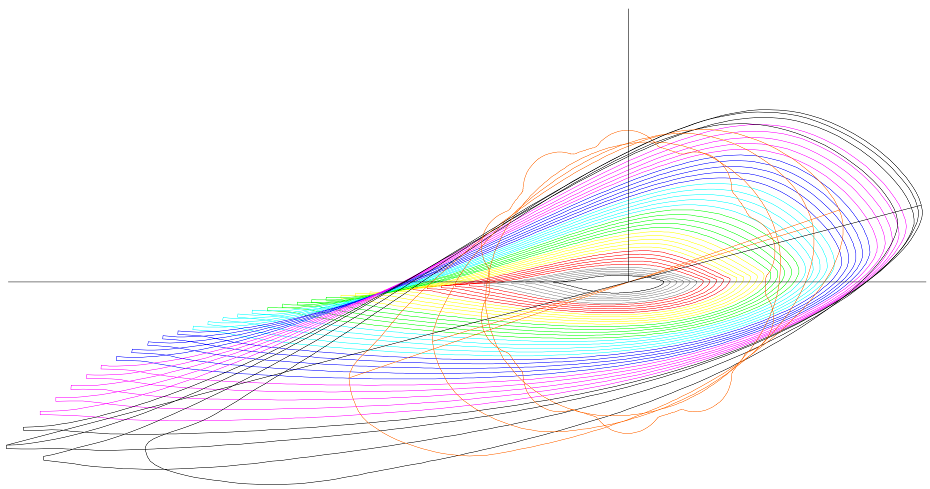

Figure 1 Original ERS-100 Station Sections

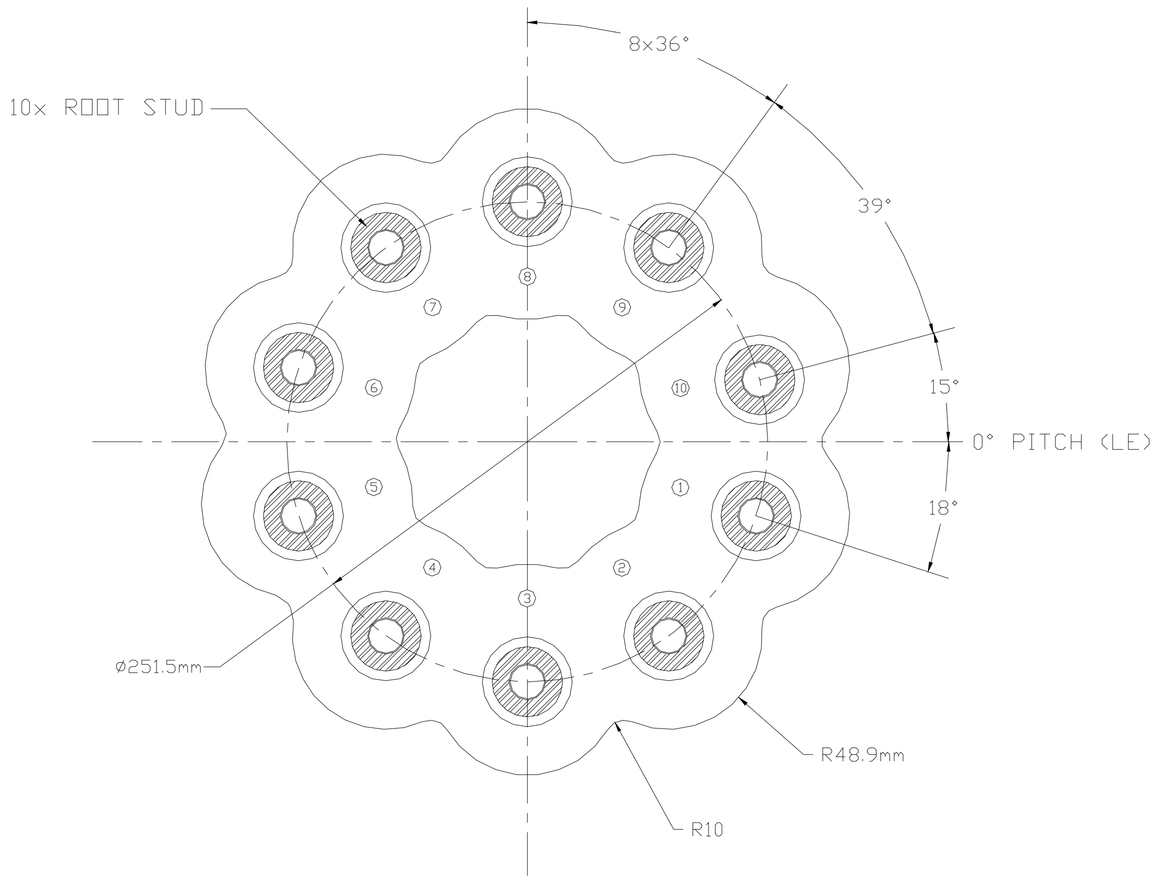

Figure 2 Original ERS-100 Root Pattern

1.2 CX-100 Plug Design

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 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, the CX-100 would need an adapter plate to fit onto the Micon test turbine in Bushland, TX – the chosen location for CX-100 field testing. When considering the options for the enlarged CX-100 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 produced for remote environments [2]. TPI 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) [3]. The team decided to use the NPS-100 root configuration in the CX-100 blade. This configuration is shown in Figure 3. It includes 12 bolts on a bolt circle diameter of 300mm.

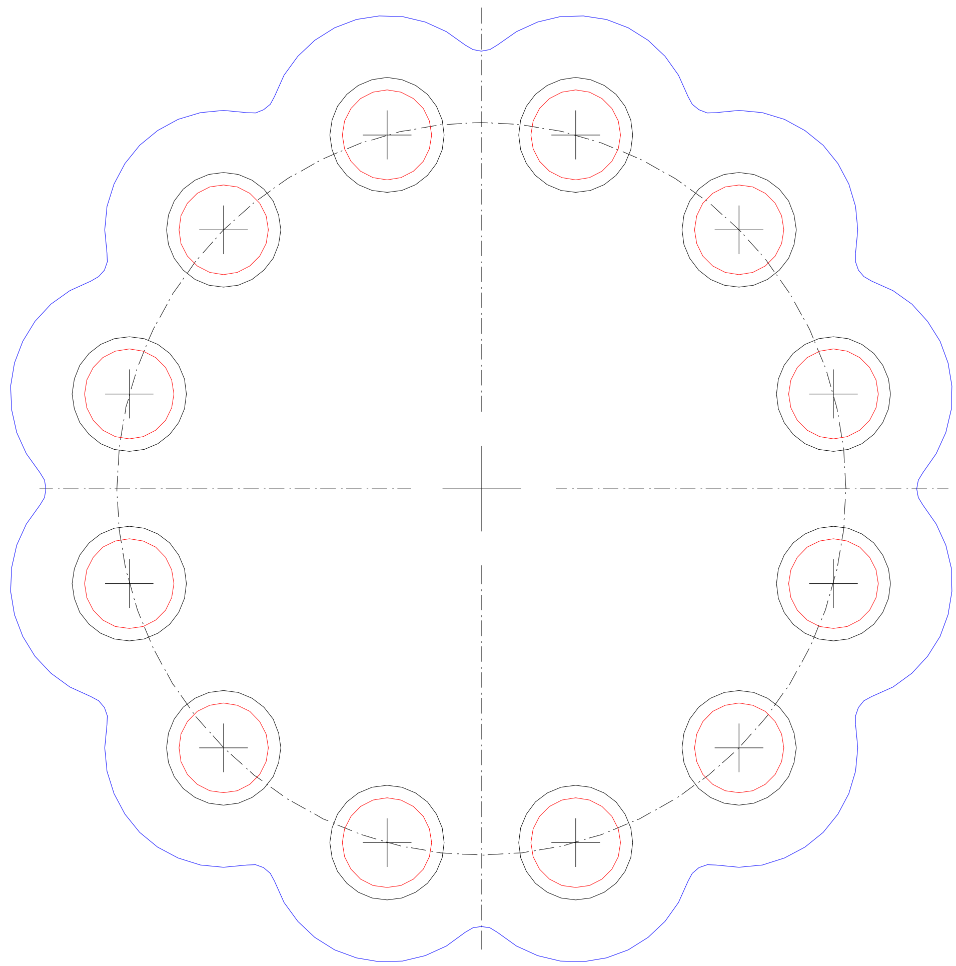

Figure 3 NPS-100 Root Configuration

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 above. 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 believe 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 is much more consistent and repeatable to produce the blade root in the shape of a simple cylinder. Therefore, the decision was made by the team to design the CX-100 root with a cylinder for the outer shape. As shown in Figure 4, the resulting CX-100 root configuration still utilized

12 bolts on a bolt circle diameter of 300mm – but also maintained a simple circular outer shell.

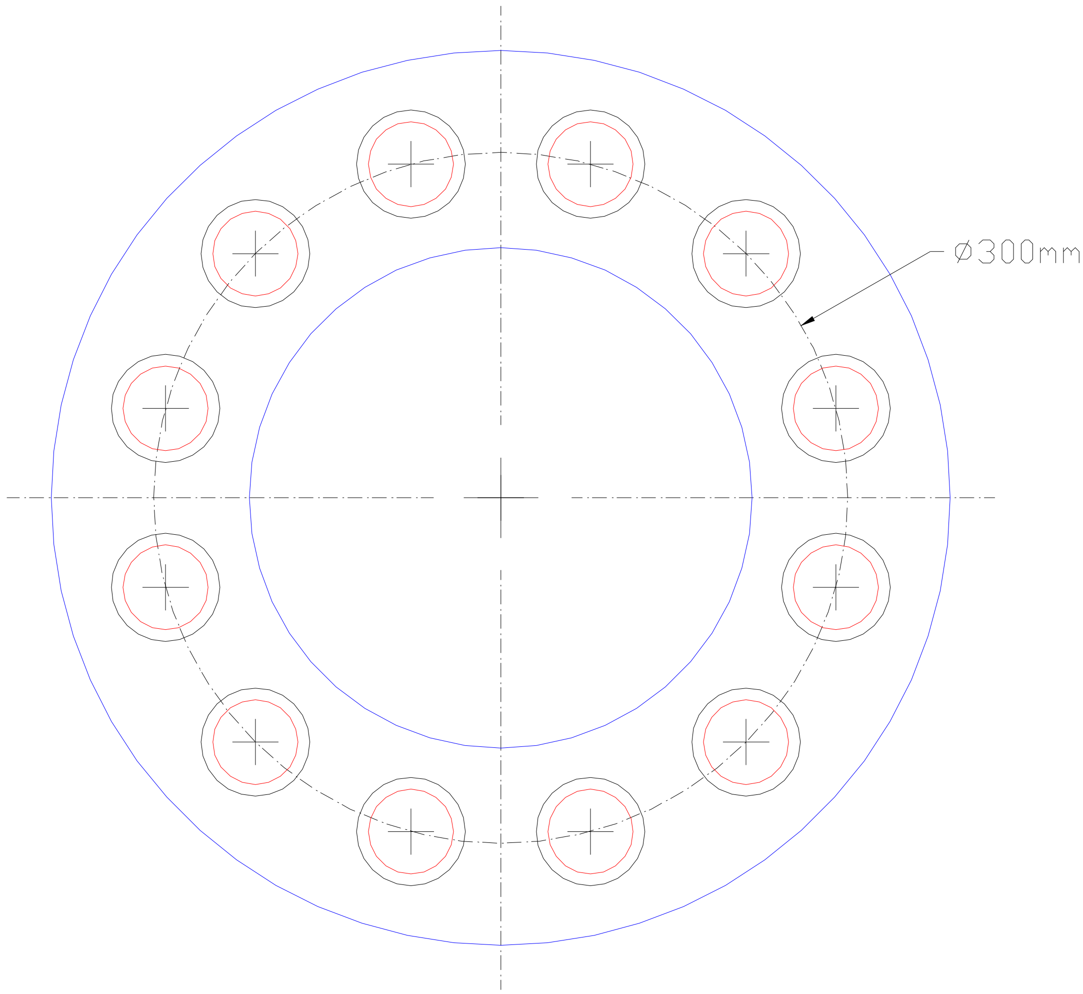

Figure 4 CX-100 Root Configuration

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 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, 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.

1.3 CX-100 Root Design

After deciding to revise the existing skin plugs in the root region, the next task was to determine the best outer geometry of the mold in order to achieve the most efficient use of the carbon fiber spar caps in the blade skins. This would require an inside-out approach to laminate design for the blade root section. Our starting point was the CX-100 detailed design laminate that had been presented during the CX-100 Design Review Meeting at Sandia during December of 2003 [4]. This laminate, presented in tabular form in Figure 5, placed the seven carbon spar cap layers into the mold before any of the root build-up layers were placed in. This configuration has been typical for all of the ERS and NPS 9m blades built up to this point. In the laminate schedule, material types are represented by different designations. For example, the nomenclature DBM-1708 represents fiberglass material in the plus and minus 45 degree direction with a quarter ounce mat stitched on the back. The '17' in the 1708 indicates 17 ounces per square yard of +/-45 degree material. The '08' in the 1708 represents ¾ ounces per square foot of random fiber mat. For the term C520, the 'C' designates unidirectional fiberglass. The '520' indicated 52 ounces per square yard of the unidirectional material. This approach is also similar for the C260 material. The term Hybrid Triax describes the carbon fiber material used in the CX-100 blade. It is a 'hybrid' because the material layer contains both fiberglass and carbon fiber. The 'triax' stands for triaxial and indicated that the fibers in the layer run in three directions. The carbon fiber runs in the 0 degree (or unidirectional) direction, while the fiberglass runs in both the positive and negative 45 degree directions.

CX-100 Skin (LP and HP) Laminate Schedule			
Layer #	Material	Length (mm)	Notes
1	Gel Coat	N/A	Entire surface
2	3/4oz Mat	N/A	Entire surface
3	DBM-1708	N/A	Entire surface / Mat Up
4	DBM-1208	N/A	Pattern: cover entire root area / extend from balsa to LE (under flange) / to tip
5	Balsa Kit #1 (1/4")	N/A	5cm from TE / 130cm from tip (to be flush with TE of spar cap)
6	Hybrid Triax	8,966	Spar Cap Region - cover entire root
7	Hybrid Triax	8,966	Spar Cap Region - cover entire root
8	Hybrid Triax	8,966	Spar Cap Region - cover entire root
9	Hybrid Triax	4,675	Spar Cap Region - cover entire root
10	Hybrid Triax	4,500	Spar Cap Region - cover entire root
11	Hybrid Triax	3,325	Spar Cap Region - cover entire root
12	Hybrid Triax	3,200	Spar Cap Region - cover entire root
13	Balsa Kit #2 (1/4")		In LE panel
14	C260	675.0	Entire Root Width - from STA0000 to length shown
15	C260	642.0	Entire Root Width - from STA0000 to length shown
16	DBM-1208	634.0	Entire Root Width - from STA0000 to length shown
17	C260	626.0	Entire Root Width - from STA0000 to length shown
18	C260	618.0	Entire Root Width - from STA0000 to length shown
19	C260	610.0	Entire Root Width - from STA0000 to length shown
20	C260	602.0	Entire Root Width - from STA0000 to length shown
21	C260	594.0	Entire Root Width - from STA0000 to length shown
22	C520	586.0	Entire Root Width - from STA0000 to length shown
23	C520	570.0	Entire Root Width - from STA0000 to length shown
24	C520	554.0	Entire Root Width - from STA0000 to length shown
25	Root Stud Cavities		
26	C520	538.0	Entire Root Width - from STA0000 to length shown
27	C520	522.0	Entire Root Width - from STA0000 to length shown
28	C520	506.0	Entire Root Width - from STA0000 to length shown
29	DBM-1208	498.0	Entire Root Width - from STA0000 to length shown
30	C520	482.0	Entire Root Width - from STA0000 to length shown
31	C520	466.0	Entire Root Width - from STA0000 to length shown
32	C520	450.0	Entire Root Width - from STA0000 to length shown
33	C520	434.0	Entire Root Width - from STA0000 to length shown
34	C520	418.0	Entire Root Width - from STA0000 to length shown
35	C520	402.0	Entire Root Width - from STA0000 to length shown
36	C520	386.0	Entire Root Width - from STA0000 to length shown
37	C520	370.0	Entire Root Width - from STA0000 to length shown
38	C520	354.0	Entire Root Width - from STA0000 to length shown
39	C520	346.0	Entire Root Width - from STA0000 to length shown
40	C520	338.0	Entire Root Width - from STA0000 to length shown
41	C520	330.0	Entire Root Width - from STA0000 to length shown
42	DBM-1208	326.0	Entire Root Width - from STA0000 to length shown
43	C520	318.0	Entire Root Width - from STA0000 to length shown
44	C520	310.0	Entire Root Width - from STA0000 to length shown
45	C520	302.0	Entire Root Width - from STA0000 to length shown
46	C520	294.0	Entire Root Width - from STA0000 to length shown
47	C520	286.0	Entire Root Width - from STA0000 to length shown
48	C520	278.0	Entire Root Width - from STA0000 to length shown
49	C520	270.0	Entire Root Width - from STA0000 to length shown
50	C520	262.0	Entire Root Width - from STA0000 to length shown
51	C520	254.0	Entire Root Width - from STA0000 to length shown
52	C520	246.0	Entire Root Width - from STA0000 to length shown
53	C520	238.0	Entire Root Width - from STA0000 to length shown
54	DBM-1208	N/A	Pattern: cover entire root area / extend from balsa to LE (under flange) / to tip
55	DBM-1708	N/A	Entire surface / Mat Down

Figure 5 Original CX-100 Detailed Design Laminate

We knew, however, that using carbon in the spar caps would force a change in the approach of interweaving the spar cap plies into the root build-up plies. It is very important to provide as straight a path as possible for the carbon fiber to enter the root area. Our first attempt to achieve this goal was simply to move the spar cap plies into the middle of the root build-up plies. We centered the seven carbon spar cap plies on either side of the root stud cavity insert – three plies below and four plies above. This became revision 1.0 of the CX-100 root design and is shown in tabular form in Figure 6.

CX-100 Root Laminate Schedule					
Layer #	Material	Thickness (in)	Length (mm)	Length (in)	Notes
1	Gel Coat	0.020	N/A		Entire surface
2	3/4oz Mat	0.007	N/A		Entire surface
3	DBM-1708	0.023	N/A		Entire surface / Mat Up
4	DBM-1208	0.018	N/A		Pattern: cover entire root area / extend from balsa to LE (under flange) / to tip
5	C260	0.024	675.0	26.57	Entire Root Width - from STA0000 to length shown
6	C260	0.024	642.0	25.28	Entire Root Width - from STA0000 to length shown
7	DBM-1208	0.018	634.0	24.96	Entire Root Width - from STA0000 to length shown
8	C260	0.024	626.0	24.65	Entire Root Width - from STA0000 to length shown
9	C260	0.024	618.0	24.33	Entire Root Width - from STA0000 to length shown
10	C260	0.024	610.0	24.02	Entire Root Width - from STA0000 to length shown
11	C260	0.024	602.0	23.70	Entire Root Width - from STA0000 to length shown
12	C260	0.024	594.0	23.39	Entire Root Width - from STA0000 to length shown
13	C520	0.048	586.0	23.07	Entire Root Width - from STA0000 to length shown
14	C520	0.048	570.0	22.44	Entire Root Width - from STA0000 to length shown
15	C520	0.048	554.0	21.81	Entire Root Width - from STA0000 to length shown
16	C520	0.048	538.0	21.18	Entire Root Width - from STA0000 to length shown
17	C520	0.048	522.0	20.55	Entire Root Width - from STA0000 to length shown
18	C520	0.048	506.0	19.92	Entire Root Width - from STA0000 to length shown
19	DBM-1208	0.018	498.0	19.61	Entire Root Width - from STA0000 to length shown
20	C520	0.048	482.0	18.98	Entire Root Width - from STA0000 to length shown
21	C520	0.048	466.0	18.35	Entire Root Width - from STA0000 to length shown
22	C520	0.048	450.0	17.72	Entire Root Width - from STA0000 to length shown
23	Hybrid Triax	0.038	8,966		Spar Cap Region - cover entire root
24	Hybrid Triax	0.038	8,966		Spar Cap Region - cover entire root
25	Hybrid Triax	0.038	8,966		Spar Cap Region - cover entire root
26	Root Stud Cavities				
27	Hybrid Triax	0.038	4,675		Spar Cap Region - cover entire root
28	Hybrid Triax	0.038	4,500		Spar Cap Region - cover entire root
29	Hybrid Triax	0.038	3,325		Spar Cap Region - cover entire root
30	Hybrid Triax	0.038	3,200		Spar Cap Region - cover entire root
31	C520	0.048	434.0	17.09	Entire Root Width - from STA0000 to length shown
32	C520	0.048	418.0	16.46	Entire Root Width - from STA0000 to length shown
33	C520	0.048	402.0	15.83	Entire Root Width - from STA0000 to length shown
34	C520	0.048	386.0	15.20	Entire Root Width - from STA0000 to length shown
35	C520	0.048	370.0	14.57	Entire Root Width - from STA0000 to length shown
36	C520	0.048	354.0	13.94	Entire Root Width - from STA0000 to length shown
37	C520	0.048	346.0	13.62	Entire Root Width - from STA0000 to length shown
38	C520	0.048	338.0	13.31	Entire Root Width - from STA0000 to length shown
39	C520	0.048	330.0	12.99	Entire Root Width - from STA0000 to length shown
40	DBM-1208	0.018	326.0	12.83	Entire Root Width - from STA0000 to length shown
41	C520	0.048	318.0	12.52	Entire Root Width - from STA0000 to length shown
42	C520	0.048	310.0	12.20	Entire Root Width - from STA0000 to length shown
43	C520	0.048	302.0	11.89	Entire Root Width - from STA0000 to length shown
44	C520	0.048	294.0	11.57	Entire Root Width - from STA0000 to length shown
45	C520	0.048	286.0	11.26	Entire Root Width - from STA0000 to length shown
46	C520	0.048	278.0	10.94	Entire Root Width - from STA0000 to length shown
47	C520	0.048	270.0	10.63	Entire Root Width - from STA0000 to length shown
48	C520	0.048	262.0	10.31	Entire Root Width - from STA0000 to length shown
49	C520	0.048	254.0	10.00	Entire Root Width - from STA0000 to length shown
50	C520	0.048	246.0	9.69	Entire Root Width - from STA0000 to length shown
51	C520	0.048	238.0	9.37	Entire Root Width - from STA0000 to length shown
52	DBM-1208	0.018	N/A		Pattern: cover entire root area / extend from balsa to LE (under flange) / to tip
53	DBM-1708	0.023	N/A		Entire surface / Mat Down

Figure 6 CX-100 Root Design - Revision 1.0

We decided then to represent the data in an alternative format in order to better understand the nuanced details of the root laminate. Although very time consuming, the only way to really evaluate the efficacy of the root solution was to draw the laminate – layer by layer – in a computer-aided drafting program. The result of this approach for revision 1.0 of the CX-100 root design is presented in Figure 7.

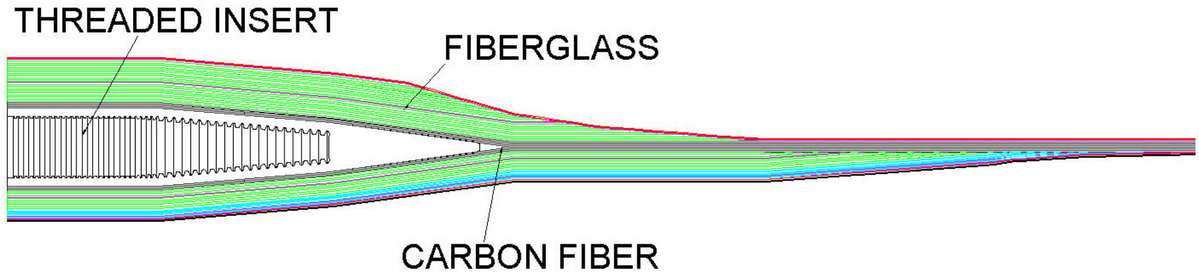

Figure 7 CX-100 Root Design Graphic - Revision 1.0

Two things became obvious to us looking at the graphic representation of revision 1.0 of the CX-100 root design. The first was that although the carbon (represented by the grey layers) proceeded into the root area on center and in without diversion, it had to sustain a rather large angular redirection to follow the shape of the root stud cavity. We felt that we had to reduce this angle – measuring at over seven degrees inclusive – by moving the initial splitting of the carbon layers further outboard. This would allow a more gentle transition and thus a reduced angular change in direction. The second feature that became obvious to us was the imbalance of the root build up around the centerline of the blade. Up to this point, the root build-up plies had always been inserted into the mold proceeding from the longest to the shortest layer. With the CX-100, however, this produced a laminate that seemed to jog first outward and then back inward – giving us an uncomfortable feeling about the load path in the root section of the blade.

In our next revision – 2.0 – we attempted to reorganize the root build-up plies to soften the angle of the carbon split and to balance the overall root laminate. Because the original root build-up performed so well in testing, we did not want to change the overall number or length of the original plies – just the sequence. The result of this approach can be seen in Figure 8 (the tabular format of the data) and Figure 9 (the graphic format of the data).

CX-100 Root Laminate Schedule						
Layer #	Material	Thickness (in)	Length (mm)	Length (in)	Notes	Delta
1	Gel Coat	0.020	N/A		Entire surface	
2	3/4oz Mat	0.007	N/A		Entire surface	
3	DBM-1708	0.023	N/A		Entire surface / Mat Up	
4	DBM-1208	0.018	N/A		Pattern: cover entire root area / extend from balsa to LE (under flange) / to tip	
5	C520	0.048	507.0	19.96	Entire Root Width - from STA0000 to length shown	
6	C520	0.048	533.0	20.98	Entire Root Width - from STA0000 to length shown	-26.0
7	C520	0.048	559.0	22.01	Entire Root Width - from STA0000 to length shown	-26.0
8	DBM-1208	0.018	572.0	22.52	Entire Root Width - from STA0000 to length shown	-13.0
9	C260	0.024	585.0	23.03	Entire Root Width - from STA0000 to length shown	-13.0
10	C260	0.024	598.0	23.54	Entire Root Width - from STA0000 to length shown	-13.0
11	C260	0.024	611.0	24.06	Entire Root Width - from STA0000 to length shown	-13.0
12	C260	0.024	624.0	24.57	Entire Root Width - from STA0000 to length shown	-13.0
13	C260	0.024	637.0	25.08	Entire Root Width - from STA0000 to length shown	-13.0
14	C260	0.024	650.0	25.59	Entire Root Width - from STA0000 to length shown	-13.0
15	C260	0.024	663.0	26.10	Entire Root Width - from STA0000 to length shown	-13.0
16	Hybrid Triax	0.038	8,966		Spar Cap Region - cover entire root	
17	Hybrid Triax	0.038	8,966		Spar Cap Region - cover entire root	
18	Hybrid Triax	0.038	8,966		Spar Cap Region - cover entire root	
19	C260	0.024	474.0	18.66	Entire Root Width - from STA0000 to length shown	
20	C260	0.024	461.0	18.15	Entire Root Width - from STA0000 to length shown	13.0
21	C520	0.048	435.0	17.13	Entire Root Width - from STA0000 to length shown	26.0
22	C520	0.048	409.0	16.10	Entire Root Width - from STA0000 to length shown	26.0
23	DBM-1208	0.018	396.0	15.59	Entire Root Width - from STA0000 to length shown	13.0
24	C520	0.048	370.0	14.57	Entire Root Width - from STA0000 to length shown	26.0
25	C520	0.048	344.0	13.54	Entire Root Width - from STA0000 to length shown	26.0
26	C520	0.048	318.0	12.52	Entire Root Width - from STA0000 to length shown	26.0
27	Root Stud Cavities					
28	C520	0.048	325.0	12.80	Entire Root Width - from STA0000 to length shown	
29	C520	0.048	351.0	13.82	Entire Root Width - from STA0000 to length shown	-26.0
30	C520	0.048	377.0	14.84	Entire Root Width - from STA0000 to length shown	-26.0
31	DBM-1208	0.018	403.0	15.87	Entire Root Width - from STA0000 to length shown	-26.0
32	C520	0.048	416.0	16.38	Entire Root Width - from STA0000 to length shown	-13.0
33	C520	0.048	442.0	17.40	Entire Root Width - from STA0000 to length shown	-26.0
34	C260	0.024	468.0	18.43	Entire Root Width - from STA0000 to length shown	-26.0
35	C260	0.024	481.0	18.94	Entire Root Width - from STA0000 to length shown	-13.0
36	Hybrid Triax	0.038	4,675		Spar Cap Region - cover entire root	
37	Hybrid Triax	0.038	4,500		Spar Cap Region - cover entire root	
38	Hybrid Triax	0.038	3,325		Spar Cap Region - cover entire root	
39	Hybrid Triax	0.038	3,200		Spar Cap Region - cover entire root	
40	C260	0.024	663.0	26.10	Entire Root Width - from STA0000 to length shown	
41	C260	0.024	650.0	25.59	Entire Root Width - from STA0000 to length shown	13.0
42	C260	0.024	637.0	25.08	Entire Root Width - from STA0000 to length shown	13.0
43	C260	0.024	624.0	24.57	Entire Root Width - from STA0000 to length shown	13.0
44	C260	0.024	611.0	24.06	Entire Root Width - from STA0000 to length shown	13.0
45	C260	0.024	598.0	23.54	Entire Root Width - from STA0000 to length shown	13.0
46	C260	0.024	585.0	23.03	Entire Root Width - from STA0000 to length shown	13.0
47	DBM-1208	0.018	572.0	22.52	Entire Root Width - from STA0000 to length shown	13.0
48	C520	0.048	559.0	22.01	Entire Root Width - from STA0000 to length shown	13.0
49	C520	0.048	533.0	20.98	Entire Root Width - from STA0000 to length shown	26.0
50	C520	0.048	507.0	19.96	Entire Root Width - from STA0000 to length shown	26.0
51	C520	0.048	312.0	12.28	Entire Root Width - from STA0000 to length shown	195.0
52	C520	0.048	299.0	11.77	Entire Root Width - from STA0000 to length shown	13.0
53	C520	0.048	286.0	11.26	Entire Root Width - from STA0000 to length shown	13.0
54	C520	0.048	273.0	10.75	Entire Root Width - from STA0000 to length shown	13.0
55	C520	0.048	260.0	10.24	Entire Root Width - from STA0000 to length shown	13.0
56	C520	0.048	247.0	9.72	Entire Root Width - from STA0000 to length shown	13.0
57	C520	0.048	234.0	9.21	Entire Root Width - from STA0000 to length shown	13.0
58	C520	0.048	221.0	8.70	Entire Root Width - from STA0000 to length shown	13.0
59	DBM-1208	0.018	N/A		Pattern: cover entire root area / extend from balsa to LE (under flange) / to tip	
60	DBM-1708	0.023	N/A		Entire surface / Mat Down	

Figure 8 CX-100 Root Design - Revision 2.0

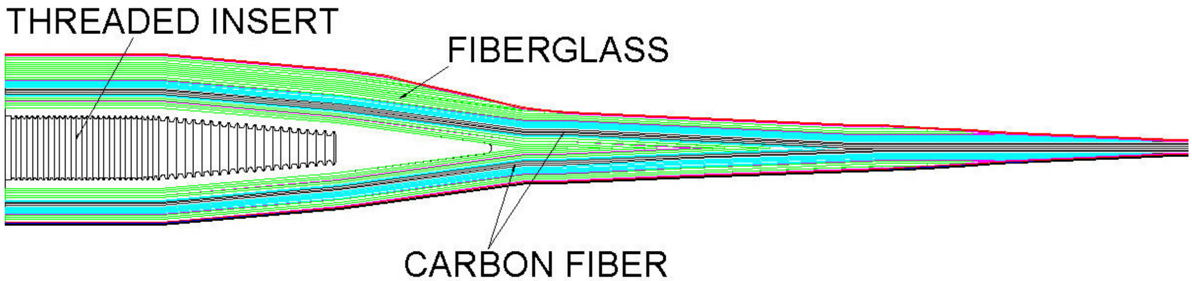

Figure 9 CX-100 Root Design Graphic - Revision 2.0

As is evident in the graphical form of revision 2.0 of the CX-100 root design, the root build-up laminate has become much more balanced. The general load path in the root is centered on the root stud cavity and thus on the root studs themselves. We were also successful in moving the split of the carbon further outboard – providing an initial angular change of direction that is reduced from revision 1.0 (from over seven degrees to about 4 degrees). Upon reviewing the drawing, however, we did discover one detail that negated our effort to reduce the angular direction change of the carbon. Moving inboard from the improved carbon split location, the existing details of the root build-up plies between the carbon spar cap layers forced the carbon plies to "level-out" before angling again at the onset of the root stud cavities. Because the carbon plies were once again parallel upon their approach to the root stud cavity, they were forced to deflect the entire seven degrees to diverge around the cavities. In effect, the positive results of moving the carbon split location outboard were entirely negated by this detail.

Therefore, our final approach – revision 3.0 – focused on adjusting the lengths of the individual root build-up plies located between the carbon spar cap plies to prevent the "leveling-out" effect seen in revision 2.0. The results of this effort can be seen in Figure 10 (in tabular form) and Figure 11 (graphical form).

CX-100 Root Laminate Schedule						
Layer #	Material	Thickness (in)	Length (mm)	Length (in)	Notes	Delta
1	Gel Coat	0.020	N/A		Entire surface	
2	3/4oz Mat	0.007	N/A		Entire surface	
3	DBM-1708	0.023	N/A		Entire surface / Mat Up	
4	DBM-1208	0.018	N/A		Pattern: cover entire root area / extend from balsa to LE (under flange) / to tip	
5	C520	0.048	477.0	18.78	Entire Root Width - from STA0000 to length shown	
6	C520	0.048	504.0	19.84	Entire Root Width - from STA0000 to length shown	-27.0
7	C520	0.048	532.0	20.94	Entire Root Width - from STA0000 to length shown	-28.0
8	DBM-1208	0.018	559.0	22.01	Entire Root Width - from STA0000 to length shown	-27.0
9	C260	0.024	570.0	22.44	Entire Root Width - from STA0000 to length shown	-11.0
10	C260	0.024	584.0	22.99	Entire Root Width - from STA0000 to length shown	-14.0
11	C260	0.024	597.0	23.50	Entire Root Width - from STA0000 to length shown	-13.0
12	C260	0.024	611.0	24.06	Entire Root Width - from STA0000 to length shown	-14.0
13	C260	0.024	625.0	24.61	Entire Root Width - from STA0000 to length shown	-14.0
14	C260	0.024	639.0	25.16	Entire Root Width - from STA0000 to length shown	-14.0
15	C260	0.024	653.0	25.71	Entire Root Width - from STA0000 to length shown	-14.0
16	Hybrid Triax	0.038	8,966		Spar Cap Region - cover entire root	
17	Hybrid Triax	0.038	8,966		Spar Cap Region - cover entire root	
18	Hybrid Triax	0.038	8,966		Spar Cap Region - cover entire root	
19	C260	0.024	474.0	18.66	Entire Root Width - from STA0000 to length shown	
20	C260	0.024	458.0	18.03	Entire Root Width - from STA0000 to length shown	16.0
21	C520	0.048	429.0	16.89	Entire Root Width - from STA0000 to length shown	29.0
22	C520	0.048	400.0	15.75	Entire Root Width - from STA0000 to length shown	29.0
23	DBM-1208	0.018	386.0	15.20	Entire Root Width - from STA0000 to length shown	14.0
24	C520	0.048	357.0	14.06	Entire Root Width - from STA0000 to length shown	29.0
25	C520	0.048	328.0	12.91	Entire Root Width - from STA0000 to length shown	29.0
26	C520	0.048	300.0	11.81	Entire Root Width - from STA0000 to length shown	28.0
27	Root Stud Cavities					
28	C520	0.048	314.0	12.36	Entire Root Width - from STA0000 to length shown	
29	C520	0.048	343.0	13.50	Entire Root Width - from STA0000 to length shown	-29.0
30	C520	0.048	372.0	14.65	Entire Root Width - from STA0000 to length shown	-29.0
31	DBM-1208	0.018	393.0	15.47	Entire Root Width - from STA0000 to length shown	-21.0
32	C520	0.048	415.0	16.34	Entire Root Width - from STA0000 to length shown	-22.0
33	C520	0.048	444.0	17.48	Entire Root Width - from STA0000 to length shown	-29.0
34	C260	0.024	466.0	18.35	Entire Root Width - from STA0000 to length shown	-22.0
35	C260	0.024	481.0	18.94	Entire Root Width - from STA0000 to length shown	-15.0
36	Hybrid Triax	0.038	4,675		Spar Cap Region - cover entire root	
37	Hybrid Triax	0.038	4,500		Spar Cap Region - cover entire root	
38	Hybrid Triax	0.038	3,325		Spar Cap Region - cover entire root	
39	Hybrid Triax	0.038	3,200		Spar Cap Region - cover entire root	
40	C260	0.024	653.0	25.71	Entire Root Width - from STA0000 to length shown	
41	C260	0.024	639.0	25.16	Entire Root Width - from STA0000 to length shown	14.0
42	C260	0.024	625.0	24.61	Entire Root Width - from STA0000 to length shown	14.0
43	C260	0.024	611.0	24.06	Entire Root Width - from STA0000 to length shown	14.0
44	C260	0.024	597.0	23.50	Entire Root Width - from STA0000 to length shown	14.0
45	C260	0.024	584.0	22.99	Entire Root Width - from STA0000 to length shown	13.0
46	C260	0.024	570.0	22.44	Entire Root Width - from STA0000 to length shown	14.0
47	DBM-1208	0.018	559.0	22.01	Entire Root Width - from STA0000 to length shown	11.0
48	C520	0.048	532.0	20.94	Entire Root Width - from STA0000 to length shown	27.0
49	C520	0.048	504.0	19.84	Entire Root Width - from STA0000 to length shown	28.0
50	C520	0.048	477.0	18.78	Entire Root Width - from STA0000 to length shown	27.0
51	C520	0.048	312.0	12.28	Entire Root Width - from STA0000 to length shown	165.0
52	C520	0.048	299.0	11.77	Entire Root Width - from STA0000 to length shown	13.0
53	C520	0.048	286.0	11.26	Entire Root Width - from STA0000 to length shown	13.0
54	C520	0.048	273.0	10.75	Entire Root Width - from STA0000 to length shown	13.0
55	C520	0.048	260.0	10.24	Entire Root Width - from STA0000 to length shown	13.0
56	C520	0.048	247.0	9.72	Entire Root Width - from STA0000 to length shown	13.0
57	C520	0.048	234.0	9.21	Entire Root Width - from STA0000 to length shown	13.0
58	C520	0.048	221.0	8.70	Entire Root Width - from STA0000 to length shown	13.0
59	DBM-1208	0.018	N/A		Pattern: cover entire root area / extend from balsa to LE (under flange) / to tip	
60	DBM-1708	0.023	N/A		Entire surface / Mat Down	

Figure 10 CX-100 Root Design - Revision 3.0

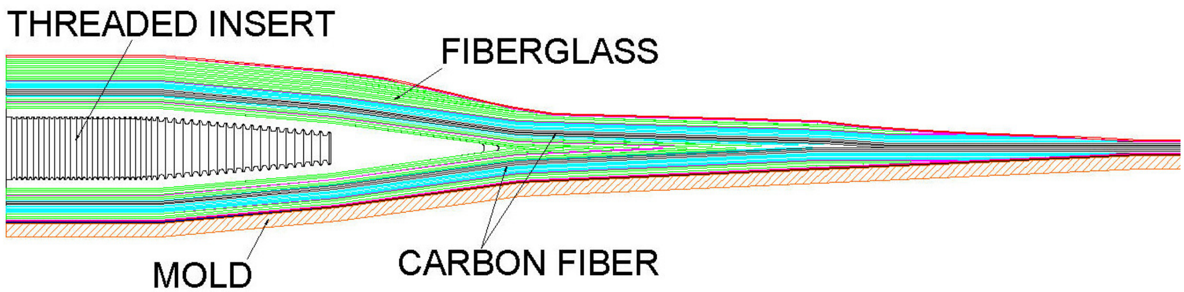

Figure 11 CX-100 Root Design Graphic - Revision 3.0

With revision 3.0 of the CX-100 root design, we reached the desired results. Our most important goal, to advance the carbon spar cap layers into the root section of the blade with as little change in direction as possible, had been achieved. Given our satisfaction with revision 3.0 of the root design, we had essentially created the required outer geometry of the CX-100 root to attain these results. This geometry can be seen in Figure 11 in the mold definition – the thick orange layer at the bottom of the drawing. This shape, revolved into a cylindrical form, was now ready to be transferred to the design drawings for the modified plug.

1.4 CX-100 Plug Detailed Manufacturing Drawings

As discussed above, the CX-100 skin plugs were to be the result of a modification to the ERS-100 Revision D skin plugs. All of the changes to the plugs would occur in the root area. Specifically, TPI's prototype department was tasked to lengthen the root by 200 mm and to provide a new shape in the root – one defined by the outer geometry shown in Figure 11 above. This section presents the manufacturing drawings that were created to guide the prototype department in the modification of the plugs.

The first drawing, shown in Figure 12 below, was to orient the prototype department to the scope of the change we would be making to the skin plugs. Note in the drawing the existing ERS-100 root shape and the new CX-100 root shape. Although we have used metric units in the design and nomenclature of all of these blades, our shop floor at TPI is much more comfortable working with standard units – so you will see in these drawings the units of inches used.

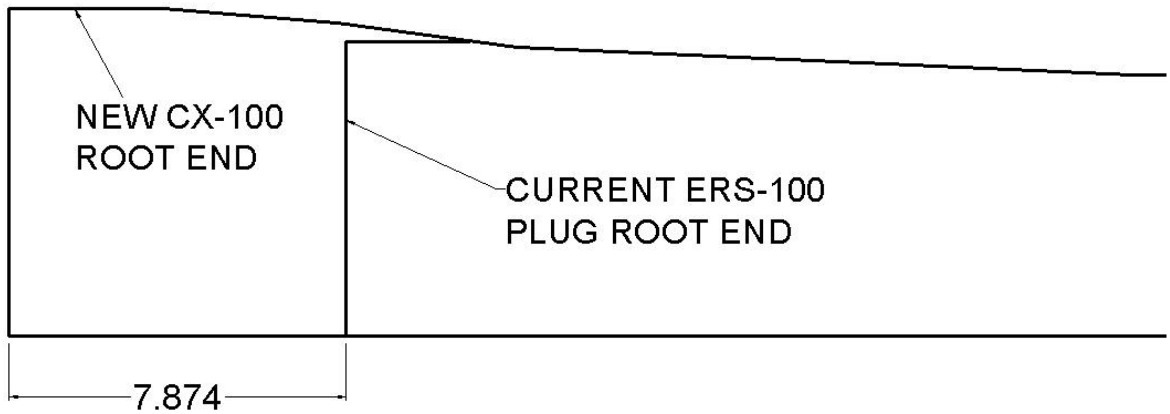

Figure 12 CX-100 Manufacturing Drawing (1)

The next drawing, shown in Figure 13, establishes five root stations, A though E, and assigns their location in relation to the new CX-100 root face. Each station indicates a shape change in the root.

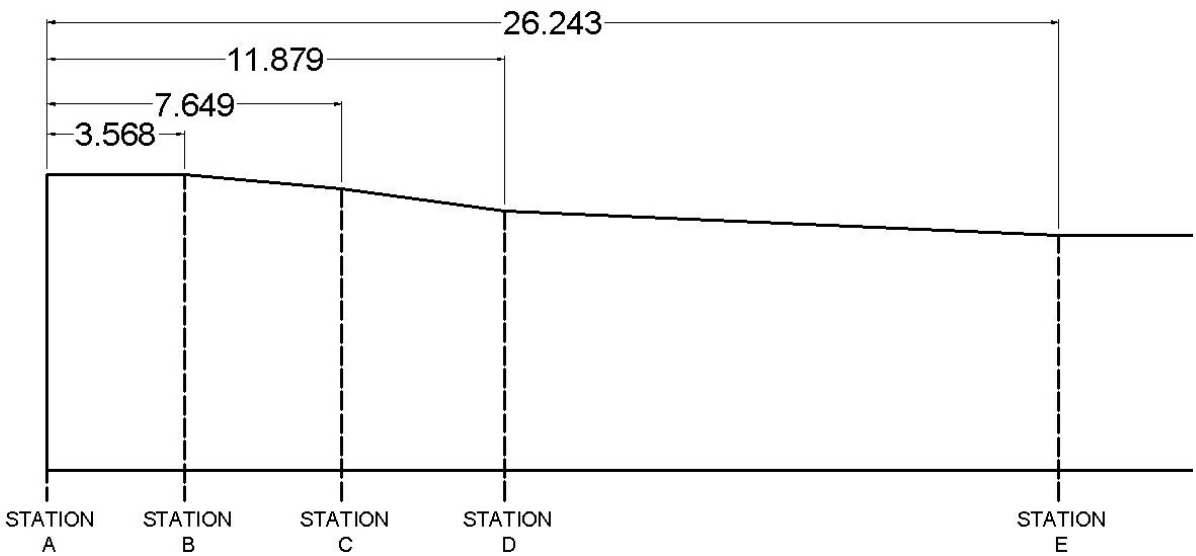

Figure 13 CX-100 Manufacturing Drawing (2)

Figure 14 shows a similar drawing, but this one gives the prototype department an indication of the slopes between each of the stations.

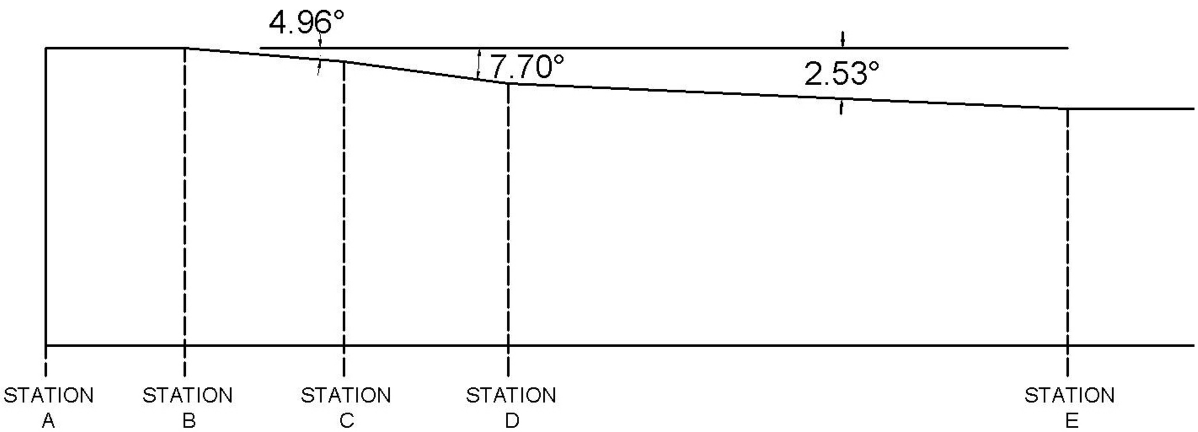

Figure 14 CX-100 Manufacturing Drawing (3)

The final manufacturing drawing presented in this report, shown in Figure 15, represents the cross section of the root at Station C. Cross sections were also produced for Stations A, B, D and E, but it would be redundant to show all of these in the report.

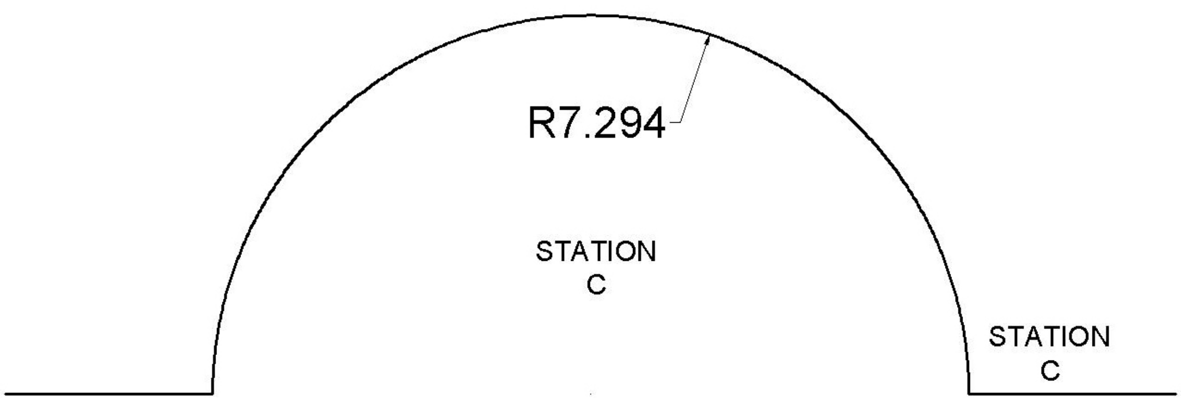

Figure 15 CX-100 Manufacturing Drawing (4)

1.5 CX-100 Plug Manufacturing

All of the station cross section drawings were printed out to full scale for the prototype department. After transferring the shapes to wood patterns, they used a laser to set the templates up with the proper centerline, rotation and distance from the new root face. Figures 16 through 18 show this process.

Figure 16 CX-100 Root Templates (1)

Figure 17 CX-100 Root Templates (2)

Figure 18 CX-100 Root Templates (3)

After the placement of the templates, work began on defining the geometry of the new CX-100 root. The first task was to grind down some areas of the existing ERS-100 root – as can be seen in Figure 19. The areas in the photograph that are white in color are the areas of the original plug that have been ground down. These high points of the ERS-100 root were the outer radius positions of the scallops.

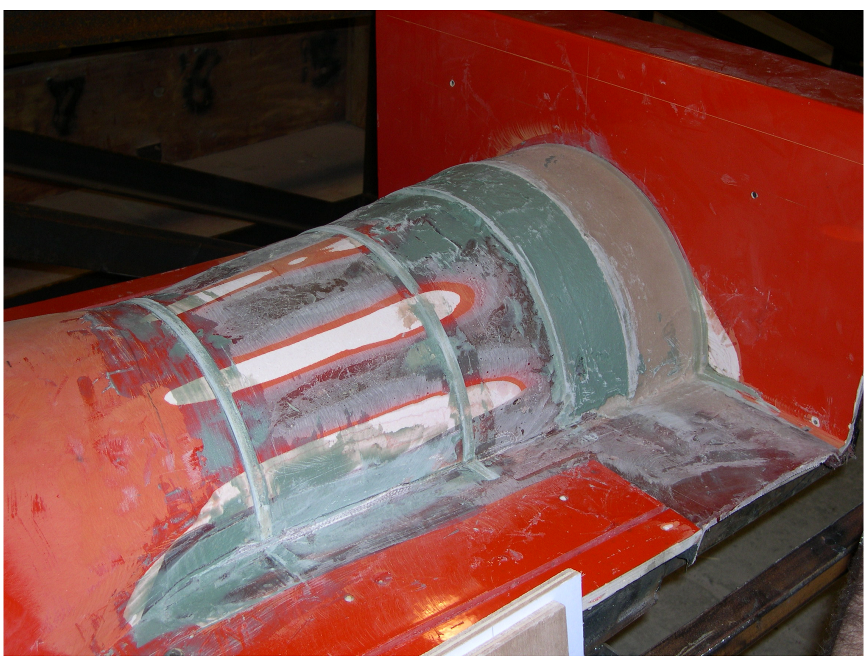

Figure 19 CX-100 Plug Root Shaping

Once all the root surface areas fell below the radii of the new CX-100 root stations, the process of building and smoothing to the new root shape began. The prototype shop used vinylesther-chopped-fiber (VE) putty to fill the voids in the plug geometry. After being allowed to cure, this filler was then sanded down to fit into the surfaces dictated by the CX-100 root templates. Figure 20 shows the CX-100 root plug immediately after the application of the VE putty. Figure 21 shows the process of shaping the root to the desired geometry.

Figure 20 CX-100 Root with VE Putty

Figure 21 CX-100 Root Sanding

The CX-100 skin plug roots were brought to the desired outer geometry through this sanding process. The templates, located at key locations, guided the prototype shop in the hand finishing of the root surface. The geometry outboard of the last root station was blended into the existing blade plug structure. One of the finished roots is shown in Figure 22.

Figure 22 Finished CX-100 Plug Root

Several additional steps were required at this point before proceeding to mold manufacturing. The first step was to perform a critical geometry check of the new root surface. The original female templates were placed onto the plug at the appropriate spanwise stations. All of the templates fit very well on the surface of the plugs. Any gaps present were less than a few thousands of an inch. After we were satisfied that we had achieved the desired outer geometry for each of the root sections, the next step was to ensure the compatibility of the two plugs. It is essential that the high pressure skin and the low pressure skin – when eventually molded and fit up for assemble – have matching bond edges. In order to ensure that our roots were a matched set, the prototype department made a female fiberglass splash of the root section of each skin plug. These female sections were then joined together to check for geometric compliance. This process is shown in Figure 23 and Figure 24.

Figure 23 Root Fit Check (1)

Figure 24 Root Fit Check (2)

The fiberglass root splashes fit together very well, enabling us to move on to the final plug preparations before manufacturing the molds. The modified area of the plugs was sprayed with tooling gelcoat. Threaded inserts were placed at predetermined locations around the perimeter of the plugs. These inserts, once incorporated into the molds, would become the receptacles of the fasteners holding the aluminum return flanges onto the molds. Finally, several coats of mold release were applied to each plug. This would ensure easy separation of the molds from the plugs.

2.0 CX-100 Skin molds

2.1 CX-100 Fiberglass Mold Structure

The first step involved in manufacturing a composites mold is to build the cored fiberglass skin structure that becomes the female geometry of the mold surface. Once mold release had been applied to the high pressure and low pressure CX-100 skin plugs, TPI's prototype department sprayed tooling gelcoat onto the plug surface. This layer of gelcoat will become the surface of the molds once the process is completed. After this first layer dried, the prototype department continued with the structural composite portion of the mold. Several layers of hand-lay-up glass as well as sprayed-chopped-fiber were applier to the entire surface. An intermediate layer of balsa core was added to provide stiffness. Finally, several more layers of chopped and hand-laid glass were added. This phase of the CX-100 skin molds is shown in Figure 25 and Figure 26.

Figure 25 CX-100 Mold Manufacturing (1)

Figure 26 CX-100 Mold Manufacturing (2)

2.2 CX-100 Mold Bracing

After building the fiberglass portion of the CX-100 molds, the prototype department fabricated the steel bracing that becomes the legs and backbone of the molds. Square steel tubing (2"x2") was welded together into a truss that mirrored the shape of the bottom of the skin molds. This steel truss was then suspended above the upside down molds (still in place on the plugs) using the shop crane. After the truss was positioned correctly, it was connected to the composite mold using fiberglass tabbing (hand-lay-up). The result of this is shown in Figure 27 and Figure 28.

Figure 27 CX-100 Steel Mold Bracing (1)

Figure 28 CX-100 Steel Mold Bracing (2)

2.3 CX-100 Mold Flanges

Both CX-100 skin molds were de-molded from the plugs and flipped onto their steel footing. At this point, the final details of mold finishing could be accomplished in preparation for blade molding. Both molds were cleaned and wiped down. The molds are shown in Figure 29, Figure 30 and Figure 31.

Figure 29 CX-100 Skin Mold (1)

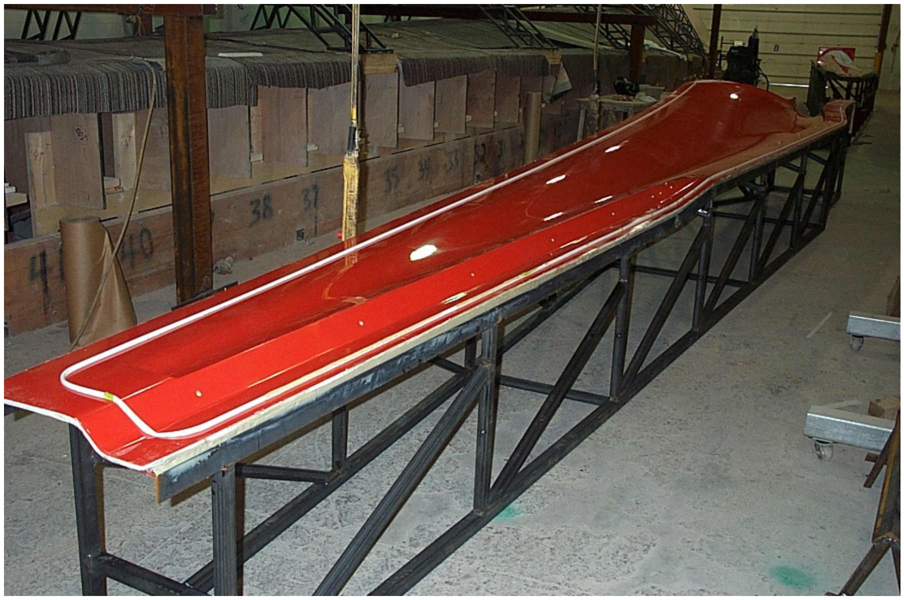

Figure 30 CX-100 Skin Mold (2)

Figure 31 CX-100 Skin Mold (3)

The molds also required aluminum return flanges to be used during blade molding. These flanges bolted to the edges of the mold and provided a return flange to lay fabric under during manufacturing. These flanges had to be designed and produced to fit the exact contour of the skin molds. As mentioned earlier, these flanges utilized embedded threaded inserts in the mold for fastening. Work on these flanges is shown in Figure 32 and Figure 33.

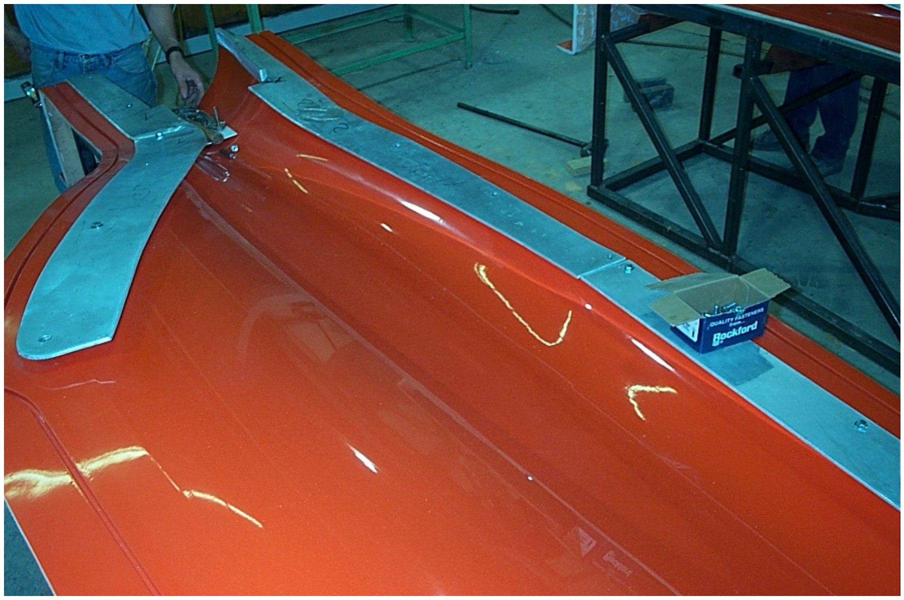

Figure 32 CX-100 Mold Flanges (1)

Figure 33 CX-100 Mold Flanges (2)

2.4 CX-100 Mold End Plates

The final piece of hardware that had to be added to the mold was the root endplate. This aluminum plate serves as the root end molding surface as well as the index for the twelve root stud cavity inserts (six per mold). The new plate was designed by TPI and sent out to be manufactured. Two plates were produced – one for each skin mold. The design of this plate is shown in Figure 34. As can be seen in the design, the plate has six bushings that will locate the six cavity inserts for each skin. These cavities, once demolded, will be used to epoxy root studs into the blade. The endplate also has five infusion holes. The root region of the skin is the most difficult to infuse because it contains a thick stack of laminate. These infusion ports augment the infusion of the root – allowing epoxy to enter at many levels of the laminate. Figure 35 shows one of the endplates attached to the mold.

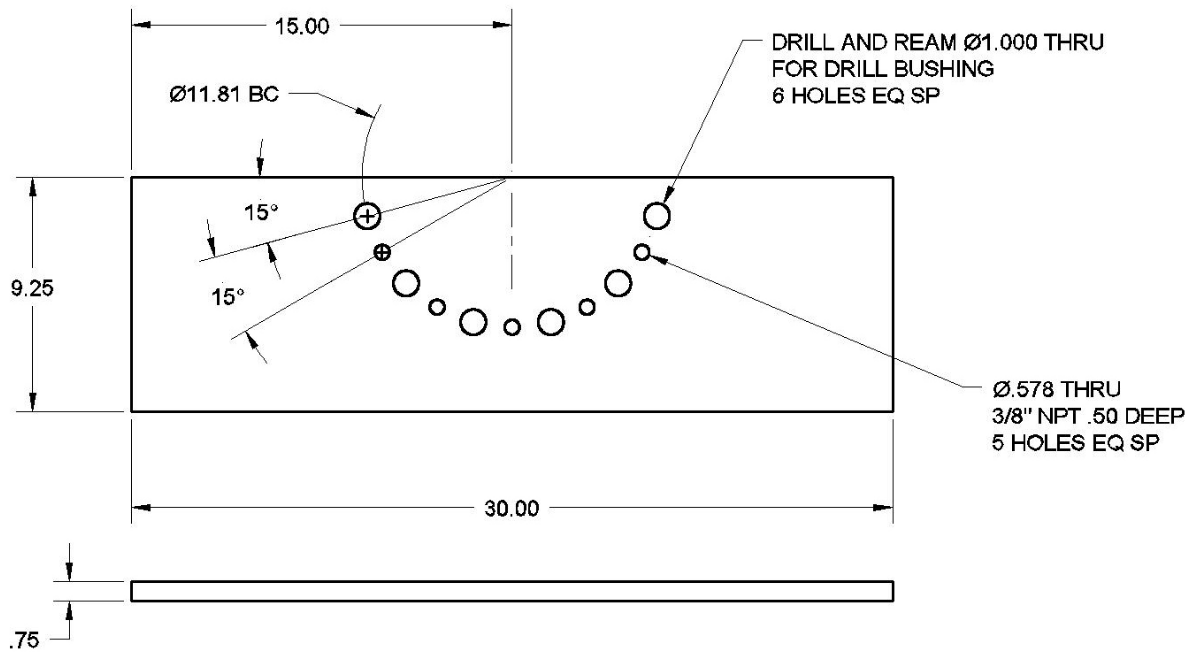

Figure 34 CX-100 Skin Mold Endplate Design

Figure 35 CX-100 Skin Mold Endplate

3.0 CX-100 Assembly Fixture

3.1 CX-100 Assembly Fixture Modifications

In preparation for the build of seven CX-100 blades, TPI modified an ERS-100 assembly fixture to serve the same purpose for the CX-100. The modifications that were required for this adaptation stemmed out of the three major differences between the ERS-100 Revision D and the CX-100. The first difference is length – the ERS-100 Revision D is 8.8 meters long while the CX-100 is 9.0 meters long. Therefore, the structure at the root end of the assembly fixture had to be moved back by 200mm. The second difference between the two blades is the outer geometry of the root. While the ERS-100 blades had the scallop shaped discussed earlier in this report, the CX-100 has a smooth tapering cylinder in the root area. This required TPI to update the shape of the splashes holding the two blade skins in the assembly fixture. The final difference between the two blades is the root connection pattern. The ERS-100 assembly fixture had an endplate to accommodate skins with five root stud cavities each. The CX-100 has six cavities per skin – thus requiring a new plate on the end of the assembly fixture.

3.2 CX-100 Assembly Fixture Endplate

As mentioned above, the modified CX-100 assembly fixture required a new endplate for skin location in the fixture. This plate contained four holes – to pick up the location of the two root stud cavities closest to the bond line on each skin. Because the bolt circle diameter for the CX-100 is somewhat larger than that of the ERS-100, the holes on the CX-100 assembly fixture endplate are located farther apart. The design of this endplate is shown in Figure 36.

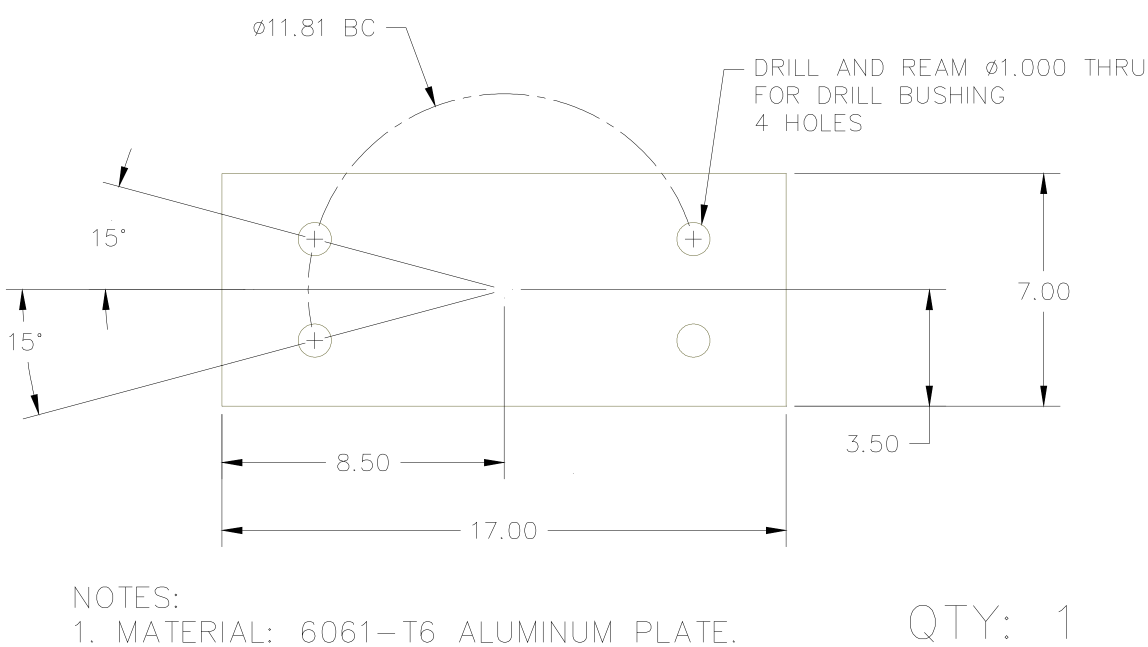

Figure 36 CX-100 Assembly Fixture Endplate Design

Figure 37 shows the CX-100 assemble fixture endplate. In this photograph, the endplate is fastened to the low pressure skin as it resides in the assembly fixture.

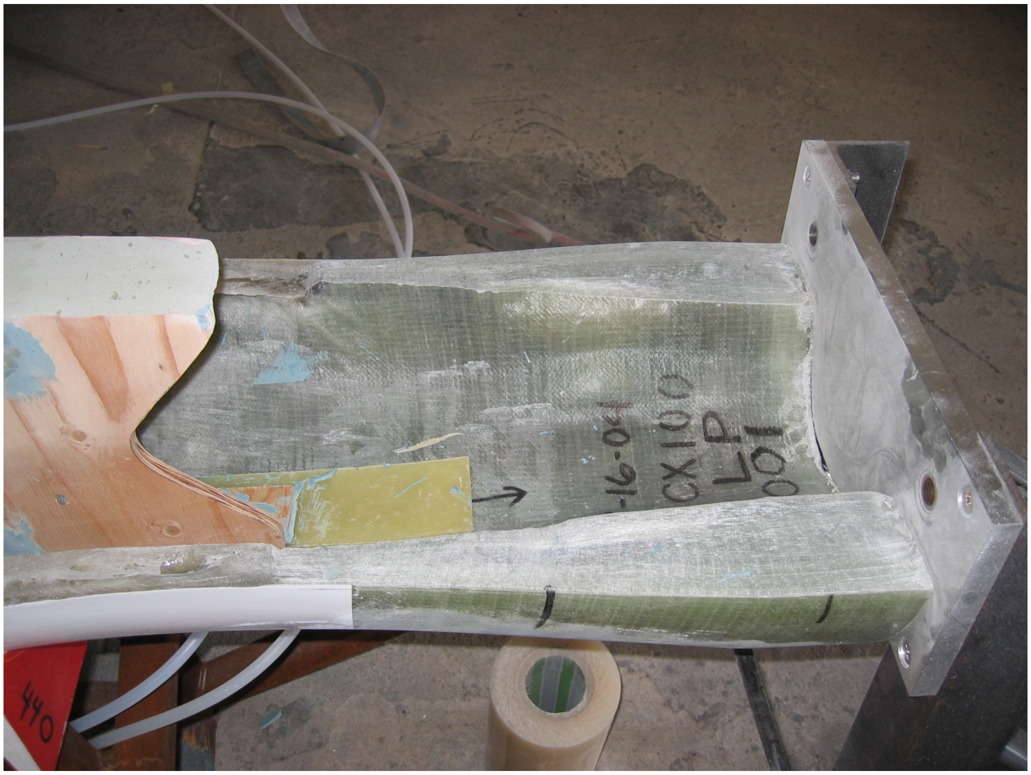

Figure 37 CX-100 Assembly Fixture Endplate

3.3 CX-100 Assembly Fixture Results

After manufacturing the new endplate, TPI incorporated the other changes mentioned in section 3.1. The endplate was affixed to the assembly fixture in a new location – 200mm further out than on the previous fixture. All other components of the assembly fixture were modified to accept the geometry of the CX-100 blade. The finished assembly fixture is shown in Figure 38 and Figure 39.

Figure 38 CX-100 Assembly Fixture (1)

Figure 39 CX-100 Assembly Fixture (2)

4.0 CX-100 Root Stud Insertion Fixture

4.1 CX-100 Root Stud Insertion Fixture Modifications

As with the assembly fixture discussed in the previous section, the CX-100 root stud insertion fixture was created by modifying the existing ERS-100 Revision D insertion fixture. Again, three major differences between the two blades drove the modification details: blade length, root area geometry and bolt circle configuration.

4.2 CX-100 Root Stud Insertion Fixture Endplate

The first step in the fixture modification was to design and produce a new plate for use with the CX-100 blade. As mentioned earlier, the CX-100 has a bolt circle diameter of 300mm with 12 bolts. The purpose of this endplate assembly on the root stud insertion fixture is to guide the root studs into the cavities and to hold them in place while the bonding epoxy is allowed to cure. The design of this plate can be seen in Figure 40. Figure 41 shows the plate together with the remainder of the assembly at the root end of the insertion fixture.

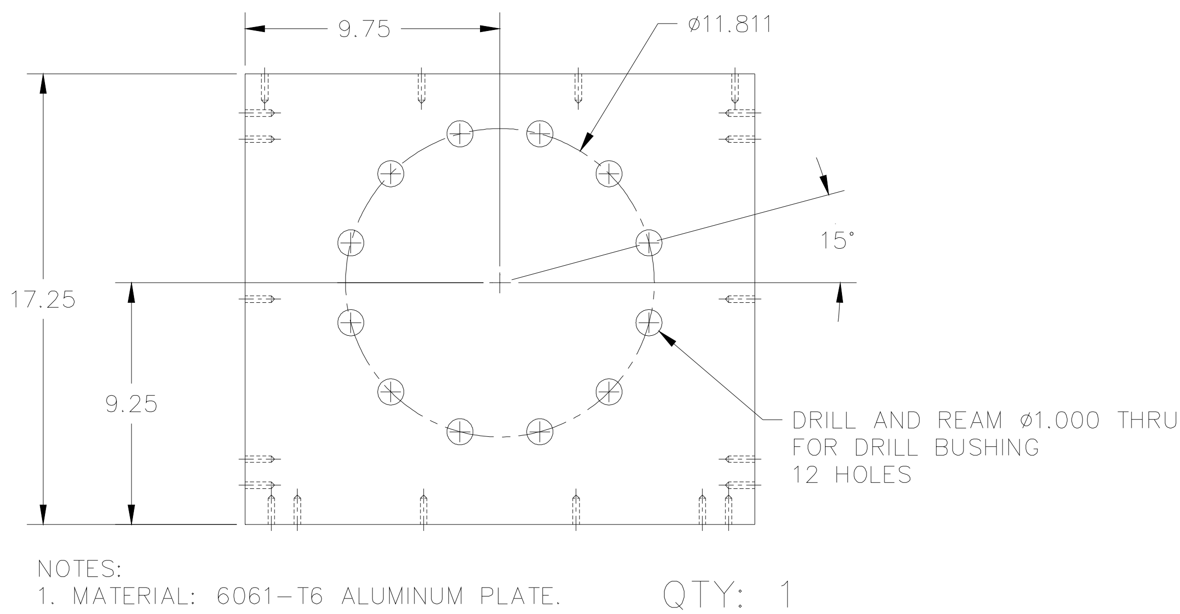

Figure 40 CX-100 Root Stud Insertion Fixture Plate Design

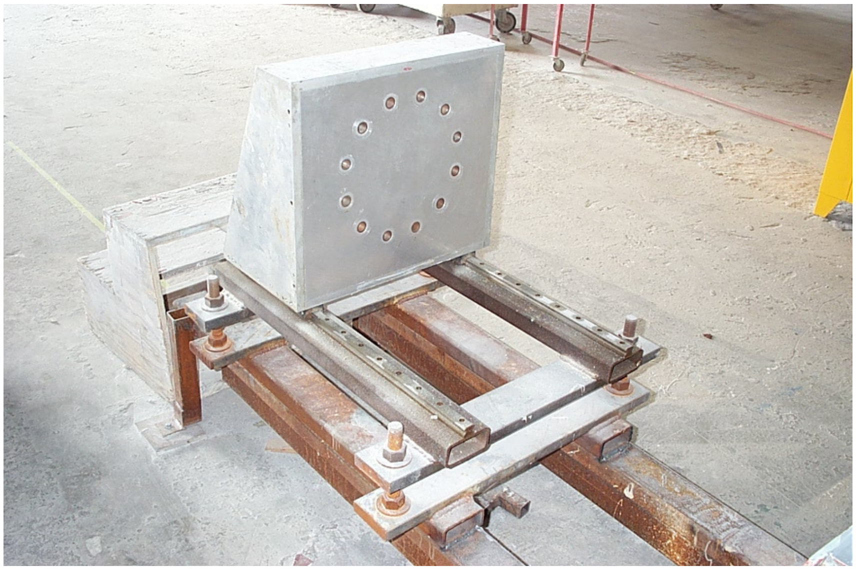

Figure 41 CX-100 Root Stud Insertion Fixture Plate

4.3 CX-100 Root Stud Insertion Fixture Results

TPI's prototype department assembled the new root end plate into the existing mechanism located at the root end of the insertion fixture. This mechanism, located atop linear slides, properly installs the twelve studs into the blade root. The entire slide mechanism had to be detached, moved back (by about 200mm) and re-welded to the frame. Several other modifications also had to be incorporated into the CX-100 root stud insertion fixture. The shape of the splash holding the blade in place was reworked to accommodate the difference in CX-100 root area geometry. Finally, this new geometry was reinforced by connecting it to the base frame of the fixture using fiberglass tabbing and welded metal joints. The resulting modified CX-100 root stud insertion fixture is shown in Figure 42, Figure 43 and Figure 44.

Figure 42 CX-100 Root Stud Insertion Fixture (1)

Figure 43 CX-100 Root Stud Insertion Fixture (2)

Figure 44 CX-100 Root Stud Insertion Fixture (3)

5.0 CX-100 Shear Web Mold

Our original intention was to use the ERS-100 Revision D shear web mold to manufacture webs for the CX-100 blade. Upon attempting the first assembly of a CX-100 blade, however, we found that there were several issues with the fit of the ERS-100 web. No matter how we adjusted the shear web inside the CX-100 blade, we were left with shear web bond gaps that were much bigger than expected – and much bigger than is acceptable.

The adhesive to assemble the CX-100, Plexus 550, can generally tolerate bond gap thicknesses between 0.060" and 0.375". An initial dry fit-up of the ERS-100 shear web in the CX-100 blade resulted in bond gap thicknesses of well over a half inch. TPI decided to modify the ERS-100 shear web mold – thus becoming a new CX-100 shear web mold- to ensure the best fit possible of the shear web in the CX-100 blade. We understood this would cost us additional time on the schedule (about two weeks) and additional cost – but we felt the need for viable test blades was important enough to justify the additional resources.

The TPI prototype department adjusted the geometry of the ERS-100 shear web to mock up the shape of a CX-100 shear web inside the blade. After determining the new shape, we then used that piece as a plug to develop a CX-100 shear web mold. The mold was built using this new plug – and then prepped for shear web production. Figure 45 shows a CX-100 shear web being manufactured in the new mold.

Figure 45 CX-100 Shear Web Mold

6.0 CX-100 Manufacturing Preparation

6.1 CX-100 Blade Design

The first step in the production of the CX-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 report documenting the original phase of this contract [4]. The final result of the design effort was a CX-100 structural design package that would serve as the entry point into blade manufacturing at TPI.

6.2 CX-100 Bill of Material

The CX-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 serves as a final laminate design tool, a material usage estimator, a material cost estimator and a blade (and component) weight estimator. There are 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 46, consists of a list of the material to be used in the construction of the blades. In the expanded version of this page, each entry is also assigned a unit weight (or part weight, if applicable), a mix ratio (if applicable) and a unit cost. The next set of inputs is the infusion assumptions. These values, shown for a few items in Figure 47, set the value of fiber volume for each material. This will in turn be 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 48, consists of different specifications for various parts of the blade. These include 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, are used to estimate overall material usage. TPI uses these estimates for ordering material and planning the production of the CX-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
Hybrid Triax	Saertex V93931 (150gsm(-45)g/669gsm(0)c/150gsm(+45)g/6gsmstch)	46016	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 46 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:	669.00	g/sq m
Carbon sq m Vol (per ply):	380.11	cc
Assumed Fiber Volume:	52	%
Matrix(c) sq m Volume (/ply):	350.87	cc
Matrix Specific Gravity:	1.10	
Matrix(c) Unit Weight:	385.96	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:	**505.42**	g/sq m
Total sq m Volume:	957.23	cc
Ply Thickness:	0.10	cm
Ply Thickness:	0.957	mm
Ply Thickness:	0.038	inches
Carbon Fabric by Weight:	65.7	%
Matrix by Weight:	34.3	%
Matrix Unit Weight:	**0.93**	**lb/sq yd**

Figure 47 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)	5.19	1.20	13	50	6.88
Entire Surface (w/out flanges)	5.19	1.20	0	0	6.23
Aft Panel Balsa	2.03	1.10	0	0	2.23
Fwd Panel Balsa	0.71	1.10	0	0	0.78
Spar Cap Cover	2.72	1.20	10	50	3.76
Spar Cap #1, #2, #3	1.29	1.00	0	0	1.29
Spar Cap #4	0.79	1.00	0	0	0.79
Spar Cap #5	0.77	1.00	0	0	0.77
Spar Cap #6	0.64	1.00	0	0	0.64
Spar Cap #7	0.62	1.00	0	0	0.62

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 48 BOM Specifications

6.3 CX-100 Laminate Schedules / Work Instructions

Before producing blades on the shop floor, a set of laminate schedules and work instructions has to be developed. As with the blade design and the BOM, the laminate schedules and work instructions were developed and presented for the CX-100 during the first phase of this contract. To serve as an example of the type of instruction presented in the shop floor laminate schedule, a page of the CX-100 High Pressure Skin Laminate Schedule is shown in Figure 49. The page layout and instruction approach shown here – in this case for the aft panel balsa – are also utilized throughout the floor documents for each layer of the laminate.

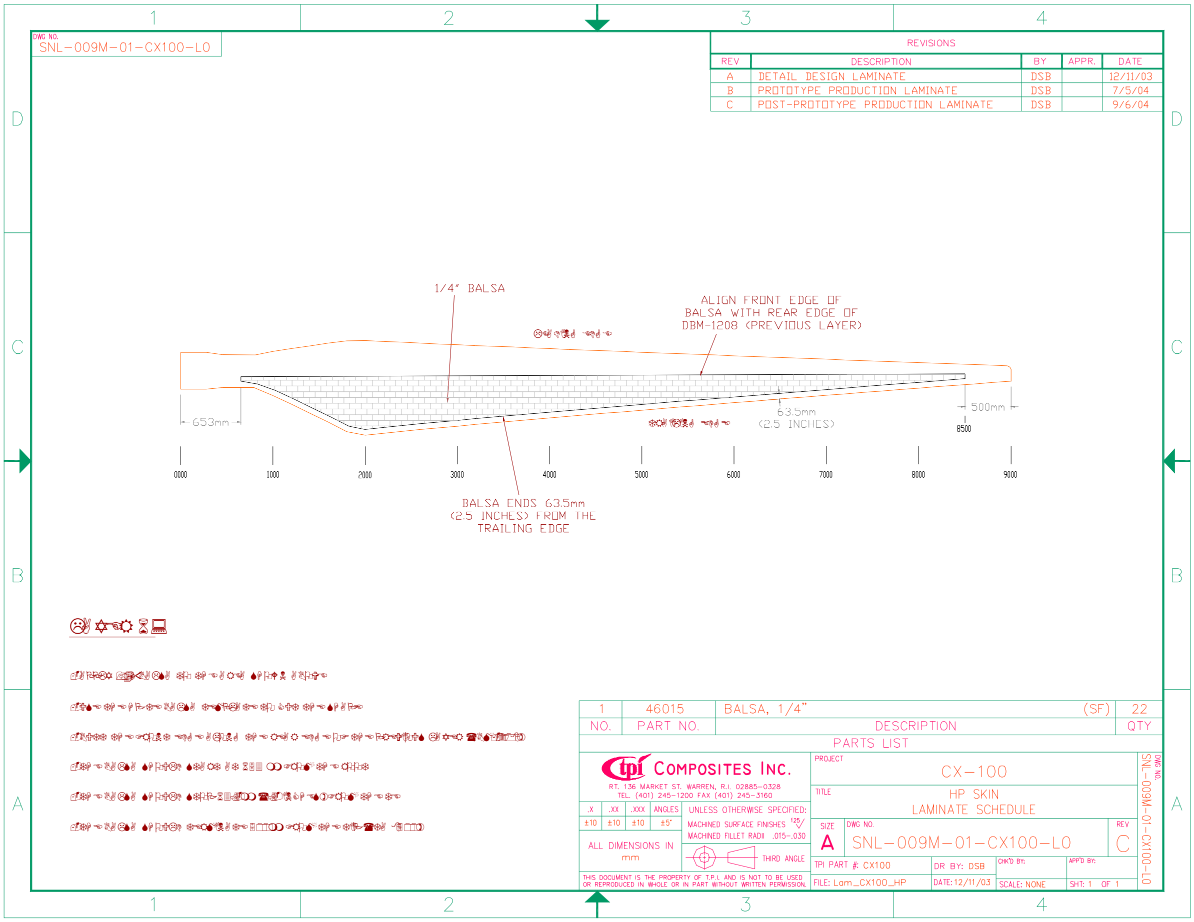

Figure 49 CX-100 HP Aft Panel Balsa Laminate Schedule

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

7.0 CX-100 Blade Manufacturing

7.1 CX-100 Pattern Cutting

Upon commencing manufacturing, the first step is to cut patterns for the entire production run. In the case of the CX-100, this included seven blades. The pattern shapes can be developed in two different ways. The first involves drawing patterns using a computer drafting program. If a three dimensional model of the blade is available, all of the material patterns can be extracted using the proper software. However, even with very accurate three dimensional representations of layer shapes, some hand trimming will 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 can be accurately drawn using a computer drafting program. Other layers have to be defined using paper patterns in the mold.

The first patterns to be defined were the seven layers of the spar cap in each skin. These layers use the Saertex triaxial hybrid fabric (glass / carbon) for the material. These patterns, of which layers 4 and 5 are displayed in Figure 50, were drawn using the information provided by the CX-100 blade design. The main parameters involved are layer length and layer width at certain spanwise stations.

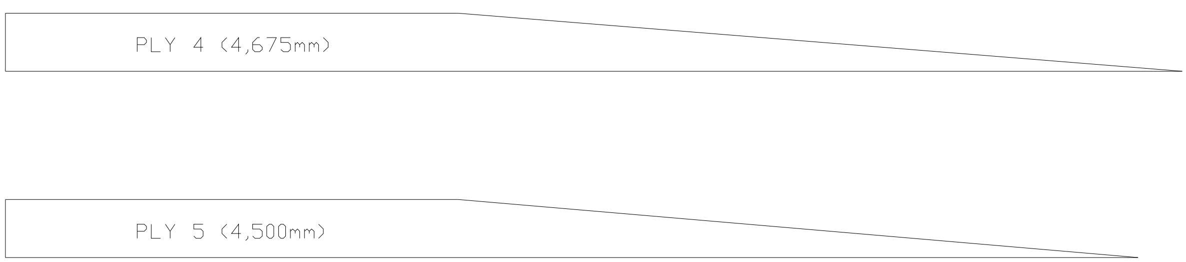

Figure 50 CX-100 Spar Cap Patterns

Another example of patterns drawn using computer drafting programs are all of the root build up layers. These shapes, some of which are shown in Figure 51, are cut using several materials, including C520, C260 and DBM-1208.

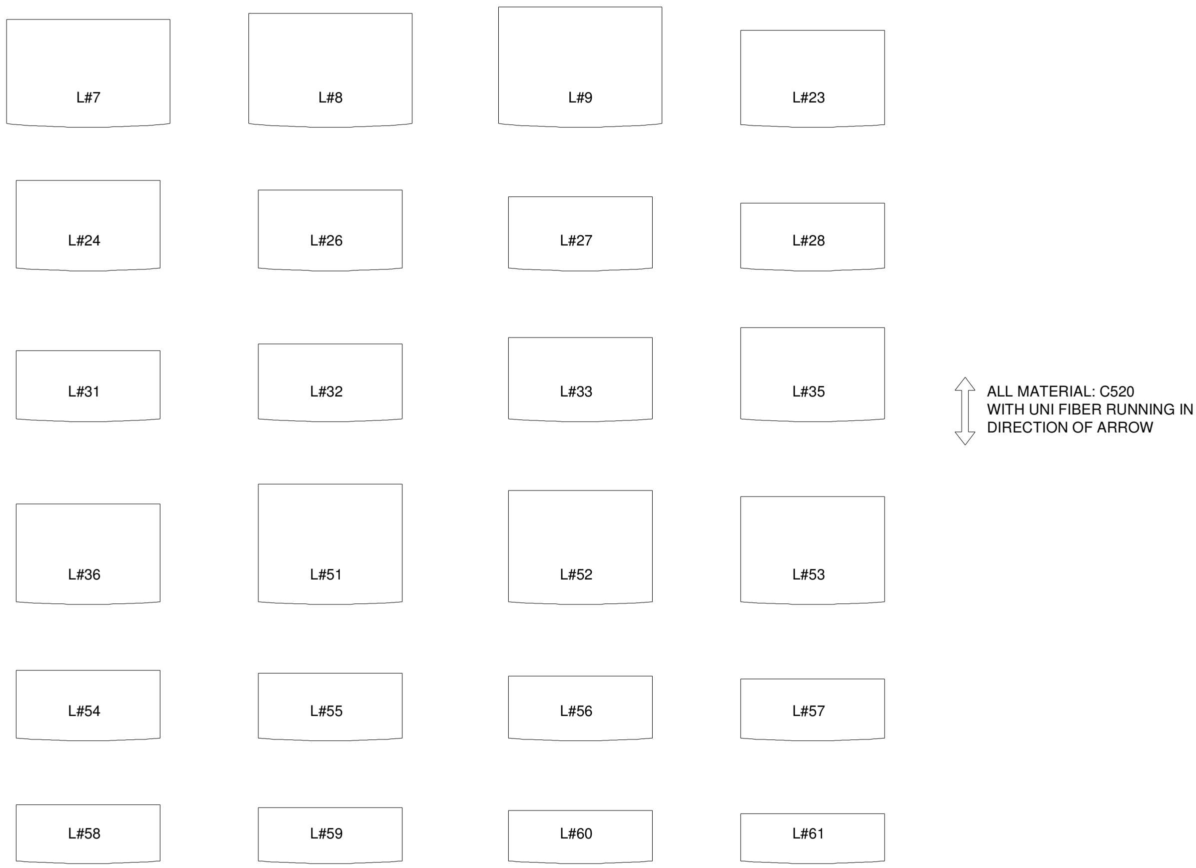

Figure 51 CX-100 C520 Root Patterns

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

Other types of patterns are defined using the mold as a template. These patterns, such as the full skin layers, are detailed by laying paper in the three dimensional mold to define the shape of the two dimensional pattern. Once the shape is defined, a more permanent template is 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 is available – when all pattern shapes can 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 CX-100 were not digitized because all patterns were cut by hand. Figure 52 and Figure 53 show the material cutting process for the CX-100 blade.

Figure 52 CX-100 Material Cutting (1)

Figure 53 CX-100 Material Cutting (2)

The final patterns created are 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, are then transferred to a more durable construction of thin wood. All of the material shapes are cut – 62 separate layers for each skin – and placed in order on a rolling manufacturing cart. These carts, called kits, are stationed next to the mold during the lay-up of the skins.

7.2 CX-100 Material Lay-Up

After cutting the material patterns, the next step in the blade manufacturing process is to place the materials into the mold. All molds have 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 is the gelcoat. This becomes 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 CX-100 – is sprayed onto the mold surface to a specified thickness. After the gelcoat is allowed to dry – or 'tack' – the rest of the laminate can then be placed into the mold. Figure 54 and Figure 55 show gelcoat after it has been sprayed into the skin mold.

Figure 54 CX-100 Gelcoat (1)

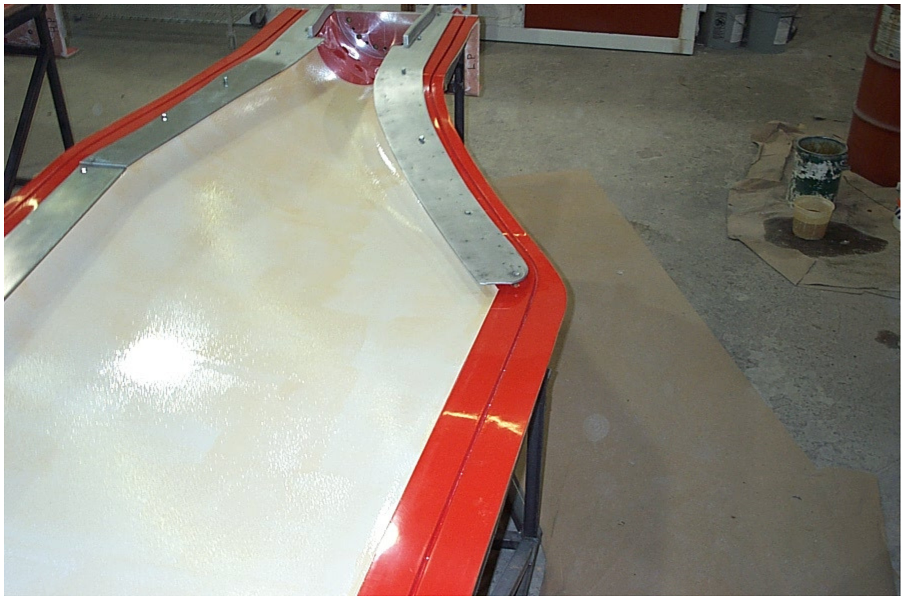

Figure 55 CX-100 Gelcoat (2)

After attaching the metal return flanges to the molds, skin layers number 2 through number 64 are placed into the molds utilizing the instruction of the floor laminate schedules. The layers include such materials as ¾ oz Mat, DBM-1708, DBM-1208, C520, C260 and balsa core. Also included in the middle of the lay-up are 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 56 through 64.

Figure 56 CX-100 Lay-Up (1)

Figure 57 CX-100 Lay-Up (2)

Figure 58 CX-100 Lay-Up (3)

Figure 59   CX-100 Lay-Up (4)

Figure 60   CX-100 Lay-Up (5)

Figure 61 CX-100 Lay-Up (6)

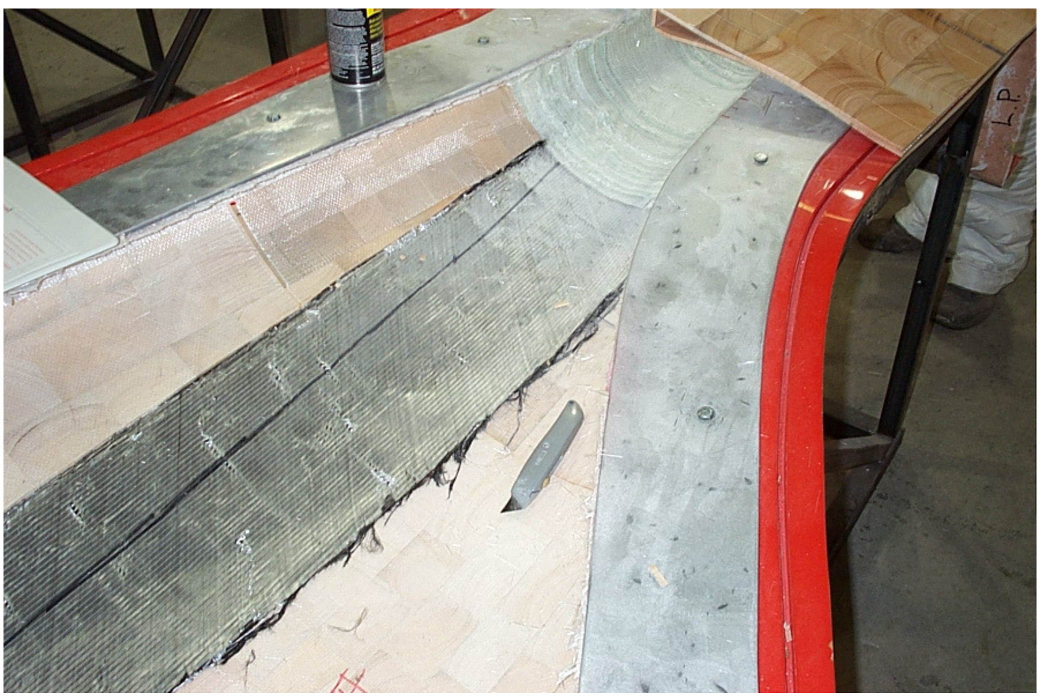

Figure 62 CX-100 Lay-Up (7)

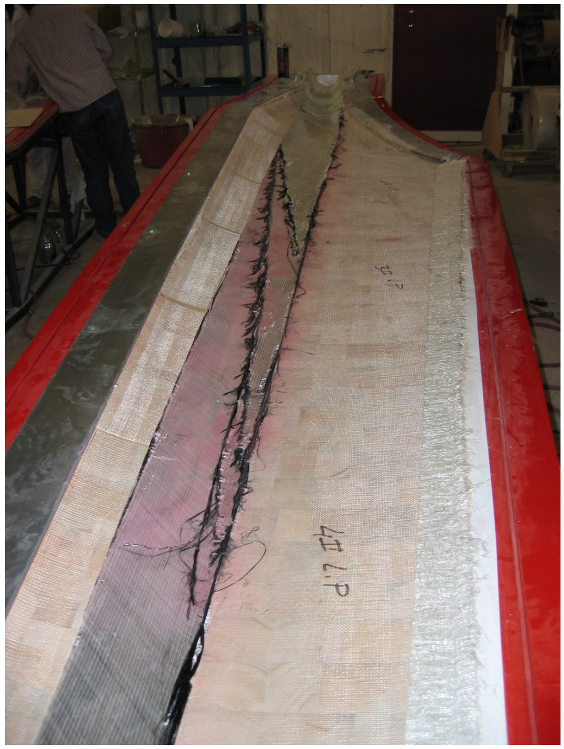

Figure 63 CX-100 Lay-Up (8)

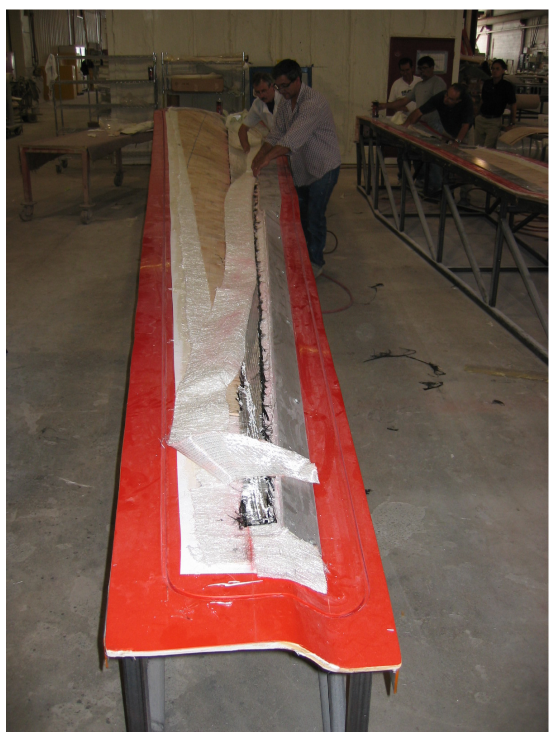

Figure 64 CX-100 Lay-Up (9)

7.3 CX-100 Infusion

The manufacturing steps following material lay-up include vacuum bagging, infusion, post curing and demolding. The first step, vacuum bagging, occurs directly after all of the layers are placed into the mold. In the absence of a silicone bag, the blade is bagged using consumable materials. The main component is the nylon film vacuum bag. This covers the entire part and is sealed at the edges of the mold. This bag will form the barrier with which to evacuate the air from the blade laminate. Also included in the process of vacuum bagging are laying down all of the resin feed lines and the vacuum lines. These features, along with peel ply and infusion flow medium, augment the infusion of resin (or in this case, epoxy) into the dry blade laminate. Figures 65 through 68 demonstrate the process of vacuum bagging.

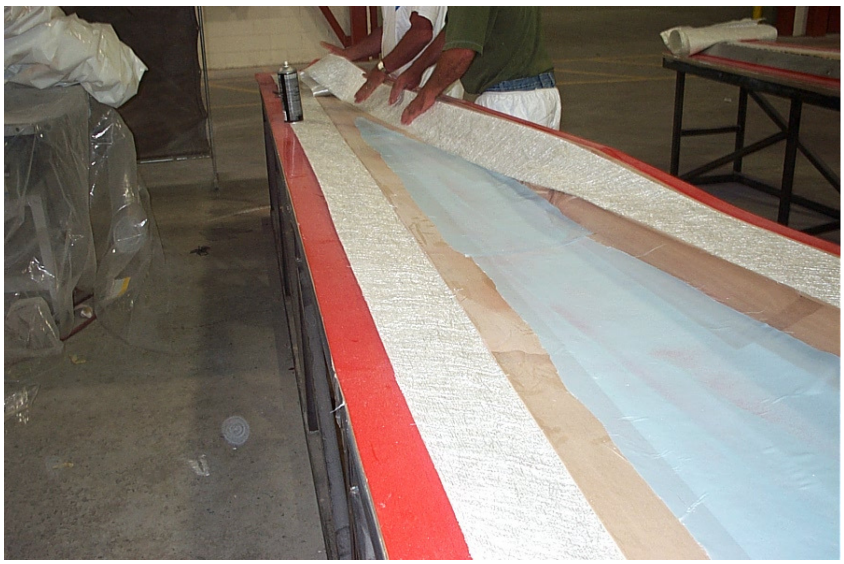

Figure 65 CX-100 Vacuum Bagging (1)

Figure 66 CX-100 Vacuum Bagging (2)

Figure 67 CX-100 Vacuum Bagging (3)

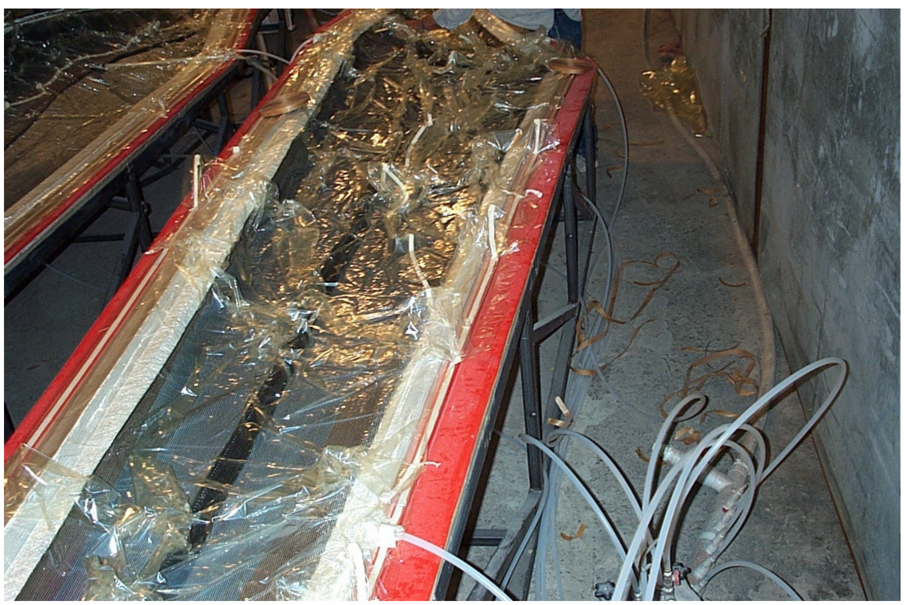

Figure 68 CX-100 Vacuum Bagging (4)

The next step is the infusion and post curing of the blade components. The CX-100 blades were infused with a Huntsman Epoxy (LY1564). All of the bagged molds are placed into an oven to be used during post cure. The epoxy is pulled into the part using the vacuum created during the bagging process. Strategically placed on the blade skins, the resin feed lines evenly distribute the epoxy during infusion. Once the entire part is filled and the epoxy begins to cure, the vacuum is turned down to a lower level and the temperature around the molds is elevated from room temperature to about 180 degrees Fahrenheit. The infusion process is shown in Figures 69 through 72.

Figure 69 CX-100 Infusion (1)

Figure 70 CX-100 Infusion (2)

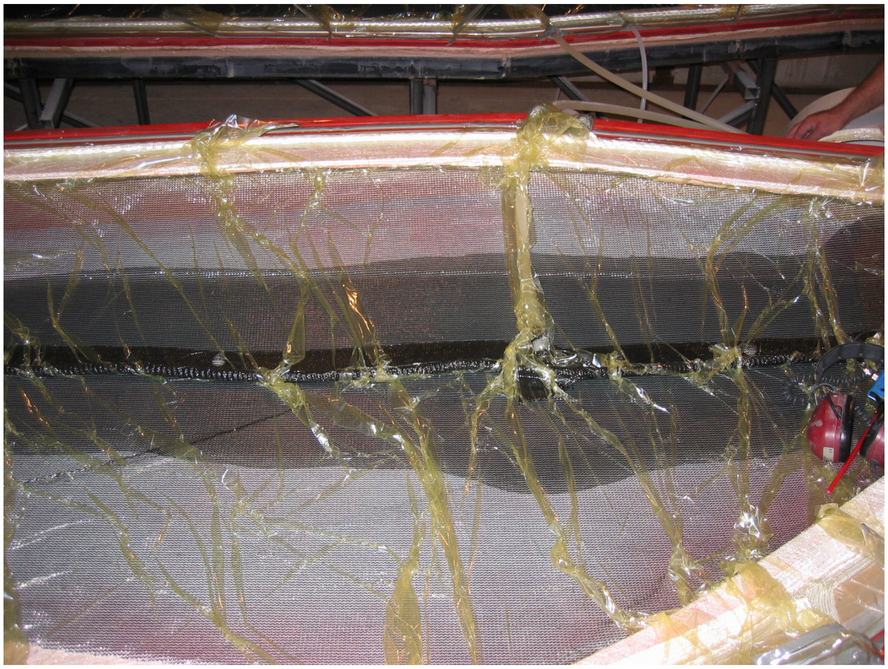

Figure 71 CX-100 Infusion (3)

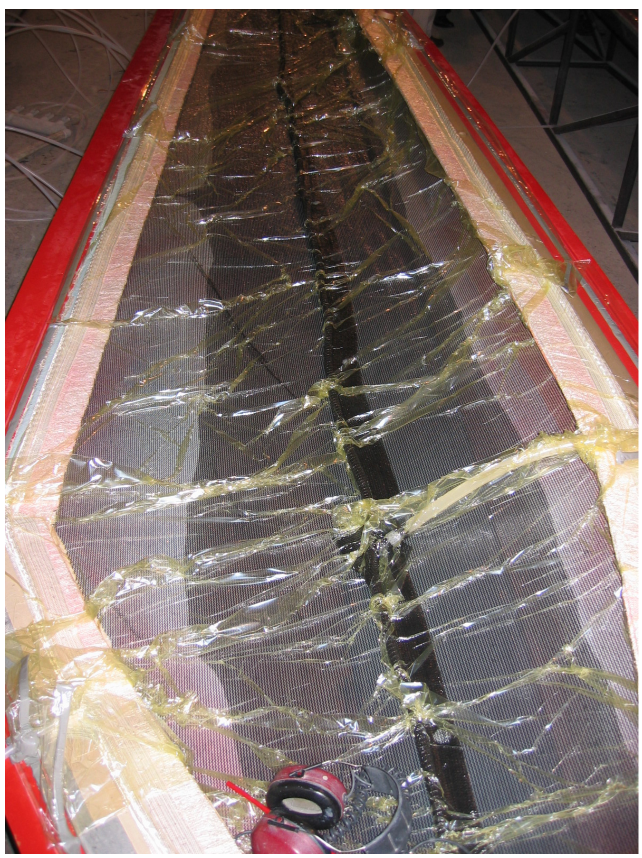

Figure 72 CX-100 Infusion (4)

The final step before assembly is demolding. This is the process of taking the composite part out of the mold. This is illustrated in Figure 73 and Figure 74.

Figure 73 CX-100 Demolding (1)

Figure 74 CX-100 Demolding (2)

7.4 CX-100 Assembly

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

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

After removing the bonded blade from the assembly fixture, it is placed into the root stud insertion fixture. The details of the insertion fixture were presented in an earlier section of this report. The purpose of the root stud insertion fixture is to align and bond the 12 threaded inserts into the root of the CX-100 blade. These inserts will be used to attach the blade to the turbine (with an adapter plate as an interface). The bonded blade is strapped into the root stud insertion fixture to ensure proper location of the root stud cavities. Twelve threaded inserts are attached to a sliding locating plate inboard of the blade root. Once all of the parts are secured in place, the adhesive used to bond the root studs into the blade root is mixed. The adhesive used in this process is West System 105/206 epoxy. The epoxy is thickened with high density 404-45B Filler and R200 Aerosil. All of the root stud cavities are back-filled with this thickened epoxy. The root studs themselves are also coated with the epoxy. At this point, the 12 inserts are slid into the blade root – displacing some of the epoxy located in the cavities. Once entirely into position, the sliding plate is locked and the assembly is left to cure overnight. Figures 75 through 78 show various stages of the CX-100 blade in the fixtures.

Figure 75 CX-100 Assembly (1)

Figure 76   CX-100 Assembly (2)

Figure 77   CX-100 Assembly (3)

Figure 78 CX-100 Assembly (4)

8.0 CX-100 Instrumentation

During the assembly process, several of the CX-100 blades were instrumented with strain gauges. A significant part of the CX-10 project includes a flight test program to interrogate the bending performance of the blade. In an effort to support the test program and obtain useful data TPI Composites and Sandia agreed to instrument four of the seven blades.

Blades #004 and #005 were fully instrumented with gages at approximately 75%, 50% and at 25% to measure flap wise bending strains. Additionally Blades #004, #005, #006 and #007 were instrumented with strain gages at the root to measure both flap wise and edge wise bending strains.

Figure 79 shows the full instrumentation applied to blades #004 and #005. Each pair of gages make up a temperature compensated half arm of a full bridge. Combining maximum and minimum bending strains (HP and LP skins) provides high bridge output for accurate strain measurement.

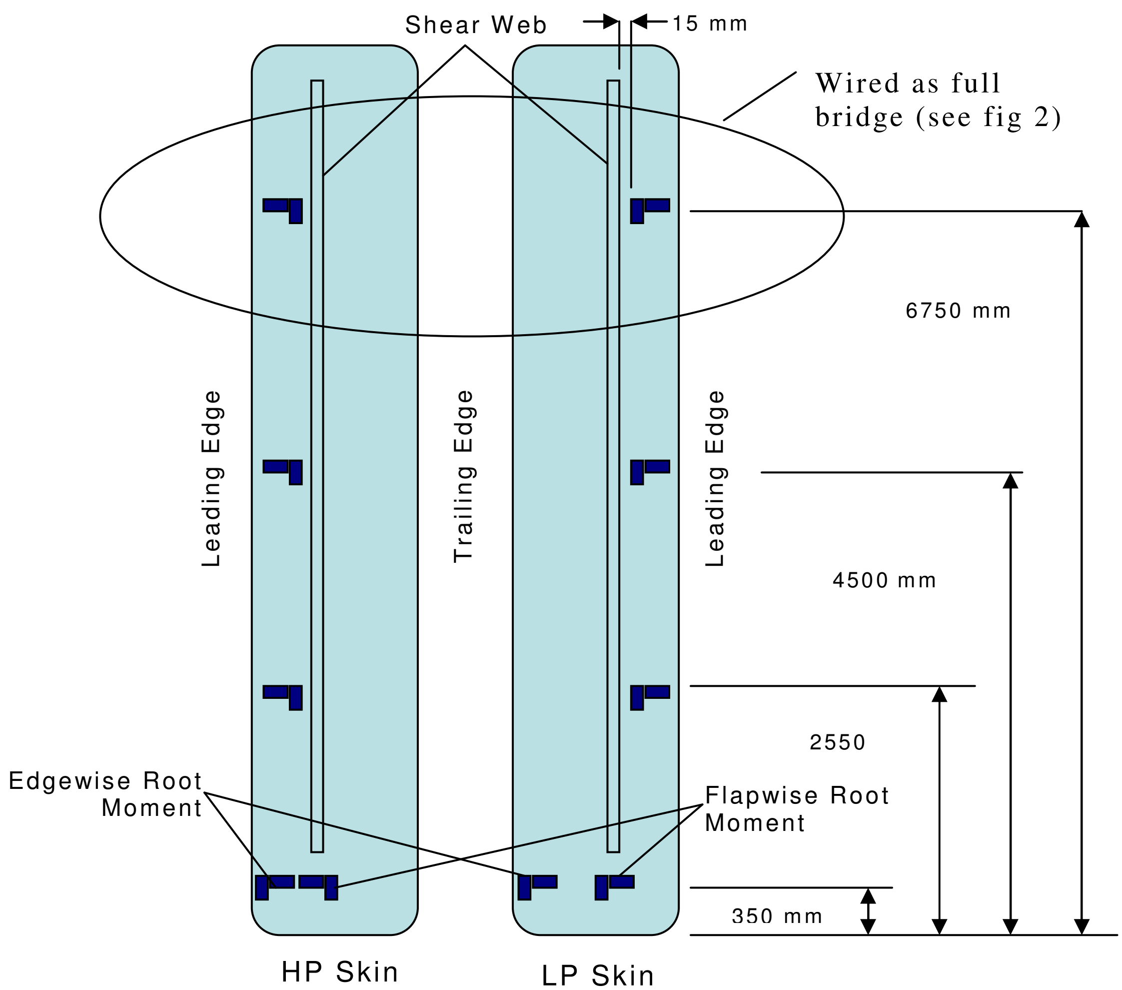

Figure 79 CX-100 Gauge Placement

Figure 80 is a diagram of the wiring of a complete Wheatstone bridge circuit. Axial gages make up the active component of the bridge while transverse gages provide temperature compensation. The axial gage on HP skin is wired to indicate positive strain (tensile face).

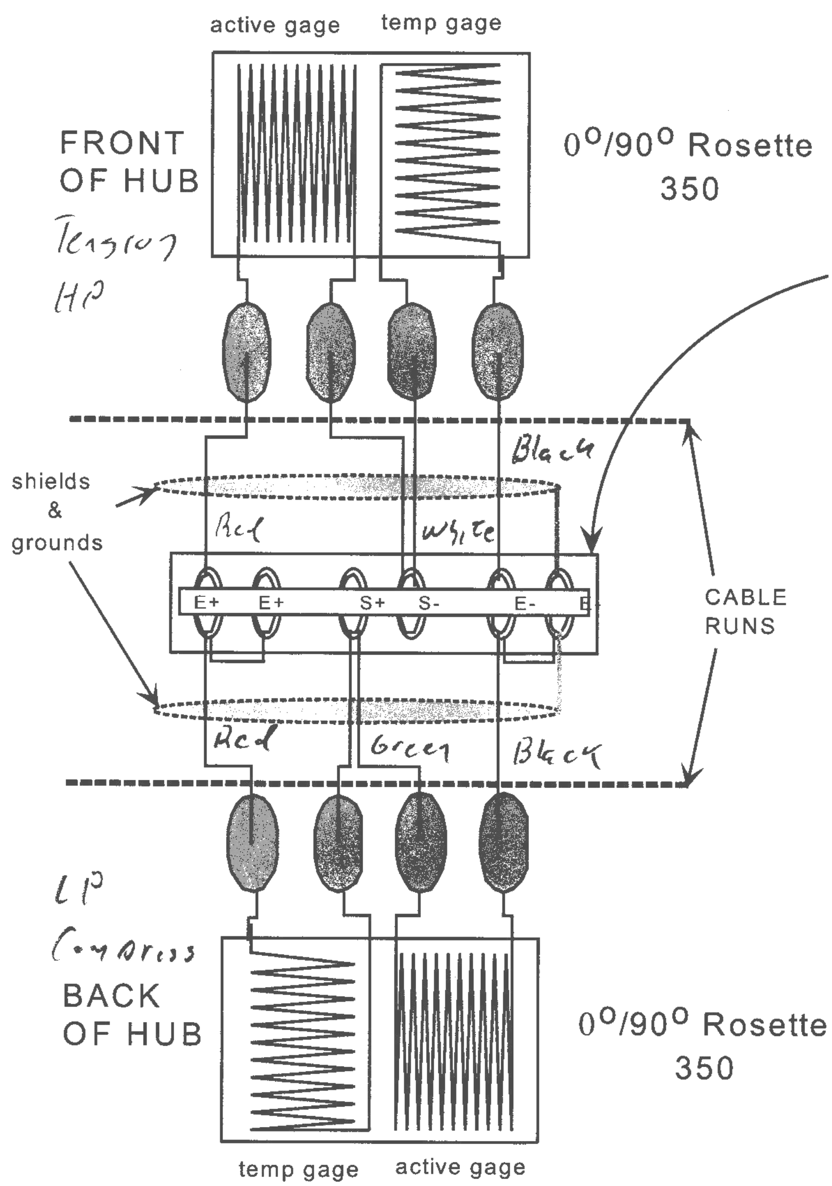

Figure 80 Wheatstone Bridge Diagram

Figures 81 through 86 show various views of the gauges installed in the CX-100 blades during assembly.

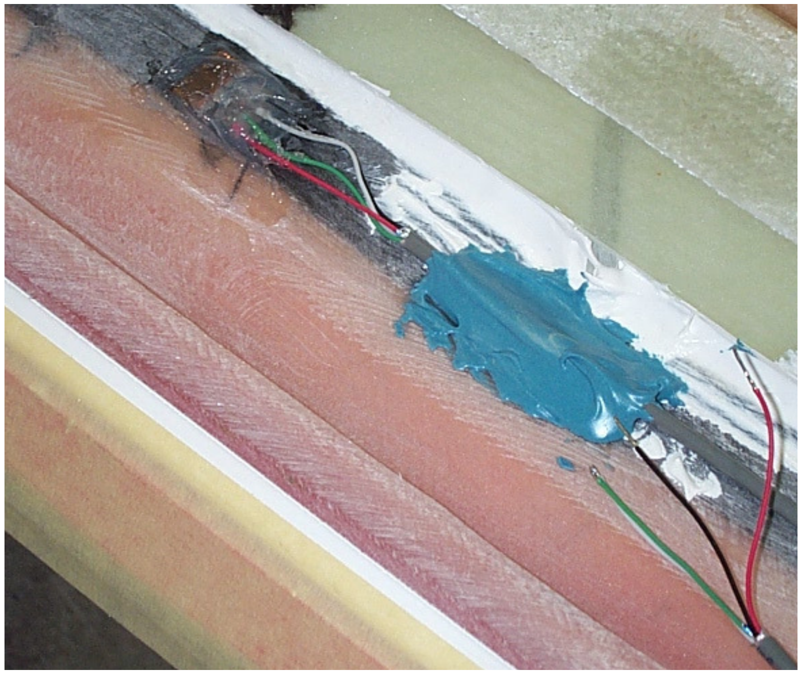

Figure 81 CX-100 Instrumentation (1)

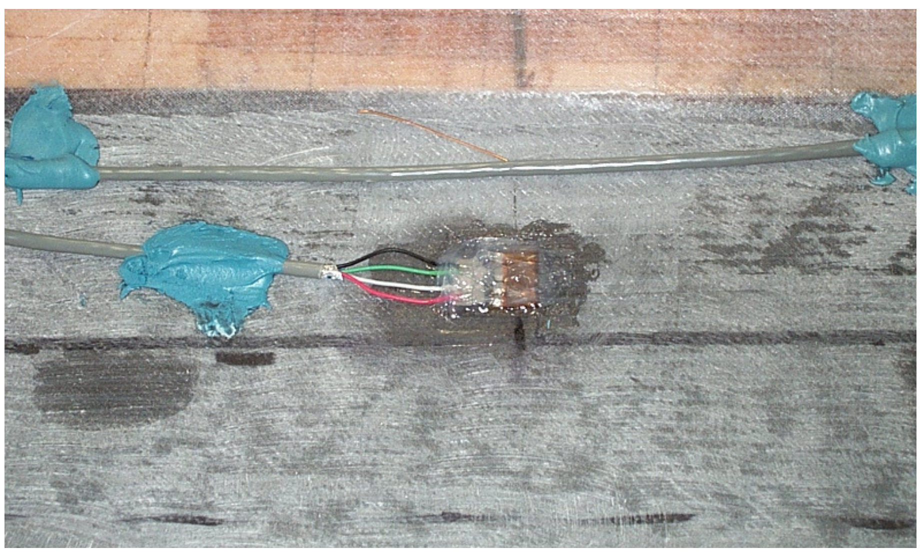

Figure 82 CX-100 Instrumentation (2)

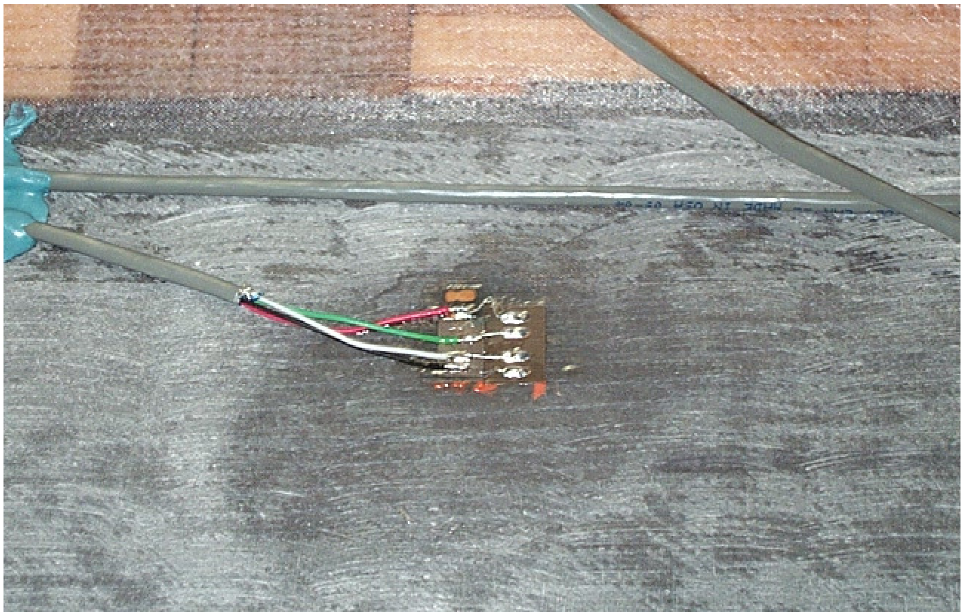

Figure 83 CX-100 Instrumentation (3)

Figure 84 CX-100 Instrumentation (4)

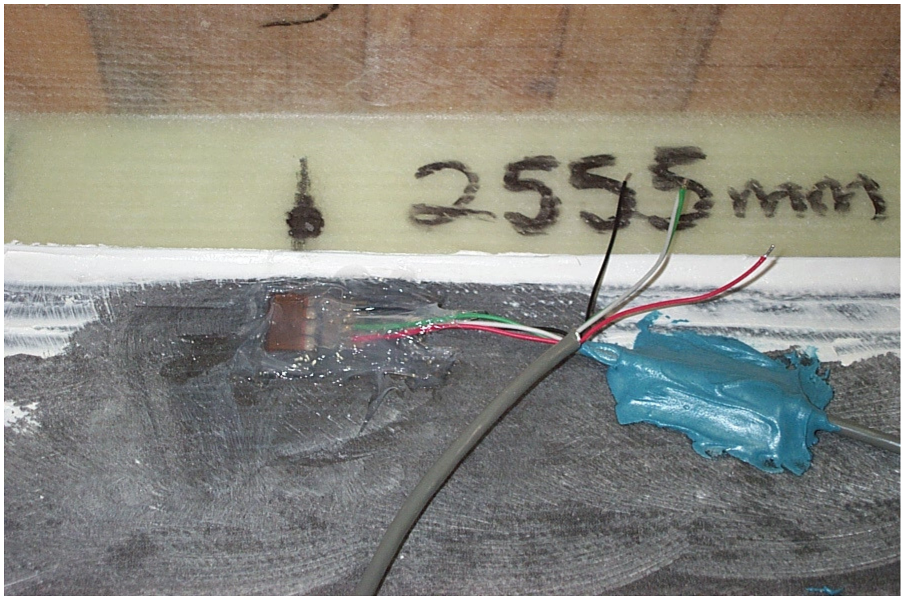

Figure 85 CX-100 Instrumentation (5)

Figure 86 CX-100 Instrumentation (6)

9.0 CX-100 Blade Shipping

Seven CX-100 blades were manufactured at the TPI facility in Warren, Rhode Island. After production, each blade was weighed. Using the root and tip weights, the center of gravity of each blade was calculated. Figure 87 shows the configuration used to weigh each blade.

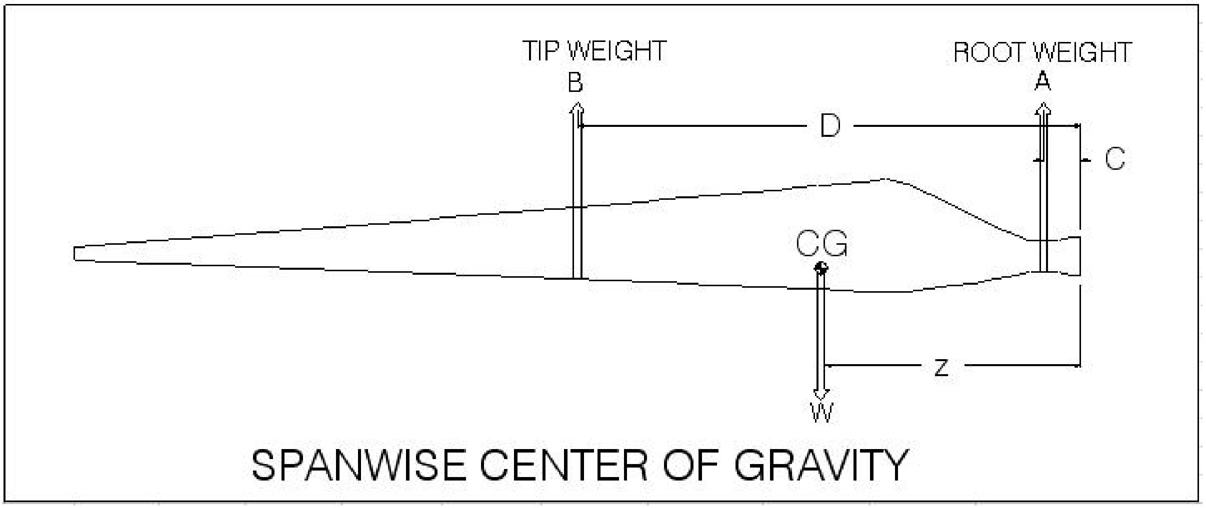

Figure 87 CX-100 Blade Weighing Configuration

The CX-100 blade weights and centers of gravity were compiled into tables presented below. Figure 88 displays results in English units, while Figure 89 displays results in Metric units. Also included in each table are static balance, tip weight, blade notes and delivery location.

CX-100 Blade Weights and CGs (Standard Units)													
Blade #	Test Location	A (lbs)	B (lbs)	C (inches)	D (lbs)	E (inches)	Blade Length (inches)	Blade Weight (lbs)	Spanwise CG (inches)	Static Balance (in-lbs)	Chordwise CG (inches)	Chordwise CG Location	Notes
001	NWTC	95.5	283.5	369.0	40.0	12.0	354.3	379.0	89.6	33,957	1.266	TE	
002	SNL	98.5	287.5	369.0	35.0	12.0	354.3	386.0	90.8	35,040	1.088	TE	Redone LE / Reinfused SC
003	NWTC	96.0	284.0	369.0	32.0	12.0	354.3	380.0	89.8	34,138	1.011	TE	SC Carbon Wrinkles (1.01m/1.13m/1.23m)
004	USDA	97.5	284.5	368.5	27.0	12.0	354.3	382.0	90.7	34,636	0.848	TE	Full Span Instrumentation
005	USDA	96.5	285.5	368.5	35.0	12.0	354.3	382.0	89.7	34,267	1.099	TE	Full Span Instrumentation
006	SNL	98.0	286.0	368.5	31.0	12.0	354.3	384.0	90.7	34,813	0.969	TE	Root Instrumentation
007	USDA	97.0	290.5	369.0	35.0	12.0	354.3	387.5	89.0	34,481	1.084	TE	Root Instrumentation / Reinfused SC
							Average	**382.9**	**90.0**	**34,476**	**1.052**		

Figure 88 CX-100 Weight and CG Table (English Units)

CX-100 Blade Weights and CGs (Metric Units)													
Blade #	Test Location	A (kgs)	B (kgs)	C (mm)	D (kgs)	E (mm)	Blade Length (mm)	Blade Weight (kgs)	Spanwise CG (mm)	Static Balance (m-kgs)	Chordwise CG (mm)	Chordwise CG Location	Notes
001	NWTC	43.3	128.6	9,373	18.1	304.8	9,000	171.9	2,276	391.2	32.169	TE	
002	SNL	44.7	130.4	9,373	15.9	304.8	9,000	175.1	2,306	403.6	27.637	TE	Redone LE / Reinfused SC
003	NWTC	43.5	128.8	9,373	14.5	304.8	9,000	172.3	2,282	393.2	25.667	TE	SC Carbon Wrinkles (1.01m/1.13m/1.23m)
004	USDA	44.2	129.0	9,360	12.2	304.8	9,000	173.2	2,303	399.0	21.543	TE	Full Span Instrumentation
005	USDA	43.8	129.5	9,360	15.9	304.8	9,000	173.2	2,278	394.7	27.927	TE	Full Span Instrumentation
006	SNL	44.4	129.7	9,360	14.1	304.8	9,000	174.1	2,303	401.0	24.606	TE	Root Instrumentation
007	USDA	44.0	131.7	9,373	15.9	304.8	9,000	175.7	2,260	397.2	27.530	TE	Root Instrumentation / Reinfused SC
							Average	**173.7**	**2,287**	**397.1**	**26.726**		

Figure 89 CX-100 Weight and CG Table (Metric Units)

Finally, Figure 90 and Figure 91 show some of the preparations for shipping.

Figure 90 CX-100 Shipping Preparation

Figure 91 CX-100 Loading

10.0 Conclusion

The CX-100 manufacturing project successfully demonstrated the design and manufacturing of a full scale wind turbine blade using a carbon fiber spar cap. The spar caps were sized in conjunction with airfoil thickness to produce an efficient use of carbon fiber to match the blade design loads. The CX-100 blade design also focused on the material geometry required to bring a relatively thin carbon spar cap into a large fiberglass blade root. Using inboard spar cap width taper and off-axis fiberglass fabric, the spar cap structural loads are efficiently distributed to the blade root fastening system.

Although the 9 meter CX-100 blade demonstrated the effectiveness of the innovation of a carbon fiber spar cap, 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.

11.0 References

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