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Blade Manufacturing Improvements Development of the ERS-100 Blade

Final Project Report

TRI Composites, Inc.

Prepared by
Sandia National Laboratories
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TPI Composites, Inc.
373 Market Street
Warren, RI 02885

PREPARED FOR

Sandia National Laboratories

Contract – AX-2111A

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ABSTRACT

The objective of this program was to investigate manufacturing improvements for wind turbine blades utilizing the Seemann Composites Resin Infusion Molding Process (SCRIMP^{TM}), reusable silicone bags and heated molds. The goal of this blade manufacturing program was to overcome primary risks that prevent commercial application of available technology and develop practical, profitable solutions for domestic and international wind energy markets. The program participants obtained these gains through design and manufacturing optimization. Implementation of this program started in July of 1998, and the first prototype ERS-100 blades were completed in July of 1999. The program included a series of test activities to evaluate the strength, deflection, performance, and loading characteristics of the prototype blades. The tests were broadly categorized as either qualification tests, which occurred in a laboratory environment, or operational tests, which took place on a wind turbine producing electricity in a commercial wind plant environment.

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1.0 PROJECT OVERVIEW

The objective of this program was to investigate manufacturing improvements for wind turbine blades utilizing TPI Composites, Inc. (TPI) patented Seemann Composites Resin Infusion Molding Process (SCRIMP^{TM}), reusable silicone bags and heated molds. TPI Composites manufacturing development efforts were funded under a Blade Manufacturing Improvements (BMI) contract from Sandia National Laboratories, (contract AX-2111A). Dynamic Design provided supporting blade design assistance under a separate contract with NREL. Working cooperatively the team designed, fabricated, and tested proof-of-concept blades denoted as the Eolidyn Rotor Systems 100 (ERS-100) Series.

The goal of this advanced blade program was to overcome primary risks that prevent commercial application of available technology and develop practical, profitable solutions for domestic and international wind energy markets. The program participants obtained these gains through design and manufacturing optimization. The SCRIMP^{TM} process allows TPI to build wind blades with an environmentally friendly process and manufacturing robustness.

Implementation of this program started in July of 1998, and the first prototype blades were completed in July of 1999. The ERS–100 blade was intended as a replacement blade for USW 56-100 turbines, but has more recently been modified for use on the North Wind 100. This blade development project was also critical for laying the technical foundation for large commercial blades in the 20 to 40 meter size range. The development of the ERS-100 served to demonstrate and refine key technologies needed for the large blades planned in the future.

The program included a series of test activities to evaluate the strength, deflection, performance, and loading characteristics of the prototype blades. The tests were broadly categorized as either qualification tests, which occurred in a laboratory environment, or operational tests, which took place on a wind turbine producing electricity in a commercial wind plant environment. Testing of the proof-of-concept blades was completed in the Fall of 1999.

2.0 MARKET REVIEW

2.1 Introduction

The wind energy market is expanding rapidly. In 1999, the cumulative installed capacity of wind power was approximately 13,400 MW and growing rapidly. A combination of wind technology improvements, cost reductions, and government policy incentives have coupled with increased fuel costs to create a strong market for wind turbines and their components. The market for utility-scale wind turbines has become global in scope and is not dependent upon a single country or region.

The cost of wind energy is only marginally higher than for conventional fossil fuels, and modest increases in fuel or emissions control costs will result in direct economic parity. Design and manufacturing improvements continue to reduce the cost of wind energy. United States utility industry and government leaders are beginning to recognize the importance of wind energy as an economic hedge against unpredictable increases in fuel costs or changes to air pollution policies.

The wind turbine market has also been carefully evaluated and documented by the Danish consulting firm, BTM Consult ApS [1]. Their estimates indicate large growth in global wind energy capacity for the near-term (Table 2.1).

Table 2.1 Wind Capacity Growth Estimated by BTM Consult

Region **Year**	**America (MW)**	**Europe (MW)**	**Asia (MW)**	**Rest of the World (MW)**	**Total World (MW)**
1999	548	3192	115	68	3922
2000	400	4010	330	145	4885
2001	800	4445	380	200	5825
2002	600	4615	530	350	6095
2003	750	5620	730	500	7600
2004	950	6570	880	775	9175
Total (00-04)	3500	25260	2850	1970	33580
Average World Market Growth				**~6700 MW per year**	

Source: BTM Consult ApS - March 2000

It may be desirable to focus marketing efforts on selected regions that offer higher potential for product acceptance. In Europe, the expanding Spanish wind industry offers better opportunity than either in Germany or Denmark, which have entrenched domestic manufacturers. There are also potential geographic advantages for a U.S. manufacturer to supply North and South American customers.

Focusing on just these selected markets, the projected growth will average 2320 MW per year between 2000 and 2004 (Table 2.2).

Table 2.2 Wind Capacity Growth in Selected Markets

Region **Year**	**United States (MW)**	**Spain (MW)**	**Latin America (MW)**	**Canada (MW)**	**Total (MW)**
2000	300	1500	50	50	1900
2001	600	1500	100	100	2300
2002	400	1500	100	100	2100
2003	500	1800	150	100	2550
2004	600	1800	200	150	2750
Total	2400	8100	600	500	11600
Average Selected Market Growth				**2320 MW per year**	

Source: BTM Consult ApS - March 2000

The wind energy industry has matured rapidly and is now dominated by medium to large industrial firms. Over the past few years there has been considerable consolidation of manufacturing capability, and the industry is increasingly international in extent. Many of the established European manufacturers have established joint venture companies in emerging markets such as Spain, India, and China. There is also a trend toward ownership of wind power plants by utility companies or their unregulated subsidiaries. This tendency can be clearly observed in the U.S. market by the emergence of FPL Energy (a subsidiary of FPL Group with $6.4 billion annual in revenues) and Enron Wind Corporation (a subsidiary of Enron Corporation with $20.2 billion in annual revenues). In a few years, FPL Energy has become the dominant wind plant operator in the United States and the largest owner/operator of commercial wind power plants in the world. Enron is now the sole remaining U.S. manufacturer of utility-scale wind turbine equipment.

The general trend suggests that the cost of market entry for major component suppliers will accelerate as the industry matures. Near-term consolidation of the wind energy industry has resulted in a relatively few experienced firms that dominate the turbine market. These companies have an established supply network to deliver turbines and associated equipment on a global scale. Entrepreneurial opportunities in the wind industry are becoming less available as it approaches maturity, therefore it is important to secure a strong market presence within the next few years.

2.2 Turbine Design Trends

Varieties of wind turbine architectures were developed, installed, and tested during the 1980's with varying degrees of technical and economic success. Today the global wind industry is dominated by turbines that are mounted on a horizontal axis, with three blades, an upwind rotor, an active yaw drive system, and a freestanding tower. This generalized architecture now represents over 95% of new turbine installations [1,2] and is the de facto industry standard. Important design variations remain within the standard architecture related to power regulation, pitch adjustment, speed control, and yaw system design.

Most manufacturers are continuing to develop new turbine designs in the megawatt size range [1]. Current trends, however, suggest that turbine size in terrestrial sites may have reached a stable design region in the general rotor size of 40 to 80 meters and rated power output of 500 to 2000 kW. Turbines on the small side of this range will have an advantage in complex terrain and less developed regions, because they can be transported and erected more easily. Turbines on the large side of the range will be preferred in densely populated and highly developed regions, along accessible ridges, and where heavy lift equipment is readily available for construction. Commercial sales of wind turbines for utility power systems are expected to remain strong within the 500 to 2000 kW size range for the long-term, with the specific turbine size selected to suit local conditions.

For nearly twenty years, a continuing reduction in the cost of wind energy has come through increasing the size of the turbines. Additional major reductions in the cost of wind energy are unlikely to result from increased turbine scale alone. Improving cost effectiveness will increasingly rely on manufacturing efficiencies, design optimization for specific site conditions, and elimination of premature component failures. This represents a change in engineering approach and development philosophy, which has not been generally recognized by the industry.

2.3 Blade Technology

Further reductions in the cost of wind energy are possible through improvements in rotor design and manufacturing processes. These enhancements can be applied to standard turbine architectures using current rotor sizes. Many of the manufacturing and engineering approaches described here are already in use, but have not been widely applied to wind blade design. Our current estimates suggest that manufacturing improvements can reduce the cost of wind turbine rotors by 25% to 30%. Our goal is to combine these gains with a 5% to 10% performance improvement to obtain a 10% to 15% reduction in the cost of wind energy.

2.3.1 Specialized Airfoils

Use of the National Renewable Energy Laboratory (NREL) special purpose airfoils will provide significant increases in annual energy production by allowing larger capture area and reduced sensitivity to environmental soiling. With the NREL airfoils, the annual energy production loss due to airfoil roughness effects can be cut in half relative to previously used aircraft airfoils. Optimizing an airfoil's performance characteristics for the appropriate Reynolds number and thickness provides additional performance enhancement in the range of 3% to 5%. Further performance enhancement can be achieved by using blade tip airfoils with low maximum lift coefficients to reduce peak loads. This allows the use of 10% to 15% more swept rotor area for a given generator size and design load.

2.3.2 Resin Infusion Molding

Modern wind turbine blades are almost exclusively fabricated from fiberglass reinforced plastic (FRP). The majority of blade manufacturers presently use a wet lay-up construction approach that is labor intensive, results in reduced laminate quality, and has considerable worker health and environmental problems. Some blade manufacturers have resorted to the use of more costly pre-impregnated (pre-preg) composites, which improve overall quality and decreases health and environmental concerns. Resin infusion processes have been applied to the manufacturing of wind turbine blades by TPI Composites, Inc. and Aerpac BV.

The conventional wet lay-up fabrication method has been widely used for wind turbine blades. This approach emits high levels of styrene gas, which is dangerous to both the worker and the environment. Wet lay-up entails considerable costs associated with protecting the employee (respirators, gloves, etc.) and minimizing atmospheric emissions to the environment (air make up units, scrubbers, incinerators, etc.) that increase manufacturing cost, but provide no added value to the product. Laminate quality with wet lay-up is reduced because resin-to-reinforcement ratios are dependent on worker skill. In typical wet lay-up applications, the glass fiber weight rarely exceeds 60% of the total laminate. Weight control of molded parts manufactured with the wet lay-up process is difficult and costly to achieve, as the weight is dependent upon the amount of resin that an operator applies.

Some wind turbine blade manufacturers use pre-preg materials, which offer improved quality and physical properties. With this approach, resin and reinforcement are combined during the material fabrication process. As a result, the resin-to-reinforcement ratio is consistent and physical characteristics are much less dependent upon the skill of individual workers. However, costs for the pre-preg materials are considerably higher than for standard materials, and the process incurs additional expenses due to the need for heat curing in an oven or autoclave. The requirement for use of a separate autoclave for final curing adds expense and complexity to the manufacturing process; both are compounded when constructing large structures such as utility-grade wind blades.

TPI Composites retains all the rights to the patented Seemans Composite Resin Infusion Molding Process (SCRIMP^{TM}) and has used this approach to build wind turbine blades and other large fiberglass structures. SCRIMP^{TM} is among the most environmentally friendly processes available to fiberglass manufacturers today, emitting less than 1 part per million (ppm) of volatile organic compounds (VOC). Control of VOC's has significant effects on improving worker health and reducing the environmental impact of industrial composite fabrication.

SCRIMP™ provides excellent laminate quality because it completely eliminates entrained air, resulting in undetectable void content. During the fabrication process, dry fiber material is tightly compressed against the mold under a full atmosphere of vacuum. Resin infuses the fiber, and the matrix fills all spaces in the material. This process produces laminates with physical properties that approach those of pre-preg autoclave composites at a fraction of the cost associated with aerospace production techniques.

SCRIMP™ provides substantial design flexibility and can be used with a full range of resin systems including polyesters, vinylesters, epoxies, and phenolics. Most of the major suppliers have developed "SCRIMP™" resins in each of these categories. SCRIMP™ is also compatible with any type of fiber reinforcement and produces finished products with 70% average fiber weight. The process allows use of heavier or higher area weight (oz/yd^2) fabrics because the resin will infuse through thick fabrics that cannot be wetted by traditional hand lay-up methods. When compared against pre-preg methods, this process eliminates costly de-bulking stages, which reduce labor hours for cutting and layout. It also uses standard glass materials, which eliminates refrigerated storage, breather materials, and porous releases associated with pre-preg molding methods.

During fabrication of components, the glass reinforcement is placed in the mold dry. Additional labor savings are realized by use of extremely thick glass materials, which reduce the number of plies that must be cut and placed in the mold. This allows for exact placement of the material for precise weight control and enhances the effectiveness of quality assurance procedures.

TPI completed internal studies [3] of wind turbine blade manufacturing showing that SCRIMP™ provided cost savings of 18% to 22% when compared to conventional wet lay-up approaches. The savings were realized through reduced labor (because of fewer laminate plies) and reduced material costs (because the laminating process provides improved physical properties of the finished part). Additional savings were realized in facility costs because SCRIMP™ eliminated the need to run expensive air make-up units to evacuate excessive styrene vapors. As a result of additional cost savings identified under the BMI contract, TPI currently believes manufacturing cost reductions of 25% to 30% are achievable in commercial blade production.

2.3.3 High-Volume Tooling

Several additional manufacturing tooling improvements have been developed to further reduce the cost of fabricating wind turbine blades. Heated molds decrease tool cycle time and provide greater control over laminate cure. Reusable vacuum bags reduce the cost of consumables and simplify bag sealing. Pre-formed materials reduce labor hours and decrease mold cycle time.

2.3.3.1 Integral Mold Heating

TPI Composites has developed a tool heating system that lowers the cost processing of epoxies, vinylesters, and urethane hybrids. This technology uses resistive heating elements that are infused into the tool surface during mold fabrication. The heating elements can be cycled many times with minimal performance degradation or loss of efficiency. The temperature gradient over the entire tool surface can be carefully monitored and adjusted using embedded thermocouples or infrared scanners. This detailed control of the thermal flux will provide heat where it is needed for thick sections or complex geometries. Maximum temperatures in the tool are only limited by the tooling matrix material and resin system. Post curing can occur without the use of costly ovens and their associated capital and maintenance expenses.

2.3.3.2 Reusable Vacuum Bags

TPI Composites has also developed reusable silicone bags for use in volume composite manufacturing. TPI 's patented concept reduces cost by eliminating the need for nylon bagging materials and resin flow mediums. The bags are designed with engineered embossed flow patterns and include all necessary resin feed lines. The reusable bags reduce bag consumables (normally a bag is used once and discarded). Past experience indicates that the bags will be capable of producing 75 to 100 parts before replacement.

2.3.3.3 Pre-Formed Materials

Pre-formed materials are another manufacturing improvement that reduces cycle time and increases factory throughput. This process involves cutting and orienting dry materials to form pre-formed parts prior to final molding. The parts can contain multiple layering and are held together by material binders. The pre-forms can be fabricated to fit complex shapes that contain stiffening elements. Once constructed, the pre-formed parts can be measured and inspected to ensure quality, be organized into manufacturing kits, and be stored indefinitely until needed for the infusion stage of production. The use of pre-formed materials significantly improves the quality and repeatability of the manufacturing process.

2.3.4 Optimized Root Studs

Many large turbines use metallic root studs for attachment of the blade at the root. However, the design of conventional studs often does not provide a smooth stiffness transition in the root region, and large stress concentrations can result. Manufacturers must overcome this disadvantage by increasing the material thickness and weight in the root region.

An improved low-cost root attachment design is available using bonded studs developed originally for use in wood-epoxy wind turbine blades. These studs are highly tapered to minimize the effects of stress concentrations in the joint. Specialized forms in the blade root create tapered cavities for bonding the root studs. During the final manufacturing step, the root studs are bonded into position using a high strength epoxy. This approach has an extensive history of success in long-term fatigue for wood-epoxy blades and delivers a structurally efficient and low-cost method of root attachment.

2.4 Manufacturers

The international wind energy community includes several major wind turbine manufacturers (Table 2.3). Denmark remains the world leader in wind turbine manufacturing capacity, followed by Germany, Spain, and the United States. In 1999, two turbine groups garnered nearly half the total market for wind turbines. Vestas and Gamesa (its Spanish affiliate) had a combined production of 1146 MW representing 29.2% of the world market, while NEG Micon produced 761 MW for a 19.4% share. All major manufacturers provide turbine equipment based upon a three-blade, upwind, active yaw architecture.

Table 2.3 Top Ten Wind Turbine Manufacturers in 1999

Manufacturer	Turbine Sales (MW)	Market Share (%)
NEG MICON (DK)	761	19.4
VESTAS (DK)	652	16.6
GAMESA (SP)	494	12.6
ENERCON (GE)	488	12.5
ENRON (US/GE)	360	9.2
BONUS (DK)	338	8.6
NORDEX (DK/GE)	306	7.8
MADE (SP)	218	5.6
ECNOTECHNIA (SP)	59	1.5
DEWIND (GE)	58	1.5
Others	298	4.7

Source: BTM Consult ApS - March 2000

2.4.1 Vestas Wind Systems

Vestas Wind Systems is among the oldest and one of the most respected turbine manufacturers in the world. Located in Denmark, Vestas Wind Systems and its subsidiaries employ over 1,300 workers. The company's production facilities occupy nearly 1 million square feet of space. At the end of 1999 Vestas had accumulated over 2,530 MW in total installed capacity worldwide.

Vestas turbines (see Table 2.4) use variable pitch blades and a limited range variable speed drive train. The newer V-47 design uses a dual generator system in which a small, lower speed generator operates in light wind conditions. This lower speed reduces rotor tip noise to extremely low levels. The same drive train approach has been applied to the large V-66 turbine, which ranks among the quietest of the megawatt scale machines. The main generator is an asynchronous type with a variable resistance electric rotor that allows speed to vary by 10%, thus reducing drive train torque loads and smoothing electric power fluctuations. The concept has been patented by Vestas under the name Optislip. Excess power generated during gusty conditions is partly reduced by increasing the turbine speed and partly through dissipation of energy in the generator rotor. This system requires the use of reactive power compensation using batteries or capacitors.

Vestas fabricates its own blades and uses a high quality pre-preg composite manufacturing approach. The blades attach to the pitch bearing through a tapered aluminum root insert and are protected against lightening strikes by a metallic button mounted near the tip. This button attaches to an electrically conductive cable that directs the charge through the blade to a connector in the root. Vestas turbines are manufactured to ISO 9001 standards and certified by Germanischer Lloyd.

Table 2.4 Summary of Vestas Wind Turbines

Model Name	Power Output (kW)	Rotor Diameter (m)	Blade Type	Pitch Type
V-39	500	39	Vestas	Variable
V-42	600	42	Vestas	Variable
V-44	600	44	Vestas	Variable
V-47	660	47	Vestas	Variable
V-66	1650	66	Vestas	Variable

Source: BTM Consult ApS - March 2000

Vestas has a joint venture in Spain with Gamesa to fabricate its wind turbines there. Gamesa Eólica was founded in 1994 and is 51% owned by Gamesa, 40% by Vestas, and 9% by Sodena. Gamesa is the dominant turbine supplier in Spain and has installed several hundred megawatts of wind capacity in that country. Gamesa obtains its blades from Fiberblade, S.A., which manufactures them to Vestas' specifications.

2.4.2 NEG Micon

NEG Micon is the second largest wind turbine manufacturer in the world after Vestas. The company was formed by a merger between Nordtank Energy Group (NEG) and Micon Wind Turbines and is located in Denmark. The company offers turbines on three product platforms, 750 kW, 1000 kW, and 1500 kW (see Table 2.5). NEG Micon turbines are fixed pitch and constant speed. They use rotor blades purchased from LM Glasfiber.

Table 2.5 Summary of NEG Micon Wind Turbines

Model Name	Power Output (kW)	Rotor Diameter (m)	Blade Type	Pitch Type
NM 750	750	44/48	LM	Fixed
NM 1000	1000	54/60	LM	Fixed
NM 1500	1500	64	LM	Fixed

Source: BTM Consult ApS - March 2000

NEG Micon has made considerable investments in the U.S. market and developed an assembly facility in Illinois. NEG Micon also has a Spanish affiliate (TAIM), which fabricates, installs, and maintains wind turbines through agreements with NEG Micon.

2.4.3 Enercon

Enercon is the largest wind turbine manufacturer in Germany. In 1999 it held fourth place in total volume of turbine sales. The company uses an innovative variable speed, direct drive generator system that eliminates the gearbox. Enercon turbines also incorporate a unique pitch control approach with independent electrical drives for each blade.

Table 2.6 Summary of Enercon Wind Turbines

Model Name	Power Output (kW)	Rotor Diameter (m)	Blade Type	Pitch Type
E-30	200	30	Enercon	Variable
E-40	500	40	Enercon	Variable
E-58	850	58	Enercon	Variable
E-66	1500	66	Enercon	Variable

Source: BTM Consult ApS - March 2000

2.4.4 Enron Wind

Enron is the largest wholesale supplier of natural gas in North America. In recent years, the company began diversifying its position and has grown to become the largest investor owned utility in the United States. Enron now has large electric generation sales within the U.S., Europe, and South America. Enron Wind was created through purchase of the assets of Zond Wind Systems in California and Tacke

Windenergie in Germany. Enron Wind presently operates manufacturing facilities in the United States, Germany, and Spain.

Table 2.7 Summary of Enron Wind Turbines

Model Name	Power Output (kW)	Rotor Diameter (m)	Blade Type	Pitch Type
750I Series	750	46/48/50	Enron	Variable
1.5 MW Series	1500	65/70.5/77	Enron LM/Aerpac	Variable
2.0 MW Offshore	2000	70.5	-	Variable

Source: BTM Consult ApS - March 2000

Enron turbines utilize both variable blade pitch and variable rotor speed. Enron offers three turbine series including design specialized for offshore marine applications (Table 2.7). The turbines are fabricated to ISO 9001 standards and certified by Germanischer Lloyd. Enron Wind has also developed its own turbine blades, which are manufactured to Enron specifications by subcontractors. Enron Wind turbines also use blades designed and manufactured by LM Glasfiber and Aerpac.

2.4.5 Bonus

Bonus is one of the original Danish wind turbine manufacturers. Bonus turbines have an adjustable pitch approach, which Bonus markets under the name of CombiStall. This control approach uses natural stalling of the rotor to regulate peak power, but provides a means for optimizing the blade pitch on relatively long time scales to account for blade soiling or changes in air density. Bonus is affiliated with Bazán Turbinas, which manufactures wind turbines in Spain under license.

Table 2.8 Summary of Bonus Wind Turbines

Model Name	Power Output (kW)	Rotor Diameter (m)	Blade Type	Pitch Type
Bonus 600 Mark IV	600	42	LM	Fixed
Bonus 1000	1000	54.2	LM	Adjustable
Bonus 1300	1300	62	LM	Adjustable

Source: BTM Consult ApS - March 2000

2.4.6 MADE

MADE, one of the primary wind turbine manufacturers in Spain, is a subsidiary of Grupo Endesa, the country's largest utility (Table 2.9).

Table 2.9 Summary of MADE Turbines

Model Name	Power Output (kW)	Rotor Diameter (m)	Blade Type	Pitch Type
AE-45 LW	600	45	APX 45	Fixed
AE-46 / I	600	46	LM 21	Fixed

Source: BTM Consult ApS - March 2000

2.4.7 Ecotecnia

Ecotecnia is an independent Spanish wind turbine manufacturer located in Barcelona.

Table 2.10 Summary of Ecotecnia Turbines

Model Name	Power Output (kW)	Rotor Diameter (m)	Blade Type	Pitch Type
Ecotecnia 44/500	500	44	LM/Aerpac	Fixed
Ecotecnia 44/600	600	44	LM/Aerpac	Fixed
Ecotecnia 48/750	750	48	LM/Aerpac	Fixed

Source: BTM Consult ApS - March 2000

2.4.8 Nordex Balcke-Durr

Nordex Balcke-Durr is a subsidiary of Deutche Babcock, with facilities in Denmark and Germany.

Table 2.11 Summary of Nordex Turbines

Model Name	Power Output (kW)	Rotor Diameter (m)	Rotor Speed (rpm)	Blade Type	Pitch Type
N43/600	600	43	18 / 27	LM 19.1	Fixed
N54/1000	1000	54	14 / 22	LM 26	Fixed
N60/1300	1300	60	12 / 19	LM 29	Fixed

Source: BTM Consult ApS - March 2000

2.4.9 DeWind

Dewind is located in Germany and manufactures turbines that use variable speed and variable pitch. The company offers two platforms and five different models (Table 2.12).

Table 2. 12 Summary of DeWind Turbines

Model Name	Power Output (kW)	Rotor Diameter (m)	Max. Rotor Speed (rpm)	Pitch Type
DeWind 41	500	41	29.3	Variable
DeWind 46	600	46	28.2	Variable
DeWind 48	600	48	28.2	Variable
DeWind 60	1250	60	23.0	Variable
DeWind 42	1000	62	20.7	Variable

Source: BTM Consult ApS - March 2000

2.4.10 Mitsubishi Heavy Industries

Mitsubishi Heavy Industries has a wind turbine manufacturing division that is part of its power systems group. The turbine equipment and blades are manufactured at MHI facilities in Nagasaki.

Table 2. 13 Summary of Mitsubishi Turbines

Model Name	Power Output (kW)	Rotor Diameter (m)	Blade Type	Pitch Type
MWT-250	275	28	MHI	Variable
MWT-600	600	44	MHI	Variable

Source: BTM Consult ApS - March 2000

2.4.11 LM Glasfiber

LM Glasfiber is the world's largest supplier of wind turbine blades. LM has more than 40 years of experience in fabrication of large composite structures and enjoys an excellent reputation within the wind industry. It operates production facilities in the United States, Germany, Spain, and India, and offers a wide product line, with standard sizes from 13.4 meters to 34 meters in length (Table 2.14). The blades are fabricated using wet lay-up with general-purpose polyester resins. The blades are manufactured under ISO 9001 guidelines and are certified by Det Norske Veritas.

Table 2. 14 Summary of LM Rotor Blades

Model Name	Maximum Diameter (m)	Blade Length (m)	Blade Weight (kg)	Bolt Size / Bolt Circle (size/mm)	Pitch Type
LM 13.4	30	13.4	750	M24/600	Fixed
LM 14.4	33	14.4	1150	M24/800	Fixed
LM 17.2 LM 17.2 P	37	17.2	1620 1570	M24/1000	Fixed Variable
LM 19.1 LM 19.1 P	44	19.1	1960 1928	M24/1000	Fixed Variable
LM 20.7	44	20.7	2190	M24/1000	Fixed
LM 21.0 LM 21.0 P	48	21.0	2250 2100	M24/1000	Fixed Variable
LM 21.5 LM 21.5 P	48	21.5	2700 2650	M30/1250	Fixed Variable
WWK	46	22.1	1590	M30/1000	Variable
LM 23.3	48	23.3	3650	M30/1400	Fixed
LM 24.0 LM 24.0 P	52	24.0	3650 3350	M30/1400	Fixed Variable
LM 25.2	54	25.2	3500	M30/1400	Fixed
LM 26.0 LM 26.0 P	54	26.0	4200 3900	M30/1400	Fixed Variable
LM 29.2 LM 29.2 P	60	29.2	6200 6020	M30/1800	Fixed Variable
LM 31.2 LM 31.2 P	64	31.2	6800 6400	M30/1800	Fixed Variable
WWK 34	70	34	-	M30/1800	Variable

Source: BTM Consult ApS - March 2000

2.4.12 Aerpac

Aerpac is located in the Netherlands and manufactures rotor blades in standard sizes. The company advertises its use of a resin infusion process. The manufacturing process may infringe on SCRIMP^{TM} patents if Aerpac blades are imported into the U.S.

3.0 BLADE MANUFACTURING

3.1 Introduction

Eolidyn Rotor Systems (ERS) was designated as the trade name for the new wind blades developed under this work. Eolidyn (a-o-li-dine), from the root *eolian dynamics*, meaning "wind power," will be used to market both wind blades and complete rotor systems. Our stated goal for this blade design project was to develop and implement blade manufacturing improvements. The SCRIMP^{TM} manufacturing process, reusable silicone bags, and the heated mold design were three methods studied during the design period. In addition, we considered several other manufacturing improvements that were utilized during the manufacturing of the ERS-100. These improvements included a strain compatible root connection and improved mold split lines that enhanced the finished product.

3.2 Design Development

3.2.1 Mold Configuration

During the design phase, we considered a number of different mold configurations (Figure 3.1). The concepts ranged from a relatively risk free clamshell design to a high risk one-piece construction method. Each of the molding methods showed merit, but our goal was to select the most cost-effective mold configuration and produce a finished blade that met the design criteria for structure and airfoil shape.

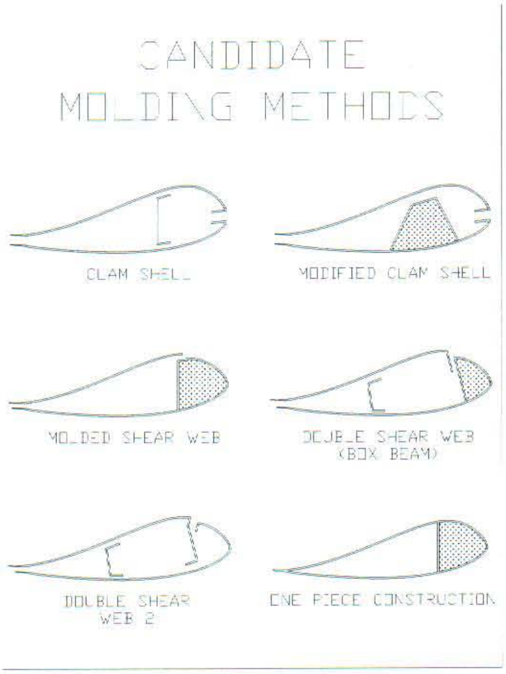

Figure 3.1 Schematic of Candidate Mold Configurations

Several configurations included a double shear web in the blade design. These designs were removed from consideration because the structure of the ERS-100 did not warrant an additional shear web. The material cost of this additional web made these methods less than ideal in a small blade; however, these molding methods may have merit in larger blades where a second web is necessary to offset panel buckling.

Integrally molded shear webs and one piece construction were also studied. Each of these concepts was found to have merit, but were considered to have significant technical and manufacturing risk. However these concepts should be reviewed in the context of large blades, which should have less space restrictions.

We performed detailed studies of the standard clamshell and modified clamshell approaches. The modified clamshell approach was attractive because it eliminated one bond line. Further study and experimentation proved that the method was not as efficient as it first appeared. The addition of foam to form the web proved expensive, and labor savings were not expected to offset the increased material cost. This method may prove to be more cost effective in larger blades where a separate mold could be used to form the web.

The clamshell design proved to be the most cost effective method for building the ERS-100, but presented significant challenges in maintaining leading edge profile tolerances. To overcome these challenges, we modified the split line to move the bond lines to an area less aerodynamically significant (Figure 3.2).

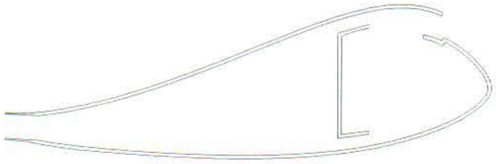

Figure 3.2 Schematic of Integrally Molded Leading Edge

This configuration offered material and labor savings in addition to quality assurance improvements. By offsetting the mold split line, we maintained the leading edge profile as a molded surface. After resin infusion, the blade shells and web can be easily inspected for flaws prior to bonding. The bond assembly fixture provided precise alignment of the blade skin and placement of the shear web.

3.2.2 Root Attachment

Two root connection methods were considered. The baseline 56-100 blade utilized a standard steel root fitting that was attached to the blade root with an epoxy bond. This approach was not strain compatible and generated large stress concentrations in the root bond. Historically there have been a large number of bond failures associated with this approach.

TPI Composites elected to adapt an existing root stud technology originally developed for wood-epoxy blades to fiberglass composites. Bonded root studs are used by LM Glasfiber, Mitsubishi, and other blade fabricators; however, these manufacturers have not employed a strain compatible stud design.

The ERS-100 root studs were bonded into cavities within the blade laminate using an epoxy adhesive. The blade root stud design, illustrated in Figure 3.3, results from a long and successful history in wind turbine blades dating to the early 1980's. These studs have undergone considerable engineering development and fatigue testing [4]. The approach provides smooth, strain compatible load transfer between the composite blade root and the steel hub. Bonded blade root studs are a cost-effective and reliable method for attaching the blade to the hub.

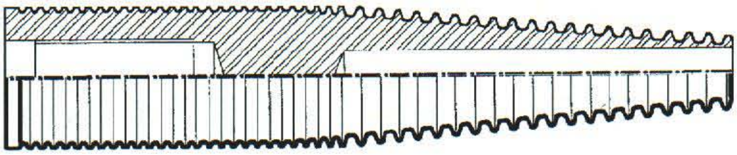

Figure 3.3 Drawing of the ERS-100 Blade Root Stud

The studs used in the ERS-100 blade were originally designed for the AOC 15/50 and AWT-26 wind turbines. They are 36.8 mm (1.45 in) in diameter, 191 mm (7.48 in) in length and threaded to mate with 3/4-16 UNF (Grade 8) fasteners. The studs have operated successfully in wood-epoxy blades on turbines in a variety of wind sites.

The greatest manufacturing challenge in adapting the root studs from wood epoxy was developing a method for providing a cavity for the studs. In wood epoxy, the cavity was created by drilling, but this approach was not practical for fiberglass. TPI developed a method for molding cavities into the blade root during the lamination process and eliminated the need for drilling. This approach also improved stud placement accuracy since the cavities were precisely molded into the part (Figure 3.4). We designed a unique external mold geometry that provided smooth load flow through the root region (Figure 3.5). By properly tailoring the strain field in the blade root, TPI was able to manufacture a joint with a significantly higher load transfer efficiency. Compared to the baseline design, we measured substantial material savings and labor savings.

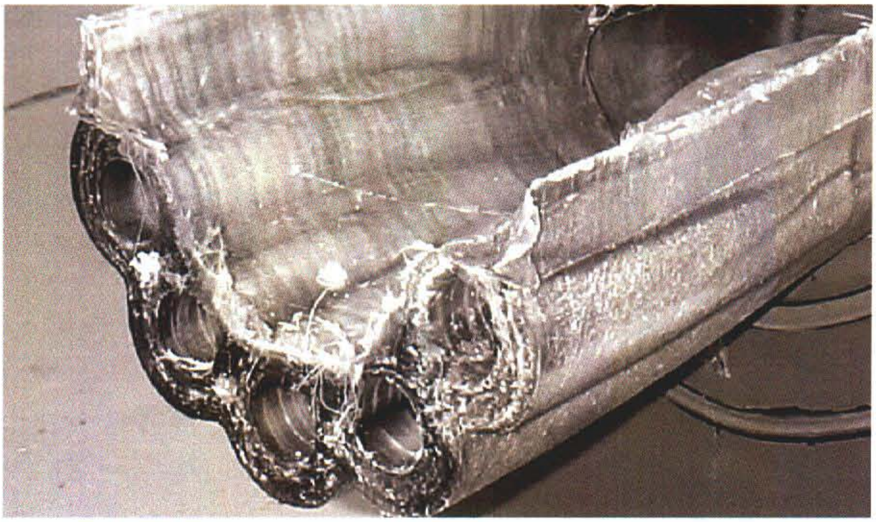

Figure 3.4 Photograph of the ERS-100 Blade Root Cavities

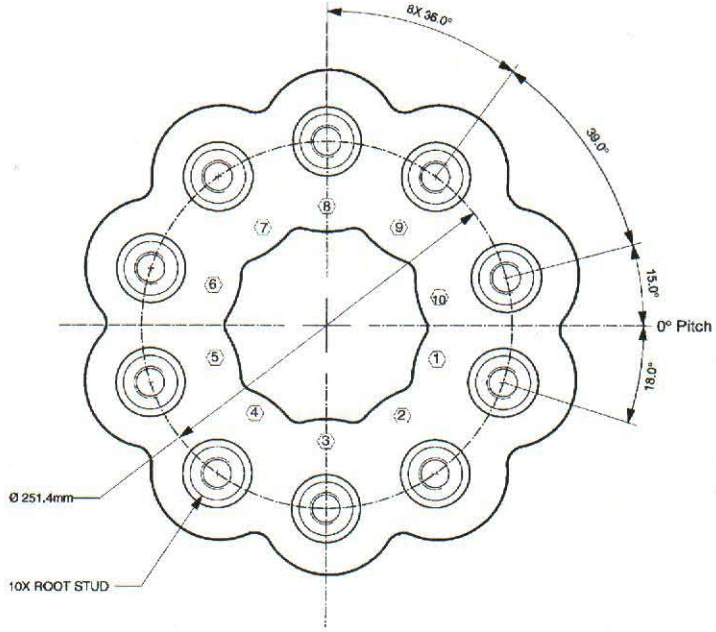

Figure 3.5 Drawing of the ERS-100 Blade Root Attachment

3.2.3 Heated Tool Surface

A heated tool surface has a number of advantages. Tool cycle times can be improved by using the heated tool surface to shorten gel times and cure times in manufacturing parts. Additionally a heated tool surface can eliminate the need for a large, costly, post cure oven, necessary when a part is manufactured using an epoxy resin.

Traditionally, heat has been applied by incorporating tubing into the molds. These tubes carry high temperature water or oil that conducts heat through the mold laminate to the part. A problem with this method has been an uneven heating of the laminate. It is also a very bulky and expensive method of applying heat to a mold because of the number of pumps and heat exchangers required.

Use of thin, resistive heating elements laminated into the mold skin laminate has several advantages over traditional heating methods. The resistive heating elements are easily integrated into SCRIMP^{TM} technology and can be designed specifically for different mold sections. Such elements will heat large surfaces, use a single power source, eliminate corrosion problems, and improve process control.

3.2.4 Reusable Silicone Vacuum Bags

SCRIMP^{TM} manufacturing, along with many other high technology molding techniques, requires that the laminates be placed under vacuum during fabrication. Traditionally, we have used a nylon film and specialized tapes in this process. Though effective, the bags and tapes are disposable and therefore costly. Additionally, the bagging phase is relatively labor intensive.

Reusable silicone bags have been used in a number of applications, but were quite expensive and have not proved to survive the number of cycles we would see with a blade mold. TPI Composites has developed a method for coating the silicone with Teflon that has increased bag life on the order of 75 to 100 molding cycles. TPI also provided a method for embossing the SCRIMP^{TM} pattern into the surface of these bags that allows the resin to flow across and through the dry laminate. The silicone bag incorporates a built-in feed and vacuum line system that eliminates the need for separate, disposable feed lines. The bags also have a ridge molded around the perimeter for a simple, efficient sealing method. The use of custom manufactured vacuum bags provides material and labor savings and has the added benefit of reducing disposal and landfill costs.

3.2.5 Surface Coatings

The original 56-100 blade had a polyurethane surface coating applied after assembly of the blade. The coating proved to be very durable and weather resistant, but application of the urethane topcoat created additional manufacturing steps and was expensive to incorporate. Each blade required sanding and transportion to a spray booth for top coat application.

An in-mold surface coating can provide material and labor costs savings compared to the original blade. In-mold coatings avoid the surface preparation labor and material costs and also improve worker safety. The urethane topcoats emit an isocynate when applied, which is dangerous for both the worker and environment.

In the 1970's and early 1980's there was a concern with using a gelcoated surface on wind blades because of the weatherability characteristics of the gelcoats. Over the last ten years, in-mold coating technology has improved dramatically. Today's gelcoats have improved weatherability and flexibility characteristics. TPI Composites has conducted independent weathering tests on both gelcoats and the urethane paints. These tests have shown that there is no advantage in using the topcoat over the gelcoat. As part of this project, TPI identified a high performance, isophthalic/neopentyl glycol (NPG) gelcoat supplied by Cook Composites and Polymers for surface coating of the ERS-100 prototypes.

3.2.6 Heavy-weight Materials

Unlike many other composite fabrication processes, SCRIMP™ allows for the use of high specific weight (oz./yd^2) fabrics without the need for numerous debulking steps. This advantage saves material cutting and laminating labor hours, as there are far fewer plies than a conventional laminate. For example, TPI applied a heavyweight fabric (C-520 unidirectional glass) in the ERS-100 blades. Labor savings are substantial, since each C-520 ply replaced two, 26 ounce plies which are the maximum weight allowed by any other laminating process. The use of heavyweight materials will increase as we develop larger blades with even thicker laminates.

3.2.7 Blade Construction

Four ERS-100 prototype blades were fabricated during this project. The blades were assembled from three primary components: a low pressure (LP) shell on the downwind side, a high pressure (HP) shell on the upwind side, and a shear web bonded between the two shells (Figure 3.6). The blade shells were composed of bi-axial (±45°) skin layers with balsa coring in the aft panels. Uni-directional (0°) material formed a spar cap on each shell surface, which was separated by the shear web. The parting (split) line between the shells was located on the HP side of the airfoil to provide accurate contours in the leading edge region and on the LP surfaces. The two blade shells and the shear web were each fabricated in separate molds and bonded together. A special bond assembly fixture was used to align the shells and root studs during final assembly of the blade.

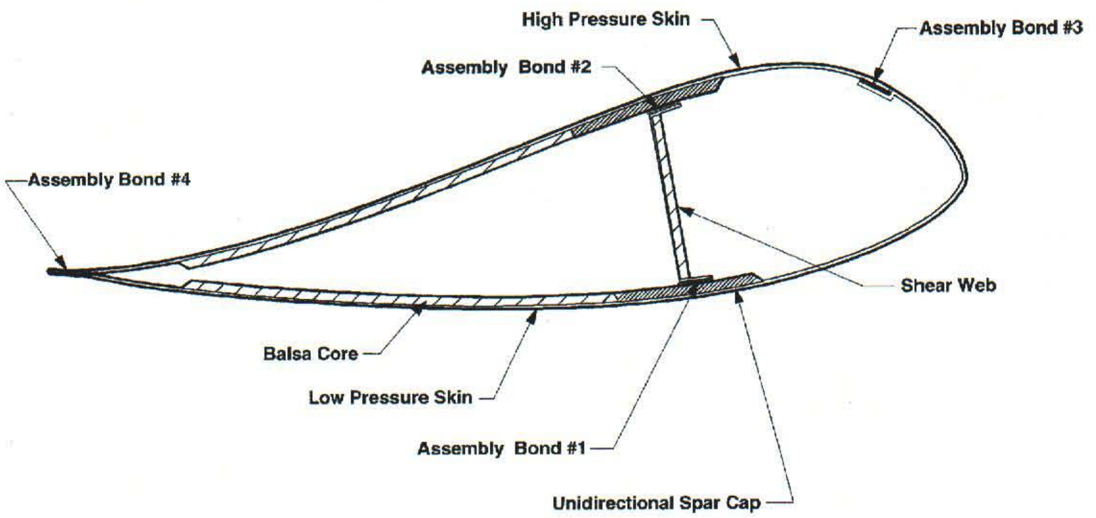

Figure 3.6 Typical ERS-100 Blade Cross-Section

The ERS-100 prototype blades were 9.0 meters in length with a 120 mm tip chord and 1034 mm root chord (Figure 3.7). Blade cross-sections were defined at forty-six (46) spanwise stations, each spaced 200 mm (8 in) apart. The blade sections were generated using the ROTOR code [5], which mathematically applies a spline in tension to interpolate between the defined input stations. The code used a circle (5% radius) and three NREL airfoils as inputs to generate the sections. The S821 root airfoil was used between 20.8% and 40% radius, the S819 primary airfoil was positioned at 70% radius, and the S820 tip airfoil was specified at 95% radius.

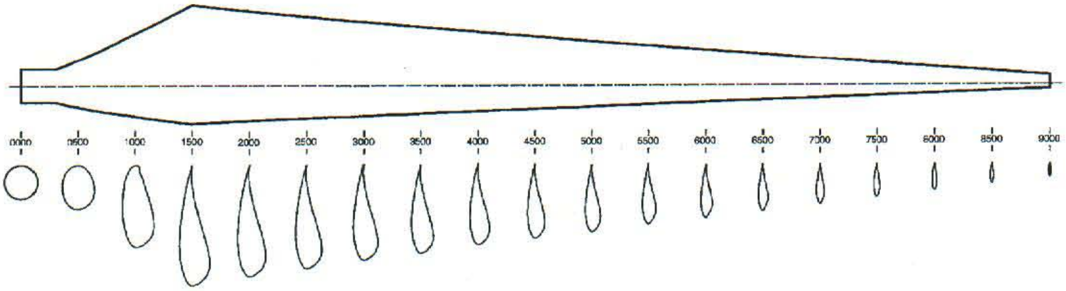

Figure 3.7 ERS-100 Blade Planform and Airfoil Sections

The ROTOR code generated interpolated sections that were output to a computer-aided drafting (CAD) system for use in generating templates. The trailing edges were modified in the CAD system to have a finite thickness. Drawings of typical sections are provided in Figures 3.8 and 3.9.

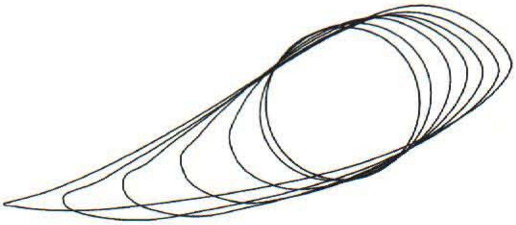

Figure 3.8 ERS-100 Blade Root Sections

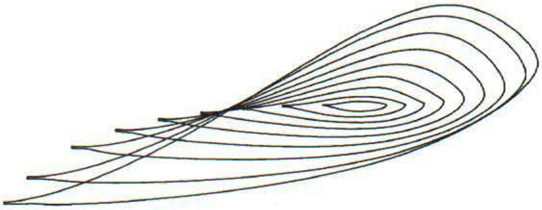

Figure 3.9 ERS-100 Blade Outboard Sections

The blade CAD drawings were the primary source for the creation of fabrication tools by TPI Composites at our manufacturing facilities in Rhode Island. These CAD files were used as input to laser cutting machines that prepared the final templates for the blade pattern (Figures 3.10 and 3.11). The individual templates were aligned on a tooling fixture and "skinned" with a polyester tooling resin to produce a master pattern. The final accuracy of the pattern was carefully verified using aluminum check templates that were laser cut from the CAD file data.

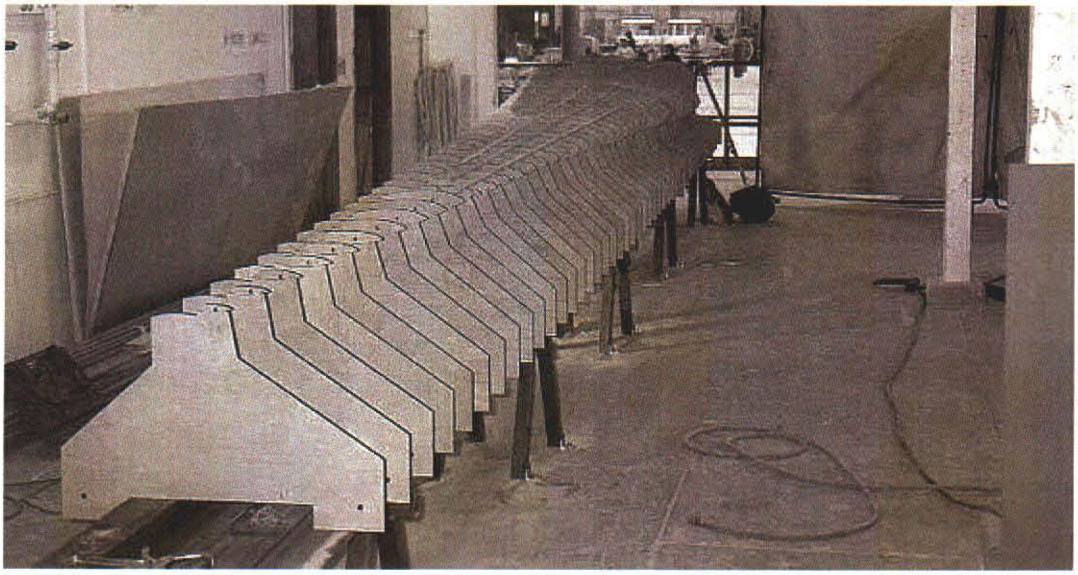

Figure 3.10 Photograph of ERS-100 Blade Pattern Templates

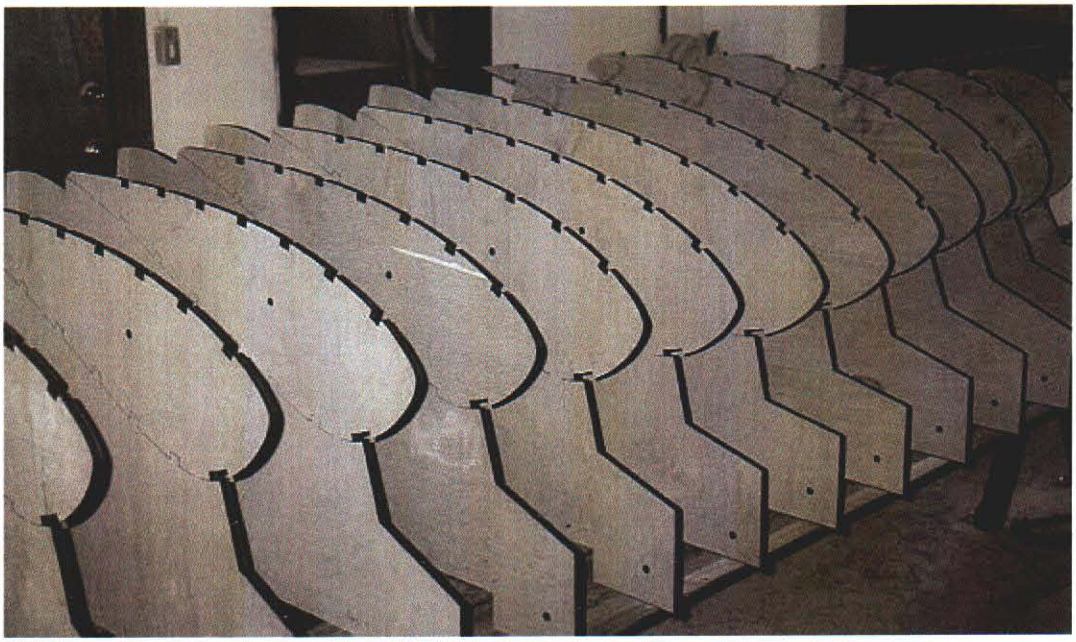

Figure 3.11 Photograph of ERS-100 Blade Pattern Templates

3.3 Blade Manufacturing Procedures

The manufacturing process for the ERS-100 is shown schematically in Figure 3.12 and began with receiving materials. This includes unloading vinylester resin, glass fabric, balsa coring, gel coat, and other chemicals and supplies needed to manufacture the blades. All materials utilized in the plant are checked against a written specification and transported to an appropriate storage location depending on the status of the material. Paper documents are used to record issues of all raw materials and include material cutting data sheets, scrap reports, resin issue sheets and shop supply slips. These documents provide for both inventory control and tractability of materials used. In all cases, a blade number is recorded for each transaction of issued raw materials, and most production supply items are posted to the using department. TPI maintains a separate account number sequence to help differentiate the raw materials and supplies for each blade.

Three complete molded pieces (the shear web, high pressure shell and low pressure shell) become the primary components in the final assembly of the ERS-100 wind turbine blades. In July of 1999, TPI manufactured four ERS-100 proof-of-concept prototypes. This effort validated many of the design decisions and outlined areas for further development. Subsequent to their construction, one prototype blade was tested statically to failure in the laboratory and three tested on operational wind turbines in the field. The following text describes the process steps for fabricating the ERS-100 blades using the improvements developed in this project (summarized in Figure 3.12).

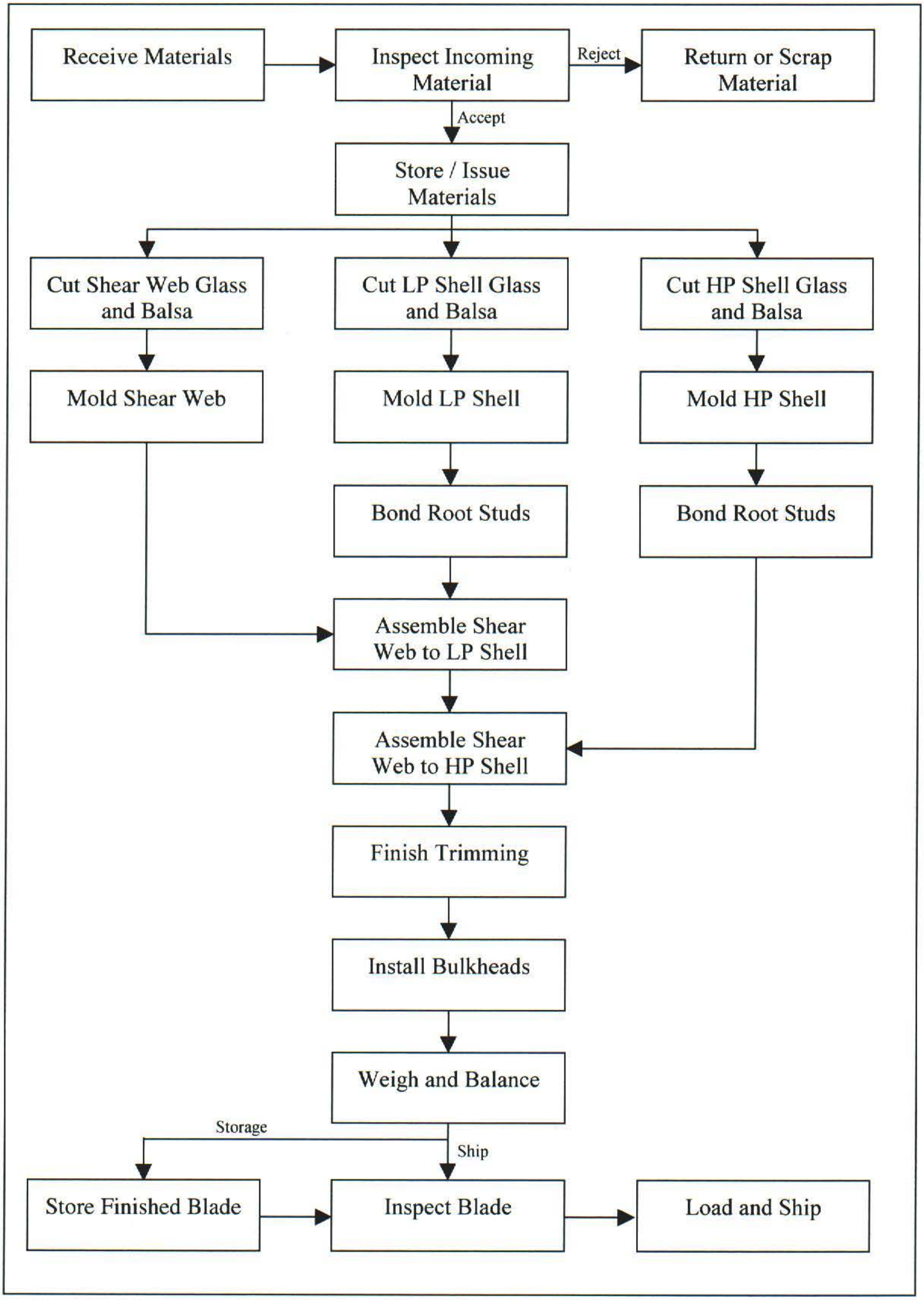

Figure 3.12 Schematic of the ERS-100 Manufacturing Process

3.3.1 Material Cutting

All fiberglass, peel-ply and balsa are cut during a separate manufacturing operation prior to insertion in the ERS-100 mold. The scrap from each material is removed from the cutting table and weighed. Cut material is numbered for each layer in the blade construction. Once numbered, the materials are placed on a cardboard roll and loaded onto a material transport truck.

3.3.2 Mold Surface Preparation

After the previous parts have been demolded, the mold is gently scraped to remove any resin from flanges and vacuum trough. The mold edges, where the flanges are mounted and the bag seal is located, are cleaned. A release wax is applied to the mold, flange surfaces and the vacuum trough are then wiped to remove any excess.

3.3.3 Insertion of Dry Materials

Before the blade lay-up begins, the blade number identification sticker is attached to the mold. The first layer in the mold is the gel coat, applied to a thickness of 0.020-0.025" wet. The gel coat is allowed to cure for 15-20 minutes before the placement of dry materials. Glass materials are positioned in the mold so they lie flat and are free of wrinkles, folds, bumps or air pockets.

Material alignment is critical inside the root and along the shear web axis. Orientation is checked against the laminate drawings. All layers contain complete lengths of glass, and no splices are allowed in the skins. If any filler pieces are necessary, they are neatly butt jointed, not overlapped. All loose strands and balsa chips must be removed from the lay-up surface before the next layer is unrolled. This avoids hidden bumps, which result in flaws in the molded process. The pre-cut balsa is inserted in a numbered sequence, and any gaps are filled with balsa slivers or 0.25" chopped fibers. After the last layer of glass has been inserted into the mold, a layer of peel-ply is applied as the last layer. Next, the SCRIMP$^{\text{TM}}$ distribution materials are placed over the mold; this includes the feed and vacuum lines and reusable silicone bag. Prior to infusion, a vacuum check is performed to check for leaks in the system per TPI standard operating procedure. Any leaks are repaired before the process continues.

3.3.4 Mixing of Resin

The group leader or other trained personnel prepares the resin batches required to infuse the parts (blade shells and shear web). Standard manufacturing recipes are used with appropriate adjustments for atmospheric conditions (temperature, humidity and resin activity). Extra attention is given to measuring amounts precisely and uniform mixing of ingredients to reduce unexpected variations in gel times. Once the decision is made to infuse the part, the resin batches, one after another, are mixed with catalyst. Test samples from each resin batch are taken and placed on the process control timer.

3.3.5 Blade Shell and Shear Web Infusion

The mold is pre heated to 90°F for at least 15 minutes or until the mold surface is at equilibrium. Three zones in the blade mold are monitored and controlled to this temperature. The resin batches are placed near the feed lines, and feed lines are opened in sequence once the resin reaches its respective feed line. Resin infuses into the mold via the pressure differential between the resin feed ports and vacuum. After about 30 minutes, the part is saturated with resin and begins to gel. The mold surface temperature is then increased to 120°F for 20 minutes.

Once initial curing has occurred, the heaters are turned off and the mold and part are allowed to cool for approximately 30-35 minutes. To insure the part has attained an adequate green strength to demold, a barcol hardness reading of 30 or higher must be measured. This value is noted in the manufacturing record. The reusable silicone bag, feed lines, vacuum lines, and peel-ply are removed from the part, and the area is cleaned of any debris (Figure 3.13).

3.3.6 Root Stud Bonding

Cavities for root stud bonding are prepared by sanding the interior of each cavity using a conical sanding tip. Once this is complete, five root studs are placed inside the root stud assembly fixture. The fixture is slid forward to perform a dry check fit on each of the studs, and each stud centered in the cavity with a 3mm gap. The studs are cleaned with a solvent to remove debris, grease and oil on the surface of the stud and to provide a clean bonding surface. Each stud is coated with a thin layer of epoxy adhesive. The epoxy is pumped into each cavity until approximately half full. The fixture assembly is slid into the root and locked into place. Excess epoxy from the root stud area is removed and curing proceeds. A portion of the epoxy mix is kept and a barcol reading made and recorded.

3.3.7 Blade Shell Demolding

Demolding starts by lifting the tip skin from the mold by hand and sliding a strap under the skin. The sling is attached to a crane and the skin is lifted approximately 2 ft. Another longer sling is used to raise the skin out of the mold and to the bond assembly area.

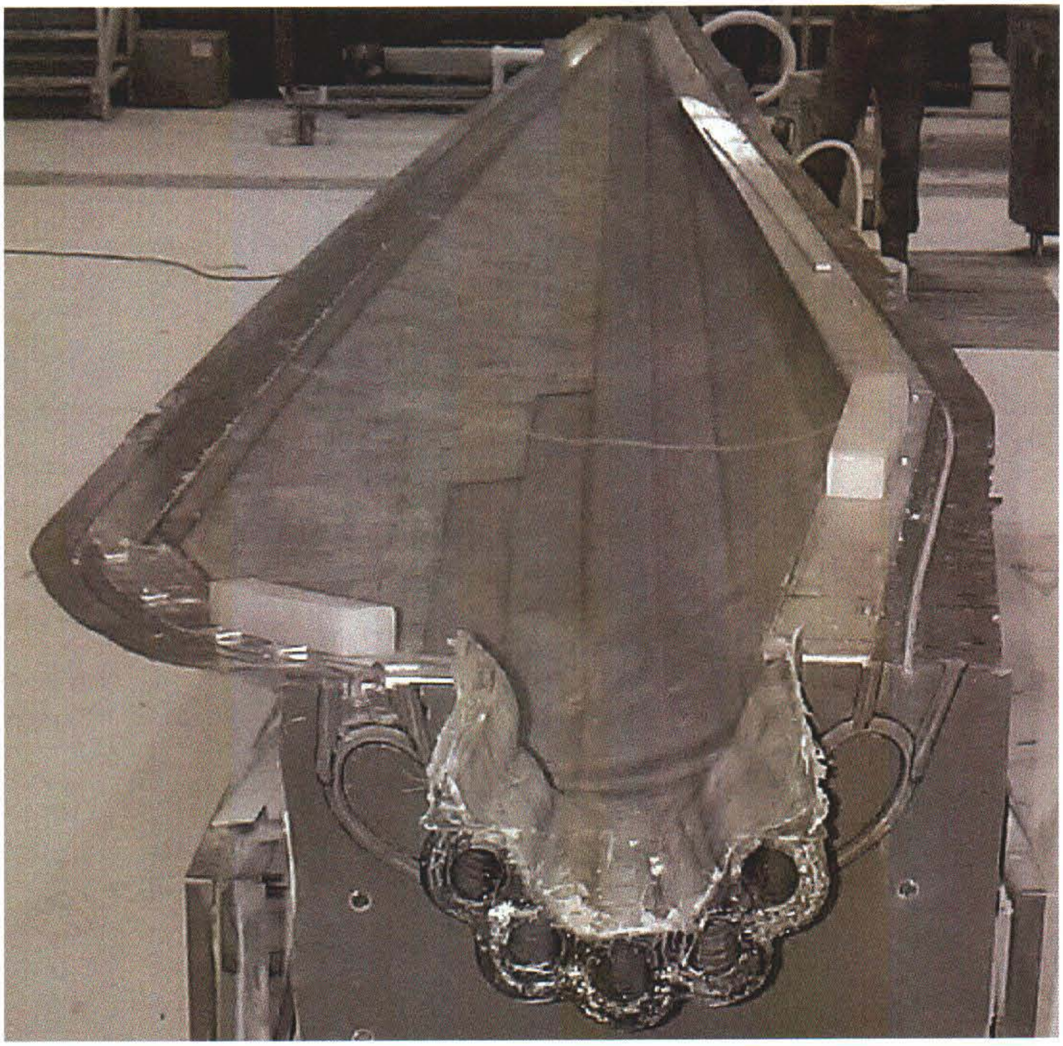

Figure 3.13 Photo of the ERS Blade Low-Pressure Shell and Mold

3.3.8 Finished Blade Assembly

The finished blade is assembled and bonded in a specialized bond assembly fixture. The low pressure blade shell and shear web are bonded together first, followed by bonding of the high pressure shell.

3.3.8.1 Low-Pressure Shell and Shear Web Bonding

The low pressure (LP) shell is moved to the bond assembly area. The shells (skins) are inspected inside and outside for any flaws that might adversely affect the bond assembly process or finished blade quality. Barcol hardness readings are checked at the root, near the leading edge, at the tip and along the trailing edge. All hardness readings must be 30 or higher before demolding, and the test results are recorded on the process quality sheet.

The LP shell of the blade is placed on a stationary saddle which is part of the bond assembly fixture. The shell location is adjusted until correct and secured in position using clamps along the leading edge and tip locator. A bonding surface is prepared with 100 grit sandpaper along the leading edge, trailing edge, and lower shear web bond area. All dust is removed with a vacuum.

The shear web is then moved to a preparation area and placed in trimming saddles. Again, all the surfaces are inspected for flaws that might adversely affect bonding or finished blade quality. Barcol hardness readings are obtained in four locations along the length of the shear web to assure the part is properly cured before assembly.

The trimming jig is placed on the lower leg of the shear web and clamped into place. The shear web is trimmed using a diamond cutter, which is guided by the jig. The process is repeated for the shear web upper leg. Again, the bonding surfaces along the outside of both shear web legs are sanded using 100 grit paper. Any bumps along the edge of the shear web legs are sanded smooth and the dust removed with a vacuum. The shear web is checked for length and recorded on the process quality form. Once the shear web has been properly sanded and trimmed, it is moved to the bond assembly fixture or the shear web storage rack.

Using a hoist and two lifting straps, the shear web is moved over the low-pressure shell on the bond assembly fixture. The shear web is lowered until it is properly seated on the LP shell. A tip alignment guide is used to aid in positioning the shear web along the length of the skin. One by one, the shear web positioning arms are set up. Once all the arms are tightly clamped into place, the shear web is properly positioned along the blade axis, and the position is recorded.

Once proper placement of the shear web has been verified, the shear web is lifted about 12" above the blade skin and a methymethacrylate adhesive is applied to the LP shell. A 0.25" bead of adhesive is applied to the bonding surface. A sample portion is retained to insure that a minimum reading of 60 Shore-D durometer is achieved. The excess adhesive is removed and the bond allowed to cure for 90 minutes.

3.3.8.2 High-Pressure Shell Assembly

The assembly of the low-pressure (HP) shell to the high-pressure shell/shear web is similar. The HP shell is moved to the bond assembly area and inspected inside and outside for any surface flaws. A Barcol hardness reading is obtained in the root, near the leading edge, at the tip and along the trailing edge. As before, all readings must exceed a Barcol value of 30 before demolding and are recorded on the process quality sheet.

The high-pressure shell is placed on the movable saddle of the bond assembly fixture. The shell is adjusted until the location in the fixture is correct. Using metal safety clamps along the leading edge and tip locator, the high-pressure shell is secured into position. Bonding surfaces are sanded with 100 grit sandpaper along the leading edge, trailing edge and upper shear web area. All bumps are sanded smooth, and dust and debris are removed via a vacuum.

A hoist is attached to the middle arm of the HP shell moveable saddle. Suction cups are used on the HP shell, and visual feedback is provided to the operator to insure that all vacuum is maintained in each cup. The HP shell saddle is lifted and rotated toward the LP shell/shear web. Once the HP shell has pivoted past the vertical position, it is slowly lowered onto the LP shell/shear web. Any gaps or areas of misalignment are noted and corrected. After the HP shell is properly aligned, it is rotated back into the original resting place. A 0.25" bead of a methylmethalcrylate adhesive (ITW Plexus) is applied to the bonding surface. The HP shell is rotated back into place verifying proper alignment of the leading edge. Excess adhesive is wiped, then cure is allowed for 90 minutes.

3.3.9 Trimming the Trailing Edge

After the adhesive has cured, the bonded blade is moved to a cradle with the LP shell facing up. Any excess adhesive or flashing that will interfere with the trimming process is removed. A diamond wheel cutter is used to carefully cut the trailing edge down the center of the trim line. Finally, any flash from the blade tip is trimmed and/or sanded. The entire outside is inspected for any flaws and the findings are recorded on the process quality data sheet.

3.3.10 Weight and Balance Measurement

The blade is moved to the balancing and weighing area and placed in holding saddles with the leading edge up. The balance is tared (zeroed) with the scale used to weigh the blades. Once the scale is zeroed, the insert and tip weighing jigs are placed on the blade. After both jigs are secure, the blade is raised off the saddles and leveled with an aluminum leveling pole. With a level blade, the tip, root and total weight are recorded on the process quality information sheets.

Next the length between the scales (LBS) is determined by measuring the distance between the delineation marks on the root and tip jigs. The tip weight, root weight and length between the scales are entered into a computer spreadsheet to determine the blade's center of gravity, static balance and static balance category. Once the final static balance is determined, an aluminum identification tag is made and attached to the blade. The tag includes the part number, blade serial number, total weight, center of gravity and static balance category.

TPI Composites performed weight and balance tests on the prototype blades after fabrication. The weight and balance results are provided in Table 3.1. The weight increase in sample A3 was due to the liberal application of adhesive at the bonding flanges. Excess adhesive not contributing to the bond remained attached adjacent to the bond flange. Additional process control in bonding operations will be performed on future blades to insure consistent blade weights.

Table 3.1 ERS-100 Prototype Blade Weight and Balance

Blade ID Number	Blade Weight (kg)	Spanwise C.G. Position (mm root)	Static Balance (m-kg)	Chordwise C.G. Position (mm axis)	Chordwise C.G. Location
A1	166.9	2,621	437.5	24.8	Toward TE
A2	165.4	2,613	432.2	20.5	Toward TE
A3	172.4	2,647	456.3	23.3	Toward TE
A4	163.5	2,616	427.8	27.0	Toward TE

4.0 QUALIFICATON TESTING

The basic objectives of laboratory testing were to verify design calculations for sub-components and the completed blade assembly. Qualification testing consisted of root stud strength tests and full-scale blade static load tests.

4.1 Root Stud Testing

The goal of the blade program was to develop engineering technology and manufacturing procedures that could be applied in commercial, utility-grade blade markets. The original root design of the 56-100 blades had acceptable performance, but the approach was not successful when applied to larger blades. The one piece steel root fitting used in the Kenetech blade design was not strain compatible at the interface with the fiberglass, which resulted in large shear flows at the tip of the fitting. This design approach was heavy, expensive, and inefficient when applied to blades used by current commercial wind turbines.

The ERS-100 blade was designed to employ an efficient and cost-effective root stud system adapted from U.S. designed wood/epoxy blades. Bonded studs also dominate the blade root designs of European turbines, and this approach has achieved wide acceptance in the industry. Qualification testing was used to begin development of the information required for successful adaptation of the wood/epoxy stud design to fiberglass blades. The database for the static and fatigue strength of studs in wood/epoxy laminate is quite extensive, and the correlation to design methodology is well established. However, there is currently not a comparable database and correlation for use with fiberglass laminates.

Much of the design methodology and test experience from wood/epoxy root studs is expected to be directly relevant, once adjustments for the modest differences in laminate properties are made. Nonetheless, there are differences between the materials. For instance, the wood shearing failure mode that limits static and low-cycle strength for wood/epoxy laminates was expected to be absent for fiberglass laminates. A single fatigue curve slope is anticipated for the entire cycle range, rather than the dual mode curve for wood/epoxy design, with a consequent increase in static and low cycle strength. The formed cavities of the SCRIMP™ process also present geometric differences compared to the drilled holes from the wood/epoxy technology. Furthermore, the SCRIMP™ technology provides many attractive fabrication options, such as casting the studs in place, which simply did not exist with the previous stud technology.

The purposes of stud qualification testing were to:

- Provide a framework to verify that the bonded stud technology performed as expected in a SCRIMP^{TM} fiberglass laminate.
- Establish baseline fatigue curves for lifetime calculations.
- Provide a test methodology so that future process variations can be readily compared to the epoxy bonded baseline for static and fatigue strength.

This initial test plan concentrated on axial tensile tests, since this was historically the most demanding loading mode. Specimens with a single stud in each end, suitable for use in a typical materials test load frame were the baseline, so data could be generated quickly and cost effectively. Whole root tests were not conducted during this initial effort.

Special tooling was created by TPI to produce double ended specimens with a stud in each end. These specimens were tested in axial loading, rather than the cantilever bending mode that loads the blade root. This difference in loading mode means that the laminate had to be balanced differently for the axial test specimens than for the blade root.

In the blade root, more laminate was placed on the inside of the studs, to compensate for the lower strain values which exist there, in order to obtain relatively uniform load flow into the stud around its perimeter. For the axial loading, this unbalanced strain distribution did not occur, so a symmetrical material layout was used to provide the desired load flow distribution.

The stud testing evaluated two bond line thicknesses as shown in Figure 4.1. The 0.2" thick epoxy bond line was the standard that has been studied extensively in previous stud performance test work. The zero bondline thickness case represents direct embedment, which offers considerable potential for manufacturing economy.

A specimen of each root attachment type was tested to failure in static tension. The 0.2" epoxy annulus design failed under a static load of 301 kN (67.6 kip), while the directly embedded stud failed at 318 kN (71.5 kip). These results were in good agreement with predicted strength values, thereby generating confidence that the design methodology had been accurately transferred to the new design.

The static results were reviewed prior to fatigue testing of the two root stud approaches. For each root attachment type, an $R = 0.1$ tension load fatigue test at 65% of the static load result was used to provide an initial fatigue test at an intermediate cycle level. As was the case with the static test, the fatigue results were found to be in good agreement with estimated strength values (Figure 4.2). The results also showed that the direct embedment approach could achieve necessary performance levels under fatigue loading.

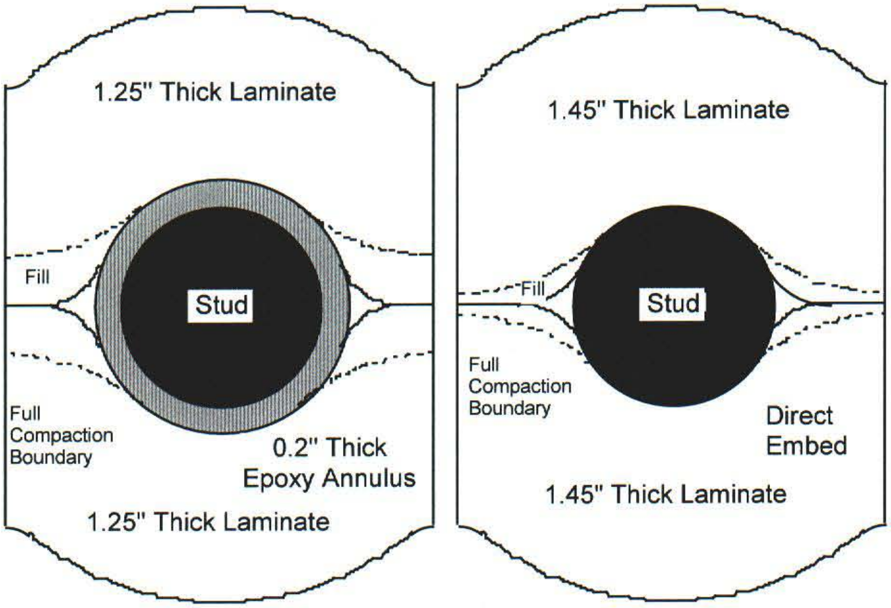

Figure 4.1 Stud Test Specimen Cross-Sections

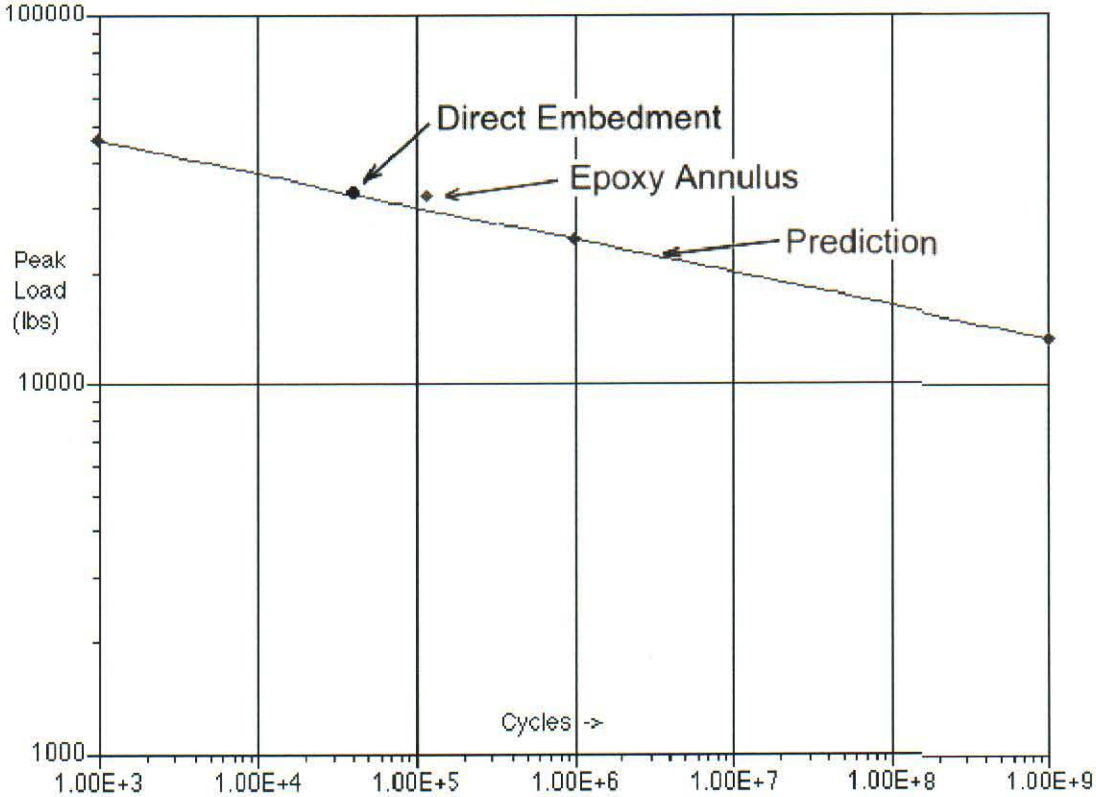

Figure 4.2 Root Stud Qualification Test Results

4.2 Static Load Testing

Static load testing of one ERS-100 prototype blade and one baseline LS-1 blade was conducted at the National Wind Test Center. The work was conducted by NREL test staff, and test results [6] were used to assure the accuracy of engineering models and identify areas for additional design effort.

4.2.1 Test Stand Description

The front mounting plate of the test stand was tilted down 6.3 degrees from vertical. This tilt was necessary to maximize the overhead clearance needed to reach the maximum tip displacement and to minimize the measurement errors due to blade angle. The blade was attached to the test stand via an adapter plate. The adapter plate is a 2-inch thick steel disk, 36 inches in diameter. This adapter plate was used for baseline tests on 56-100 blades and was modified to accept the ERS-100 blades, which have threaded female root studs. The blade was fastened to the adapter plate with eight 3/4"-16 UNF, Grade 8 bolts. These are the same fasteners used in the field and they were torqued to 350 ft-lbf, as in field application.

Loads were applied using a 5-ton hydraulic gantry crane and loading was distributed with a four-point whiffle tree. The whiffle tree was composed of three spreader-bars, which distributed the crane load to each of four saddles (Figure 4.4). The spreader bars were made from two opposing c-channels to form an I-beam. Linkages between spreader bars and saddles were constructed as short as possible to maximize overhead clearance. The whiffle tree assembly was statically balanced by attaching ballast weight. This eliminated bending moments in the blade caused by the whiffle tree apparatus.

Saddles were used to introduce the test loads into the blade. The saddles were made from laminated wood, 3 inches thick. An opening the shape of the airfoil at each span-wise location was cut in the center of the laminated wood block. Airfoil profiles were cut 3/8 inch oversize, and the space was filled with a two-part polyurethane (durometer 80 Shore A) mixture. The polyurethane evenly distributed the load over the surface area and allowed flexibility in the saddle-to-blade interface. The polyurethane also reduced the chance that the saddles would slide outboard on the blade under applied loading. The twist angle of the blade was incorporated into the two outboard saddles, so that the bottoms of the saddles remained horizontal during the test.

The two outboard saddles incorporated a pivoting mechanism to allow the load to be applied at or near the blade chordline. This pivoting yoke design reduced the moment that would be introduced due the large deflection angles. For these blades, only the outer saddles required the pivoting design. A comparison between the two styles of saddles is provided in Figure 4.3, and a photograph of the test stand with the blade installed is shown in Figure 4.4.

A Transducer Techniques (TT) 10 Kip load cell (model SW0-10K, serial number 90132) was used to measure crane load. This load cell was positioned between the crane and the whiffle tree. A pre-test calibration check was done using 1,000 lbf and 2,000 lbf calibrated dead weights.

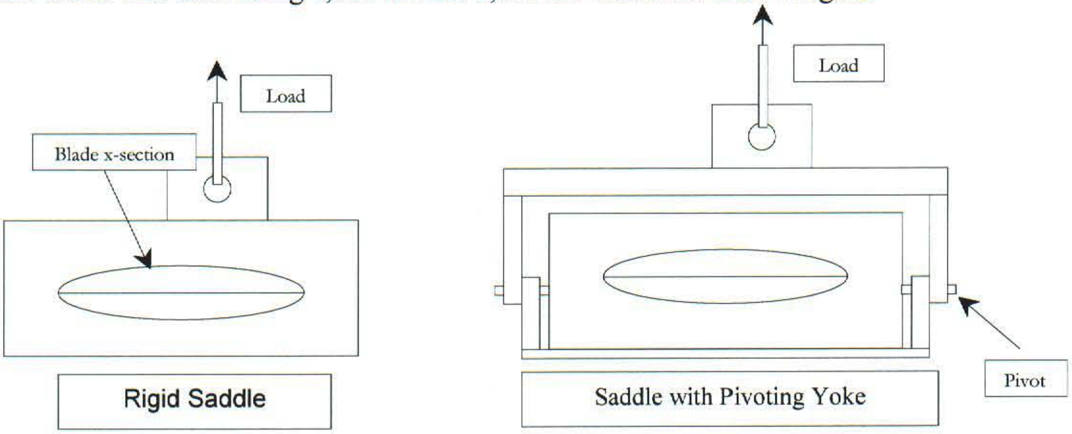

Figure 4.3 Schematic of Saddle Details

Figure 4.4 Photograph of the ERS-100 Blade in the Test Stand

4.2.2 Strain and Deflection Measurement

Deflections were measured using linear retractable scales at each saddle (load introduction) location and at the blade tip. The instrumentation had a resolution of 0.01 feet; reading were recorded manually. The strain distribution was measured by thirty-one (31) gages installed on the outside surface of the blade. The placement was developed by NREL to provide continuity with earlier test efforts and to locate gages for the field tests.

4.2.3 Static Test Results

The procedure for static testing consisted of monotonically increasing the applied load until the blade failed. Blade loads were applied using a hydraulic winch mounted to a gantry crane and transmitted through a four-point whiffle tree designed to reproduce the aerodynamic loading distribution. The applied load was then slowly increased to 1000 lbf, then held at that position so that the displacement measurements could be read and recorded (Figure 4.5). This procedure was repeated, in 500 lbf increments, until an obvious failure of each blade.

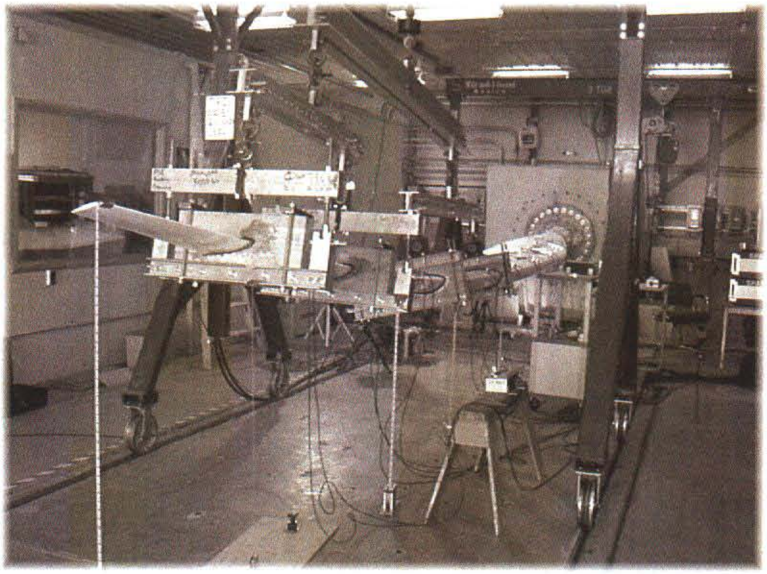

Figure 4.5 Photograph of the ERS-100 Blade Under Load

The ERS-100 blade failed at a root flange moment of 90,601 ft-lbf. (Table 4.1). The blade failure was characterized by catastrophic buckling of a wider inboard section and was preceded by local dimpling of the forward panel near the point of failure. Results indicate that the ERS-100 blades had slightly lower global load carrying capabilities than the LS-1 baseline (wet lay-up, fiberglass blades manufactured by TPI for U.S. Windpower).

Table 4.1 Comparative Summary of Baseline Blades to ERS Blades

	Baseline NACA	Baseline LS-1	ERS-100
Failure Load Root Moment (ft-lbf)	110,975 to 145,465	102,286 to 111,871	90,601
Deflection Rate (in/kip)	12.1	13.5	13.9
Compressive Strain Rate at 37.5% Span (μstrain/kip)	-804	-1003	-900

The ERS-100 blade experienced catastrophic failure at a load cell reading of 5056 lbf. (Figure 4.6). The failure region was characterized by a slanted chordwise crease that extends from about 1.73 m at the leading edge to 2.16 m at the trailing edge which is approximately at 31% span (Figure 4.7). The location was on the leading edge side of the shear web. Also noted from the video and observed during the test was that at least one other buckling zone, at about 40% span, was oil canning or dimpling at the time of failure.

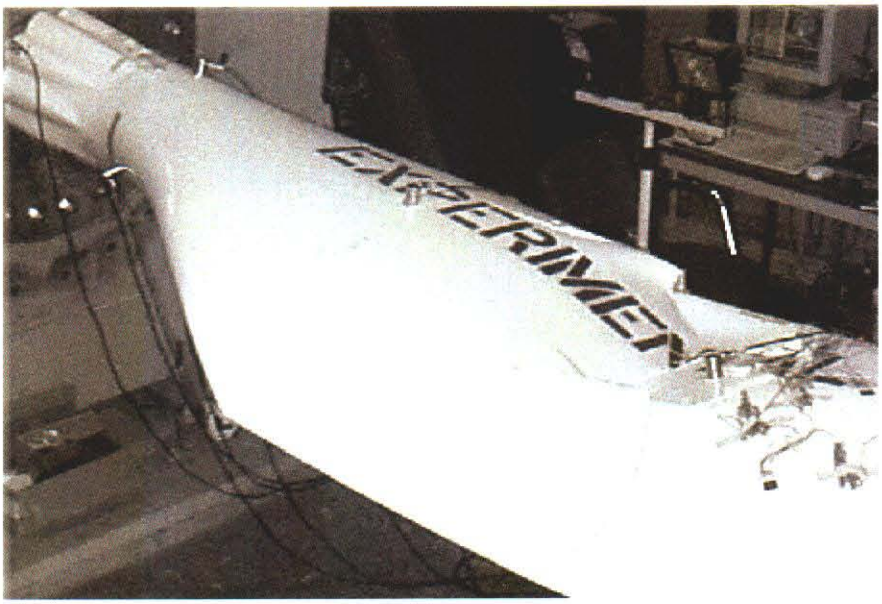

Figure 4.6 Photograph of the ERS-100 Blade After Static Failure

The buckling strength of the ERS-100 blade can be increased by modifying the laminate design in the failure region and by changing the shear web design. Subsequent failure analyses suggested that the leading edge panel stiffness could easily be improved by the addition of balsa core in the leading edge panels forward of the shear web. The production blades will be modified based upon the test results to increase buckling strength.

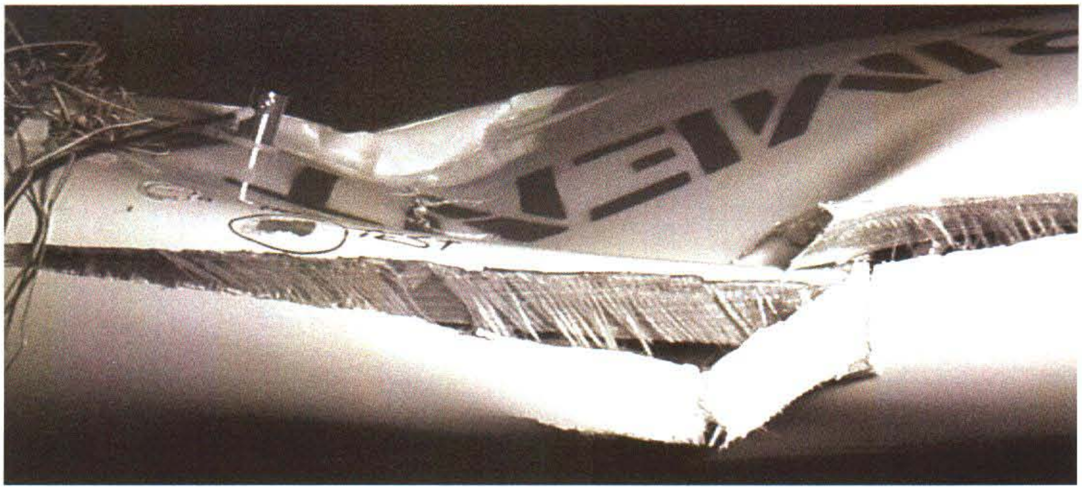

Figure 4.7 Photograph of the ERS-100 Panel Buckling Location

4.2.4 Blade Deflection Data

The ERS-100 blade is significantly longer than the LS-1 baseline blade, and minimizing tip deflection was a major design issue. Measurements of blade deflection were obtained at several spanwise stations during the static test. The qualification test data were compared to predicted blade tip deflection with excellent results (Figure 4.8).

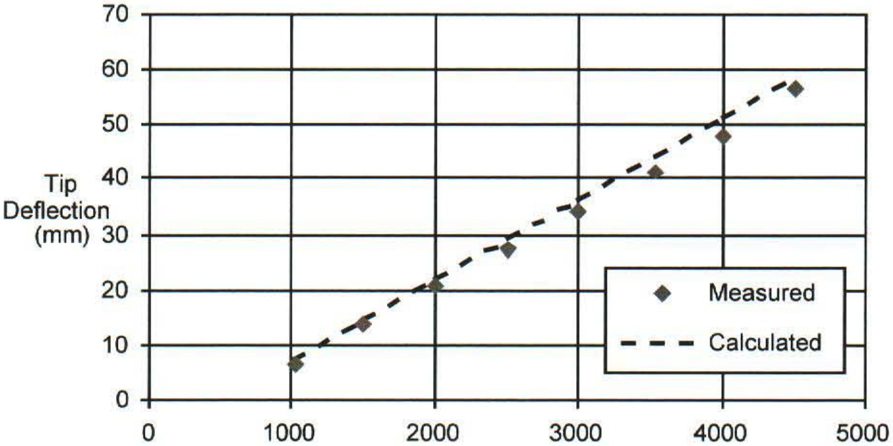

Figure 4.8 ERS-100 Blade Deflection Comparison With Test Data

4.2.5 Blade Strain Gage Data

Strain gages were attached to the blade outer skin along the radial axis (spanwise) to measure local strains. In general the measured strains were in good agreement with predicted values. The blade was designed to have nearly constant strain in the mid-section and have a smooth transition to low strain in the root region. The test results showed a nearly uniform strain between 2 and 6 meters transition (Figure 4.9). This graph indicates measured strain as a function of blade span for various applied loads as measured by the load cell. The blade failed due to buckling instability, so the ultimate strength of the laminate was not determined in this test.

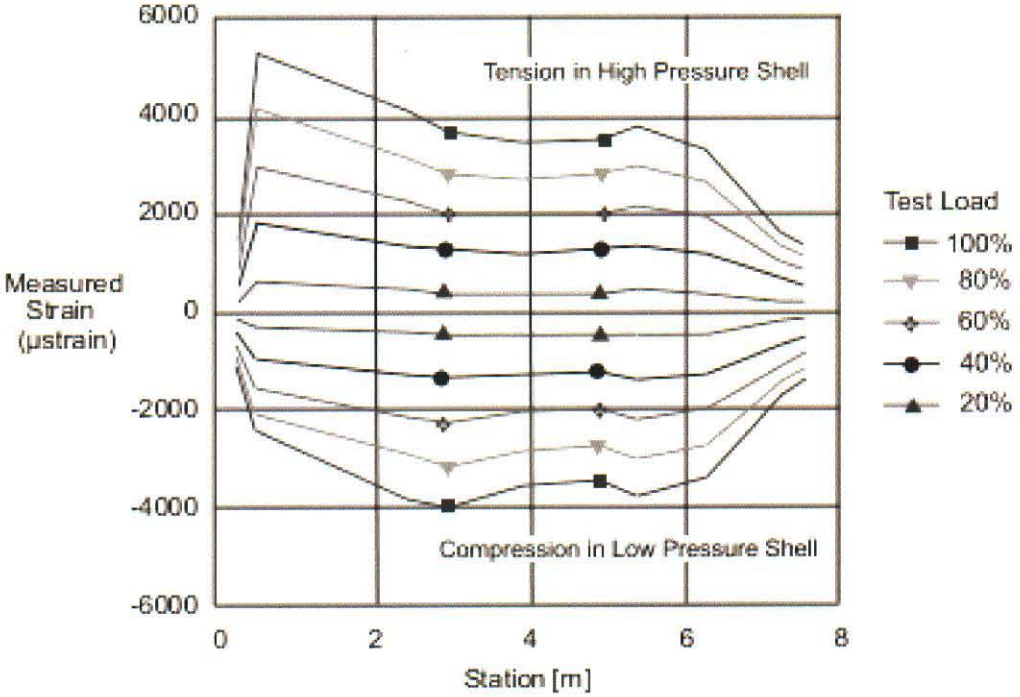

Figure 4.9 Measured Strain Along the ERS-100 Blade Span

Abnormally high tensile strains were observed in the inboard root region (station 0.475 m). After completion of testing, the blades were sectioned to inspect the internal structure and evaluate failure modes. It was determined that the high inboard strains were caused by an overly abrupt termination of the internal shear web. A design change to taper the shear web termination will be implemented in the production blades.

5.0 OPERATIONAL TESTING

5.1 Test Site Description

Operational testing was conducted in a large commercial wind plant comprised of more than 600 turbines. The test site was located in Solano County, California in a region of low rolling hills. The prevailing winds come from a westerly direction and are strongly influenced by thermal differentials between inland valleys and the coastal marine layer. Winds at the site flow directly from Suisun Bay and are generally low in turbulence.

Field testing was used to compare performance (power) and blade loads between the original and the replacement rotors. Two turbines were instrumented for testing, as shown in Figure 5.1. Turbine A (located in the foreground) had the ERS-100 replacement blades installed, while Turbine B (in the background) was equipped with newly constructed LS(1) baseline blades. The sensor suite was identical for both machines.

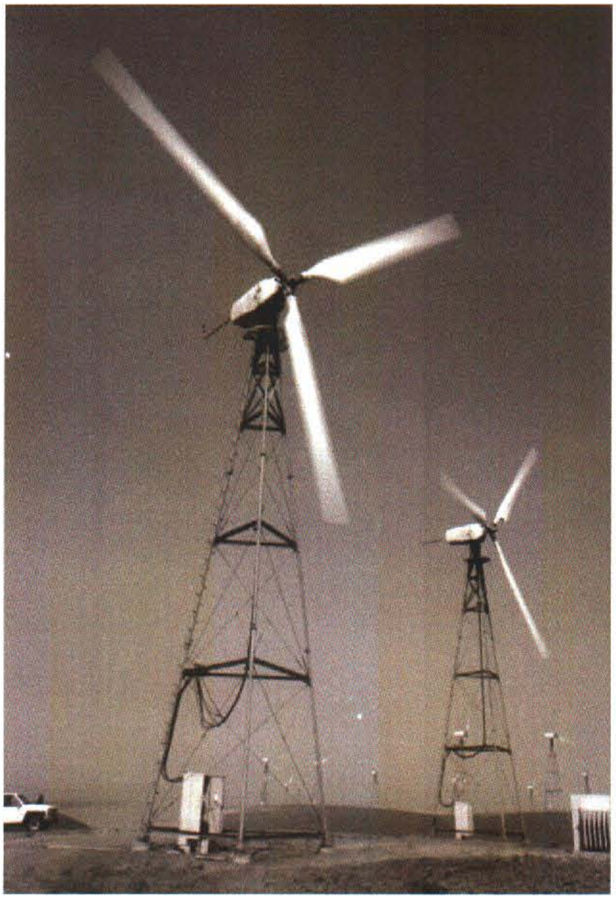

Figure 5. 1 Photograph of the Two Operational Test Turbines

Equipment installation and data collection were supported by a test van located upwind of the test turbines near the meteorological tower (Figure 5.2). The test computer was located in the van along with tools and equipment necessary for preparing the site.

Figure 5. 2 Photograph of the Test Van and Meteorological Tower

5.2 Site Meteorological Calibration

The meteorological instruments were mounted on an existing tower located directly upwind of Turbine A. The meteorological tower included a calibrated anemometer, wind direction sensor, and temperature sensor mounted at hub height as shown in Figure 5.3. An electronic barometric pressure sensor was located at ground level.

The topography at the test site was sufficiently complex that a site calibration was required between each of the turbine towers and the met tower. Three anemometers were calibrated against one another on a test frame (Figure 5.4) to obtain a direct correlation with the met tower anemometer. This initial test provided data for each of the three instruments under the same wind conditions, providing a direct (least-squares) curve fit between them.

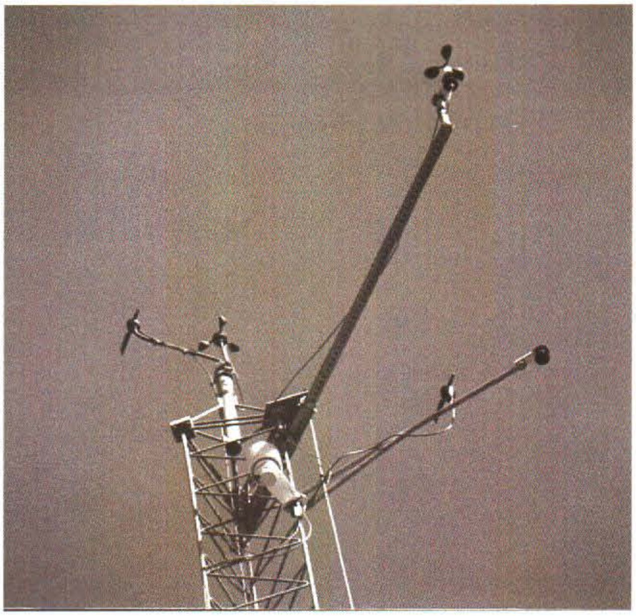

Figure 5. 3 Photograph of the Meteorological Tower and Instruments

Figure 5. 4 Photograph of the Anemometer Calibration Frame.

Once the instrument calibration had been completed, each of the test turbines was equipped with an anemometer mounted to an upwind boom (Figure 5.5). Data from all three anemometers (met tower, Turbine A and Turbine B) were collected while the turbines were not operating. These data were used to derive a mathematical relationship between the local wind speed at each individual turbine and the met tower.

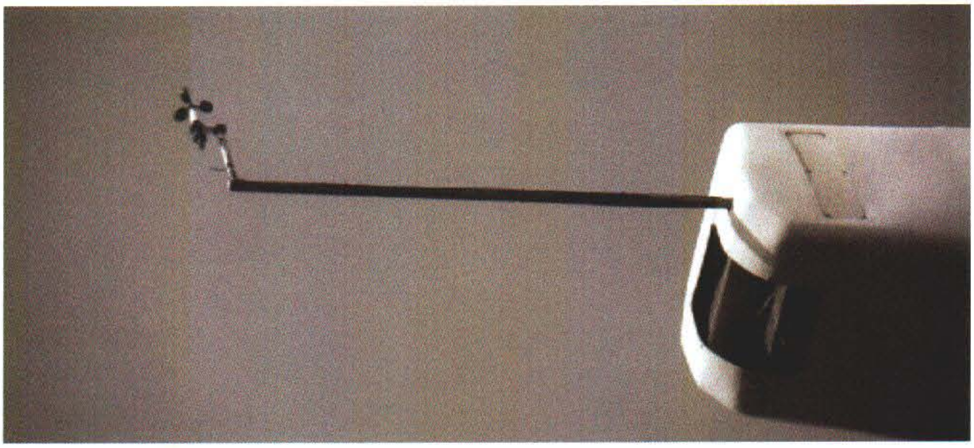

Figure 5. 5 Photograph of the Turbine Site Calibration Boom.

5.3 Test Instrumentation and Procedures

The test turbines were equipped with a variety of sensors to measure key parameters. Two ground based data acquisition modules were used to measure meteorological data. In addition, sensors in each of the test machines provided turbine power output, tower fore-aft and side-side acceleration, pitch motor power draw, and blade pitch angle.

Strain gages were installed at the TPI Composites factory in both the ERS and the LS(1) test blades. The gages were mounted inside the blade shell on the upwind surface and the wiring was connected to exterior terminal blocks at the blade root (Figure 5.6). The blades were equipped with flatwise strain gages mounted at 0.5, 2, 4, and 6 meters from the blade root; a single edgewise gage was mounted at 0.5 meters.

The test blades were installed on the turbine (Figure 5.7), and rotor measurements were obtained from data acquisition modules attached to the main shaft of the turbine (Figure 5.8). The rotor modules collected voltage measurements from the blade strain gages. The measured voltages were calibrated using known applied loads (Figure 5.9). Each turbine was also equipped with an instrumented blade pitch link, which was factory calibrated.

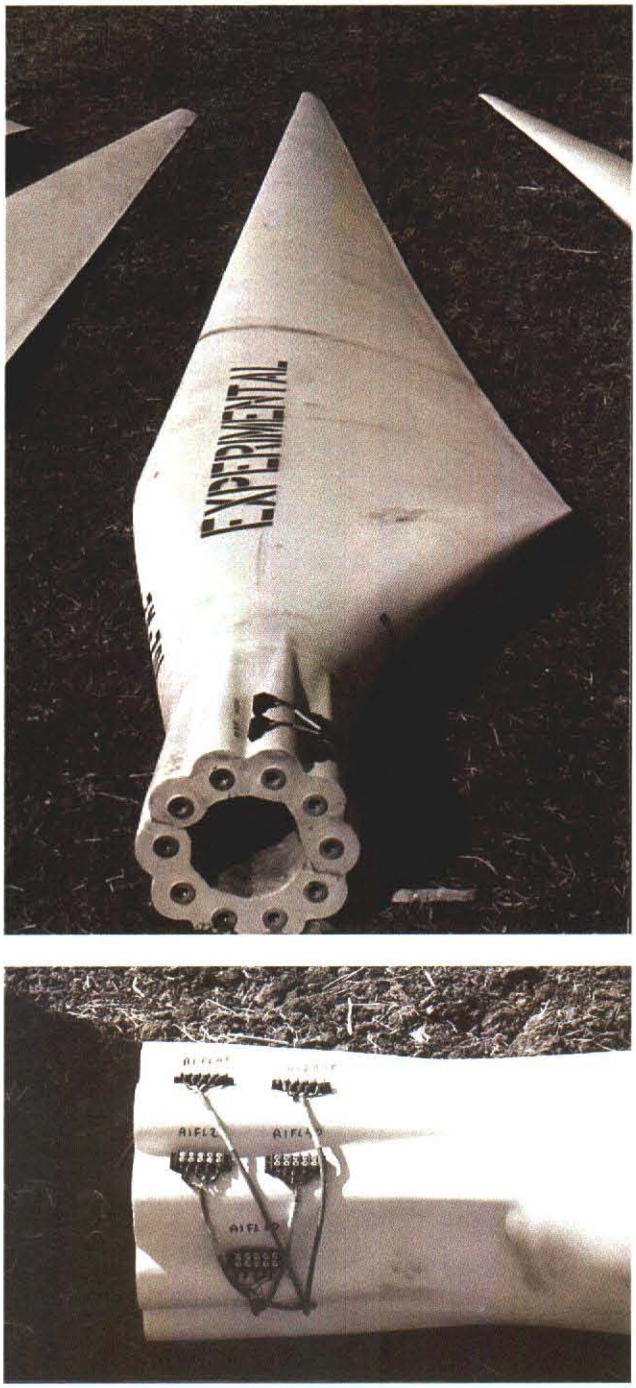

Figure 5. 6 Photographs of an ERS Test Blade

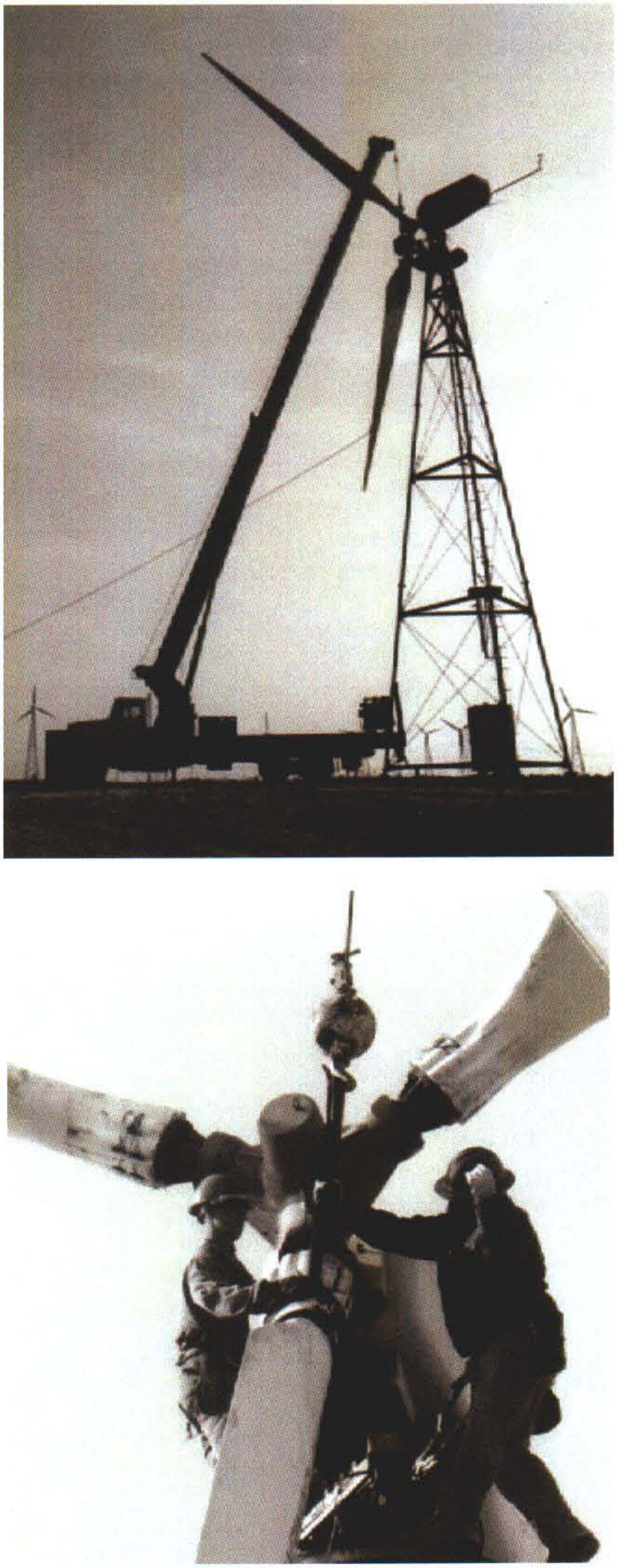

Figure 5. 7 Photographs of the Rotor Blade Installation

Figure 5. 8 Photograph of the Rotor Instrumentation

Figure 5. 9 Photograph of Blade Strain Gage Calibration

5.4 Operational Test Results

Power measurements were collected from the test turbines prior to installation of the new blades and these data served as the primary basis for comparison. Winds during the test period did not provide significant data at rated power, but good results were obtained over most of the operating range. A comparison between the calculated power output for the ERS-100 blades and the measured power curve is provided in Figure 5.10.

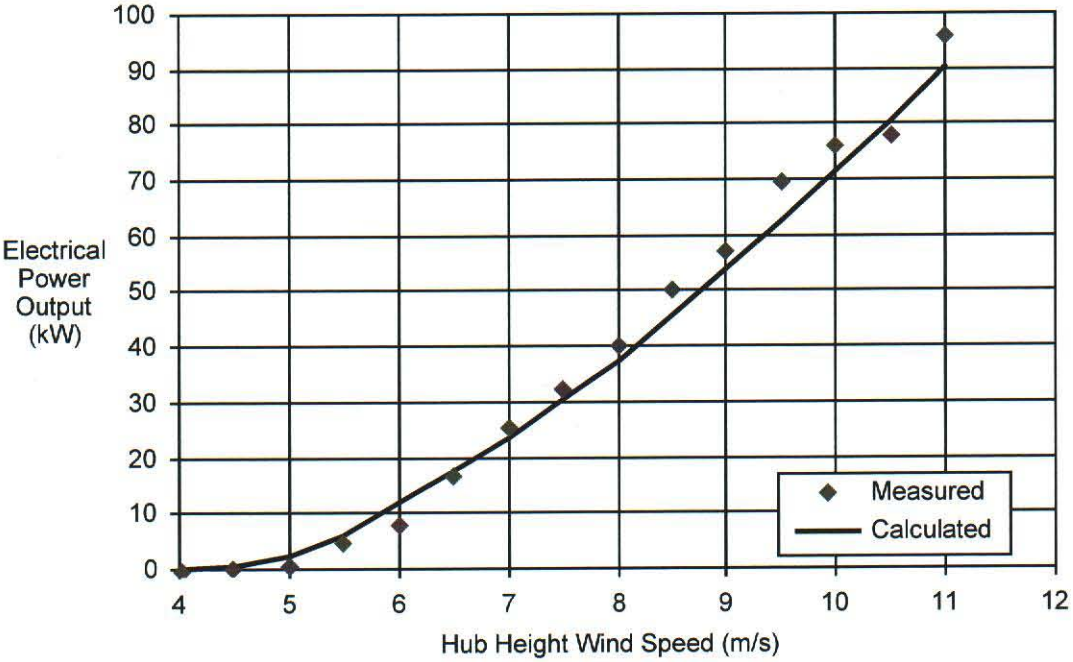

Figure 5.10 ERS Power Curve Comparison With Test Data

The design of the ERS-100 was expected to result in operating loads that were of the same magnitude as those produced by the baseline blade. Although more detailed testing will be required prior to commercialization, the initial results indicate that peak-to-peak flatwise bending moments for the ERS blades are roughly equivalent to the LS-1 baseline design. A sample time series test record is provided in Figure 5.11 comparing the strain measurements for each of the blades at a location 2 meters from the blade root. These data were collected over a ten minute test period when winds ranged between 8 and 12 m/s. The maximum peak-to-peak bending moment recorded at the 2 meter position during normal operation was approximately 14 kNm for both blade types.

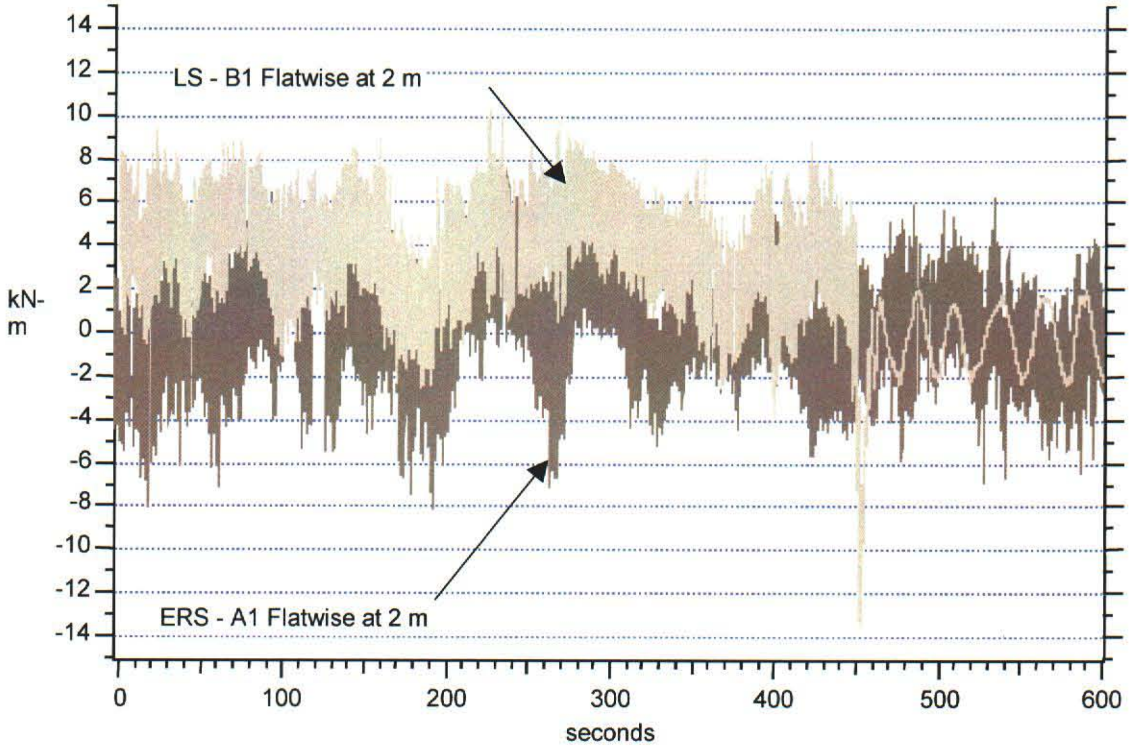

Figure 5.11 Flatwise Bending Moment Comparison Between Blades

The mean flatwise loads were lower for the ERS design because the blade's static moment was higher. Although the blades in both the LS(1) and ERS rotor sets had similar weight, the ERS center of gravity was located farther outboard due to its additional length. This increased the static bending moment and centrifugal (upwind) bending on the blade, which lowered average flatwise moments during operation. While the higher static moment offered some beneficial effect in flatwise bending, it also increased centrifugal loads on the rotor hub. Another negative effect of the higher static moment was a reduction in drive train natural frequency and a consequent increase in power ripple due to dynamic amplification through the drive train. As tested, the ERS proof-of-concept prototype blades exceeded the manufacturer's recommended static balance. The production blades will be modified to reduce blade weight and bring the static moment within the allowable range.

The graph in Figure 5.11 also includes a shut-down sequence for Turbine B, with the LS(1) rotor, about 450 seconds into the run. The flatwise bending moment at the 2 meter position was –13.8 kNm (upwind) during this event as compared to –15.0 for the ERS blade (Figure 5.12). The field test data showed large negative (upwind) flatwise bending moments during both shut-down and start-up (Figure 5.13) of the turbine. These large upwind loads are a normal function of rapid blade pitching during start-up and shut-down.

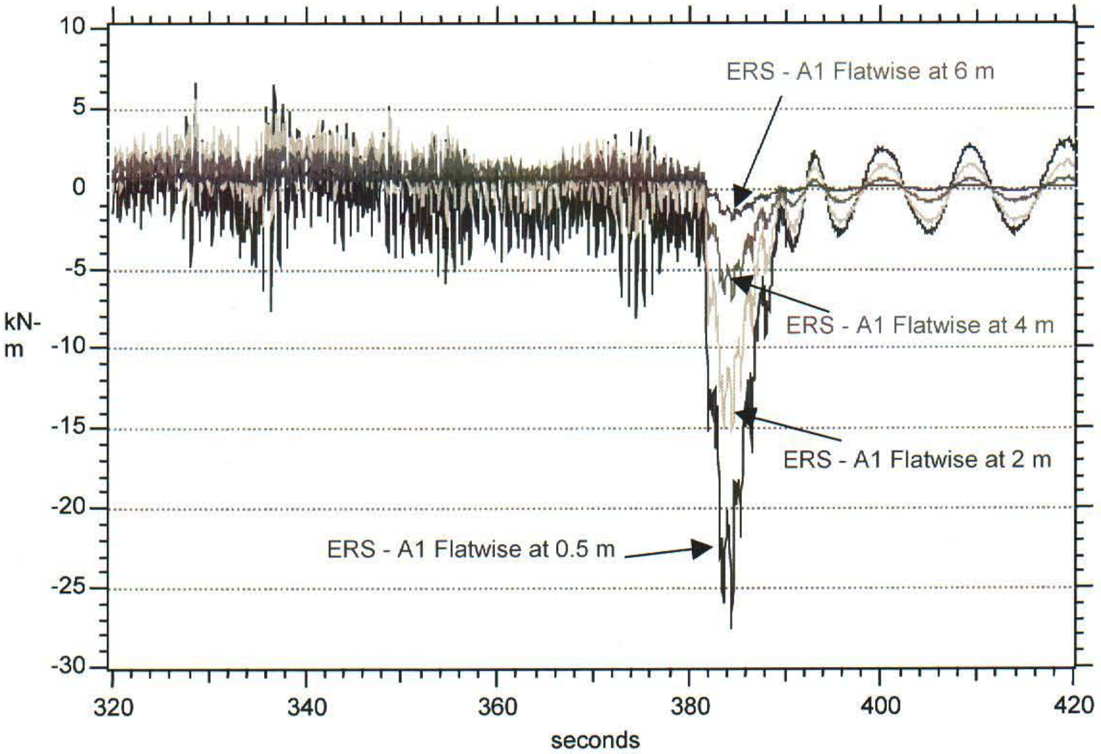

Figure 5.12 ERS Spanwise Bending Loads During Shut-Down

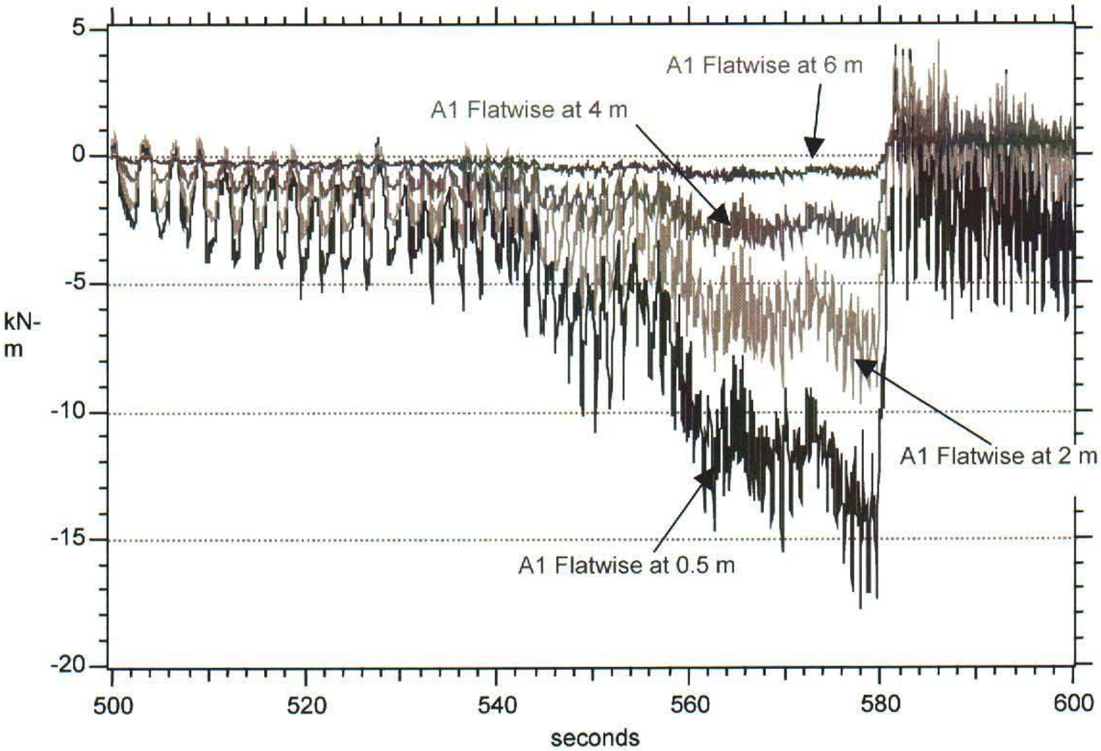

Figure 5.13 ERS Spanwise Bending Loads During Start-Up

6.0 PROJECT SUMMARY

6.1 Blade Manufacturing

- TPI Composites successfully developed and implemented a number of blade manufacturing improvements.
- The ERS-100 blade pattern tool was fabricated to excellent tolerances, and the fabrication process proved to be accurate and cost effective.
- The ERS-100 blade shell molds were also found to meet desired tolerances for airfoil shape.
- An improved approach for placing unidirectional laminate using fixed width materials was developed and tested.
- The strain-compatible bonded root stud approach was successful.
- The electric resistance heated mold was successfully implemented and tested.

6.2 Blade Testing

- Static and fatigue testing of blade root stud specimens agreed with design calculations.
- Blade buckling instability was initiated near a change in the uni-directional laminates and was the direct result of an overly abrupt change in laminate thickness. In addition, placement of the shear web resulted in increased forward panel length on the low pressure shell compared with the high pressure shell. The increased length created a large reduction in panel buckling strength.
- Unexpectedly high tensile stresses were identified at one blade station and found to be caused by abrupt termination of the shear web and an overly rapid stiffness change.
- Excess bonding adhesive (Plexus) used during manufacturing contributed to higher overall blade weight and static bending moment.
- No problems appear to exist with the root studs or the new retention system under static loading.
- Rotor operational performance and loads were in good agreement with engineering estimates.

6.3 Project Conclusions

- Production SCRIMP^{TM} ERS-100 blades, using heated molds, silicone bag technology and pre-formed materials, exhibited 25-30% labor saving over traditional fabrication methods.
- Blades manufactured using the SCRIMP^{TM} vacuum infusion process significantly reduced hazardous VOC air emissions as compared to conventional open molding systems.
- The blade root stud attachment approach was successfully implemented and met design expectations for static and fatigue strength.
- Static tip deflection was less than the baseline values and within acceptable margins.
- Blade power performance met design expectations and annual energy capture is expected to increase in excess of 10% at typical sites.
- Measured blade root bending loads were similar to the baseline blade. Further testing is needed to define the blade operating loads in detail.

6.4 Production Blade Refinements

- Blade static bending strength was somewhat less than baseline values. Modest changes to the laminate placement will be needed to increase panel buckling strength.
- Although blade weight was equivalent to the baseline, the static moment was larger. Static moment reduction can be accomplished by minimizing the adhesive used during assembly and small reductions in laminate thickness in the tip region.
- The blade chordwise center of gravity was located aft of the blade pitch axis, resulting in higher operating loads for the pitch system. Changes in laminate position and a reduction in trailing edge adhesive are expected to shift the chordwise center of gravity forward.
- Initial testing suggests that direct infusion of the root studs can provide sufficient strength. Further testing is planned to refine the engineering design and manufacturing procedures for direct embedment of the blade root studs.

6.5 Acknowledgements

The successful execution of this project was possible through the generous support of several different organizations and many dedicated individuals.

- Sandia supplied primary funding and technical support by Tom Ashwill, Dale Berg, and Henry Dodd.
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- Dynamic Design, led by Kevin Jackson, provided design analysis of blade planforms and testing.
- Mike Zuteck of MDZ Consulting provided ongoing engineering, design, and analysis throughout the project and was directly responsible for the root system development.
- Forrest Stoddard assisted with blade strain gage system specification and installation.
- EnXco provided the Solano test site, installed much of the equipment, and supplied excellent support courtesy of John Opris, Kirk Garlick, and the field crew.

7.0 REFERENCES

1. BTM Consult ApS, " International wind Energy Development: World Market Update 1999: Forecast 2000-2004," March 2000.

2. Aries Ingeneria y Sistemas S.A., “Spanish Wind Turbine Market Study,” October 1998.

3 TPI Composites, Inc. Internal Memo, 1998.

4. Spera, D. A., Structural Properties of Laminated Douglas Fir/Epoxy Composite Material, DOE/NASA/20320-76, May 1990.

5. Andrews, B. C.,"A Method for Geometric Modeling of Complex wind Turbine Blades," Master of Science Thesis, West Texas State University, May, 1993.

6. Hunsberger, R., Musial, W., Ultimate Static Load Testing on TPI Composites USW 56-100 LS-1 and ERS-100 Rotor Blades, National Renewable Energy Laboratory, NWTC-ST-TPI-STA-01-1299-FR, 25 April 2000.