Executive Summary

Two safety-related incidents involving small wind systems occurred in New Jersey in 2011, prompting the New Jersey Office of Clean Energy (OCE) to temporarily suspend the wind component of the Renewable Energy Incentive Program (REIP). One incident occurred on January 8, 2011, at a home in Villas, New Jersey, and involved a fire in a 10-kilowatt (kW) Xzeres unit. The second incident occurred on March 2, 2011, on a site owned by Jim Knoeller in Forked River, New Jersey, and involved the separation of three rotor blades from a 40-kW Enertech E44A turbine. Related to these two incidents, an Enertech E44A turbine installed on a site owned by Spyro Martin in Forked River, New Jersey, was shut down pending a determination of the cause of the rotor blade separation incident at the Knoeller site. The Martin wind turbine was later put back into service after Enertech conducted an internal review and provided new blades with an alternate blade root attachment structure.

The New Jersey OCE contracted with the National Renewable Energy Laboratory (NREL) to conduct a thorough and comprehensive investigation of the two incidents at the Villas and Knoeller sites. This assessment included, but was not limited to visits to each site for a visual inspection of the equipment and surrounding areas; interviews with each of the customers, installers, and component manufacturers; and inspection of the blades, inverters, and other system components involved in the incidents. Work was performed under a technical services agreement (TSA) with the State of New Jersey, TSA 11-372.

This report covers the investigation of the Enertech E44A wind turbine incident at the Knoeller site. The objectives of the investigation were to determine the cause of the turbine's failure and whether it was an isolated incident or a potential problem that would reoccur in existing and new E44A wind turbines. This report provides background information and a description of the events, actions, documentation, and assessment process. In addition, the report describes the site evaluation and design and testing assessments and provides conclusions and recommendations.

NREL contracted with Dynamic Designs and Wetzel Engineering to conduct a technical assessment of the failure of the Enertech E44A and its blades at the Knoeller site. Investigators collected information from all parties involved in the turbine's design, installation, and operation and examined the modified blades installed on the turbine at the Martin site.

The primary conclusions of the Enertech blade failure assessment include the following:

- The Knoeller blades failed because of excessive stress concentrations in the blade roots (as described in Section 6.2.2)
- Unbolstered blades present a high risk of failure
- Lack of documentation provided for this study prevented the investigators from endorsing the redesigned, bolstered blade configuration. As a result, investigators came to the following conclusions regarding the bolstered blade:
    - Discrepancies in data and information indicate a lack of design stability
    - Stress levels observed in the bolster-to-laminate bond in the characteristic model exceed certification body guidelines

- Bolstered blades appear to represent a reduced, but still serious, risk of failure.

- Enertech stated in the design review and written comments (Enertech 2012a) that the blade meets the requirements of the IEC 61400-2. However, the discrepancies in the approach used by Enertech in the design and testing of the turbine blades relative to the IEC standards (as described in Section 6.2.4 of this report) indicate that the turbine would not meet the IEC 61400-2 or IEC 61400-23 standards.

Compared to the level and amount of information that is normally expected for a rigorous design or certification assessment, this assessment was impaired by the limited amount of information provided by Enertech. Enertech did not provide the technical information needed to properly determine if the turbine conformed to a finalized and stable Enertech design, and whether or not the design met the Enertech-stated performance and reliability expectations (statements of compliance to IEC 61400-2, IEC 61400-23, or any other standards should be made by qualified certification agencies, rather than manufacturers or designers). A draft report of the assessment was circulated for comment and Enertech's responses were included (Appendix B).

In addition to the cause of failure assessment, investigators provided protocol recommendations for accepting turbines into the New Jersey REIP (as described in Section 10 of this report). The investigators recommended an incentive program that encourages rigorous design, testing, and manufacturing practices that are consistent with internationally accepted wind turbine standards. Although this is not a required or common practice, turbines with IEC 61400-1 type certification are subjected to the most rigorous design evaluation and testing requirements. Systems with this certification are most likely to perform according to specifications and offer high levels of reliability. The following recommendations were provided by the investigative team to the State of New Jersey for accepting small wind systems into its REIP:

- Require turbine certification to IEC standards by an agency accredited by the International Organization for Standardization
- Consider withholding incentives for systems with pending certifications until type conformity is issued from the certification body
- Scrutinize groups that provide turbine certification or evaluation services and/or require that they have proven competency in design evaluation and certification.

Because the small wind certification process is in a nascent phase, requiring IEC type certification may be too restrictive for emerging small wind systems. As a result, qualification by a noncertifying body may be an option for systems that fall into this category; however, this approach is open to interpretation as to what constitutes a qualified reviewing agency.

1 Background

Two safety-related incidents involving small wind systems occurred in New Jersey in 2011, prompting the State of New Jersey Office of Clean Energy (OCE) to temporarily suspend the wind component of the New Jersey Renewable Energy Incentive Program. The first incident occurred on January 8, 2011, at a home in Villas, New Jersey, and involved a fire in a 10-kilowatt (kW) Xzeres unit (information on this incident is provided in a separate report). The second incident occurred on March 2, 2011, at the Knoeller site in Forked River, New Jersey, and involved the separation of three rotor blades from a 40-kW Enertech E44A turbine. As a consequence of the rotor blade separation at the Knoeller site, a separate Enertech E44A turbine installed at the Martin property (also in Forked River, New Jersey) was shut down, pending a determination of the cause of the rotor blade separation incident in Forked River. The Martin wind turbine was later put back into service after Enertech conducted an internal review and provided new blades with an alternate blade root attachment structure.

The New Jersey OCE contracted with the National Renewable Energy Laboratory (NREL) to conduct a thorough and comprehensive investigation of the two incidents at the Villas and Knoeller sites. This report covers the investigation of the Enertech E44A wind turbine incident. This assessment included visits to each for a visual inspection of the equipment and surrounding areas; interviews with each of the customers and installers and the manufacturer; and a detailed inspection of the blades. This work was performed under a technical services agreement (TSA), funded by the State of New Jersey, TSA 11-372.

2 Investigation Objectives

The objectives of the investigation of the Enertech E44A wind turbine blade failures at the Knoeller site were to:

- Identify the cause(s) of the Knoeller E44A turbine failure
- Determine whether the cause(s) represent(s) an ongoing risk to existing and new E44A turbines
- Develop and recommend improvements that will enhance safety and consumer protection.

To meet the objectives, investigators:

- Collected as much first-hand information as possible from the turbine owner, installer, and manufacturer through review meetings and interviews
- Conducted a post-mortem inspection of failed components at the Knoeller site
- Conducted design and testing assessments that were based on information provided by Enertech and developed a model of the E44A to simulate its performance and loads
- Engaged in a detailed discussion of the methodology to be employed in the investigation
- Assessed whether any of the modifications made to the equipment could have been a primary source of failure
- Gathered facts regarding installation, operation, weather conditions, and environmental factors to determine if any of these factors contributed to the turbine failure
- Performed a design assessment of the bolstered blade used at the Martin site
- Determined whether the cause of the Enertech incident represents a potentially ongoing risk that may recur in existing or new E44A turbines, or whether the cause represents an isolated incident
- Provided conclusions and recommendations.

3 The Assessment Process

NREL contracted with Dynamic Designs and Wetzel Engineering to provide technical assessments of the Enertech E44A wind turbine and its blades. This investigative team has a demonstrated track record in the design, manufacturing, and testing of wind turbine blades and full turbine systems. The team's experience dates back to the nascent small wind industry in the 1980s, and on through the engineering, development, and deployment of modern utility-scale machines. In addition, the team's collective knowledge includes the detailed design, analysis, and testing of composite structures.

3.1 Dynamic Designs' Assessment

Dynamic Designs conducted a technical assessment of the blade failure event at the Knoeller site and investigated the root cause. During the assessment, Dynamic Designs' investigators:

- Conducted a physical investigation of the Knoeller site, inspected the failed blades, collected photographs, and interviewed the turbine owner and installer
- Compared measured field test data collected in 1991 from an instrumented Enertech E44/40 wind turbine operating at a commercial wind site near Palm Springs, California, to analytic estimates from the Enertech E44A to define typical operating loads in service
- Developed an NREL FAST computer model to show the relative impact of dynamic stall and air density on rotor performance and loads
- Provided a comprehensive report of the investigation, referred to in this document as the Jackson Report (Jackson 2012).

3.2 Wetzel Engineering's Assessment

Wetzel Engineering conducted a scope of work similar to Dynamic Designs by providing an independent assessment of the Enertech blade design variants. During the assessment, Wetzel Engineering's investigators:

- Reviewed the Jackson Report covering the Knoeller blade failure
- Evaluated the May 11, 2011, Enertech report on the blade failure
- Examined Enertech's drawings and specifications for the Martin replacement blade
- Reviewed Enertech's load calculations
- Participated in a teleconference during the design review meeting with Enertech and NREL on January 17, 2012
- Interviewed the installer of the two Enertech turbines (the failed turbine at the Knoeller site and the turbine at the Martin site) on January 24, 2012
- Conducted an independent structural analysis of the root designs of the failed blades at the Knoeller site and the replacement blades installed on the turbine at the Martin site

- Provided a comprehensive report of the investigation and analysis, referred to in this document as the Wetzel Report (Wetzel Engineering 2012).

3.3 NREL's Assessment

NREL conducted an assessment of the test methods and results using information provided by Enertech.

4 Description of Events and Actions

4.1 Description of Event

Three turbine blades separated from an Enertech E44A wind turbine on a property owned by Jim Knoeller in Forked River, New Jersey. The incident occurred on March 2, 2011, at approximately 1:50 p.m. Eastern Standard Time. Two blades were found near the base of the turbine, while the third failed blade landed approximately 200 feet north of the tower. No recorded site meteorological data was available; conditions noted at the time of failure were described as sunny with scattered clouds, light winds at 5−10 mph, and a temperature around 42°–44°F. No unusual or extreme weather was reported at the time of failure.

Supervisory control and data acquisition data that may have been available was not provided for this investigation.

4.2 Field Inspection

Dynamic Designs engineers Kevin Jackson and Rob Kamisky attended a project kick-off meeting on November 29, 2011, (Fingersh et al. 2011 and Knoeller Chronology 2011) in Trenton, New Jersey, and were provided with background information to support the review effort. Later that day, the engineers inspected the failed blades at the Knoeller site. Jackson and Kamisky performed a physical examination and collected detailed photos of the rotor blades, with a special emphasis on the root attachment region. On November 30, 2011, Jackson and Kamisky inspected the operating wind turbine at the Martin site. During their inspections, the Dynamic Designs engineers interviewed Jim Knoeller, Spyro Martin, and Roger Dixon (turbine owners and installers). More detailed information on the onsite investigations is provided in the Jackson Report.

Jackson and Kamisky received a number of related Enertech reference documents, including an installation, operation, and maintenance document and a product support bulletin [Enertech (undated) and Enertech 2011]. Figure 1 provides a photograph of the turbine hub at the Knoeller site showing the blades detached at the root interface.

4.3 Modifications Assessment

Dynamic Designs determined that several modifications were made to the turbine at the Knoeller site after its initial installation. For example, Enertech had installed "winglets" at the blade tip brakes in an attempt to aid yaw stability and allow the turbine to keep operating in its proper downwind configuration. In addition, stall strips were added to outboard stations of the blade, which are intended to decrease aerodynamic loads, thereby decreasing the system's power output.

The owner and Enertech modified the control system. A partial listing of these modifications was provided in a document containing an email history between Enertech, the system installer, Roger Dixon, and the owner, Jim Knoeller (Knoeller Email History 2012). The assessment did not focus on turbine control modifications.

Figure 1. The Knoeller site turbine hub after the blades had separated

Source: Dynamic Designs 2012

4.4 Design and Project Review Meetings

On January 17, 2012, Trudy Forsyth and Scott Hughes of NREL participated in a review meeting at the Enertech office in Newton, Kansas. In addition, Kyle Wetzel of Wetzel Engineering attended this meeting via phone and Web conference. During the meeting, participants reviewed the information provided by Enertech. Afterwards, Trudy Forsyth and Scott Hughes were given a tour of the blade test rig and blade production facility.

On February 27, 2012, a summary meeting was held in Trenton, New Jersey, at the New Jersey Board of Public Utilities facilities. Kyle Wetzel and Scott Hughes presented the work of the Dynamic Designs team and the results of the investigation (Wetzel 2012 and Hughes 2012).

At this meeting, Enertech reported on a series of in-house tests it performed to quantify the static and fatigue performance of several design variants of the blade. In addition, during the January

17, 2012, review meeting, the company stated that the current blade design was being tested and was expected to conform to the International Electrotechnical Commission (IEC) 61400-2 (small wind) and IEC 61400-23 (blade testing) standards (IEC 2006 and IEC 2001–2004). However, Enertech did not provide any evidence of third-party certification for the E44A wind turbine. See Section 6.2.4 for an assessment of the testing done at Enertech.

5 Certification Background

IEC provides a number of guidelines and standards for wind turbines under the IEC 61400 series. This framework provides a set of design requirements and testing conditions required to demonstrate (to a reasonable level) that turbine systems are adequately designed to last a given lifetime. Although certification is not a guarantee that a turbine will last a given lifetime, it confirms that a system has been designed to meet accepted industry standards and underwent evaluation by qualified third parties.

The IEC standards and guidelines provide the technical conditions that the manufacturer must adhere to for certification by an independent third party and are not intended for self-certification. To demonstrate compliance, manufacturers must comply with the entire standard. For example, adhering to only selected parts of a standard does not demonstrate compliance. To verify compliance, the design and test results are assessed by an independent certification body such as Germanischer-Lloyd or Det Norske Veritas (DNV). Additionally, certification bodies can impose requirements that go beyond what is written in standards by applying their collective knowledge. More established and experienced certification bodies can provide a greater depth of knowledge in the certification process.

For due diligence, field and laboratory testing is performed by ISO 17025-accredited institutions for an IEC 61400-22 compliant type certification. This level of rigor is necessary to demonstrate that the institution is qualified to perform testing to a given standard. That said, in-house testing can be performed by the manufacturer, provided that the certifying body has qualified the manufacturer to do so. Accreditation or qualification by the certification agency is required before the start of a test program.

The fundamental purpose of conducting a wind turbine blade test to the IEC 61400-23 standard is to demonstrate to a reasonable level of certainty that a blade type, when manufactured according to a certain set of specifications, has the prescribed reliability with reference to limit states developed by the manufacturer. In addition to full-scale blade tests, tests are performed to determine blade properties and to validate critical design assumptions used as inputs for the design load calculations. The blade test standard specifies minimum requirements for testing that are considered accepted industry practice.

For certification testing, a substantial amount of information about the design must be known to properly define test loads. Blades are designed according to accepted standards or codes, including the IEC 61400-1 standard, which is the industry benchmark for design requirements (IEC 2005–2008). Test loads are required to encompass the entire envelope of blade design loads, derived according to accepted standards. Furthermore, test loads are higher than the design load to account for other influences, including environmental effects, test uncertainties, and variations in production. To account for these influences, test load factors are applied to design loads to achieve target test loads. The determination of the actual margins to the design values quantifies the margins of the actual safety of the blade relative to the design.

The IEC 61400-2 standard provides design requirements for small turbines using simplified design load case assessment and limited testing. In theory, the simplified load case assessment and limited testing requirements are offset by higher safety factors. The IEC 61400-2 standard provides three methods to derive design loads: 1) aeroelastic simulations (similar to IEC 61400-1); 2) simplified equations (only if several turbine configuration requirements are met); and 3) direct measurement with extrapolation. Each method will cover a range of load cases that must be included in the design. Depending on the design, different load cases can become design-driving (e.g., extreme direction change for a free yaw wind turbine). Although mixing of the different methods is allowed, it is not encouraged. Because each method has a different level of accuracy, various safety factors for loads must be used and based on the method that is applied. For the simplified analysis, conservative safety factors must be used—unless lower safety factors can be demonstrated through testing and/or analysis. In particular, a static blade test is always mandatory.

The blade is deemed to survive an IEC 61400-23 test if adequate margins between design calculations and test data are demonstrated, with the conditions that material characterization, strength, and fatigue formulation are conservative and the blade is manufactured according to the design specifications. The blade must not exhibit permanent structural deformations. Test deflections must be consistent with design values, and must demonstrate that mechanical strains are within design calculations. Minimum strain measurement locations include:

- The main load-carrying structure at multiple span-wise locations (four or more stations)
- The strain at trailing edge and leading edge at max chord
- The measurement of highest loaded connecting bolts, both in tension and bending
- The blade locations where geometry transitions and critical design details or stress risers may be present
- The areas identified from design calculation of high strain.

Static tests are performed in multiple orientations and typically include a minimum of four directions: maximum flap, minimum flap, maximum edge, and minimum edge.

Fatigue test loads are developed through industry-accepted methods. These common methods use accelerating fatigue loads based on as-built material S-N curve and Goodman-Diagram curves (material performance is based on load level and number of cycles applied) and damage equivalent load (DEL) calculation through damage summations (Freebury and Musial 2000). Fatigue mean loads applied during testing are as close as possible to the mean load at the operating conditions that are most severe to the fatigue strength. Fatigue test DELs can be applied in independent flap and edge tests, or more conservatively in a dual-axis test where flap and edge loads are applied at the same time, with a representative phase difference between the two.

For a given blade, both flap-wise and edge-wise testing will be conducted, typically in the following order: static in four to six directions, fatigue testing in two directions, and static testing in one to two directions.

Testing of critical mechanical blade subsystems, such as tip brakes, is not covered in the IEC 61400-23 standard. However, the standard does recommend verifying the structural integrity of these subsystems through independent means. In cases where damage is observed during a test, the blade is sectioned to provide quantifiable information on the mechanisms of failure.

Per the IEC 61400-23 standard, the manufacturer is required to record traceable documentary evidence for the design and construction of the test blade, including:

- Unique identification
- Relevant drawings and specifications
- Lamination plans and work instructions
- A list of manufacturer and type identification numbers for all important materials used
- Supplier's certificate and blade manufacturer's laboratory acceptance report for all important materials used
- Curing history thermographs for thermosetting resins and adhesives at critical locations
- Differential scanning calorimetry or other control of curing
- Manufacturing quality record sheets signed by the responsible person
- Weight and balance report detailing total mass and center of gravity
- Relevant nonconformity reports
- Representative examples for repair procedures for manufacturing defects and in-service damage that are qualified with the test blade (if applicable)
- Repairs performed due to damage caused by test loads that are higher than the target loads (if applicable).

The IEC 61400-23 standard has very specific requirements for the documentation of test log books, test plans, and test reports that are to be maintained and produced during a test. Items that are included in test plans and reports are:

- Blade geometry
- Blade identification
- Mass and center of gravity
- Blade surface condition
- Blade mounting details:
    - Lifting and handling procedures
    - Maximum expected deflections under load
    - Table of contents
    - Test contractor
    - Test dates and locations

- Scope of test program
- Test setup and procedures
- Description of test load
- Test equipment used (including make, model, and serial numbers)
- Reference to calibration records of measurement equipment per ISO/IEC 17025
- Locations of sensors and measurement points
- Blade-specific calibration details (such as tare loads and strains)
- Estimated uncertainties
- Description of inspections and observations
- Summary of tests and test results
- Deviations from test plans, laboratory procedures, or normative references
- References list (such as test plans, laboratory procedures, and normative references).

The IEC 61400-2 standard requires that the test demonstrate that no damage occurs that will prevent the safe operation of the turbine. During the test, this includes the demonstration that buckling, cracking, plastic deformation, or loss of stiffness do not occur. Test loads per the IEC 61400-2 must also consider all salient forces, including centrifugal loads.

While the above overview is not a comprehensive specification for performing a certification test, it does provide the basis for the critical elements that constitute a conforming test. Testing per the standard is contingent upon having detailed design information beforehand, with test data used to validate the design calculations.

Certification and certification testing can only be performed by qualified agencies.

6 Assessment Documentation

6.1 Information Provided by Enertech

In addition to available manuals and bulletins, Enertech provided two documents relevant to the design and testing used for this assessment. The first document was a March 7, 2011, conference presentation titled, *Designing a Modern Small Wind Turbine Blade and Associated Manufacturing Systems* referenced in this report as the Enertech Presentation (Wadsworth, Nelson, and Kaufman 2011). Enertech indicated that this presentation was originally given at a conference in 2010. In this document, the date references the date indicated in the presentation and provided for review (Enertech 2012). This document provides high-level information on the design, manufacturing, and testing of Enertech blades. The second document, dated May 11, 2011, is titled *Enertech 44a Wind Turbine 13 m Fiberglass Blade Failure Analysis and Solution*, and is referred to in this document as the Enertech Analysis Document (Enertech 2011a). The "13 m" in the document title relates to the rotor diameter and not the actual blade length [actual blade length is stated as 6.4 meters (m)]. The Enertech Analysis Document provides information on the blade testing and comments on the design of a blade with a steel bolster. These documents include 22 slides and 11 pages of information.

Enertech did not provide detailed design information on the turbine blades and indicated that they were relying on laboratory testing to demonstrate the structural performance and adequacy of the product.

The Enertech Analysis Document provides background on two blade design variants. There are several design versions of the blade that are referenced in this report and in the supporting documents. The two blade designs can be summarized as follows:

- **Rev A (Knoeller Blade)**–Baseline design that failed on the turbine installed at the Knoeller site. Also referred to as the "unbolstered" blade.
- **Rev B (Martin Blade)**–Replacement blade used at the Martin site, also referred to as the "bolstered" blade. The Martin blade was modified from the Knoeller design by adding a welded steel structure, or bolster, and incorporating changes in the root laminate schedule. Rev B (unbolstered) refers to a future blade design where the bolster would not be installed.

Figure 2 provides photographs of the Rev A and Rev B blade roots.

Figure 2. Unbolstered (left) and bolstered (right) root designs

Source: Wetzel Engineering 2012

A recurring topic in this assessment has been the lack of detailed information or technical justification of statements provided by Enertech. Requested information included documents that cover the design and manufacturing of the blade. In typical engineering practice, this type of documentation is available prior to the manufacturing and testing of a product. However, the documents provided by Enertech included very high-level summary information and no technical detail. Without technical detail or justification, it is not possible to assess the validity of the information or assertions.

Several Enertech documents were provided to Wetzel Engineering during the design review meeting; however, these documents were not made available by Enertech to the entire assessment team [*Entertech's Drawings and Specifications for the Martin Replacement Blade* and *Enertech Loads Calculations* (Enertech 2012)]. The content of these restricted-access documents were considered in the Wetzel Report.

Enertech provided feedback on the Jackson Report and Wetzel Report and the company's comments were included for consideration in the preparation of this report (Enertech 2012, Enertech 2012a, *Comments embedded in existing PDF* (Enertech 2012), and Kaufman 2012).

The Enertech Presentation provides a power curve but no detailed information on the assumptions for conditions that were used to generate this curve (shown in Figure 3).

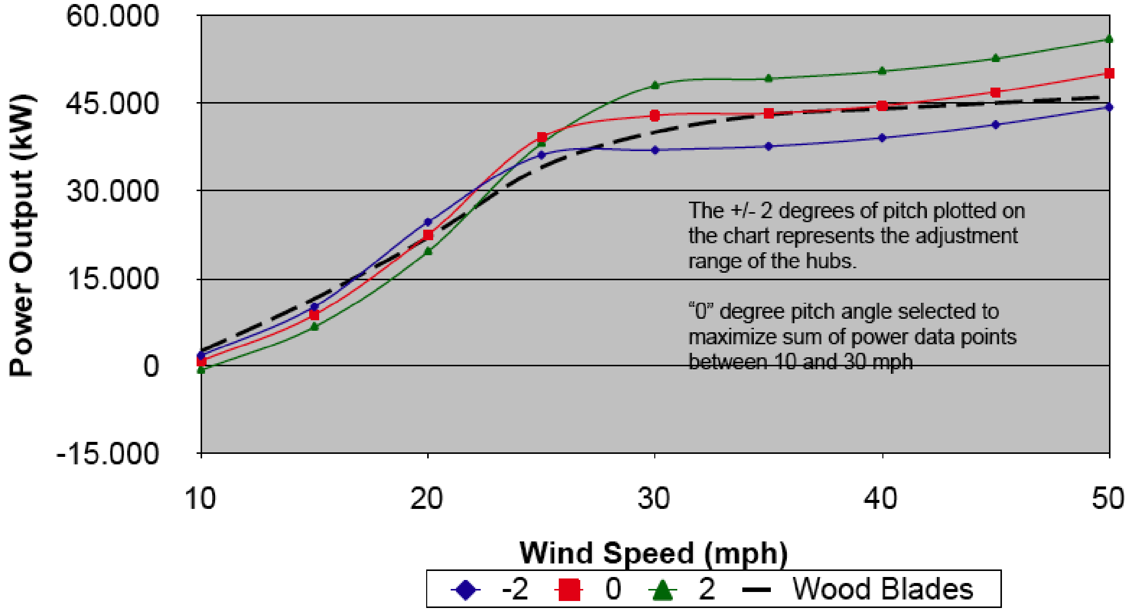


Figure 3. Power curve developed by Enertech

Source: Wadsworth, Nelson, and Kaufman 2011

The Enertech Analysis Document provides an overview of the blade manufacturing process. During an internal audit, Enertech considered several possible causes of blade failure and concluded that the presence of a foam fillet, which was not removed during the manufacturing process, caused the premature failure of the blades. Figure 4 shows the root steel plate and foam core with and without the fillet.

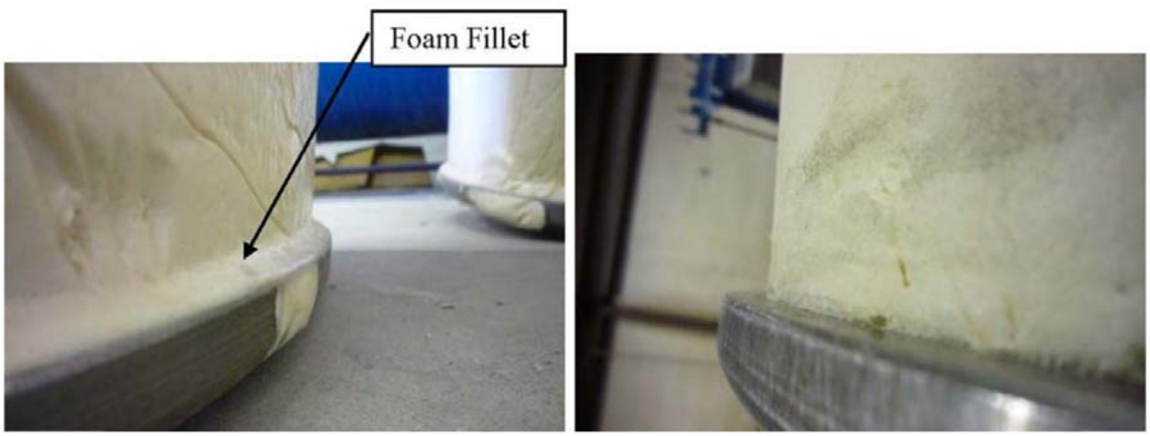


Figure 4. Root plate and foam core with (left) and without (right) the fillet

Source: Enertech 2011a

Figure 5 provides a schematic of the design intent, showing the laminate schedule and a representation of tension and compression plies. Figure 6 provides a schematic on how loads are designed to be carried in the root laminate and steel root plate.

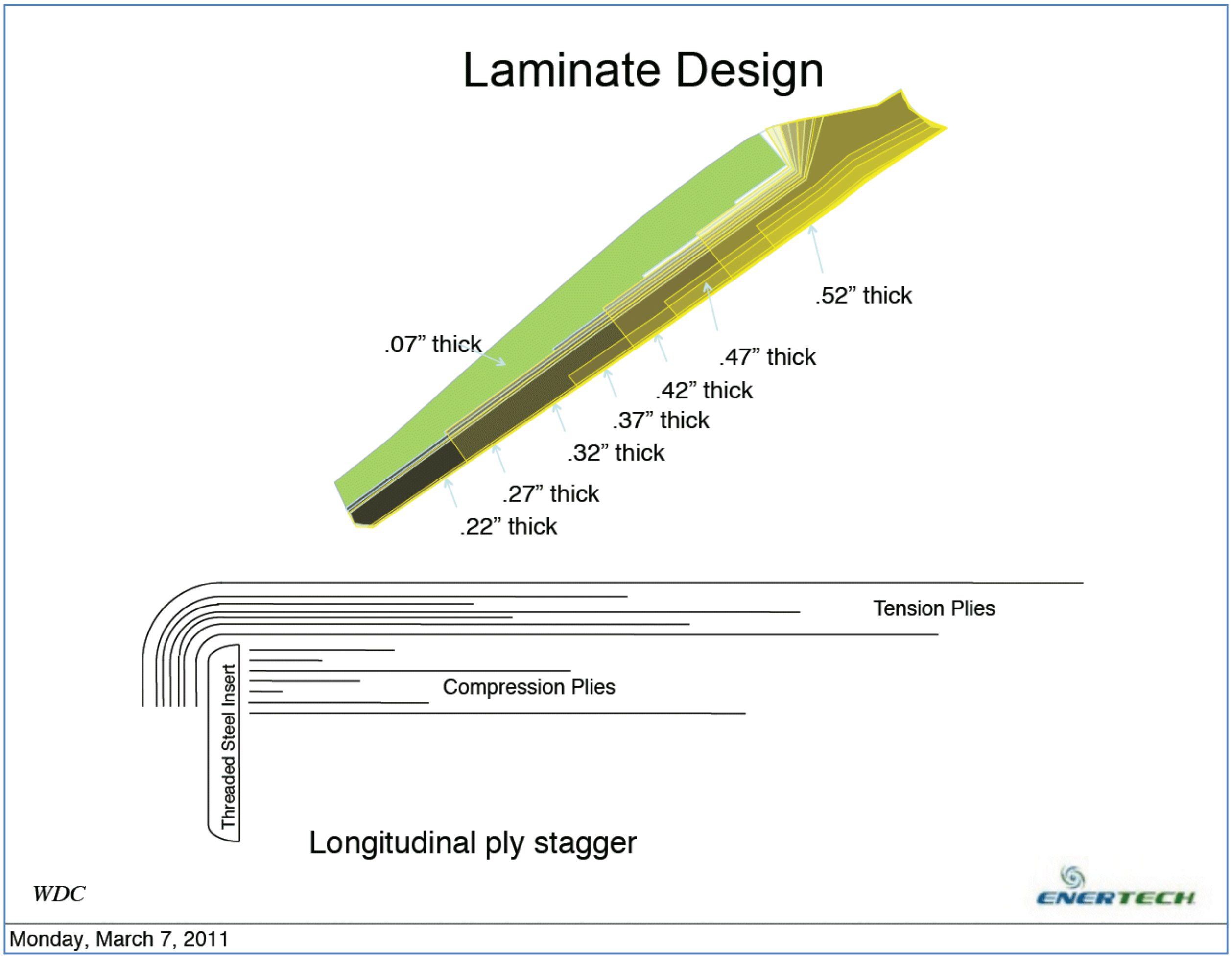


Figure 5. Laminate design

Source: Wadsworth, Nelson, and Kaufman 2011

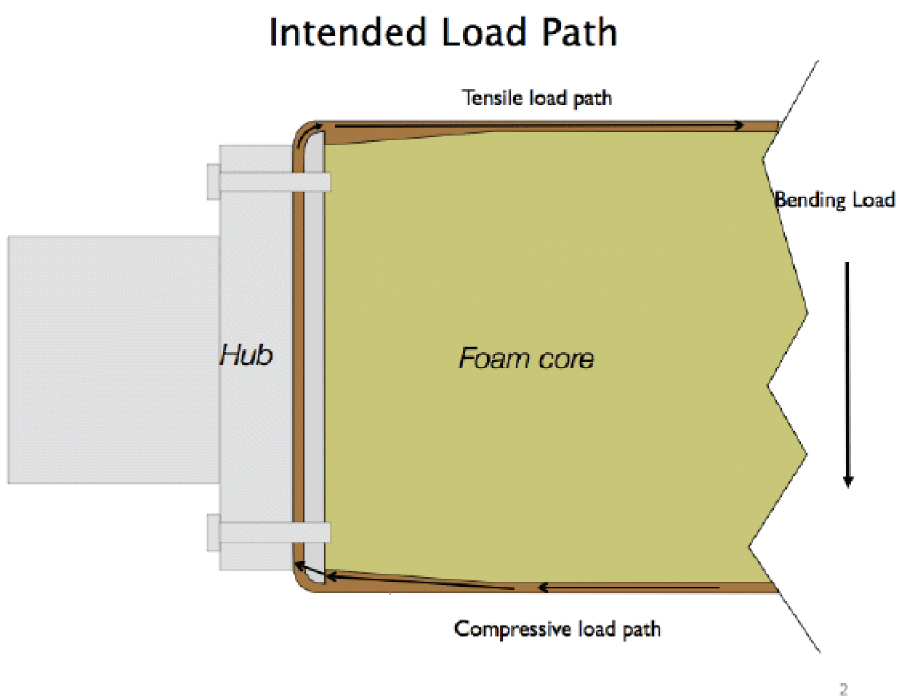


Figure 6. Enertech-stated load path in the root region

Source: Enertech 2012

During the January 17, 2012, design review, Enertech stated that design calculations of the blade structure were made; however, no documentation of the analysis was provided for review. In addition, Enertech provided justification for the theory that the presence of the foam fillet was the root cause of field failures because of the deviation in the intended load path. Figure 7 shows a description provided by Enertech on how the presence of the foam fillet was the sole source of the blade failures.

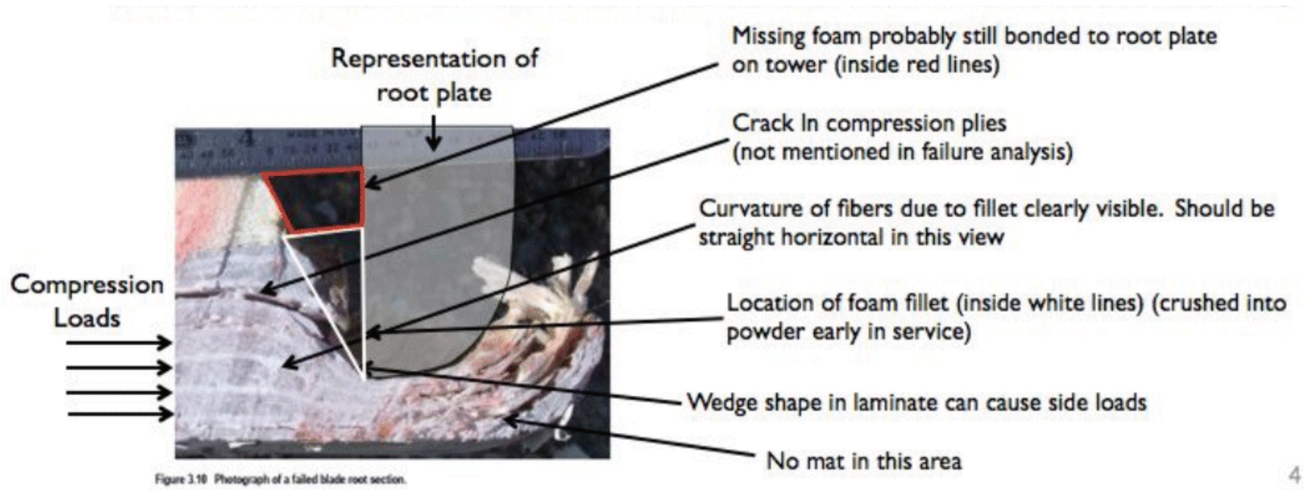


Figure 7. Enertech assumptions of failure mechanism

Source: Enertech 2012

The Enertech Analysis Document provides a summary of the design and test loads. Enertech stated that the simplified load calculation method from the IEC 61400-2 was used to determine the design fatigue load ranges. Additionally, Enertech employed a method for accelerating fatigue test loads that assumed small fiber and coupons, resulting in a relationship of the target test load at 1×10^5 cycles being double the value of the load at 1×10^9 cycles, with 1.8×10^9 being the Enertech design basis (Mandell, Samborsky, and Cairns 2002). Enertech also stated that the above relationship was based on similar materials tested at an R-ratio (minimum load/maximum load) of 0.1. Blade testing was conducted at R = -1. Table 1 provides the design and target test moments used for fatigue testing. Enertech identified the E44A as being a small wind turbine Class II machine.

Table 1. Fatigue Design and Test Moments

Fatigue Loads Provided by Enertech	Design Load [kiloNewton (kN)-m] for 1.8×10^9 Cycles	Target Test Load (kN-m) for 1×10^5 Cycles
Flap-wise peak-to-peak moment provided by Enertech	14.61	21.94
Edge-wise peak-to-peak moment provided by Enertech	11.14	16.73

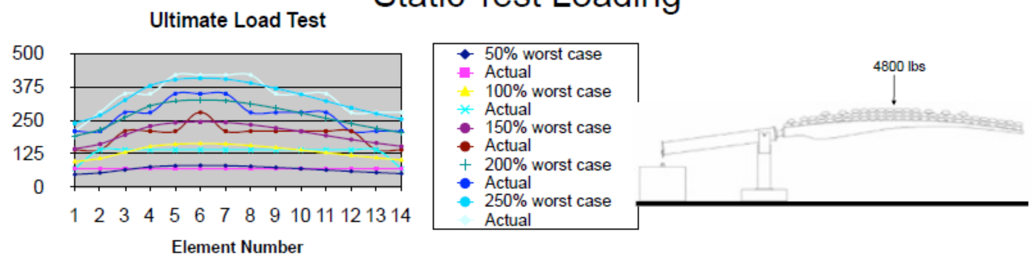
The Enertech Analysis Document describes the turbine modeling that was conducted with simulation software while using specified IEC 61400-2 "wind conditions." However, the document does not provide detailed information on all of the load cases that were simulated or the necessary inputs that were used to model the turbine. At the January 17, 2012, review meeting, Enertech stated that the static design loads were based on the parked 50-year extreme wind speed case. The design and target test loads for static testing from the Enertech Analysis Document are provided in Table 2. Only maximum positive test loads were provided, no values were provided for negative test loads, if conducted, and it was not stated if centrifugal loads were evaluated.

Table 2. Static Design and Test Moments

Static Loads Provided by Enertech	Design Load (kN-m)	Target Test Load (kN-m)
Flap-wise	36.82	71.08
Edge-wise	11.72	22.63

Figure 8 provides the static loading details included in the Enertech Presentation and provides the sand bag distribution used for loading the blade at increasing load levels. The information includes the distribution of the test load, as applied through the weight of sand bags, and provides the total weight applied by the sandbags: -4,800 lbs near mid-span. The total load applied (4,800 lbs) matches the weight distribution shown in the graphic in the upper left for 68 sand bags, which is consistent with the Enertech-stated 250% level in the tabular information.

Static Test Loading



Element	50%		75%		100%		125%		150%		175%		200%		225%		250%	
1	1		1		1		2	+1	2		2		3	+1	3		3	
2	1		1		2	+1	2		2		3	+1	3		3		4	+1
3	1		1		2	+1	2		3	+1	3		4	+1	4		5	+1
4	1		2	+1	2		3	+1	3		4	+1	4		5	+1	5	
5	1		2	+1	2		3	+1	3		4	+1	5	+1	5		6	+1
6	1		2	+1	2		3	+1	4	+1	4		5	+1	5		6	+1
7	1		2	+1	2		3	+1	3		4	+1	5	+1	5		6	+1
8	1		2	+1	2		3	+1	3		4	+1	4		5	+1	6	+1
9	1		2	+1	2		3	+1	3		4	+1	4		5	+1	5	
10	1		1		2	+1	2		3	+1	3		4	+1	4		5	+1
11	1		1		2	+1	2		3	+1	3		4	+1	4		5	+1
12	1		1		2	+1	2		3	+1	3		3		4	+1	4	
13	1		1		2	+1	2		2		3	+1	3		4	+1	4	
14	1		1		1		2	+1	2		3	+1	3		3		4	+1

WDC Bag Distribution Table: ENERTECH

Monday, March 7, 2011

Figure 8. Static load distribution

Source: Wadsworth, Nelson, and Kaufman 2011

The Enertech Presentation states that the predicted load limit for blades was expected to be 200% of calculated levels and the measured failure load was 250% of the calculated level.

A series of full-scale tests were performed by Enertech on different design versions of the blade at the company's facilities in Newton, Kansas. Although formal documentation of these tests was not provided, descriptions of the testing are included in the Enertech Analysis Document. Table 3 summarizes the testing performed on the blades, as described in the Enertech Analysis Document.

Table 3. Full-Scale Tests Conducted by Enertech at the Company's Facilities

Test Identifier	Blade Type	Test Type	Date	Applied Moment or Loading Description by Enertech	Reported Test Result by Enertech
"Blade Sample"	Unbolstered	Static positive flap	June 2010	In excess of 2.5 times the survival load for 120-mph wind (120-mph based on steady-state analysis)	Localized buckling approximately 40 inches from root
SN B1057	Unbolstered	Static positive flap	March 5 or 6, 2011	In excess of 1.75 times the calculated survival load	Failure at blade root
SN B1067	Unbolstered	Static positive flap	March 5 or 6, 2011	Similar to June 2010 blade	Compression skin buckling approximately 50 inches from blade root
Dynamic tests	Unbolstered	Flap and edge fatigue	Not specified	Alternating flap and edge loading. One-hundred-mph wind alternating direction. Load estimated by deflections.	Initiated and propagated cracks to imminent failure. Failure location not stated.
SN 1021-1	Unbolstered /Bolstered	Edge-wise fatigue and static	Not specified	**1.** Three-hundred hours in-field operation **2.** Edge-wise fatigue for 1.5 hours **3.** Bolster installed **4.** Edge-wise fatigue – 141,000 cycles at 44,000 ft-lb range (59.7 kN-m) **5.** Flap-wise fatigue – 102,000 cycles at 33,000 ft-lb range (44.7 kN-m)	**1.** Small cracks in root **2.** Leading-edge and trailing-edge cracks grow significantly **3.** No result (bolster installed) **4.** Steps four and five: small cracks outboard of bolster top edge, extending periodically 3 feet along the trailing edge

6.2 Information Assessment

6.2.1 Load Information

The Jackson Report contains a detailed description of the development and operational experience of the original Enertech 44/40 turbine. Additionally, the Enertech website cites the reliability and number of the original 44/40 machines still in operation and states that the E44A machine is the latest in the E44A design series (Enertech website 2012). Enertech did not provide any detailed technical information on the differences between the 44/40 and E44A beyond the general description of the new fiberglass blades and changes to the control system (Enertech 2012).

The background section of the Jackson Report covers the development and issues involved with a free-yaw downwind machine. It is important to note that the machine evolved and that, during the field verification program, knowledge was gained about unexpected loads from rapid yaw rates. The Jackson Report contains a detailed summary of field test campaigns of the original Enertech machines. The field test program for the original 44/40 was a comprehensive test program with standard engineering practice used to calibrate sensors and measure data. Figure 9 provides time-block-averaged data for the flat-wise bending moments that were collected for the field testing. The highest average value recorded was 29 ft-kip at 35 mph (1 kip = 1,000 lbs). Note that the highest loads for wind turbines do not necessarily correlate with increasing wind speed, as loads can be generated by yaw events, turbulence, or other load cases. This is shown in the data set as the flat-wise maximums occur at 35 mph. Edge-wise loads from the same campaign are shown in Figure 10.

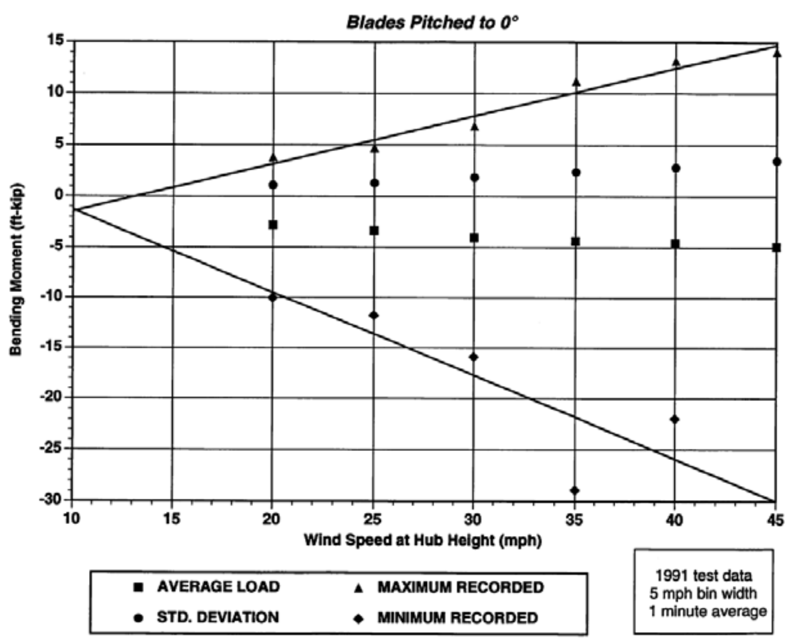


Figure 9. Enertech 44/40 blade root flat-wise bending moment recorded (maximum and minimum versus wind speed), as measured during the California field testing

Source: Jackson 2012

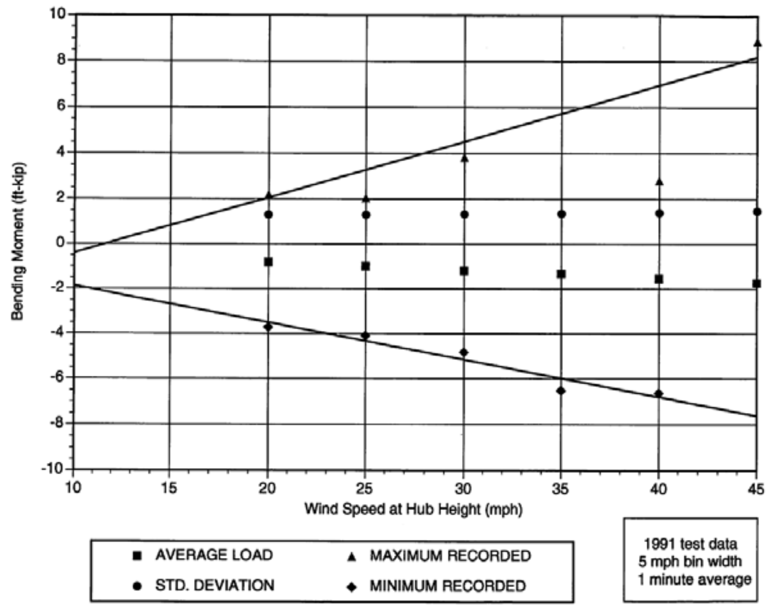


Figure 10. Enertech 44/40 blade root edge-wise bending moment recorded (maximum and minimum versus wind speed), as measured during the California field testing

Source: Jackson 2012

Fatigue measurements were also conducted as part of the testing. Figures 11 and 12 provide data for the flat-wise and edge-wise fatigue alternating loads (half of peak-to-peak loads), as a function of frequency of occurrence (counts per minute). Flat-wise data are provided for a wind speed of 35 mph with locked and free yaw configurations. Note from the data how locking the yaw degree of freedom decreases the measured load, thereby underscoring the nature of downwind free yaw turbines being load sensitive to load cases that are dominated by yaw rates. Edge-wise data are provided across different wind speeds.

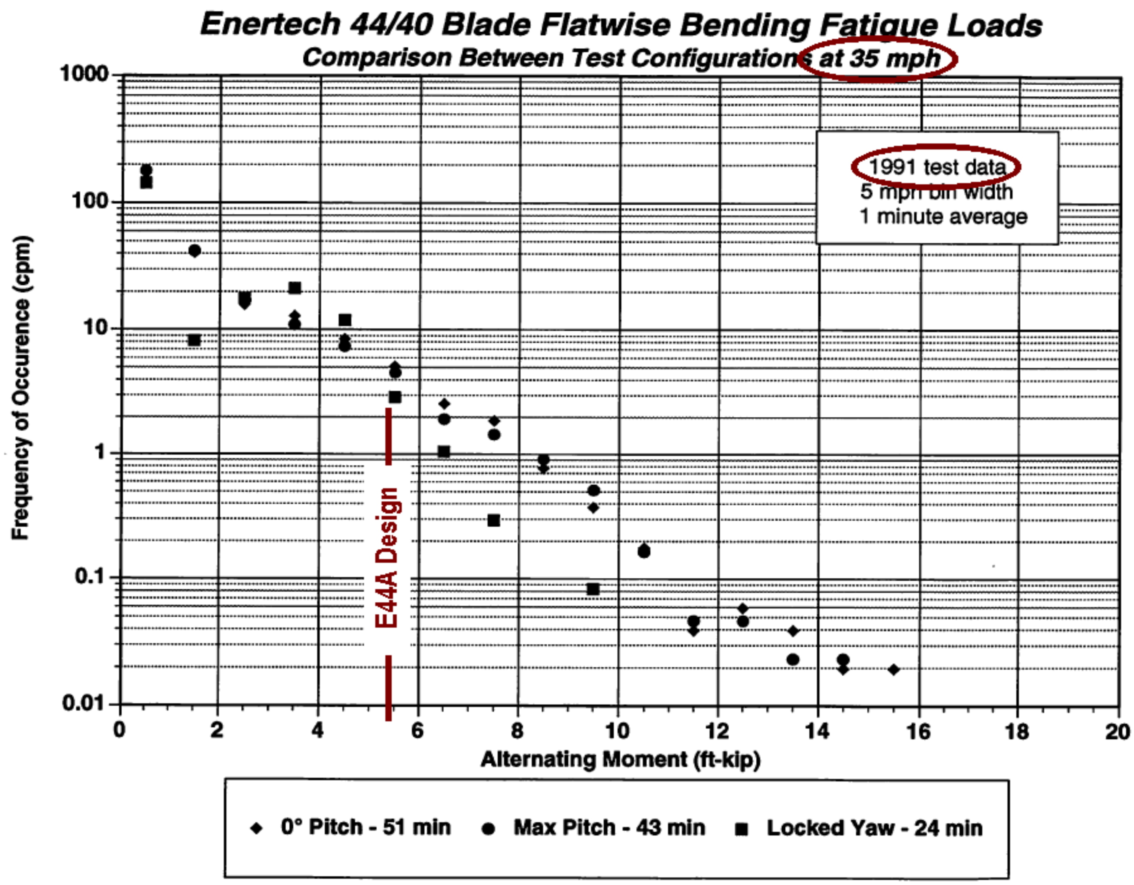


Figure 11. Enertech 44/40 blade root flat-wise alternating bending moment versus wind speed, as measured during the California field testing

Source: Jackson 2012

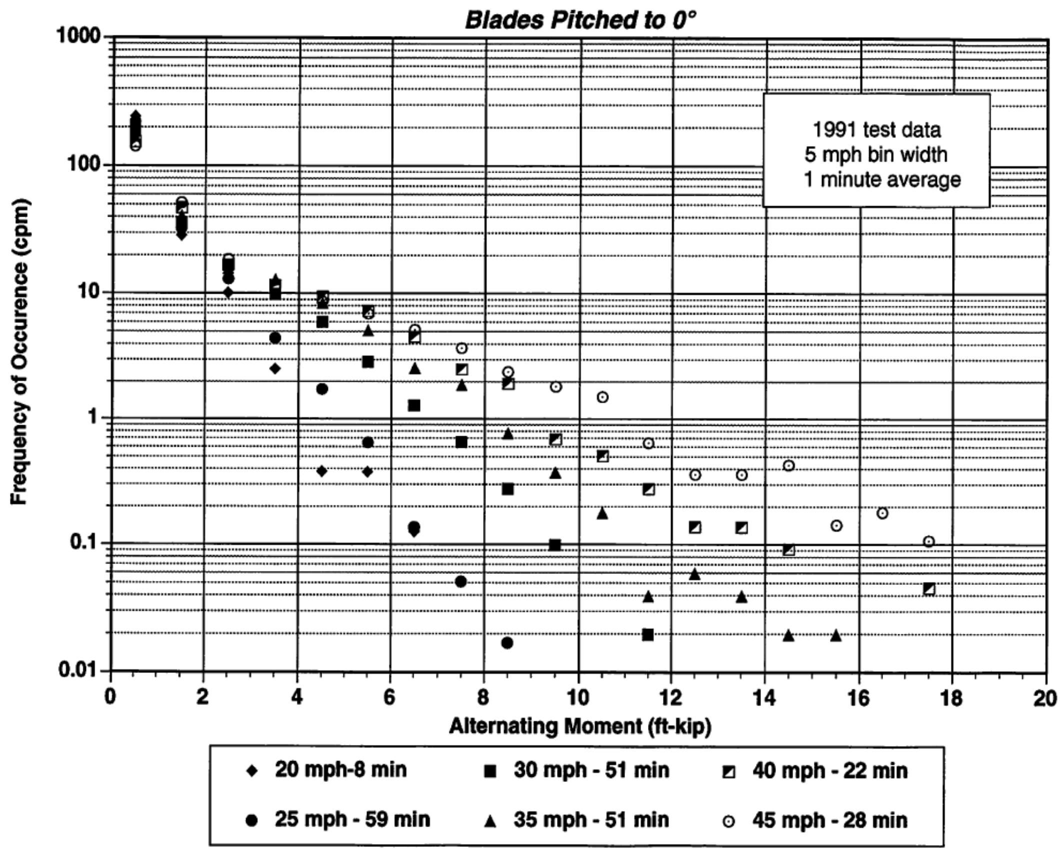


Figure 12. Enertech 44/40 blade root edge-wise alternating bending moment versus wind speed, as measured during the California field testing

Source: Jackson 2012

Loads measured in the field are used to validate design assumptions for both extreme events (periodic high load) and fatigue loading (repetitive bending and loading of a structure over its lifetime). To meet a specified lifetime, structures must be designed to handle both extreme and fatigue conditions. Furthermore, field loads testing is required for IEC 61400-1 certification.

The Jackson Report details the development and simulation of a turbine aeroelastic model. This model was developed to benchmark performance and load characteristics of a turbine with specifications and a design equivalent to the E44A. The model also provides a technical basis for the sensitivities of the wind turbine power production and mechanical loads that are caused by unsteady aerodynamic effects, dynamic yaw motions, and the influence of air density on loads and power. The significant issues with downwind free yaw designs include:

- High Coriolis or gyroscopic effects from yaw that can exceed aerodynamic moments
- Unsteady aerodynamic loading caused by misalignment of the rotor with the prevailing wind direction
- Dynamic stall caused by changing angles of attack, leading to increased blade loading.

In addition, the Jackson Report includes the following information that supports the need for advanced engineering and testing for stall-regulated, free-yaw wind turbines:

- Fixed-hub, rigid-blade downwind machines are predicted to be unstable in yaw at high wind speeds, using standard blade element momentum theory.
- Corrections for skewed wake effects are typically made to the basic blade element momentum method when the rotor operates at a yaw angle.
- Dynamic stall hysteresis is important in determining yaw moment and dynamics. Existing models are adequate in predicting stall hysteresis, provided that the empirical constants are known in advance.

The Jackson Report also describes the influential loading cases for downwind free-yaw machines. The model (discussed above) was built using the NREL aeroelastic simulation code FAST. The analysis considered a normal turbulence model running multiple load cases (33 for each power production database), including:

- Eleven wind speeds, from 5 to 25 meters per second (m/s)
- Three random turbulence "seeds" at each wind speed
- NREL code Turbsim used to build the inflow files for the normal turbulence model
- Yaw and generator degrees of freedom
- Three set pitches
- Two densities (standard–1.225 kg/m^3 and cold–1.474 kg/m^3)
- Steady-state and dynamic stall cases.

Per the IEC 61400-1, a loads analysis includes the simulation of many additional load cases and system degrees of freedom. While the approach and results presented here are valid for the examined load cases, they should not be considered as conservative, as the evaluation of additional load cases could result in the identification of load cases with higher loads.

Figure 13 shows a comparison for root-flap loads, comparing the model and field data for steady and dynamic stall cases. The comparison indicates that the model is able to suitably predict actual moments from field tests.

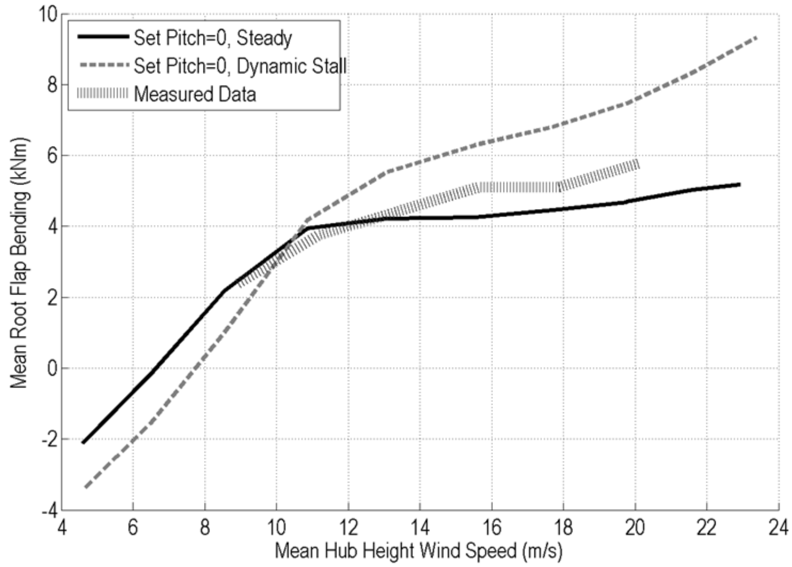


Figure 13. Mean flap moment comparison between the California field test data with FAST simulations

Source: Jackson 2012

Comparing the modeled result with field data is important, as this is a critical step in not only validating the design assumptions but also for validating the inputs used in the simulation tools. Simulation tools are only as good as the user inputs and how the user analyzes and interprets the results. Comparing simulated estimates with actual field data provides an end-to-end check on the design, simulation, and test and validation process.

Figure 14 provides a comparison between the FAST run simulations for the steady state under dynamic stall conditions with data from a WT_Perf simulation. WT_Perf is an NREL code employed to estimate the steady-state operating conditions and is typically used as a first-order design tool to estimate the power performance and steady-state loads. WT_Perf simulations do not include dynamic events that are present in actual turbine operation. The comparison in Figure 14 shows that the Enertech values fall between the Jackson model values, with the Enertech curve below the dynamic stall case. It is important to note that the steady-state evaluation will underpredict power and loads relative to aeroelastic simulations, including dynamic stall. Note the sensitivity in the range due to the dynamic stall. Power curves were developed for comparison as Enertech did not provide load curves.

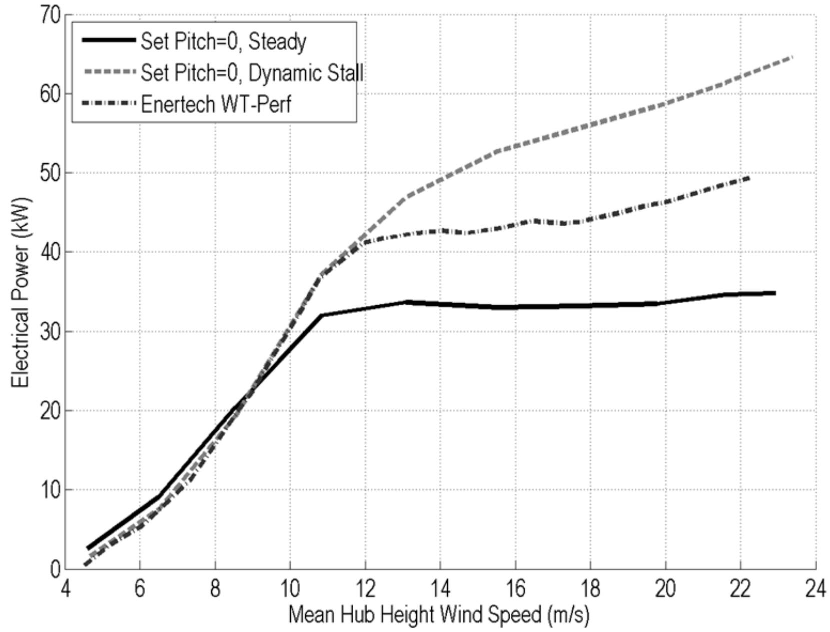


Figure 14. Simulation results of the power for steady and dynamic stall cases that were run using NREL FAST compared to steady-state values that were run using WT_Perf

Source: Jackson 2012

The potential range in power (roughly relatable to loads) shown in Figure 14 is wide, which demonstrates a need to use refined tools to improve model results and provide conservative power and load estimates.

Figure 15 compares bending curves at different densities and pitch settings. Note the influence of air density on the loads. The Enertech design value is also shown.

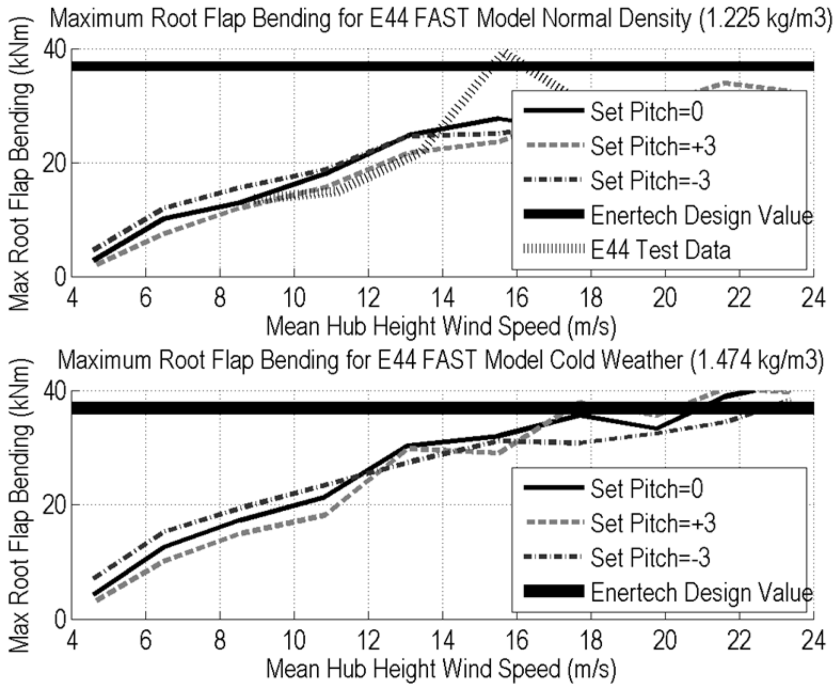


Figure 15. Maximum root flap-wise moment as a function of wind speed under standard and high air density conditions

Source: Jackson 2012

The Jackson model was based on the available blade information from the Enertech Presentation and according to specifications of the original 44/40 (for the balance of the system). The performance specifications provided by Enertech for its new E44A match parameters from the original Enertech 44/40 1984 specification. Although there could be differences between the as-modeled E44A and the as-built 44/40, the Jackson model demonstrated its ability to represent the characteristic power and loads of both turbines. Additionally, results of the Jackson simulation demonstrated the effect of unsteady aerodynamics and yaw dynamics, showing that:

- Dynamic stall has a strong influence on and ability to increase both power and bending moments by a factor of two
- Yaw characteristics have an appreciable influence on the loads of downwind, free-yaw turbines
- Simulation tools are an effective means of determining this influence when dynamic stall parameters are known in advance (through field tests, measurements, and validation)
- Air density is very influential and can increase loads by 25% in cold, humid conditions
- A standard approach exists and can be used to develop, model, document, and validate a loads analysis.

6.2.2 Blade Forensic Information

Both the Jackson and Wetzel Engineering reports contain detailed forensic assessments. All three unbolstered blades inspected at the Knoeller site had the steel root plate and fasteners torn away. The blade root laminate showed a consistent line of laminate fracture near the edge of the steel plate and the laminate surrounding the fasteners was torn away during the failure event. Figure 16 shows a photograph of the failure that is representative of all three blades. In addition, two areas commonly referred to in the assessment—the flange and periphery—are identified.

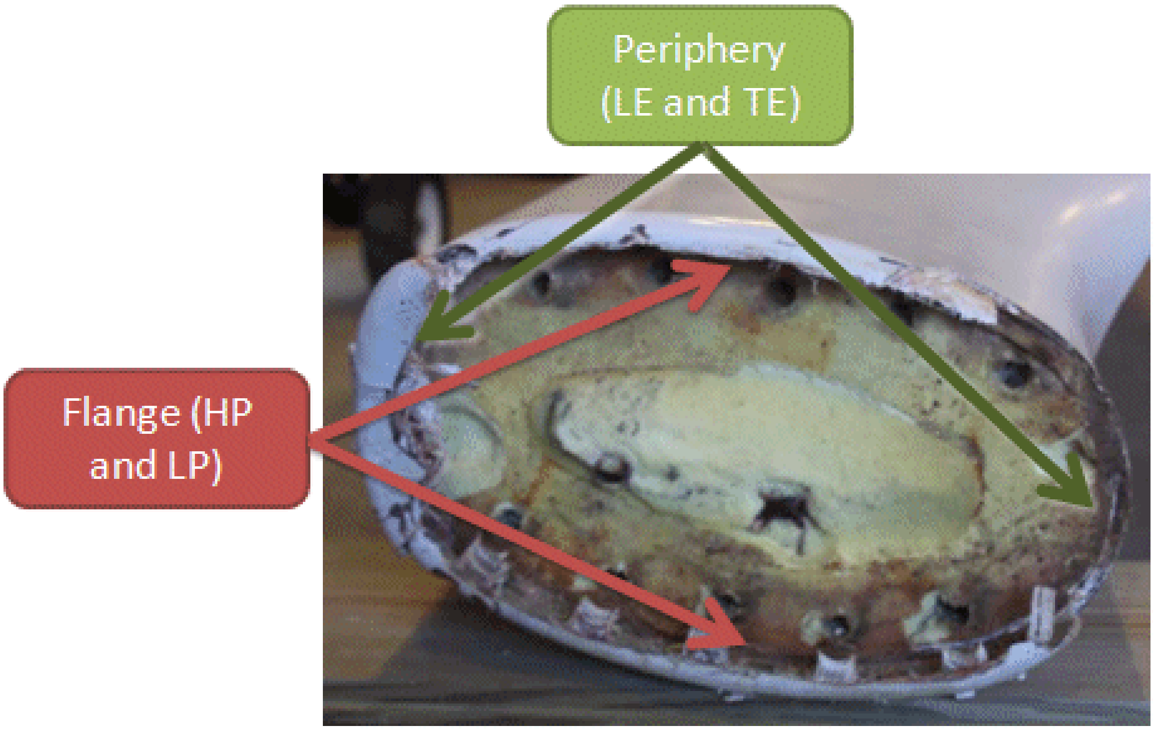


Figure 16. A failed blade root section
Source: Dynamic Designs 2012

As shown in Figure 17, a section cut was made in the low-pressure flange to reveal a cross section of the laminate in the root-to-tip plane. The steel root plate is not shown (still attached to the hub).

Figure 17. Root-to-tip section of low-pressure skin in the root area

Source: Dynamic Designs 2012

Figure 18 shows the above section (Figure 17) from a slightly different angle. Note in this figure that there is a region of composite laminate that is bearing against the steel plate.

Figure 18. Contact area of composite against steel plate (steel plate missing)

Source: Dynamic Designs 2012

Figure 19 indicates the location of the failure on the flange relative to the steel root plate. The fiberglass laminate at the blade root showed evidence of inter-laminar failure of the resin.

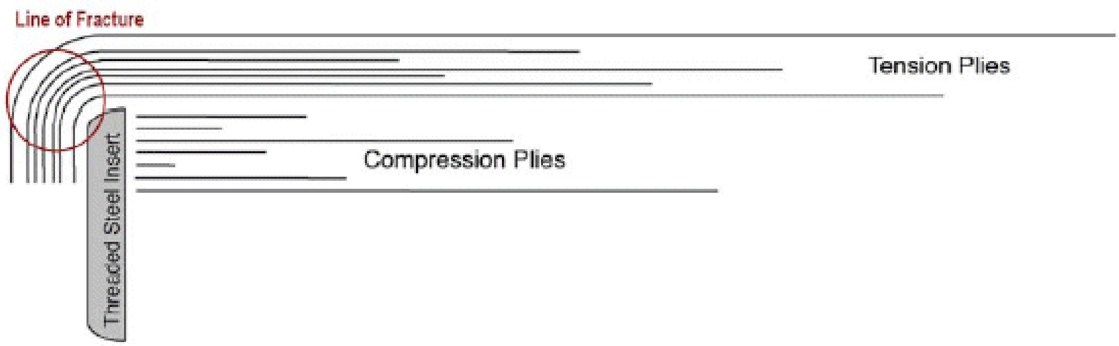


Figure 19. Location of blade failure in the laminate

Source: Wadsworth, Nelson, and Kaufman 2011

Figure 20 provides a description of stress concentration factors that are present in the root region of the unbolstered blade design. These stress concentrations would also be present in bolstered designs, however, the load path through the bolster would influence the effect of the stress concentrations on the composite structure.

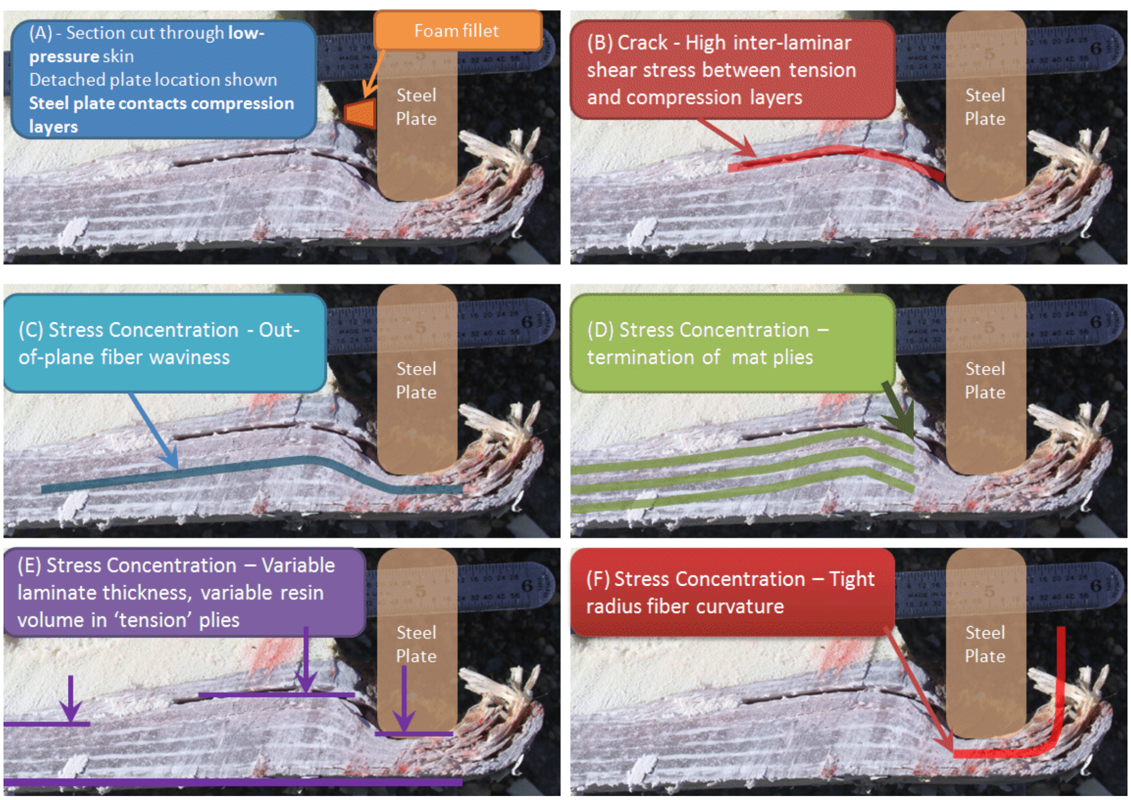


Figure 20. Identification of stress concentrations in the root laminate

Source: Dynamic Designs 2012

Each of the details shown in Figure 20 are defects that could add significant stress concentrations (such as reducing nominal strength and fatigue lifetime) to the nominal performance of a given design. These defects are described as follows:

- **A crack between tension and compression plies**. The presence of this crack validates that there are significant inter-laminar shear stresses between the "tension" and "compression" plies. Without proper adhesion or through-thickness composite properties, this can be an area that is susceptible to damage due to the stress concentration at the termination of the "compression" fibers at the steel plate.
- **Out-of-plane fiber waves**. The strength and fatigue properties of composites with waves are softer and weaker than composites with straight fibers, as the wavy material has properties that are more similar to the resin than the fiber.
- **Ply drops**. Termination of laminate plies is a well-characterized stress concentration, as the load is transferred from thicker to thinner material.
- **Variable laminate thickness**. Variations in laminate thickness can behave similarly to the laminate waves described above, with properties closer to the neat resin properties and stress concentrations caused by the changing fiber alignment.
- **Small radius laminates**. Stress concentrations are present because of the small radius of curvature around the steel plate resulting from both axial and bending loads being transferred around the radius.

In addition to the stress concentrations, there is a large change in stiffness in the root design of the unbolstered blade design, as either tension or compression loads are transferred from the laminate into the steel plate. Additional information on stress concentrations is provided in the Jackson Report.

6.2.3 Design Assessment

Wetzel Engineering performed a design assessment of the blades and included detailed information in the Wetzel Report. This assessment was the most comprehensive analysis possible, given the level of detail provided by Enertech. Enertech supplied only high-level documentation on the design and manufacture of the blade and included basic descriptions of laminate schedules, a one-page manufacturing plan, and material (not structural composite) data sheets from material suppliers (these documents are identified in the Wetzel Report). Load information came from the basic summary information from the Enertech Analysis document and the Enertech Load Summary document. Substantial additional documentation detailing loads, design, and manufacturing assurance would have been necessary to conduct an assessment to demonstrate conformity with standard design practices or compliance with relevant standards. The Wetzel Report used the available information to assess the Rev A (unbolstered) and Rev B (bolstered) designs. Figure 21 provides a schematic of the load path and general design intent between the unbolstered and bolstered designs.

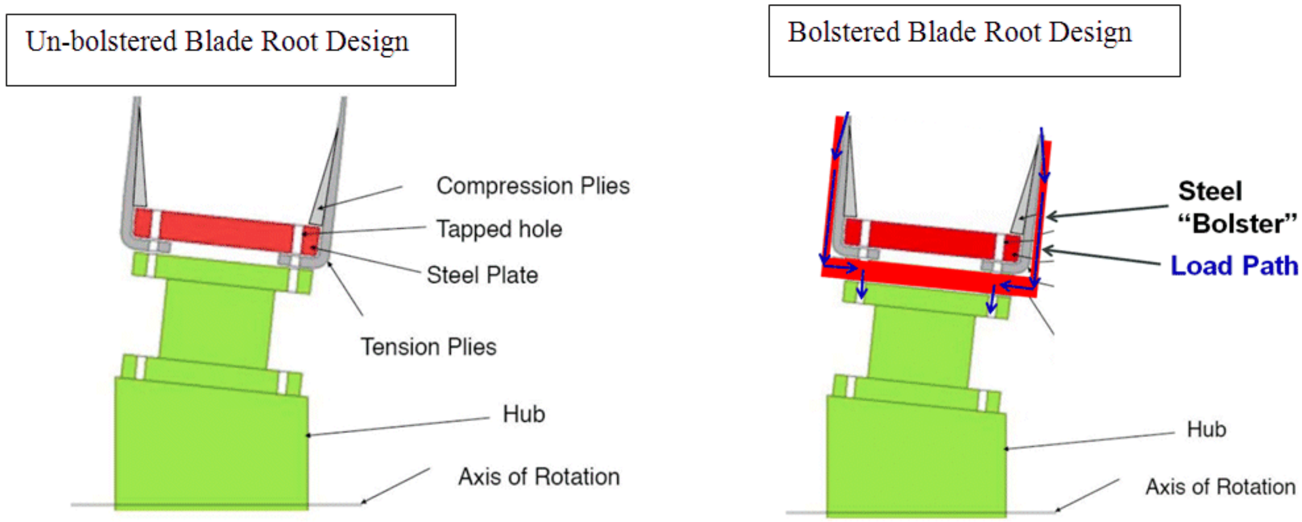


Figure 21. Unbolstered (left) and bolstered (right) designs

Source: Wadsworth, Nelson, and Kaufman, 2011 (left), and Wetzel Engineering 2012 (right)

The Enertech Presentation includes basic information on the laminate schedule. Information provided by Enertech to Wetzel Engineering indicated a change in laminate schedules between the Rev A (unbolstered) and Rev B (bolstered) designs. These changes were indicated as:

- **Compression plies**. The Rev A blade used 4 plies of unidirectional glass fabric that was oriented along the axis of the blade completely around the perimeter at the root plate. The Rev B design used 1 ply of bidirection +-45 glass against the foam core, plus 5 plies of unidirectional glass that was oriented along the axis of the blade completely around the perimeter of the root plate, with 5 plies of continuous filament mat in between the unidirectional glass.
- **Leading edge**. Starting at the foam core, the Rev A blade used 9 plies of continuous glass filament mat. The Rev B design used 5 plies of unidirectional glass, starting at the foam core, with 4 plies of continuous filament mat in between the two.
- **Trailing edge**. The Rev A design used 4 plies of continuous filament mat. The Rev B design used 5 plies of unidirectional glass, starting at the foam core, with 4 plies of continuous filament mat in between the two.

Drawings provided to Wetzel Engineering by Enertech (Enertech Drawing 130000 that was not provided for group review) were understood to be for the Rev B (but without bolster) design. However, during the design review, Enertech staff indicated that the identified changes above may not be representative of the actual build. Differences in unidirectional, double-bias, and continuous filament mat locations and quantities varied between Enertech sources. Enertech indicated that the drawing was not the same as those used on the production floor, which were engineering drawings only. Enertech provided an additional description of the laminate schedule indicating that the drawings were correct, but with additional notations (Kaufman 2012). It is possible, but not confirmed through documentation from Enertech, that the drawings or information provided do not represent the final Rev B version.

Using information provided by Enertech, Wetzel Engineering performed a first-order structural analysis of model blade roots that represented both Rev A (unbolstered) and Rev B (bolstered) designs. The model is detailed in the Wetzel Report. The structural analysis performed was consistent with standard industry practices. Values used for determining limit-state stresses and strains in wind turbine design were consistent with industry and certification body guidelines (Germanischer Lloyd 2010 and DNV 2010). Finite-element analysis was used to build representative structures of both bolstered and unbolstered designs. Loading was applied to the model in a single direction. It was acknowledged that the models may not exactly represent the as-built blades, given the lack of detailed design information provided by Enertech. However, the models were characteristic because they captured the ideal material properties and the geometry of the structure. Therefore, the results represented an Enertech blade with ideal material properties.

The results of both the Wetzel Engineering characteristic Rev A and Rev B models indicated that nominal stress and strain levels were high compared to standard design practices. The Wetzel models represented an ideal structure. Decreases in strength and fatigue performance of the as-manufactured blades would be expected, as the presence of stress risers within the laminate (noted in Figure 20) were not considered in the Wetzel model. The characteristic Rev B bolstered design indicated very high stress levels in the adhesive bond that holds the bolster to the fiberglass shell. The stress levels modeled in the adhesive bond would exceed the accepted Germanischer Lloyd (certification body) level of 1,000-psi, which would be the stress level used for certification in the absence of test data.

If manufacturing revisions are made to the blade by reducing the foam core volume, resin-rich areas could increase in scale, and the severity of the fiber waviness in the area could increase. Both of these effects could increase the severity of the stress concentration in the root region.

6.2.4 Testing Assessment

It was not possible to assess the accuracy of the Enertech test results. All test results included in this report are based on information provided in the Enertech documents. The Enertech testing was not done at an accredited blade test laboratory. Furthermore, evidence of a comprehensive quality management system was not provided by Enertech.

Figure 8 (from the Enertech Presentation) provides basic information on the load magnitudes applied by Enertech during the static loading. The total static test load shown (4,800 lbs), compared to the bag distribution for the 250% of 68 bags, resulted in a per-bag weight of 70.6 lbs. A root-bending moment of 50,188 ft-lb was obtained by using the information in the bag distribution table for the Enertech-stated 250% load. Appendix A provides the analysis for this calculation. The weight of the blade added an additional moment to the total applied test root moment. Using an assumed blade weight of 325 lbs, with a center of gravity at 8.5 ft from the root of the blade, resulted in a root moment of 2,763-ft lbs. The total applied root moment during the static test would be the sum of bag weights and blade weight moment. For the Enertech-stated 250% target loading, the root moment would be 50,188 + 2,763 = 52,951 ft-lb (71.8 kN-m). While the weight and center of gravity was estimated, differences between estimated and actual values would have a very small effect on the analysis that follows.

Using the same approach, and with information from the bag distribution table in the Enertech Presentation, the 100% survival load (120 mph) would result in a root bending moment of 21,161 ft-lb (28.7 kN-m).

Enertech provided results in both metric and imperial units. A conversion factor of 1 ft-lb = 1.3558 N-m was used for unit conversion in this document. Table 4 provides information on the test and design loads. A characteristic load based on the Jackson Report is given in Table 4 and employs conservative parameters for air density observed in cold environments. The characteristic load estimated from information provided in the Jackson Report was factored according to the same partial load factors used by Enertech as the basis for the Enertech-reported target test load. Enertech stated that respective blades failed at loads "in excess" of stated levels (Enertech 2011a). As the actual level was not specified, the levels reported by Enertech are provided in Table 4.

Table 4. Design and Test Load Summary

Design or Test Load Description	Calculated or Stated Moment [kN-m]
Enertech-stated 100% of survival load (120 mph)	28.7
Enertech-stated test result of blade "SN B1057"	50.3
Enertech-stated 200% of survival load (170 mph) – Enertech-stated predicted limit load	53.0
Enertech-stated target test load	71.1
"Blade sample" (stated 250%) result	71.8
"SN B1067" (stated 250%) result	71.8
Characteristic load based on Jackson analysis	77.2

There are several items to note from the results of the Enertech testing, compared to the design and analysis targets. These items include:

- The Enertech Presentation states that the blade had a predicted static flap limit load of 200%, indicating that the blade was designed for an ultimate root moment of 57.44 kN-m. This is below the factored target test load of 71.1 kN-m.
- There is a minimal safety margin between two of the stated static test results and the Enertech target test load. Standard design practice is to have a design that has an appreciable safety margin between factored test loads and the ultimate strength of the blade.
- Blade SN B1057 failed at a load less than the Enertech-stated target test load.
- The failure modes of the three blades were different: blade B1057 failed at the root, blade B1067 failed 50 inches from the root, and blade B1067 failed 40 inches from the root.

- The disparity of the load levels and locations of the failures for each of the test articles could call into question the applicability of Enertech's use of a 1.1 factor (10% coverage factor) for blade-to-blade variation. The variation in failure load between the articles tested is on the order of 30%.
- The characteristic load based on the Jackson Report is higher than all blade failure loads tested at Enertech.

In contrast to the static load analysis, where aeroelastic simulation tools are used to generate target test loads, Enertech used the simplified loads approach from the IEC 61400-2 to determine blade fatigue loads. Equation (49) from the IEC 61400-2 standard is cited by Enertech as the basis for the fatigue load, but it does not consider the full clause (7.9.2) of the standard. Section 7.9.2 of the IEC 61400-2 standard prescribes that, when no material performance data (S-N data) is available, ultimate material strength estimates should be used with a factor of safety of 10 (10 times multiplier) to establish the fatigue design basis and corresponding test loads. Enertech did not provide material performance data. Therefore, section 7.9.2 of the IEC 61400-2 standard is not met, based on the information provided by Enertech. The fatigue testing reference provided by Enertech to justify the acceleration of design cycles to test fatigue cycles and levels pertains to very specific testing of small strand composite, low-force coupon testing (Mandell, Samborsky, and Cairns 2002). This reference cites difficulties in interpreting results for larger volumes of materials that represent wind turbine composite construction. Enertech did not justify the use of this approach in the documentation. Standard accepted methods for accelerating fatigue loading are available and recommended for future analysis and testing (Freebury and Musial 2000).

The Enertech Analysis document asserts that the IEC 61400-2 allows mean values of the load ranges to be ignored. In addition, the Enertech Analysis document did not provide information on the design basis for the fatigue load acceleration method using an R-ratio (minimum load/ maximum load) of R = 0.1, while testing was performed at R = -1. The IEC 61400-23 requires a description of R-ratio effects (section 6.4 of the standard) and the IEC 61400-2 (section 9.5.2 of the standard) requires that, when fatigue testing is performed, it shall meet the requirements of the IEC 61400-23.

Without further information on the blade design and calculated or estimated material properties, it is not possible to: determine if the design or target test loads are representative of testing the full design life of the turbine; assess the actual performance of the tested blades.

For all tests, no information was provided by Enertech that indicated if plastic deformations of the blade had occurred or if the stiffness (load/displacement) of the blade had changed during the testing. No strain data was provided to check local deformations and material responses. This information is necessary for compliance with both IEC 61400-2 and IEC 61400-23 standards.

For all blade tests, no information was provided by Enertech regarding post-mortem inspections or procedures where the blades were cut to determine the root cause of failure. Enertech described cracks and probable causes of failure, but further sectioning and documentation of the results are needed to validate the assumed root cause of failure, and the effect that damage might have on turbines operating in the field.

7 Fact Findings and Determination of Causes

7.1 Fact Findings

The findings presented here are inclusive of all comments and documentation provided by Enertech, NREL, and NREL subcontractors Dynamic Designs and Wetzel Engineering. These findings are a comprehensive assessment of the failure and blade design based on all of the information provided by Enertech at the time of the assessment. The main outcomes of the assessment are identified below.

- Failure event:
  - Three Enertech blades failed at the root connection from the Enertech E44A machine at the Knoeller site in New Jersey
  - Failure of the blades occurred during normal operation
  - Control system modifications were not considered a primary or contributing source of failure.
- Failure assessment:
  - The unbolstered blades at the Knoeller site separated from the hub, with the incipient failure plane in the region of the embedded steel plate
  - Post-mortem inspections of the failed blades at the Knoeller site revealed geometric and material stress concentrations in the highly stressed root region and included out-of-plane fiber waves, variable composite resin fraction, cracks between “tension” and “compression” plies in the laminate, tight-radius fiber curvature, laminate ply drops, and change in stiffness between steel and composite elements
  - The embedded steel plate of the Knoeller blades was found to be in contact with the “compression” plies in areas on the low-pressure (compression) surface. This countered the Enertech assertion that the presence of the foam fillet was the sole cause of failure.
  - There was no evidence that the failure was caused by improper installation or operation, including control system modifications.
- Design assessment:
  - Enertech provided only summary blade root bending moment information for static and fatigue loads. This information lacked sufficient detail to properly assess the validity of design loads and how they were derived.
  - Lack of design information provided by Enertech limited the ability of the investigators to perform a detailed assessment
  - The method used to develop design fatigue loads would not comply with IEC 61400-2 because:
    - There were no data on the material fatigue performance

        - There was no certification body review
        - There was no evidence of a quality assurance system (required per section 5.3 of IEC 61400-2)
        - There were no material strength safety factors
        - There was a lack of consideration for environmental effects
    - There was no field data measurements to validate power performance or design loads
    - Discrepancies in information provided by Enertech suggested that the blade design and manufacturing process is still changing
    - Characteristic models showed sensitivity of air density, pitch, dynamic stall, and yaw motion on downwind free-yaw machines
    - Characteristic structures modeled showed high stresses in the root areas for both the bolstered and unbolstered designs
    - Fatigue load estimates were calculated by Enertech using simplified methods of IEC 61400-2, whereas static load estimates were calculated by Enertech using aeroelastic analysis. Information regarding consistency between these methods or why different methods were used was not provided.
- Blade testing did not conform to either IEC 61400-2 or IEC 61400-23 standards, because:
    - The blade test documentation did not contain key requirements for certification testing, including data confirming no loss or loss of stiffness, effect on structure due to observed cracks, or plastic deformations
    - There was no root cause documentation of test results provided by Enertech
    - There was no verification of the methods used to accelerate design fatigue loads to test equivalents
    - There was no substantiation of the applicability of the test R-ratio
    - There were large variations observed in failure loads and mechanisms in blades tested at Enertech
    - The load factors used for testing could not be substantiated
    - Testing was not completed at an ISO 17025-accredited test lab
    - Ultimate failure loads of two test articles were shown to have a limited margin relative to the target loads
    - One test article failed at the root below the Enertech target test load.

7.2 Determination of Causes

The stress concentrations in the blade root laminate are considered here to be the primary cause of failure of the Rev A (unbolstered) blades. These defects are caused by the blade design and manufacturing process. The defects include fiber waviness, variable resin thickness, small radius curvature, and high inter-laminar shear stress. All of these defects exist in a small region near the root and together constitute a complex joint with very high stress concentration factors. The presence or nonuniformity of the foam fillet would add an additional stress concentration to the region. As a result, this combination of stress concentrations in a small area led to excessive fatigue strains that exceeded material capabilities in the composite resin and subsequently caused the complete failure of the fiberglass reinforcement.

8 Ongoing Risk Versus an Isolated Incident

The characteristic loads and structural analyses documented in the Jackson and Wetzel reports indicated that there are high loads imposed on turbines and structures of this type and significant stress concentrations in the blade as manufactured. The margins of safety in the technical analyses conducted for the characteristic structures indicated that the blades could be susceptible to further field failures regardless of the design [such as Rev A, Rev B (unbolstered), and Rev B (bolstered)] being used.

To predict the likelihood of field performance, a small population of test articles can be tested. However, this approach requires that the testing program sufficiently captures representative load cases and addresses the sensitivity of load, design, and manufacturing deviations. This involves a substantial amount of engineering analysis to quantify the design and materials used in the structure as well as testing to validate design assumptions. Without a design basis, it is not possible to ensure the reliability of a fleet of blades that have undergone only limited sample testing. The blade-to-blade variations seen during the testing performed at Enertech, combined with the results that there was a small or negative margin between target and test loads, and questions on the design stability (e.g., it is unclear if Rev B is the final production version), indicate that a continued problem with serial field failures is possible.

Enertech has not provided sufficient technical data or documentation to the investigation team to confirm that the blades are compliant with IEC 61400-2 and IEC 61400-23 requirements, or that the current design (bolstered or unbolstered) can survive the stated 20-year lifetime of field operation.

9 Conclusions

This investigation was impaired by the limited amount of information provided by Enertech, compared to the level and amount of information that is normally expected for a rigorous design or certification assessment. Enertech did not provide the technical information needed to properly determine if the turbine conforms to a finalized and stable Enertech design, and if this design meets the Enertech-stated performance and reliability expectations. Statements of compliance to IEC 61400-2, IEC 61400-23, or any other standards, should be made by qualified certification agencies rather than manufacturers or designers. The primary conclusions of this work are:

- The Knoeller blades failed because of excessive stress concentrations in the blade roots (as described in Section 6.2.2)
- Unbolstered blades present a high risk of failure
- Lack of documentation provided for this study prevented the investigators from endorsing the redesigned, bolstered blade configuration. As a result, investigators came to the following conclusions:
    - Discrepancies in data and information indicate a lack of design stability
    - Stress levels observed in the bolster-to-laminate bond in the characteristic model exceed certification body guidelines
    - Bolstered blades appear to represent a reduced, but still serious, risk of failure.
- Enertech stated in the design review and written comments (Enertech 2012a) that the blade meets the requirements of the IEC 61400-2. However, the discrepancies in the approach used by Enertech in the design and testing of the turbine blades relative to the IEC standards (as described in Section 6.2.4 of this report) indicate that the turbine would not meet the IEC 61400-2 or IEC 61400-23 standards.

10 Recommendations

The investigators recommend an incentive program that encourages rigorous design, testing, and manufacturing practices that are consistent with internationally accepted wind turbine standards. although this is not required or common practice, turbines with IEC 61400-1 type certification have been subjected to the most rigorous design evaluation and testing requirements. Systems with this certification lineage are most likely to perform according to specifications and offer high levels of reliability. For general consideration, the following recommendations are provided to the State of New Jersey for accepting small wind systems into its Renewable Energy Incentive Program:

- Require turbine certification to meet IEC standards by an agency accredited by the International Organization for Standardization.
- Consider withholding incentives for systems with pending certifications until type conformity is issued from the certification body
- Scrutinize groups that provide turbine certification or evaluation services and/or require that they demonstrate competency in design evaluation and certification
- Consider allowing qualification for small wind systems by a noncertifying body. Because the small wind certification process is in a nascent phase, requiring IEC type certification may be too restrictive for emerging systems. Therefore, qualification by a noncertifying body may be an option for systems that fall into this category; however, this approach is open to interpretation as to what constitutes a qualified reviewing agency.

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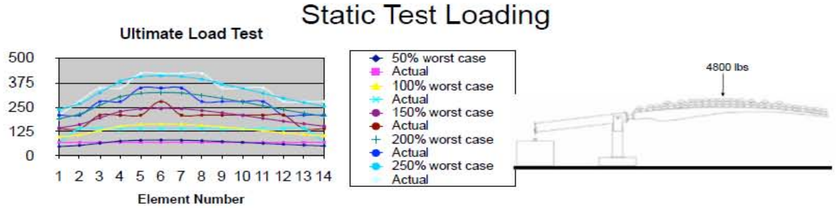
Appendix A

Blade Static Loading

Static Test Loading



Element	50%		75%		100%		125%		150%		175%		200%		225%		250%	
1	1		1		1		2	+1	2		2		3	+1	3		3	
2	1		1		2	+1	2		2		3	+1	3		3		4	+1
3	1		1		2	+1	2		3	+1	3		4	+1	4		5	+1
4	1		2	+1	2		3	+1	3		4	+1	4		5	+1	5	
5	1		2	+1	2		3	+1	3		4	+1	5	+1	5		6	+1
6	1		2	+1	2		3	+1	4	+1	4		5	+1	5		6	+1
7	1		2	+1	2		3	+1	3		4	+1	5	+1	5		6	+1
8	1		2	+1	2		3	+1	3		4	+1	4		5	+1	6	+1
9	1		2	+1	2		3	+1	3		4	+1	4		5	+1	5	
10	1		1		2	+1	2		3	+1	3		4	+1	4		5	+1
11	1		1		2	+1	2		3	+1	3		4	+1	4		5	+1
12	1		1		2	+1	2		3	+1	3		3		4	+1	4	
13	1		1		2	+1	2		2		3	+1	3		4	+1	4	
14	1		1		1		2	+1	2		3	+1	3		3		4	+1

WDC Bag Distribution Table: ENERTECH

Monday, March 7, 2011

Average Weight of sand bag from figure above is 70.59-lb

Element	# of bags (from table and figure)	Weight on Blade (lb)	Element Distance from root (ft)	Moment (weight * Distance) (ft-lb)
1	3	211.8	0.75	159
2	4	282.4	2.25	635
3	5	352.9	3.75	1324
4	5	352.9	5.25	1853
5	6	423.5	6.75	2859
6	6	423.5	8.25	3494
7	6	423.5	9.75	4129
8	6	423.5	11.25	4765
9	5	352.9	12.75	4500
10	5	352.9	14.25	5029
11	5	352.9	15.75	5559
12	4	282.4	17.25	4871
13	4	282.4	18.75	5294
14	4	282.4	20.25	5718
SUM	68	4800		50188

4800-lb shown on figure	4800	lb
Load Applied at shown on figure	9.6	ft
Test root moment based on location of 4800-lb	46080	ft-lb

Enertech-stated 250% root moment applied by sand bags is 50188 ft-lb

50188 ft-lb = 68046 N-m

Figure A1. Assessment of the 250% bending moment using the sand bag distribution table

Appendix B

Comments Provided by Enertech on This Report

Enertech makes these general comments concerning the "New Jersey Small Wind Turbine Failure Assessment, Enertech E44A Blades, Forked River, New Jersey Draft Final Report – October 15, 2012"

1. Statements are made throughout this report suggesting Enertech did not provide enough information to the investigative team. Enertech provided <u>all</u> information that was asked for. If certain data was missing for this report, it was never requested.
2. The investigation made by both Dynamic Designs and Wetzel Engineering was extremely limited and flawed. No one from either company traveled to Enertech facilities to examine blade tooling, look at blade testing, or interview Enertech designers, engineers or fabrication personnel in person. Wetzel Engineering only made contact via a telephone conference call. Dynamic Designs made no contact at all. This suggests the efforts by these firms were incomplete, biased, and not a serious investigative attempt. Again, the authors of this report repeatedly state that Enertech did not provide enough information. It should be the responsibility of the investigative team to obtain the information they need and we question why no one from either team made any effort to travel to our facilities to gain this knowledge directly.
3. In Section 9, the author(s) state "Stress levels observed in the bolster-to-laminate bond in the characteristic *model* exceed certification body guidelines". This statement is unfounded as no one "observed" or conducted any physical testing of the bolster-to-laminate bond. A computer test was reportedly done by Wetzel Engineering with, as the report stated, "limited information". How can one then determine that bolstered blades will not be successful?
4. Previous comments by Enertech personnel have been submitted that cast doubt on the investigation's conclusions, but these are not printed anywhere in the report but only referenced by title at the end. These comments should be known and printed.
5. Enertech follows design and testing as per SWCC requirements. The small wind industry is not required to have testing as per Germanischer Lloyd, DNV or other certification bodies used by utility-scale wind turbines, nor to have testing "completed at an ISO 17025-accredited test lab" as the report suggests. Additional requirements, if any, should be assessed to all manufacturers in the small wind industry and not to Enertech only.
6. Enertech is the only manufacturer of wind turbines in this size class that is based in the United States. Competitive models and their blades are produced in Canada, China or imported from other parts of the world. We find it interesting that a organization like NREL and the New Jersey Board of Public Utilities, which are funded by U.S. taxpayers, have participated in this "investigation" against Enertech, while ignoring competitors who produce machines and blades overseas with no oversight or testing requirements like what is contained in this report. Enertech, like its competitors, can easily outsource blades produced in China, thus eliminating the concerns made in this report, but at the expense of American workers. This possible outcome appears to some to be the intent of this entire "investigation".

Figure B1. Final Comment.pdf (email from <u>djones@enertechwind.com</u>, October 31, 2012)