Wind Turbine Blade Composites Design:
Leveraging Aerospace Advances for Improved Durability

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DASSAULT SYSTEMES

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Introduction

With wind installed capacity growing at a rate of 35% per year, wind turbines are the composite industry's fastest growing application. Ultra light, strong, highly resistant and durable, composites are ideal for producing lightweight blades with tremendous performance capabilities.

With such high hopes riding on this alternative energy source, the wind turbine blade industry is working hard to improve manufacturing efficiency and address blade failure issues, but challenges remain great, with failure rates as high as 20% within three years.

Borrowing best practices for the design and production of composite rotorcraft blades from the aerospace industry can vault wind turbine blade manufacturers to the forefront of the wind energy industry. These techniques have the potential to reduce development costs and cycle times by integrating the entire design and manufacturing process within a single environment. Simulation can be used to virtually verify the manufacturability and durability at almost no cost, avoiding the high cost of trial and error in the real world and achieving significantly lower failure rates.

Importance of wind power

According to the World Resources Institute, wind is already the least expensive renewable energy source for producing electricity. In regions geographically suited to harnessing wind power, this clean energy source can produce electricity at a cost competitive with coal or natural gas – without the greenhouse gases such fuels emit. Production of wind turbines and systems has increased by a factor of 5.2 since 2000 and by a factor of 115 since 1990. In 2007, composite wind turbine blades worth an estimated $4.3 billion were delivered globally and this figure is projected to rise to $5.9 billion in 2008. The global value of all wind turbine blades is projected by Composites Market Reports (CMR) to reach $34 billion by 2017.

Wind turbine power ratings have steadily increased. This has been accomplished primarily by increasing the blade length, which increases power by the square of the blade length. According to CMR, the fastest growing segment of the wind turbine blade market is for turbines with a capacity of 1.6 MW and higher. The blades for these turbines measure from 37 meters (123 feet) to more than 60 meters (200 feet) and weigh more than 12,000 pounds each. Conceptual designs are even appearing for 120 MW turbines with rotor diameters of up to 250 meters (820 feet).

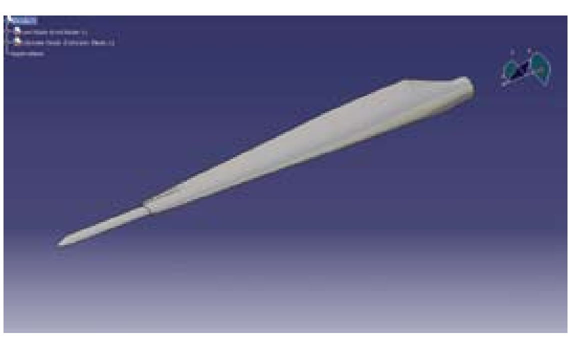
The production of wind turbine blades accounted for about 2.5% of all thermoset composites manufactured in North America. By 2017, CMR projects that wind turbine blade production will account for nearly 4.6% of all thermoset composite production.

Wind turbine blade design

From a design and manufacturing standpoint, wind turbine blades have many similarities to helicopter rotorcraft blades. The loading on a wind turbine blade and a rotorcraft blade consist primarily of aerodynamic pressure loads. Of course, the speed of a wind turbine blade is much slower, so it experiences much lower aerodynamic pressures.

Loading is also applied at the root of both wind turbine and rotorcraft blades. The overall pressure field on the blade causes a “bending moment” and torque at the root. A “bending moment” refers to the tendency of wind turbine blades to bend and twist during operation, which effectively alters their angle of attack and in turn has a negative effect on loads and energy production. For these reasons, blades are designed with a high level of bending stiffness. There is also typically a requirement that all the major modes of the blade must be above approximately 20 Hz so that the blades are not excited at normal operating speeds.

Composites dominate the wind turbine blade market because of their superior fatigue characteristics and stiffness-to-weight ratio, ability to fabricate complex geometries and potential for aeroelastic tailoring. The outermost section of the blade is typically a gelcoat layer, which provides a smooth surface to enhance aerodynamic properties. Next typically comes a layer consisting of Nexus, a soft material that provides a relatively smooth but absorbent surface on which to mount the gelcoat. The next layer is a double-bias stack of composite plies made by twisting unidirectional fibers around a core at 45 degrees in both directions to make a torsion tube. At the blade trailing edge, the double-bias laminate splits into two layers to accommodate a core material such as balsa, foam or honeycomb. The core-material laminate augments the buckling strength of the trailing edge of the blade.



Frontier Wind Blade

The interior of the midsection of the blade is made up of a composite box-spar. The outer layer of the box-spar, which interfaces with the Nexus line, normally consists of a double-bias lining. This lining provides strength to guard against shear and prevents the unidirectional layer below from splaying. The next layer consists of unidirectional composite laminates that primarily contribute bending strength to the box-spar. Unidirectional fibers provide tensile strength, running from the blade’s tip to its root through the box-spar, around the mounting bushings and back out the root. In many cases, the double-bias and unidirectional plies are interspersed to form a single laminate. The interior of the box-spar consists of an embedded core material to guard against buckling.

Challenges of traditional wind turbine blade design

Optimizing the properties of the blades is critical to delivering the needed bending strength and fatigue performance while minimizing cost and weight. The properties of composite blades can be tightly controlled and varied over their span through the appropriate selection of ply orientation, thickness and lay up. Yet a survey conducted by Sandia National Laboratories of five wind energy plants with more than 400 turbines, most of which were greater than three years old, found that an average of 80 blade replacements had been required per plant. Replacement times ranged from two weeks to two months. Issues cited as causes for the replacements included:

- ***Manufacturing errors such as waviness and overlaid laminates***
- ***Bad bonds, delamination and voids***
- ***Leading-edge erosion***
- ***Trailing-edge splits***
- ***Lightning strikes***

Four of the five causes of failure can be attributed to sub-standard design and manufacturing practices that could be eliminated by adopting many of the best practices developed for composites design and manufacturing in the aerospace industry. A significant part of the challenge may be that nearly all composite blades today are designed on basic CAD systems intended for making solid metal and plastic parts of far less complexity than today's sophisticated, multi-layered composites. The limited capabilities of the CAD systems means that analysis and manufacturing engineering are carried out in separate and disconnected environments, creating inefficiencies and introducing the potential for error.

In the typical process, the aerodynamicist first defines the outer shape of the blade using specialized fluid flow software packages and wind tunnel testing. This design is then provided to mechanical engineers, who define the detailed design and basic ply guidelines for the blade. The CAD software has no facility for keeping track of the laminate information involved in composites design, so the engineer typically tracks this information in a spreadsheet.

The engineer might start by defining areas of the part with similar thicknesses as zones. The zone information is usually maintained manually in a spreadsheet. Then the engineer will define a ply stack that delivers the mechanical properties required in each zone, as indicated by previous experience. Most companies involved in composite design have design rules that are used to guide this process. For example, the smaller plies may be located on the inside of the stack and the thicker plies on the outside.

An analyst typically creates a finite element model from scratch to evaluate the bending strength and other characteristics of the blade. Various loading conditions are used to simulate different wind conditions. The proposed blade design may be challenged by load-time histories to predict its fatigue strength. The analyst recommends changes to the plies based on the analysis results. The design typically goes back and forth between the engineer and analyst multiple times – all being manually tracked via spreadsheet, which has room for error.

Wind turbine blade manufacturing process

Defining the manufacturing process comes next. In the traditional approach, the final shapes of the flat patterns are determined on the shop floor by expensive and time-consuming trial and error: cutting plies, laying them onto the molding tool using manual measurement, checking for distortion, re-cutting and trying again. The complex aerodynamic shape of wind turbine blades makes it hard to predict how composite materials will conform to the mold's complex surface. Sometimes distortion causes the material to draw away from the mold. In other cases, a ply sequence imbalance across a 3D shape generates stresses that cause wrinkling or warping. A major difficulty is developing flat patterns that will meet the ply guidelines without fabric distortion, such as bunching up on the mold. Using conventional methods, this process cannot even begin until the molding tool is built.

At this point, the normal procedure is to cut fabric plies by hand and try to fit them on the mold tool. Inevitably a considerable amount of distortion is seen. Assemblers use darts and splices in an effort to solve the problem. The trial-and-error nature of this process means that the material is finally fit to the mold using far more darts and cuts than would be necessary if the flat pattern shapes were optimized, resulting in a weakened final product. It is also not a repeatable process. The flat patterns that result from this process are measured and used for volume production, which means that the waste is repeated on every blade built. The entire first-part process typically takes large amounts of time and consumes substantial amounts of expensive composite materials.

Applying lessons learned in the rotorcraft blade industry

Lessons learned in the rotorcraft blade industry can be used to dramatically improve wind turbine design and manufacturing. Taking into account best practices learned from the rotorcraft blade industry, Dassault Systèmes has developed CATIA Composites Design, a Product Lifecycle Management (PLM) solution that provides a dramatic improvement over conventional CAD systems by providing a complete end-to-end solution for preliminary design, engineering detailed design, manufacturing detailed design and manufacturing export. The similarities between wind turbine and rotorcraft blades mean that these best practices can integrate structural zone-based modeling into the design environment or grid-based approach using analysis thickness laws or stacking sequences at the beginning of the lifecycle of the part. Either design approach saves large amounts of data entry time, which can be devoted to more productive tasks and innovation. It also becomes possible to generate conceptual solids to quickly integrate the composites part in the mock-up, enable concurrent engineering with mating parts and even provide preliminary inputs for tooling to start working on the mold.

CATIA Composites Design automatically generates splices from the solid model based on the zone or grid design, while keeping full associativity between the plies and solid. They organize the ply buildup by recording non-geometric information and creating sequence charts per company standards, material tables and lay-up books. The ability to design the composite lay up within context of the complete blade assembly streamlines the design process. It also ensures a higher level of accuracy that reduces the number of physical prototypes needed to finalize the design. This in turn cuts costs, eliminates trial and error, improves accuracy, improves durability and minimizes splices and darts. CATIA Composites Design contains powerful design optimization tools, providing advantages such as the ability to swap ply edges to optimize drop-offs, shape plies and re-route sets of plies along a preferred path.

Tighter integration with analysis

The new best practices pioneered in rotorcraft blade design substantially improve the analysis process by integrating design with finite element analysis (FEA) for fast design-analysis iterations in full associativity with the zones and plies definition. Bidirectional communications are provided between design and analysis at both the conceptual and detailed design stages. The ability to directly transfer accurate fiber angles and ply thicknesses from the design to the analysis environment improves the simulation accuracy. The ability to transfer updated design information from analysis back to design enables designers and analysts to work closely together, ensures the analyzed model matches the final structure and prevents the specification of plies and structures that cannot be manufactured.

Abaqus FEA software provides engineers with advanced, state-of-the-art capabilities for simulating realistic composites behavior, including delamination and damage. These complex, nonlinear effects are modeled using cohesive elements and VCCT (Virtual Crack Closure Technique). The VCCT technology in Abaqus was initially developed by Boeing for predicting fracture and failure of composite materials in their aircraft wings. The VCCT capabilities in Abaqus enables engineers to identify the overall load at which a crack initiates and to predict the behavior of the structure as the crack propagates. It also helps users understand the stability and load-carrying capacity of the composite structure after failure.

Evaluating manufacturability in the virtual environment

Aerospace best practices also provide dedicated features to ensure that the detailed design is manufacturable and avoid trial and error on the shop floor. The lay-up of the composite plies onto the mold tool is simulated to identify areas where the part geometry will cause fabric distortion. The engineer can then add darts or splices or make other changes to the ply and receive immediate feedback on whether the changes have corrected the design problem.

The program then automatically generates the resulting pattern geometry for each ply within the CAD environment. This geometry can be exported to a ply-cutting machine to produce the patterns for prototyping, saving the time that would normally be spent cutting the patterns by hand. More important, with simulation identifying manufacturing problems in the virtual environment, the first iteration of the design should be correct or very close to correct, eliminating the need for trial and error on the shop floor.

Composites design and manufacturing data can easily be linked to nesting systems, as well as all industry-standard laser projection systems. This approach provides the ability to preview and optimize laser projection on screen before actually reaching the shop floor, to eliminate trial and error. It also eliminates the need for manual measurement during the lay-up process. Close coordination with tape laying and fiber placement machine providers ensures that the process flow will be seamlessly tailored to their machines. Finally, shop floor documentation is available either as a traditional drawing-based ply book or a digital ePly book to dynamically integrate the 3D master with all associated operations and work instructions.

Conclusion

Composites materials are ideal for producing wind turbine blades because of their strength, light weight and ability to be tailored to provide the precise mechanical properties needed for any blade design. But the traditional manual, sequential and trial-and-error-based composites design process makes it difficult to take full advantage of composites' tremendous performance capabilities due to long manufacturing cycles and inexact manufacturing processes. Now, best practices originally developed for rotorcraft blade manufacturing can be applied to composites design for wind turbine blades to enable a complete set of process-oriented solutions to design, simulate and manufacture composites blades on a single virtual platform.

The new approach saves time and avoids errors by managing all aspects of the preliminary and detailed design in a single associative environment. The design can be optimized from a manufacturability standpoint in the virtual environment to save time and material on the shop floor. Bidirectional links to powerful analysis tools reduce the time required to meet the design specifications while minimizing weight and cost. Links are provided for the digital design information to drive pattern cutting, laser projection, nesting, etc. All in all, the new approach improves performance and quality while reducing development time and costs.

Dassault Systèmes CATIA Composites Design is the leading design and manufacturing system in the aerospace industry and the industry standard for rotorcraft blade design. Dassault Systèmes Abaqus FEA software is used throughout the aerospace industry to accurately model and predict performance of composites-based structures. CATIA Composites Design now provides a complete solution for wind turbine blade design based on best practices that incorporate the latest lessons learned in rotorcraft blade design.

To learn more, visit 3ds.com/composites or contact Rani Richardson at Rani.Richardson@3ds.com.

Appendix:

Achieving design success with CATIA composites design

Frontier Wind: Longer Blades Equal Increased Energy Output

Frontier Wind, LLC, located in Sacramento, California, grew out of Energy Unlimited, Inc. (EUI), owners and operators of more than 400 wind turbines located in Palm Springs, California. EUI has been at the forefront of the wind energy industry since the mid-1980s, and in 2007 launched Frontier Wind to develop technology solutions that increase the energy production of wind turbines.

Frontier Wind's VariBlade will be the first commercially available, variable-length wind turbine blade. The blade is designed to extend, increasing its length to capture more wind at low wind speeds, and retract to operate safely and efficiently at high wind speeds. Other products are also in development to address opportunities to improve blade performance and improve generated output.

John McCoury, Vice President of Engineering, came to the wind turbine industry from the aerospace sector, bringing years of experience in aircraft design and analysis to Frontier Wind. "While there are many similarities between the two, the lofted surface of a wind turbine blade is more complex than that of an aircraft wing – which presents unique design and manufacturing challenges," McCoury observed.

Already familiar with Dassault Systèmes CATIA solutions, McCoury and his team chose CATIA Composites Design as the design solution for the VariBlade, based on CATIA's strong knowledge-based modeling and lofting functionality capabilities. "We needed the best lofting tool we could find because the variable-length blade has very sophisticated contours," McCoury says. "In addition we'll be reverse engineering some existing blade designs to allow incorporation of VariBlade, and CATIA has the open CAE interfaces necessary to perform knowledge-based parametric and NASTRAN simulation analysis. Most of today's turbine blades, based on their current load environment, can't be made longer using standard wind industry materials and construction methods. With CATIA, we can perform the analysis, based on modern materials, necessary to reduce weight, enabling us to retrofit turbines with longer blades that incorporate our load reduction technology."

CATIA enables Frontier Wind to add rigor to the process of wind blade design and manufacturing. "Until recently, designing wind turbine blades could be described as more of an art than a science, with materials and construction methods based on minimal engineering and more on trial and error, without the benefit of today's parametric solid modeling, including ply-by-ply construction detailing, and simulation tools," McCoury says. "Many of the materials used for blades could have been better utilized and apportioned, including improved orientation of the fibers, based on ply-by-ply structural simulation.

In the past, the turbine industry hasn't done a good job of leveraging existing state-of-the art design and analysis tools, which has resulted in negative impacts on blade weight and premature failures. The VariBlade will bring new challenges, because of the embedded variable-length mechanism, as compared to traditional non-movable blades. To address this challenge, we are incorporating graphite and other advanced materials into the design to reduce weight, improve strength, increase fatigue resistance and ultimately increase energy output. The CATIA Composite solution provides the required tools for ply-by-ply definition and analysis that is critical for the success of our product."

CATIA Composites Design is enabling Frontier Wind to successfully design and analyze VariBlade. VariBlade is in the advanced stages of design and test and promises increased energy production and availability.

Frontier Wind

- ***Challenge:***

  Frontier Wind wanted to develop longer, potentially heavier wind turbine blades to increase the energy output per wind turbine.

- ***Solution:***

  Frontier Wind chose CATIA Composites Design to perform sophisticated parametric modeling, reverse engineering and lofting analysis to ensure that its longer, variable length VariBlade could withstand extreme environmental and engineering conditions.

- ***Benefits:***
  - **Significantly reduced risk of load problems**
  - **Shorter design and testing phase, enabling faster time to market**
  - **Facilitates design reuse, innovation and best practices**

www.frontierwind.com

About Dassault Systèmes

As a world leader in 3D and Product Lifecycle Management (PLM) solutions, Dassault Systèmes brings value to more than 100,000 customers in 80 countries. A pioneer in the 3D software market since 1981, Dassault Systèmes develops and markets PLM application software and services that support industrial processes and provide a 3D vision of the entire lifecycle of products from conception to maintenance. The Dassault Systèmes portfolio consists of CATIA for designing the virtual product – SolidWorks for 3D mechanical design – DELMIA for virtual production – SIMULIA for virtual testing – ENOVIA for global collaborative lifecycle management, and 3DVIA for online 3D lifelike experiences. Dassault Systèmes' shares are listed on Euronext Paris (#13065, DSY.PA) and Dassault Systèmes' ADRs may be traded on the US Over-The-Counter (OTC) market (DASTY). For more information, visit http://www.3ds.com.

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