Final Technical Report
for Project on

Establishment of a National Wind Energy Center

by

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Executive Summary

The DoE-supported project objectives are to: establish a national wind energy center (NWEC) at University of Houston and conduct research to address critical science and engineering issues for the development of future large MW-scale wind energy production systems, especially offshore wind turbines.

The goals of the project are to: (1) establish a sound scientific/technical knowledge base of solutions to critical science and engineering issues for developing future MW-scale large wind energy production systems, (2) develop a state-of-the-art wind rotor blade research facility at the University of Houston, and (3) through multi-disciplinary research, introducing technology innovations on advanced wind-turbine materials, processing/manufacturing technology, design and simulation, testing and reliability assessment methods related to future wind turbine systems for cost-effective production of offshore wind energy.

To achieve the goals of the project, the following technical tasks were planned and executed during the period from April 15, 2010 to October 31, 2014 at the University of Houston:

(1) Basic research on large offshore wind turbine systems
(2) Applied research on innovative wind turbine rotors for large offshore wind energy systems
(3) Integration of offshore wind-turbine design, advanced materials and manufacturing technologies
(4) Integrity and reliability of large offshore wind turbine blades and scaled model testing
(5) Education and training of graduate and undergraduate students and post- doctoral researchers
(6) Development of a national offshore wind turbine blade research facility

The research program addresses both basic science and engineering of current and future large wind turbine systems, especially offshore wind turbines, for MW-scale power generation. The results of the research advance current understanding of many important scientific issues and provide technical information for solving future large wind turbines with advanced design, composite materials, integrated manufacturing, and structural reliability and integrity. The educational program have trained many graduate and undergraduate students and post-doctoral level researchers to learn critical science and engineering of wind energy production systems through graduate-level courses and research, and participating in various projects in center's large multi-disciplinary research. These students and researchers are now employed by the wind industry, national labs and universities to support the US and international wind energy industry. The national offshore wind turbine blade research facility developed in the project has been used to support the technical and training tasks planned in the program to accomplish their goals, and it is a national asset which is available for used by domestic and international researchers in the wind energy arena.

1. Project Objectives

The project objectives are to: establish a national wind energy center (NWEC) at University of Houston and conduct research on critical science and engineering issues for the development of future wind energy production systems, especially for large MW-scale offshore wind turbines.

2. Project Goals

The goals of the project are: (1) establishment of a sound technical knowledge base for solutions to critical science and engineering issues for developing future MW-scale wind energy production systems, (2) development of a state-of-the-art national wind rotor blade research facility at the University of Houston, and (3) through multi-disciplinary research, introducing technology innovations on advanced wind-turbine materials, processing/manufacturing technology, design and simulation, testing and reliability assessment methods related to future wind turbine systems for cost-effective production of offshore wind energy.

3. Project Activities

To achieve the goals of the project, the following *technical tasks* were planned and executed during the period from April 15, 2010 to October 31, 2014:

(1) Basic research on large offshore wind turbine systems
(2) Applied research on innovative wind turbine rotors for large offshore wind energy systems
(3) Integration of offshore wind-turbine design, advanced materials and manufacturing technologies
(4) Integrity and reliability of large offshore wind turbine blades and scaled model testing
(5) Education and training of graduate and undergraduate students and post- doctoral researchers
(6) Development of a national offshore wind turbine blade research facility

3.1 Task 1: Basic Research on Large Offshore Wind Turbine Systems

3.1.1 Major Activities

During the reporting period the following major activities in this task have been conducted:

(1) Aerodynamics and power generation of counter-rotating and co-rotating wind turbine systems
(2) Advanced wind turbine materials: Structural polymers and their fiber composites, structural-foam core materials, foam core-fiber composite sandwiches, structural adhesives.
(3) Exothermic polymer reaction and cure kinetics modeling: Selected thermoset resins (polyester and vinyl ester), and their thick-section composites and composite-foam sandwich laminates
(4) Process modeling, VARIM simulation and control: Selected thermoset resins (polyester and vinyl ester), and their thick-section composite laminates, foam-composite sandwich panels, shear webs, rotor blade airfoils, and turbine blade structures
(5) Processing-structure-property relationships: Selected thick thermoset composite laminates, polymer foam-core materials, and foam-composite sandwiches

(6) Fundamental aerodynamics of co-rotating and counter-rotating wind turbine (CRWT) Systems and computational fluid dynamics (CFD) simulation
(7) Aeroelastic modeling, analyses and simulation: Large offshore wind turbine structures And scaling effects (with turbine blade length equal to and exceeding 100m)
(8) Rotor pitching and yawing operations on large offshore wind turbine dynamics in GOM shallow water in 100-year return hurricane wind
(9) Wind rotor structural performance evaluation and their stability and dynamics: Large offshore wind-rotor blade structures in extreme environments (i.e., hurricane winds)

3.1.2 Specific Objectives

The objectives of this task are to: (1) achieve clear understanding of offshore atmospheric boundary-layer wind profiles and modeling, offshore wind turbine aerodynamics, large offshore rotor materials and structural dynamic behavior and failure under nominal and extreme wind loading, (2) develop fundamental aerodynamics theories for co-rotating and counter-rotating wind turbines and refine the aerodynamics theories with computational fluid dynamics simulation of detailed flow interaction between rotors, (3) provide solutions to establish a sound scientific base to advance science and engineering of offshore wind modeling, modern wind turbine materials, cost-effective VARIM processing and manufacturing, advanced blade structural modeling and computational simulation, and long-term reliability for next-generation MW-scale, large offshore wind rotors.

3.1.3 Scope, Results and Significant Accomplishments

New fundamental theories [28] (The number in the bracket refers to the publication number listed in Section 4.1) have been developed for co-rotating and counter-rotating wind turbine (CRWT) systems. Governing fluid dynamics equations are formulated based on linear momentum theory with associated wind rotor parameters. Critical turbine variables are determined and conditions established to achieve the maximum total power coefficient for the CRWT system. The effect of front and rear rotor interaction on the airflow within the inner stream tube is determined. With the results obtained, axial thrusts on front and rear rotors are also determined and later used as input for computational fluid dynamics (CFD) simulation to determine flow characteristics across the rotors. Based on the flow pattern between the rotors, the total power coefficient of a dual-rotor wind turbine is found to relate to the rotor separation distance. Advances of the CRWT aerodynamics are made further to include the effect of wake rotation of the wind rotors. The strong interaction between front and rear rotors on axial and tangential (rotational) induction factors has been determined and their effects on the total power coefficient are obtained. Computational fluid dynamics simulation of co-rotating and counter-rotating wind turbines are carried out to examine detailed flow interactions between the two rotors. The results are compared with those from a corresponding single-rotor wind turbine in the same wind field and operational conditions. The significant benefits of CRWTs over the conventional single rotor turbine are determined.

To better understand offshore wind conditions and subsequently model ocean wind profiles for offshore wind-turbine power generation [5], wind-speed data obtained from an offshore meteorological tower have been analyzed in detail. The vertical wind speed distribution functions are formulated from the measured data, based on different models, as recommended by commonly used offshore wind standards and regulations. The accuracy of each individual model has been checked against the actual data and the Lidar measurements obtained at the same site. The most suitable model has been established to extrapolate the wind profile from a reference elevation to the desired height (currently up to 250 m) of wind turbine operation. The effect of marine boundary-layer on the wind profile and the criticality of wind shear are examined for up-scaling of large offshore wind turbines and aerodynamic loads in the subsequent wind rotor blade design and reliability analyses.

A comprehensive study [17] has been conducted on advanced structural foam core materials and fiber-composite materials for wind turbine blades. For the improvement of properties and microstructures of the foams produced, an effort has been made to compare the core materials made of currently developed physical and those of chemical foaming processes, involving different types of resin and curing agent selected, as well as relative concentrations of the constituents, with different curing times. The optimum weight percent of the selected solid cure agent and the amount of the blowing agent are determined. Also, development of hybrid foam systems and study of effects of different ratios of components are made on foam property and microstructure. AFM techniques are developed and associated facilities set up to measure surface energy and surface tension of the resin systems and blow agents for evaluation of the most important factor controlling the ultimate foam structure and property. A parallel study [17] has been conducted to determine microstructure characteristics of strong foam core materials and establish a micromechanics basis of the microstructure-property relationship for use of the foam core in a large wind turbine blade structure. New test methods are developed for accurate measurements of all directionally dependent mechanical and strength properties of the core foam materials. Through-thickness variations of foam compressive mechanical behavior and their relationships with cell microstructure are determined [24] on several industrial foam core materials. Specifically, the results obtained on H80 and H200 foams are analyzed, including mechanisms of deformation and cell-collapse induced failure, and interpreted in conjunction with foam-cell microstructure and micromechanics. Closed-form solutions are derived to predict mechanical strength of closed-cell foams under both shear, tensile and compressive loading. The closed-cell foams are modeled as transversely isotropic materials with strength in the foam rise direction different from those in planar (plane of isotropy) directions. To account for foam microstructure and cell-shape anisotropy on foam strength, a unit-cell model is introduced [17] for the foam microstructure and for deriving equations to assess tensile and shear strengths of foams. The effect of stretching foam cell walls in the rise direction on strength of the foam-matrix polymer is also taken into account in modeling the mechanical strength of closed-cell foams. The strength theory of the foams under compression is found different from that under tension.

The vacuum-assisted resin infusion molding (VARIM) method has been used in the current study of manufacturing large composite wind structures, such as MW-scale wind turbine blades, due to structural size, cost-effectiveness and out-of-autoclave curing requirements. Among various material and processing parameters, 3D permeability of composites with thick-section laminate construction is critical in controlling resin flow in an efficient manufacturing process development and in accurate numerical modeling and simulations. Resin flow in a mold with complex geometries, such as a wind turbine blade with a perforated foam core and multiple fabric orientations, is controlled by its through-thickness, 3D permeability. The 3-D composite permeability research [25] here enables us to: (1) establish analytical models to include 3D resin flow and off-axis flow front tracking, (2) investigate effects of scaling and compressibility during the manufacturing process of thick composites and (3) determine orientation and principal components of permeability tensor for different reinforcement fabrics in both homogeneous and symmetric, hybrid lay-ups, such as those found in a spar cap.

The development of cost-effective manufacturing technology for large wind turbine blade construction requires clear understanding of VARIM processing fiber-composite laminates and foam-composite sandwich structures, especially thick-section composites. VARIM processing experiments, modeling and simulation studies [3] have been carried out on thick-section glass/polyester composite laminates and glass/vinyl ester composites.

Exothermic reaction and curing kinetics of the glass/polyester laminates are investigated on thick composite laminates up to 120 plies (≅ 5.6 inches in thickness). Exothermic temperature evolution, maximum temperature change, the degree of cure, and the curing rate through the laminate-thickness direction are all determined. A semi-empirical law on curing kinetics of the glass/polyester composite has been developed for VARIM processing of thick-composite spar caps and foam-composite shear webs for wind turbine blades. Both DSC and in-situ DEA experiments [2] are conducted on a glass/vinyl ester to establish the relationship between the cure index and the degree of cure in the composite at different temperatures and frequencies. In the post-cure study, design and fabrication of a long heating chamber with individual zone control are completed for manufacturing composite box beams and other wind blade components. Composite shear webs, spar caps and assembly of composite box beams of several cross section dimensions have been made up to 12-feet in length for subsequent structural integrity and reliability testing and analyses, which will be reported later in Task 5.

In the study of aerodynamic and aeroelastic responses of large wind rotor blades, focuses are on developing aerodynamic and structural modeling methodologies, analyzing large wind turbine blade deformation, and evaluate their load-bearing structural components and resulting blades under bending and bending-twisting loads in nominal and extreme wind conditions [9]. Detailed models have been established for an all glass-fiber composite 100m baseline blade (SNL-100-00). Advanced finite-element blade structural deformation and stability analyses, both static and dynamic, have been conducted on the baseline large wind rotor blade, i.e., the Sandia 100m all glass composite turbine blade, in extreme winds (i.e., hurricane in GOM) with 50-year and 100-year return periods. The results obtained are used in the subsequent studies as baseline information for comparison and evaluation. Technical issues and current design deficiencies are identified for the baseline, large 100m blade of an offshore wind turbine in GOM. Improvement of the models has been made to better simulate material tailoring and blade construction details[1].

3.1.4 Key Outcomes, Milestones and Other Achievements

General solutions for (counter-rotating and co-rotating) dual-rotor wind turbines have been developed in the research [28]. The solutions show that the largest total power coefficient that can reach 0.814 for a dual-rotor turbine system with a rotor-separation distance of 2.8 times the rotor diameter. Specifically, for counter-rotating wind turbines of equal size rotors, their energy conversion efficiency, as expressed by the *total* power coefficient, could be enhanced to exceed 0.8, which is significantly higher than the well-known Betz limit for conventional single rotor wind turbines. The results of the study are compared with those reported in the literature. Discrepancies in the largest possible power coefficient of dual-rotor wind turbines obtained in various investigations are examined. The new aerodynamics theory developed in the study has established quantitative relationships among rotor parameters, rotor rotation, and induction factors of angular and axial flows through the wind rotors. Contributions of individual rotors to the total power coefficient and the thrust coefficient in a CRWT have been determined. The CFD simulations are performed to establish critical relationships among the total power coefficient, the separation distance between rotors, and the turbine size ratio. To realize the maximum power conversion of a CRWT, the rotor separation distance depends not only on the sizes of the rotors and their area ratio, but also on corresponding induction factors of axial and angular flows.

Atmospheric stability of offshore wind boundary layer has been found [5] to be a critical indicator at the presence of wind shear in the vertical wind profile from the analysis of offshore wind data. The stability relates the resistance of air parcel to vertical motion. In the lower part of the boundary layer, atmospheric stability is primarily driven by thermal gradients and thus buoyancy force of air flow. The temperature effect is defined with the parameter, potential temperature, which may also account for pressure and humidity changes along with elevation in ocean. Three classes of stability have been introduced to determine the influence of the marine boundary-layer: stable, neutral and unstable, which are commonly quantified by the Obukhov length and Richardson number. A set of offshore wind data, measured up to 100 m in the German offshore FINO1 tower, along with Lidar measurements collected at the same site, have been used to evaluate the wind shear effect. The unstable profiles are relatively uniform due to large-scale turbulence generated mixing, which significantly reduces vertical gradients of velocity. Thus the wind shear effect is relatively small, whereas the very stable condition has limited turbulence and mixing and the wind shear is relatively large. The stable and unstable wind profiles have been used in the study to identify the presence of wind shear and determine power generation and aerodynamic loads of large offshore wind turbines under these conditions

In the development of a suitable physical foaming process, the amount of a solid curing agent and its surface energy have been found to be critical in producing very low density structural foams with desirable physical properties. Current results show that the use of the solid curing agent with a conventional cure agent produces good low-density structural foams with compressive strength up to 0.8 MPa at a yield strain of about 0.9. Both above and below the optimum weight ratio, adverse effects are observed to occur in process control and in resulting mechanical properties. The optimum ratio of different resin components has been explored in selected hybrid foam systems. A high ratio system has been found to compromise foam structural properties and increase difficulties in processing. An AFM and an appropriate probe are used for measurements of surface tension and surface energy of the foam systems. Microstructure evaluation of selected commercial foams reveals that both foam cell size and density change through the thickness direction and are also distinct from those of the in-plane direction. Moreover, the appreciable differences between foam stiffness and strength along the foam rise direction and those of the in-plane direction require a careful study of the anisotropic nature of the core material properties and failure modes for the large offshore turbine blade structural use. Closed-form solutions [17] for predicting compressive strength of closed-cell foams have been obtained in the project from approximate micromechanics theories, based on an earlier study of compressive strength of unidirectional composites. The validity of the new foam strength theory is demonstrated through comparison of predictions with test results on DIAB H80 foam obtained from a systematic in-house experimental program. Good agreement is obtained between the test results and the predicted strength. A comparison is also carried out between the strength predictions and test results of a foam manufacturer for PVC foams with a wide range of density. Excellent agreements are found for all cases studied, which support the applicability of the foam strength theory developed for assessing the mechanical strength of closed-cell PVC foams.

For the important 3D composite permeability study [25], a non-invasive point infusion method has been developed with vinyl ester resin as the infusing medium. In our experiments, the flow front is tracked by a video camera and both laminate thickness and mass flow rate are evaluated. The measurement requires the development of an isotropic transform solution for relating the flow rate through the inlet tube, Darcy's Law, and an expanding hemisphere. The orientation of the principal axes has been determined with in-plane flow fronts along the 0°, 45° and 90° axes. The analytical models developed in the study provide an effective method to determine the permeability tensor with resin-flow front position, laminate thickness and fabric and resin properties. The solutions also provide accurate 3D components of permeability tensor and demonstrate that the analytical models predict well as the laminate thickness and flow front radius increase.

The critical issues on exothermic reaction and associate reaction-induced temperature surge are of serious concern during VARIM processing glass/polyester thick laminates. For a thick 100-ply glass/polyester laminate, exothermic temperature has been found [6]to reach 108°C in the middle of the composite laminate about 100 minutes after the resin infusion is stopped, whereas temperatures in bottom plies has values less than half of the top-ply temperature. The maximum temperature difference between the middle ply and some plies during the thick-composite VARIM process reach more than 70°C one and a half hour after the resin infusion process starts. The high-temperature raise near the middle plane of the laminate and the large through-thickness temperature gradient introduce severe differential curing through the laminate thickness direction. The degree of cure and the cure rate through the laminate thickness direction in the thick composite have been quantitatively determined by in-situ dielectric measurements (with DEA) and heat flux and enthalpy data (with DSC). The differential curing leads to significant mechanical and physical property gradients and undesirable thermally-induced deformation and residual stresses in the composite. The results provide important insight in developing improved VARIM processing methods and manufacturing equipment for large composite wind rotor blades. The relationship established in the study between the in-situ measured cure index and the thermodynamically-determined degree of cure enables a subsequent systematic study on curing reaction of thick glass/vinyl ester composite processing for manufacturing next-generation offshore composite rotor blades.

Design and manufacturing studies [1, 20, 26] have been completed on foam-composite sandwich structural components, such as shear webs and blade box beams. Development efforts are also made on advanced test methodologies for the sandwich structures under complex loading modes. Several test and analysis programs have been established for experimental and analytical investigations on determination of deformation and failure modes in composite spar materials, composite-foam sandwich structures, foam-composite shear webs of wind turbine internal structures, and wind turbine blade box-beam structures.

A baseline 100m large wind turbine structural model has been constructed with laminate composite shell elements [10]. In the computational structural mechanics studies, mesh sensitivity, solution convergence and accuracy and computational cost are established first. Critical design issues are identified for the baseline offshore wind-rotor blade (SNL-100-00): heavy weight, buckling resistance in hurricane winds, aeroelastic flutter,…, etc. The results revealed that potential structural buckling instability and aeroelastic flutter of the 100m all-glass composite turbine blades could occur at its nominal operating speed. Furthermore, the current study has led to alternative design concepts, internal structural modifications, changes in material selection and aeroelastic tailoring to ensure large wind rotor blade integrity, power-generation efficiency, and long-term material and structural reliability.

The comprehensive study [22] of wind turbine blade pitching and yawing and their effects provides critical information regarding turbine operations in extreme hurricane conditions. Low blade pitching is found to be detrimental to turbine safety due to high thrust forces (torque and axial force) on both the wind rotor and the support tower structure. A combination of 90-degree wind rotor yawing and 0-degree blade pitching may provide the most desirable safe wind-turbine operation during a 100 year return extreme hurricane wind and ocean waves and current. Wind turbine rotors may stall when blades are all pitched between 55 to 65 degrees without any RNA yawing and wind-wave alignment. The 100-year return hurricane loads is proven to be very critical in designing large offshore wind turbine structures from both aeroelasticity/structural dynamics and material strength considerations.

3.2 Task 2: Applied Research on Innovative Wind Rotors for Deepwater Offshore

3.2.1 Major Activities

During the reporting period the following major R and D activities in the task have been conducted:

(1) Marine atmospheric boundary -layer effects and wind -shear induced aerodynamic load fluctuation on wind rotor dynamics and fatigue design
(2) Design and siting considerations for developing efficient offshore wind turbines in the Gulf of Mexico (GoM) region.
(3) Developing effective processing methods for manufacturing light-weight, high-strength core foam materials and foam-composite sandwich structures, shear webs and spar caps, sandwich airfoils and panels in large offshore composite wind turbines.
(4) Aerodynamic load analysis and aeroelastic up-scaling laws for coupled wind load and structural dynamics modeling of large wind turbine blades
(5) Aerodynamic design for maximum power generation and other turbine performance of co-rotating and counter-rotating horizontal-axis multi-rotor wind turbines
(6) Wake interference associated with co-rotating and counter-rotational wind rotors and its effect on individual turbine power output, static and dynamic loads and turbulence characteristics in wake flows behind the wind rotors

3.2.2 Specific Objectives

The objectives of this task are to: (1) identify critical issues concerning design, manufacturing, and performance of large offshore wind turbine systems operating in offshore environments, especially along the Gulf of Mexico (GOM), (2) optimize aerodynamic design of multi-rotor wind turbines with critical turbine parameters to achieve maximum power generation and minimum rotor thrust, (3) develop effective processing methods for manufacturing light-weight, high-strength core foam materials and foam-composite sandwich structures for large offshore turbines, and (4) develop innovative wind rotors (with new internal structures and/or modular configurations) to mitigate offshore O & M, extreme hurricane wind environments, and ocean degradation problems.

3.2.3 Scope, Results and Significant Accomplishments

Benefits (i.e., power generation) and technical barriers of multi-rotor wind turbine systems have been investigated through new aerodynamic design of CRWT rotors 28], based on the aerodynamics theories of flow behavior between the rotors established in Task 1. Thrust (static and dynamic) loads on the CRWTs are determined for different design and operation conditions. Both tangential and axial air flows are obtained by the newly formulated theories, including the effect of wake rotation. The maximum power conversion of the CRWT has been found to exceed the Betz limit and its relations are established with critical rotor design parameters (e.g., ratio of rotor rotational speeds, direction of rotor rotation, axial and tangential induction factors, and rotor area ratios). The optimal performance of the dual-rotor wind turbines is determined for both co-rotating and counter-rotating wind turbines. Also, robust computational fluid dynamics (CFD) models have been constructed to predict the near wake behavior and to design the details of CRWTs with desired flow behavior for construction of optimal wind turbines, especially in the dual-rotor wind turbines.

A comprehensive investigation [22] of wind-rotor blade pitching and yawing operations has been completed on large offshore wind turbine dynamics during a 100-year return hurricane wind in the Gulf of Mexico (GOM) shallow water. A combined aerodynamics analysis and structural dynamics modeling with incremental-iteration computational mechanics scheme is established for the very large offshore turbine system [15]. Maximum and minimum hurricane loads and hydrodynamic loads on the wind turbine are determined for different degrees of blade pitching and rotor yawing on the 100-m composite offshore wind turbine in the extreme metocean environment. Structural dynamic responses of the wind rotor and the supporting tower are obtained in the 100-year return hurricane wind and sea waves and current. Also, determined are the maximum overturning moment and axial and shear forces at the mud line in the wind turbine tower structure. A new comprehensive Campbell diagram has been constructed to address the strong interaction among top wind-rotor dynamics, supporting wind tower structural dynamic response, and wind-rotor rotating speed and other design parameters.

New physical and chemical processes have been developed for manufacturing next-generation, ultra-low density structural epoxy, epoxy/PVC, and epoxy/PE foams down to the density of 30 kg/m^3. The processing study discussed in Task 1 for wind blade core material manufacturing of low-density hybrid (or integrated) and interpenetrating network polymer foams, are demonstrated by chemical processing methods. The chemical foaming process study reveals that the foam production rate by the blow agent must achieve the critical level to drive rapid nucleation in order to produce the desirable fine and uniform foam structure.

The processing study and manufacturing methods developed in Tasks 1 and 3 are used to: (1) fabricate thick composite laminates for evaluation of spar components in turbine blades; (2) investigate reacting resin flow characteristics during the VARIM and subsequent curing kinetics,(3) manufacture and assemble box-beam components for turbine blade structural failure modes and load prediction, and (4) construct scaled prismatic wind turbine blade sections and components for material evaluation and failure prediction and also for demonstration of advanced materials, optimum turbine blade design and innovative manufacturing integration.

Critical issues have been investigated [4]in the research on wind turbine siting, large wind rotor design and performance of large offshore wind turbine systems in the Gulf of Mexico (GOM) environment. In addition to the determination of offshore wind speed profile, especially extreme hurricane winds with 100 year return in the GOM, with other local boundary conditions, ocean waves and currents and their hydrodynamic loads on wind turbines are also examined. Hydrodynamics parameters governing short- and long-term statistical distributions of GOM oceanographic conditions are calculated. For a 100-year return period, significant and maximum wave heights and their periods, maximum crest elevations and peak spectral periods from NBDC and NOAA data banks are determined for the selected locations of interest. Also determined are current speeds, current headings and associated surge and tide amplitudes at the possible turbine sites. The focus has been on offshore turbine towers, subsea structural design and their upscaling. The API 2 Met and ICE offshore wind turbine design approaches are used in the study. The addition of offshore oceanographic conditions require establishment of unique GOM wind turbine design and modifications of the current turbine merit rating (TMR) parameter, for siting, turbine configuration, and design and cost evaluation.

The influence of wind shear [5] on up-scaling of wind turbines has been investigated and the results are integrated into the updated aerodynamic scaling models with L>100m. The stable and unstable wind profiles determined in Task 1 are used to analyze a selected offshore wind turbine in these conditions. The wind turbine chosen in the study [9] is modeled with three conceptual 100m blades, first proposed by Sandia National Lab., with a hub height of 146.4 m. The wind profiles are input to AeroDyn to compute the aerodynamic forces on the blades. The results obtained are then used as input into FAST to perform further turbine blade aeroelastic analysis, structural design, and failure evaluation. Aerodynamic forces along the blade axis are determined as a function of time. During the load cycles with stable wind profiles, large amplitudes of aerodynamic force are found whereas the unstable wind profiles result in relatively small normal force amplitudes to the blades.

The Innovative concept development [1, 10] of large offshore wind turbines has been completed for introducing future wind rotors to mitigate the ocean environment, extreme wind and O/M problems. An efficient design strategy [10] is established for development of large offshore wind blades, including determination of optimum sectional properties, evaluation of extreme aeroelastic loads and analyzing detailed structural responses of the blade structures. Results, both static and dynamic responses, obtained from the analyses of 100-m all glass-fiber composite baseline turbine blades provide reference turbine structural performance in extreme hurricane wind conditions. Based on the available hurricane wind data along the Texas Gulf Coast for the past 100 years, a 3-second hurricane wind gust of 90 – 93.5 m/sec with a 100-year return is found necessary and must be included in evaluation of structural integrity and reliability of large offshore turbine blades. The overall ability of the baseline 100-m blade structures with all glass-fiber construction is found to be inadequate to withstand the extreme hurricane wind gust. Root causes of these inadequacies are identified, and design modifications and changes, as well as alternative blade constructions, are introduced and investigated. A new offshore wind turbine blade model (NWEC-B1) has been constructed and analyzed to examine its capability of withstanding the GOM 100-year return, 90 m/s hurricane wind. For validation of various new blade design concepts and performance predictions, construction of small wind blade airfoil models has been made and design and material selection of the test turbine airfoil section are completed.

3.2.4 Key Outcomes, Milestones and Other Achievements

Aerodynamic and aeroelasticity analysis and design [28] of newly introduced CRWTs have been completed, including such parameters as directions of individual rotor rotation, rotational speeds, axial and rotational induction factors, etc., for maximum power generation of co-axial multi-rotor wind turbines, especially, counter-rotating horizontal-axis wind turbines (CRWT). Also aerodynamic loads on the CRWTs are determined and significantly higher dynamic loads are found on counter-rotating wind rotors than those on co-rotating rotors. The magnitudes of thrust load and drag and lifting forces are related to individual rotor size, ratio between upwind and downwind rotor sweeping areas, rotating tip-speed of each rotor, and their blade airfoil configurations. Innovative dual wind turbine concepts and design methodology have been developed for maximum power generation with alternative rotor blades of advanced composite systems, internal structures, and aeroelastic tailoring.

The chemical foaming process study reveals that hybrid and IPN polymer foams may be most promising, exhibiting excellent cell microstructures with attractive mechanical properties suitable for foam-composite sandwiches in design and construction of large turbine blades. The foaming process developed in the project produces very low density, structural core foams for use in light-weight composite sandwich structures. New manufacturing development for large-size foam sheets has been conducted with different curing agent mixtures, blow agents, surfactants, and multi-step process schemes.

The results of the thick-composite processing research and the manufacturing methods [3, 6, 26] developed in Tasks 1 and 3 are used to: (1) successfully fabricate thick composite laminates for evaluation of spar components in turbine blades, (2) validate the reacting resin flow characteristics obtained during the infusion process and the subsequent curing, (3) manufacture and assemble box-beam components for determination of turbine blade structural failure modes and load prediction, and (4) construct scaled prismatic wind turbine blade sections and components for material evaluation and failure prediction and also for demonstration of advanced materials, optimum turbine blade design and innovative manufacturing integration.

The innovative design [1, 10, 16]of large offshore wind rotors addresses several turbine airfoil and blade structural/material alternatives and changes to ensure turbine performance and integrity of an 100m all glass-fiber, baseline wind turbine blade to withstand extreme (e.g., 100-year return hurricane) winds in the GOM environment. Maximum loads on the wind turbine are determined for offshore wind turbines with blade pitch and rotor yaw, and with and without wind-wave misalignment in the 100-year return hurricane. The effects of blade pitch and rotor yaw on turbine structural dynamics are found to be very significant, whereas the effect of wind-wave misalignment is small in the context of structural design in turbine strength [16]. The study provides deep insight to wind turbine dynamics and its structural reliability in the extreme hurricane. Turbine blade design strategy and computational models have also been established. The development of a new blade (NWEC-B1) has been made to withstand the extreme hurricane wind and coupled bending-twisting loads. The new offshore wind turbine blade model (NWEC-B1) is found to have the capability of withstanding the GOM 100-year return, 90 m/s hurricane wind. An up-scaling procedure has been developed for design and simulation of the desired new offshore wind turbine structure, as uncertainties of aerodynamic loads, which affect rotor structural instability, aeroelastic flutter and material fatigue become critical.

Marine atmospheric stability has been studied [5] on the year-round wind data of German coast offshore. The presence of prevalent wind shear has been identified, based on the atmospheric stability conditions. The wind speed profile is found to have direct effect on turbine power generation and the aerodynamic forces on blades. The stability of the wind profile, i.e., the wind shear effect, governs the amplitude of the aerodynamic force on the blade, consequently the fatigue life of the wind turbine. The difference in amplitude between wind profiles with and without wind shear is 11%, based on the FINO1 tower data and extrapolation. Since the aerodynamic load is cyclic, it is very important to include the wind shear effect in the turbine rotor blade fatigue analysis. The large-eddy simulation study has been completed with computational validation of a 3D flow passing a circular cylinder. Effects of grid resolution, time step interval, and sub-grid scale model on the resolution are closely explored for subsequent 3D simulation of wind flow over turbine blades. The flow field in the wake region and the pressure coefficient distribution along the cylinder surface are determined and they agree well with experimental data and other flow simulation. Understanding the numerical capabilities and limitations of large-eddy simulations, detached-eddy simulation, and other models can assist in future CFD simulations on flow passing a rotor blade or the entire turbine. (The results on a basic flow passing a 3D cylinder establishes a validation case for future CFD developments.) The CFD simulations on wind rotor blades provide substantial improvement of BEM model predictions and understanding limitations of the computational models and their suitability. The current 3D CFD simulation of large wind turbine performance indicates that the large eddy simulation (LES) model provides results in good agreement with those obtained from the DNS approach and improvements to the commonly-used BEM method. Optimization of large offshore wind turbine blade aerodynamic design indicates that the current airfoil geometry of the baseline 100m blade gives reasonable aerodynamic performance but substantial improvements could be made in airfoil modifications, especially from inner to mid-span blade sections.

3.3 Task 3: Integration of Offshore Wind Turbine Design, Advanced Materials and Manufacturing Technologies

3.3.1 Major Activities

During the reporting period the following major activities in the task have been conducted:

(1) Identifying governing processing, material, structural and design parameters and establishing their criticality for cost-effective manufacturing of large offshore wind turbine blades

(2) Development of new and effective methods for processing and manufacturing light-weight, high-strength core foam materials of optimum microstructure and adequate strength and stiffness for construction of foam-composite sandwich panels for large offshore composite rotor structures.

(3) Integration of advanced materials and manufacturing technology with innovative aerodynamic and structural design for construction of large offshore wind rotor components and structures.

(4) Demonstration of design and manufacturing integration for construction of critical load-bearing components in typical large offshore wind rotor blades.

3.3.2 Specific Objectives

The task is aimed at developing an optimal strategy and associated methodologies to integrate wind-turbine aeroelastic and structural design, advanced materials technology, and cost-effective manufacturing and construction of large offshore wind rotors, especially for alternative rotor blades with advanced composite materials, internal structure design, and assembly methods of wind turbine blades. It also aims at conducting processing and manufacturing investigations to demonstrate the developments of composite laminates, core foam-composite sandwiches, components and structures with quality representative of production wind turbine blade airfoil shells, load-bearing spar caps and shear webs, as well scaled rotor blades. Alternative systems of large offshore wind turbines, such as counter-rotating and co-rotating wind turbines, are also investigated in the task.

3.3.3 Scope, Results and Significant Accomplishments

In this task, research has been conducted on integration of aerodynamic and structural design, advanced materials and innovative manufacturing technology for developing and constructing next-generation large offshore wind turbine rotors. A focus has been made on improving compressive strength and stiffness properties of physical-foaming processed low-density epoxy-based foams and integrating them in the wind turbine blade design and construction. The mechanical and other physical properties of the foams resulted from the process are the weak link of the turbine blade integrity and they must reach the desired levels to ensure the wind turbine blade integrity and reliability. The results of the study [17, 24] indicate that the diffusion-limited curing reaction and associated kinetics of post-processing solidification are critical controlling factors governing the foam compressive strength and stiffness development. A parallel study [24] has also been conducted to investigate the important processing effects of foam density and cell rise ratio on compressive mechanical properties and strength of closed-cell structural foams. Taking advantage of density variation in an as-received large PVC foam panel, foam compression experiments on specimens with different densities from the panel are conducted. Straight-side specimens with different gage-section length-to-width ratios are used for foam out-of-plane stiffness study. For strength and failure-mode evaluation, foam specimens with reduced gage sections were used. The results show that foam compressive stiffness does not correlate linearly with either foam density or cell rise ratio. Similar behavior is observed for the foam compressive failure strength. Compressive failure modes are found to include foam-cell micro-buckling and formation of a localized shear band across the entire specimen cross-section. Recently developed foam compressive stiffness and strength theories, based on foam microstructure and micromechanics, are used to validate analytical predictions with experimentally determined foam compressive stiffness and strength.

Innovative and alternative turbine blade designs [5, 20] have been obtained on several wind rotors with internal structures, and modular blade design and assemblage. Advanced material systems with new blade manufacturing approaches are also introduced for cost-effective construction of large offshore wind rotors. New wind turbine blades (e.g., NWEC-B1-H200G and NWEC-B1- H200H) are designed [4] with advanced materials, such as carbon- and glass-fiber hybrids, and new internal structures with local/global laminate thickness changes). The effectiveness of using hybrid glass/carbon fiber spar-cap design to improve structural integrity and performance of a large wind turbine blade to withstand extreme hurricane wind (70m/s) loads is determined and compared against those with an all glass-fiber composite construction. To further enhance the capability of the wind rotor to resist extreme-wind-induced transverse cracking, local reinforcements are introduced into the spar cap and the aft panel of the blade. The wind rotor has been found to be able to withstand 1.5 times the extreme hurricane without loss of structural and material integrity 10] . Detailed studies has been made on advanced wind-rotor materials, processing methods and parameters, design technology and economics of large turbine blades with a focus on advanced modular blade development.

An important effort on the task has been made on experimental validation of integrated design and manufacturing of thick thermoset composite laminates for turbine blade construction. To illustrate the design and manufacturing integration [3, 6] of wind-blade composite structural parts, glass/polyester laminate panels up to 5.6 inches thick with 120 plies is designed and fabricated with the controlled VARIM process developed in Task1. Exothermic reaction, heat management, curing kinetics, curing-induced structural dimensional stability and process control are all evaluated An additional study of the subject and demonstration of the integration procedure has been conducted on design and manufacturing of the most important structural components in large wind rotor blades: load-bearing composite box-beam structures and thick-section spar composite laminate panels. With the current VARIM manufacturing method, eight composite box beams of 6-ft and 12-ft in length, based on scaled wind rotor blade structural design, are manufactured. Review of the structural design and evaluation of the manufacturing procedure lead to an assessment of further improvements of the design and processing details of future development and construction of long wind blade components. The load-bearing box beams for scaled wind turbines are tested to evaluate their manufacturing variables, structural strengths and failure modes of thick-laminate composite spar caps and composite-foam shear webs, as well as the assembled structural instability (buckling collapse) characteristics.

A comprehensive study [20, 27] has been conducted to obtain detailed understanding of the structural strength and failure modes observed in testing of the adhesive-bonded composite box-beams. The composite box-beams are scaled critical component in the large wind turbine blade structures and are designed and fabricated to emulate essential characteristics of the main load-bearing component of a large composite wind turbine rotor blade. The box-beams are assembled with thick adhesive layers between spar caps and shear webs. The structural integrity of the box-beam specimens is evaluated in both 3- and 4-point bending experiments. To obtain proper understanding of the observed bending test results, detailed deformation, failure modes and strength behavior of the tested box beams are modeled and analyzed using advanced nonlinear finite element methods. A series of linear eigenvalue analyses are first conducted to determine the buckling modes and loads of the tested box beams. Incremental-iterative loading analyses are conducted to investigate the progressive development of local nonlinear deformation, instability and stress distributions in the box-beam spar caps, shear webs and adhesive layers during the bending tests.

3.3.4 Key Outcomes, Mile Stones and Other Achievements

The developments of both physical and chemical-foaming methods have been completed for manufacturing new classes of low-density, high-strength structural core materials for wind turbine foam-composite sandwich structures. Current results reveal that different curing agents had distinct and significant effects on compressive strength properties. Several curing agents (both commercially available and experimental) are employed. The low-density foam made with triethylenetetramine curing agent exhibits compressive strength and stiffness about 50% higher than those prepared with other curing agents. Also, foaming processes with different polymer resins (again with different curing agent) are conducted and the Dow 383 resin leads to low-density structural foam with the highest compressive mechanical properties, at least 25% higher than those from all other polymers. The information derived from the fundamental foam-material processing development provides the needed knowledge base, enabling us to scale up the manufacturing technique and processing molds, which would ensure proper production of structurally uniform foams with the required mechanical properties for large offshore wind turbine blade structures. Recently developed foam compressive stiffness and strength theories [17], based on foam microstructure and micromechanics, are used to validate analytical predictions with experimentally determined foam compressive stiffness and strength. The results indicate that foam density and its cell rise ratio alone cannot properly address the effect of processing and individual material and microstructure parameters on foam compressive properties. Their interactive roles and combined effect must be included simultaneously in the modeling, analysis and experimental evaluation of foam mechanical properties. For the light-weight closed-cell PVC foam tested in the study, an approximately linear relationship is obtained to relate both foam compressive stiffness and strength to the product of foam density and cell rise ratio from foam processing.

Work on thick-section composite laminate panel experiments has been completed [3, 6]. The results obtained from curing kinetics, exothermal history and dimensional stability show their significant variations in Tg and temperature along the thickness direction. The through-thickness temperature and Tg gradients are found to increase significantly with increasing laminate thickness. Improvements of the VARIM process and manufacturing methods for large turbine blade construction are devised with better process control and thermal management. Integration of innovative aerodynamic/structural design and VARIM thermoset composite manufacturing is successfully to further cost-effective development of large offshore wind rotors. The curing kinetics models developed and the VARIM experimental data obtained provide the needed information for subsequent computational simulations and evaluation of manufacturing the load-bearing composite box-beam and other turbine structural components to be reported in the next quarter.

The design, analysis and manufacturing [10, 20, 26] of high-stiffness, light-weight sandwich panels and box beams made of glass-fiber composite and core foam materials are also completed. The vacuum-assisted resin-infusion molding process developed in the previous tasks is employed for this purpose with controlled reaction kinetics and integrated with detailed design of long shear web and spar cap structural parts. The capability of manufacturing load-bearing box beams with thick spar caps and foam-composite shear webs is expanded with the recent additions of 6-m molding flanges of shear webs, patterns for the flanges and bond caps, as well as a four-zone-controlled post-cure heating chamber, which enables the upper and lower spars of a scale wind turbine blade to be manufactured in one single processing step. The associated VARIM process is refined for better manufacturing of complex thick-section composite laminates and sandwich structures for subsequent mechanical strength and cyclic fatigue testing. Current analytical results indicate that transverse shear stiffness of the foam core material in composite-foam sandwich turbine blades would have the most significant influence on buckling resistance of both hybrid and all-glass-fiber large composite wind rotors. For example, changing the foam core from H60 to H200 in a 100-m composite turbine blade, an 100% increase in buckling collapse resistance may be achieved in a 70m/sec hurricane. Also, the use of hybrid (carbon/glass) fabric reinforcements for composite spar cap construction is most effective to improve both material and structural integrity of large offshore wind turbine blade structures.

The alternative turbine blades [1, 1027] with integrated advanced fiber composite and different internal structures are found to provide appreciable weight reduction, increasing blade bending stiffness improvement and better flap-wise dynamic response. However, changing the foam core materials with different stiffnesses in both all-glass and hybrid composite blades (i. e., NWEC-B1- H200G vs. NWEC-B1-H100G and NWEC-B1-H200H vs. NWEC-B1-H100H) does not appear to affect the blades' bending and torsional natural frequencies nor their deformation characteristics. The introduction of advanced materials, such as carbon fiber composite, with a new blade manufacturing approach improves cost-effective construction of large offshore wind rotors. The effectiveness of hybrid glass/carbon spar-cap blade design (i. e., NWEC-B1-H200G vs. SNL-100) is demonstrated to affect the structural performance against that of an all glass-fiber composite construction. The wind turbine blades, e.g., NWEC-B1-H200G and SNL-100-H200G, with modified internal structures and local/global laminate-thickness changes do not exhibit significant influences on deformation characteristics and natural frequencies in torsion and bending, but their stability characteristics are substantially different in blades with a low density foam.

Mechanical strength and fatigue tests have been evaluated to demonstrate the validity of the integration process of advanced material selection, aerodynamic/aeroelastic design, and effective manufacturing. The manufacturing and design developments [26] of wind turbine rotor structural components with thick-section thermoset composite (e.g., laminate and foam-composite sandwich) systems has led to further development of 12-ft long box beams and scaled wind turbine blade airfoil models for subsequent manufacturing and testing. Bending tests were conducted on both 6-ft and 12-ft load-bearing box beams for scaled wind turbines. The composite box beams are fully instrumented and tested. The results reveal their structural strengths and failure modes are governed by critical design parameters and manufacturing defects. The box beams with different depths lead to distinct failure modes and characteristics of spar cap buckling, adhesive bond failure between the composite spar and the foam-composite shear web, and the shear web structural instability (buckling collapse). Incremental-iterative computational mechanics analyses are conducted to investigate the progressive development of local nonlinear deformation, instability and stress distributions in the box-beam spar caps, shear webs and adhesive layers during the tests. The numerical results are correlated and compared with the observed test results to obtain detailed understanding of damage and failure progression. The factors that influence the ability of the box-beam specimens to carry additional loads beyond the first buckling load were assessed. The good agreement between bending test and numerical analysis results suggests that the analysis procedures taken in the study could be used to analyze and predict the ultimate strength and failure modes of the composite box-beam component under different bending loads. Failure in the shear web-spar adhesive bond is found mainly due to manufacturing variations and surface preparation, but buckling collapse modes and strength predictions are successful. The relationships are established between the composite box beam strength (and hence the wind turbine load bearing capability) and turbine rotor design, material selection, and manufacturing and assemblage methods 20, 26]. All these results have provided important bases for developing turbine blade materials and structures with desired structural properties, processing parameters and control, manufacturing and design details for construction and demonstration of scaled wind rotors and modular offshore rotor blades.

3.4 Task 4: *Integrity and Reliability of Offshore Wind Turbine Blades and Scaled Model Testing*

3.4.1 Major Activities

(1) Offshore marine wind boundary-layer effect on wind shear and aerodynamic force fluctuation on rotor blade fatigue
(2) Stochastic wave and current distribution functions of GOM, especially in hurricane conditions
(3) Buckling instability of large offshore wind turbine blades in extreme wind conditions and mitigation
(4) Effects of curing and post-curing on mechanical properties and failure strength of VARIM turbine blade composite laminate airfoil skins and spar caps.
(5) In-plane longitudinal, shear and transverse failure modes and strengths of thin and thick-section VARIM composite laminates
(6) Interlaminar physical and mechanical properties, failure modes and strengths of thick-section VARIM composites for wind rotor blades
(7) Damage, failure modes and strength of structural-foam core materials and foam-fiber composite sandwiches
(8) Fabrication of composite spar caps, shear webs and assembled box beams of different lengths.
(9) Evaluation of failure modes and ultimate strengths and prediction of load-bearing capacities of shear webs, spar caps and box-beam composite structural components
(10) Structural integrity of large MW-scale wind turbine blades subject to extreme GOM hurricane wind conditions.

3.4.2 Specific Objectives

The objectives of this task are to conduct comprehensive investigation on

(1) Assessment of structural integrity and performance envelope of large MW-scale offshore wind turbines in extreme GOM hurricane.
(2) Metocean conditions and their statistical distribution functions of wind speed, sea waves and underwater loop current in the GOM region in nominal and extreme environmental conditions,
(3) Fundamental characteristics of 3D deformation, strengths and damage mechanisms of next-generation turbine-blade composite laminates, structural foams and foam-composite sandwich structures.
(4) Load-bearing strengths, failure modes, long-term properties and structural instability of thick composite laminates, structural foams, composite-foam sandwich components and other structural components in large offshore turbine blades.
(5) Interlaminar shear, normal and fatigue strengths and failure modes of thick glass/vinyl ester composite laminates under static and cyclic fatigue loading.
(6) Analysis, testing and predictions of load-bearing strengths, failure modes, long-term mechanical properties and structural instability of critical structural components (shear webs, spar caps, box beams) and thick-adhesive bonded joints in large offshore turbine blades and scaled wind rotors.

(7) Effects of processing conditions, material- and manufacturing-induced defects and different loading modes were examined on performance and reliability of blade composite materials and critical structural components.

3.4.2 Scope, Results and Significant Accomplishments

Structural integrity issues that affect the performance of large rotor blades have been investigated for MW-scale offshore wind turbine systems in extreme Gulf of Mexico (GOM) hurricane conditions. Analytical modeling and computational mechanics results [10] are obtained on optimum turbine blade design, detailed internal structural configuration, blade static and dynamic stability and failure modes for a baseline 100-m all-glass composite offshore wind turbine and newly designed large wind turbines with alternative design and material systems. Critical problems are identified and solved for transverse cracking of blade structures and integrity of the large composite wind rotors in extreme hurricane wind exceeding 70m/sec. The results show the effectiveness of using hybrid carbon/glass fabric composites for spar caps in construction of the rotor blades to withstand the extreme hurricane wind in the GOM. The concept of preloading the wind rotor blade is introduced and its effect on buckling stability resistance due to the extreme wind is determined.

A study [5] has been conducted on offshore marine boundary-layer effect on wind shear and metocean conditions in the GOM region. Wind data from the German offshore FINO1 tower and Lidar measurements at the same site are obtained and different wind profile models are constructed and compared. Offshore wind speed distribution functions are determined and extrapolated to the height of 250m for aerodynamic load evaluation on the 100m offshore wind rotor blades. The available, public data bases provided by NDBC, NOAA, Texas GLO and National Hurricane Center are also examined. Statistical wind speed distribution functions and stochastic wave and current distributions at selected GOM locations of interest are analyzed, especially in extreme wind gust and hurricane conditions.

In the manufacturing study, the effects of curing and post-curing have been successfully completed to identify their influences on variations and reliability in mechanical strength properties and damage resistance of wind turbine composites. Functional relationships have been obtained among reaction kinetics, processing parameters and turbine-blade composite mechanical properties, failure modes and associated strengths.

Extensive experiments have been performed on selected composite laminates, core foam materials, thick-adhesive bonded joints with different laminate layups and curing/post-curing schedules. A significant amount of data are obtained for evaluation of mechanical and strength properties and their variations in selected VARIM composite systems for offshore blade structural design and reliability assessment. Extensive experimental results are obtained on load-bearing capacities, failure modes, long-term properties and structural instability of thick composite laminates, structural foams, composite-foam sandwich components, and other structural components. Computational mechanics studies are conducted, in parallel to the experiments, on crack initiation, growth and instability in thick-adhesive bonded composite joints. In the associated experiments, its results reveal unique features of failure modes and strength characteristics in thick-adhesive bonded joints of glass fabric/vinyl ester composite. Based on the experimental observations and test results, complementary computational mechanics models and prediction methods are successfully developed to assess the integrity and reliability of thick-bond composite joints in large wind turbine blades to advance further our understanding of the subject. Composite joints of similar geometry but with thin adhesive bonds are also examined and compared to elucidate the complex nature of the failure mechanics in the thick adhesive-bonded joints. The computational study is formulated with composite laminate mechanics, nonlinear fracture mechanics and advanced finite element methods.

Of particular interest are the interlaminar properties and failure modes and strengths under different loading modes in glass fabric/vinyl ester composite laminates for offshore wind rotor construction. A series of comprehensive static and cyclic fatigue tests have been conducted on thick-section glass/vinyl ester composite laminates up to 5.6 in (120 plies). Associated theoretical modeling/analyses of interlaminar strengths and cyclic fatigue behavior of the thick composites are also performed [7, 13]. In the experimental phase of the work specially designed test fixtures and sample configurations have been developed and constructed. The results revealed unique features of the interlaminar shear, normal and fatigue properties and strength characteristics. Their mechanical and strength properties as well as failure modes are very significantly affected by the composite microstructure, processing variables and loading modes on the thick glass/vinyl ester composite laminates.

Experiments [20] have also been conducted on critical structural components, i. e, composite shear webs, spar caps, adhesive bonds in sandwich composite box beams and between the box beam and composite-foam sandwich airfoil skins, of large offshore turbine blades and scaled wind rotors under different loading modes. Predictions are also made on load-bearing strengths, failure modes, long-term mechanical properties and structural instability of the critical structural components (shear webs, spar caps, adhesive bonds) in large offshore turbines. The results reveal many important but unexpected effects of wind turbine design parameters, manufacturing variables, constituent material contributions and composite lamination variables.

Advanced finite element modeling and analysis of scaled box-beam test sections are completed [26]. Detailed computational modeling has been successfully performed on both 6-meter long box beams and also on 6-meter long scaled blade test sections. These scaled components are intended for use to evaluate the improvement of structural performance of large 100m wind turbine blades that can be obtained with different reinforcement schemes, internal structural configurations and assembly methods. The results of the finite element analysis are then used to guide the testing of these scaled components to verify the effectiveness of various methods to improve the performance of large turbine blades.

The development of suitable composite failure mechanics models has been completed in the large wind turbine blade reliability task. These models are incorporated in the detailed design, simulation and test validation of scaled wind-rotor shear webs, spar caps and primary-load- bearing box beams [10, 20, 26]. Our lab fabrication facility has been expanded for construction of 12-ft long all glass- and carbon-fiber composite wind-rotor box beam structures with sandwich shear webs. Design and fabrication of test fixtures and measurement instruments are conducted on the 6-foot sample box beam structures in static and fatigue bending loads. Deformation analysis, damage modeling and test simulations are performed to determine local geometric effects, associated stress concentrations and critical locations of failure initiation and crack growth in the planned experiments.

The studies in Tasks1, 2 and 4 on the behavior of the baseline, large offshore wind turbine blade SNL-100 reveal several major concerns with its structural failure in extreme winds (i.e., hurricanes) of the Gulf of Mexico. The results indicated that large offshore wind rotor blades are prone to buckling and flutter failure among other issues in high aerodynamic loading conditions. Alternative blades are introduced with new design, advanced materials and internal structural configurations to mitigate the important blade structural instability problem. In this task, coupled computational material mechanics and shell structural stability analysis are also conducted to address the buckling issues of large offshore turbine blades (>100 m) with alternative designs, advanced materials, new internal stiffening structures and other options, in the extreme 90 m/s wind with 100-year return.

3.4.4 Key Outcomes, Mile Stones and Other Achievements

Aerodynamic force on a 100-m large wind turbine blade has been determined with the aid of the AeroDyn software. Numerical simulations with the FAST program are conducted on the Sandia all glass-fiber composite blade to evaluate aerodynamically-induced, blade out-of-plane bending moment as a function of the azimuth angle subject to different boundary-layer stability conditions in given wind speed profiles. Significant aerodynamic load fluctuations are found as a result of the wind shear and the rotor blade rotation position. The out-of-plane blade bending moment along the flap direction is cyclic and its magnitude is determined to be significant to warrant a critical fatigue analysis for wind rotor reliability. The results are used in subsequent site selection, advanced design, subsea system reliability analysis, and rotor structural integrity of offshore wind turbine systems.

The baseline all glass-fiber composite 100 m turbine blade (SNL-100-00) is expected to collapse in the leading edge area of the blade in the extreme wind with 100-year return. A new blade design (NWEC-B1-H200G blade) with a modified internal structure is found to be adequate to withstand the extreme wind [10]. A hybrid-material blade with (50/50) carbon/glass fiber reinforced spar caps significantly improves the blade's stiffness, natural frequencies and buckling resistance over those of the all- glass (NWEC-B1-H200G) [10] blade. The effects of foam core material in shear webs and in airfoil sandwich shells control the blade collapse loads and their failure modes [10]. The use of combined heavy foam core and light-weight hybrid reinforcements in spar caps could increase the buckling resistance of the 100-m turbine blade by a factor of three when compared with that of the baseline all-glass-fiber composite blade. Aeroelastic tailoring has been conducted on the baseline 100m offshore blades by introducing carbon fiber composite-foam sandwich spar caps (or pure carbon fiber composite spar caps) with reduced chord length and airfoil height by approximate 15%. The result show that the blade mass is significantly reduced and flap-wise blade-tip bending deformation decreases significantly. The buckling resistance of the blade with carbon composite-foam sandwich spar cap is much lower than required, as contrast to the case with that of the blade with carbon composite spar caps. Much work remains to determine the aeroelastically tailored optimum blade structure to ensure its integrity and reliability.

The current wind turbine structural integrity study [10] provides a complete evaluation of structural integrity of large wind turbine rotor blades subjected to extreme hurricane wind loads. The analytical and computational mechanics models and associated failure criteria are validated for advanced turbine blade design, structural integrity and wind rotor reliability in the 100-year return hurricane. The detailed internal structural configuration introduced provides the new wind turbine rotor blades significantly higher resistance, exceeding the required static and dynamic stability, and mitigates the expected failure modes of the baseline 100-m long, all-glass-fiber composite offshore wind turbine. The large wind turbine blades with the alternative design and material systems also resolve a critical structural integrity problem involving blade composite transverse cracking in extreme hurricane wind. The use of hybrid carbon/glass fabric composites in construction of the rotor blades proves the advantages of reductions in both rotor weight and aeroelastic loads to withstand the extreme metocean condition. The concept of preloading the wind rotor blade is found less effective in improving the blade buckling stability capability in the extreme hurricane wind. For the important problem of thick-adhesive bonded composite structural joints, current work successfully address the following issues on structural strength and failure modes of the bonded composite joints in large offshore wind turbines: (1) crack formation and mechanisms, (2) crack growth, its driving force and failure modes, and (3) the effect of adhesive bond thickness. Local material strength criteria are used to identify crack initiation in the joint. Driving force for crack growth in the nonlinear adhesive of the bonded composite joint is evaluated by energy release rates associated with the crack. The adhesive bond thickness is found to govern crack formation and subsequent growth in the joint failure. Comparison of numerical results with experimental observations and test data are made to assess the validity of the computational mechanics approach and to better understand the complex nature of thick-adhesive bonded composite joint failure.

The analysis of metocean conditions of the GOM region continued with the data provided by NDBC, NOAA and Texas GLO and other organizations. Aerodynamic loads and wind speed distributions are determined for offshore wind rotors in extreme GOM wind conditions [9]. Statistical distribution functions and associated stochastic nature of ocean waves and loop currents at selected GOM locations in nominal sea, current surge and tide, and hurricane environments have been obtained for offshore wind turbine reliability analysis of large offshore wind rotor structures.

Long-term performance and reliability of wind turbine composite materials and blade structures have been evaluated in this task. Their mechanical properties, failure modes and strength, and associated variations are obtained. Predictive models and computational algorithms have been constructed, based on the material microstructure and deformation mechanisms observed for assessing long-term load-bearing reliability of critical components in large wind turbine blades.

The important 3-D through-thickness curing differentials are found to be very significant in the current manufacturing of large wind turbine blade composites with both glass/polyester and glass/vinyl ester systems [3, 6]. The significant curing gradient through the thick-composite laminates results in weak interlaminar strength with large variations as well as changes in failure models and criteria [7, 13]. Incorporation of the spatial variation of interlaminar properties has been considered in the new design and life prediction for integrity and reliability of large wind rotor structures in extreme wind conditions. Validation of scaled blade structural component performance and reliability has been conducted with static and fatigue testing of the in-house manufacturing composite load-bearing box beam structures and later the scaled airfoil turbine blades.

Significant results are obtained from experiments on selected composite laminates, foam materials, bonding adhesives for design input, optimizing laminate layups and planning curing/post-curing schedules. The mechanical and strength properties determined on the VARIM composite systems are extreme valuables for offshore wind blade structural design and reliability assessment. The experimental results are critical in validating the load-bearing strengths, failure modes, and the structural stability of thick composite laminates, structural foams, composite-foam sandwich components, and other structural components. The interlaminar properties, failure modes and strength under different loading modes are necessary for use in safe design of large wind blades [7], especially for the regions between the maximum chord section and the blade root.. The static and cyclic fatigue results on thick-section glass/vinyl ester composite laminates up to 5.6 in (120 plies) provide the need information for assessing long-term reliability of large offshore wind turbine blades. Unique features of blade thick-section shear, normal and fatigue failure and strength characteristics have been identified and illustrated in long-term failure resistance and integrity design consideration. The experimental data are invaluable on critical structural components, i. e, composite shear webs, spar caps, adhesive bonds, of large offshore turbine blades and scaled wind rotors under different loading modes. They provide important validation on computational mechanics models and analytical prediction methods for determination of load-bearing strengths, failure modes, long-term fatigue degradation, and structural instability of these components in large offshore turbines.

3.5 Task 5: Education and Training of Graduate and Undergraduate Students and Post-doctoral Researchers

3.5.1 Major Activities

(1) Offering a new course, "Wind Energy" at the graduate level to more than 30 graduate students from several different departments in the college of engineering.

(2) Training graduate students and post-doctoral level researchers to conduct multi-disciplinary research in the aforementioned technical tasks. The students and researchers have various backgrounds, ranging from chemistry, polymer science and engineering, aerospace engineering, mechanical engineering, chemical engineering, structural engineering and ocean engineering.

3.5.2 Specific Objectives

The objectives of this task are to: educate graduate students and post-doctoral level researchers to learn critical science and engineering of wind energy production systems through graduate level courses and research; train the students and researchers to assist and conduct various projects in center's large multi-disciplinary research program. These students and researchers are employed by and support the future US wind energy industry.

3.5.3 Scope, Results and Significant Accomplishments

Experimental data, analytical models and theories, computational algorithms and numerical results are obtained from all the aforementioned projects. The results provide a solid foundation and create new knowledge for advancing the projects that the individual students and researchers are involved.

3.5.4 Key Outcomes, Mile Stones and Other Achievements

A large number of technical reports and papers derived from the various projects have been prepared and published in archival journals and national/international conference proceedings. The reports and papers contribute significantly to the knowledge base for national and international wind industry and research communities. A good testimony of the center's education and training programs is that our graduate students have been recruited and hired immediately after their graduation by major national and international engineering companies and national laboratories, such as Siemens Energy, National Renewable Energy Laboratory, Baker Hughes, Schlumberger, …, etc.

3.6 Task 6: Development of a National Offshore Wind Turbine Blade Research Facility

3.6.1 Major Activities

(1) *Offshore Wind Turbine Materials Research Laboratory*

The lab is equipped with the latest state-of-the-art facilities to measure thermal, dynamic-mechanical and other physical properties of advanced wind turbine composites and engineering polymers in both molten and solid states, including ARES G2 Rheometer, RSA III Dynamic-Mechanical Analyzer (DMA), Q200 Differential Scanning Calorimeter (DSC), and Q50 Thermogravimetric Analyzer (TGA).

(2)Offshore Wind Turbine Rotor Blade Composites Processing and Manufacturing Laboratory

The lab is equipped with high- and low-temperature reactors for liquid infusion molding, particularly suitable for vacuum-assisted resin infusion molding (VARIM). The facility is developed with specialized equipment for evaluating processing variables and material alternatives. The laboratory is critical for processing and manufacturing studies of thermoset and thermoplastic composite laminates for wind turbine rotor blades. The lab is also used to conduct process trials to develop quality scaled wind turbine blades representative of production wind turbine materials, blade airfoil shell structures and load-bearing spar caps and shear webs. It is also used to evaluate new manufacturing methods and processing parameters for alternative blade design and production, including modified laminate layups, hybrid and/or nano-reinforcements, internal blade structures, modular blade joining, resin infusion flow control, fiber-optical and other sensors implementation and curing and post-curing studies. Equipment for fabricating prismatic wind turbine blades up to 10 meters and their internal structural components are available for manufacturing and advanced material processing research, including:

- Pressure- and suction-side (heated) turbine blade molds (constant X-section DU97-W-300 airfoil configuration)
- Flanges for long foam-composite shear web manufacturing
- Flat table for shear web VARIM processing
- Bond caps for wind turbine blade leading edge section
- Patterns for shear web flanges, bond caps, suction- and pressure-side molds
- Installation jigs for shear web VARIM production

(3)*Composite and Polymer Microstructure and Advanced Imaging Laboratory*

The lab is equipped with a Nikon Eclipse LV150 digital optical microscope with both reflected light and transmitted polarized light modules, a JEOL JSM-6010LV SEM (Scanning Electron Microscope).

(4)M*ulti-axial Wind Turbine Material and Structural Fatigue and Strength Laboratory*

The lab is equipped with an Instron ElectroPulse Model E10000 axial-torsion dynamic material test system, a retrofitted Instron axial-torsion close-loop, servohydraulic material test system, and a MTS 810 uniaxial servohydraulic material test system. The MTS 810 is retrofitted with a new digital electronic control system, consisting of FlexTest 40 controller and TestSuite software capable of performing desired spectrum loading tests.

(5)*Wind Turbine Blade Component Test Laboratory*

The test system of composite blade components and scaled blades features multiple 50 KN actuators with 500 mm displacement and is a self-reacting setup on a standard industrial hard floor. The test system load frame is in-house designed with high-capacity actuators, controllers and necessary utilities, including hydraulic power supply (HPS), hydraulic service manifold and high pressure hoses. To demonstrate the loading frame capability, controllers and test sample installation and operation, a 9-m wind turbine blade (200kW) was mounted on the load frame with a mounting bracket, designed in house and manufactured by a local steel fabricator. A chilled water supply system (for HPS cooling) and the needed electric outlets are added in the building. Calibration and test runs were made and some design modifications have been introduced. The test facility is capable to test mechanical response of complex blade composite laminates, foam-composite sandwich panels and scale airfoil sections, and long box beams with shear webs and spar caps up to 10 m in length subjected to complex coupled loading. It is also used to test scale turbine blades up to 9-m loaded at 60% span length for evaluation of manufacturing, materials and design features and structural elements/components representative of large offshore wind rotor blades. The test system is designed to conduct tests in various loading modes, including biaxial bending, combined bending and torsion, and other complex loads in static, cyclic and spectral loading. It bridges the gaps between coupon specimen testing and full-size blade testing in the following areas: (a) Characterization and integration of advanced materials, manufacturing, and design; (b) Effects of discontinuities, defects and repairs methods; (c) Environmental effects and development of test methodologies; and (d) Validation of advanced manufacturing methods, innovative design concepts and various turbine blade and other structural and

material models.
(6)*Scaled Wind Rotor Blade Test Laboratory:*

The facility is designed to test large wind rotor blades at approximately 1/5 scale for developing innovative wind turbines, introducing advanced blade test methodology for large wind rotor blades, and evaluating reliability of new designs and materials on scale rotor blades. It enables proper development of sophisticated test protocols involving service environmental exposure and mechanical fatigue of complete scale rotor blades. Advanced instrumentation will be added for evaluation of blade fatigue damage growth and reliability under multi axial variable- amplitude fatigue and static failure loads with advanced NDE techniques and analytical models.

(7)*Wind Turbine Design and Simulation Laboratory*

The wind turbine design and simulation lab is equipped with six multi-processor, high-speed workstations for computational research and design work on advanced wind turbines. Different software packages are installed for use in the ongoing research projects on advanced materials, manufacturing, testing, simulation and reliability assessment. The software packages installed, including those developed by MSC, Simulia, MatLab, NREL and others. New computational methods and algorithms, developed in-house, have been developed for modeling and analysis of problems on thick composite reaction kinetics, polymermaterial science, wind rotor structural dynamics, fluid-structural interaction, composite mechanics and structures, for wind turbine manufacturing, rotor blades and wind tower design. The software packages in the design and simulation lab are available for use in all projects by graduate students, research scientists and faculty. The existing software packages in operation in the computing software library include constitutive material laws for different turbine composite systems, thick-section composite processing simulation, wind rotor aerodynamics and aeroelasticity, turbine blade and tower structural dynamics, and damage mechanics and fatigue failure life prediction.

3.6.2 Specific Objectives

All the facilities developed in the aforementioned laboratories are used to support the technical and training tasks in the research program to accomplish their goals.

3.6.3 Significant Results

The experimental and computational results obtained with the aid of these facilities are reported in the individual task sections.

4. Products and Deliverables

4.1 Publications- journal and conference papers

[1] S. S. Wang and K. H. Lo, "Design, Fabrication and Testing Considerations for Large Offshore Wind Turbine Blades", Paper No. IV-1, in *Session on Design, Fabrication and Testing Considerations, JEC International Conference on Advanced Composites*, Boston, MA, November 7-9, 2012

[2] Y. Hou and S. S. Wang, "Real-Time DEA Monitoring of Glass-Epoxy Composite Material VARIM Processing and its Correlation with DSC Measurements", *Journal Composite Materials*, June, 2012.

[3] Y. Hou, K. Taniguchi and S. S. Wang, "Vacuum-Assisted Resin Infusion Processing of Thick-Section Composite Laminates for Wind Rotor Blades", (Paper No. 334), W.S. Chan, S.Nomura, and D. Dancila, Eds., *Proceedings of the 27th Annual Technical Conference of American Society for Composites*, Arlington, TX, October 1-3, 2012, pp. 982-998.

[4] F. F. Wendt, K. H. Lo, and S. S. Wang, "Design and Siting Considerations of Large Efficient Offshore Wind Turbines in the Gulf of Mexico Region", (Paper No. 0212), F. Kurokawa and I. Colak, Eds., *Proceedings of International Conference on Renewable Energy and Applications (ICRERA 2012)*, Nagasaki, Japan, November 7-9, 2012

[5] Priya Sundararaju, Ralph Metcalfe and Su Su Wang, "Analysis of Offshore Wind Profiles and Atmospheric Stability for Large Scale Horizontal Axis Wind Turbines," *Proceedings of 2013 ASME Early Career Technical Conference*, American Society of Mechanical Engineers, Tulsa, OK, April 4-6, 2013

[6] Yanan Hou and Su Su Wang, "Reaction Kinetics and Flow Simulation of Vacuum-Assisted Infusion-Molding Process for Thick Glass/Polyester Composites," *Proceedings of the 28th ASC Technical Conference, (Paper No.: 171),* C. E. Bakis, Ed., American Society for Composites, State College, PA, September 9-11, 2013, pp. 367-386.

[7] Liguo Li and S. S. Wang, "Interlaminar Properties and Failure Strength of Thick-Section, Vacuum-Assisted Infusion-Molded Composites," *Proceedings of the 28th ASC Technical Conference,* (Paper No.: 123), C. E. Bakis, Ed., American Society for Composites, State College, PA, September 9-11, 2013, pp. 31-50.

[8] Gang Liu and Su Su Wang, "Elevated Temperature Dynamic Mechanical Behavior of PTFE/PEEK Composites," *Proceedings of the 28th ASC Technical Conference*, (Paper No.: 85), C. E. Bakis, Ed., American Society for Composites, State College, PA, September 9-11, 2013, pp. 440-458.

[9] L. L. Yin, K. H. Lo and S. S. Wang, "Structural Dynamics and Load Analysis of Large Offshore Wind Turbines in Western Gulf of Mexico Shallow Water," (ASME Paper No.

OMAE2014- 24258), *Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Artic Engineering*, American Society of Mechanical Engineers, San Francisco, CA, June 8-13, 2014.

[10] K. H. Lo, T. P. Yu and S. S. Wang, "Structural Integrity of large Composite offshore Wind Turbine Rotor Blades," Paper No. 292, *Proceedings of the 29th Technical Conference, American Society for Composites,* September 8-10, 2014, La Jolla, CA.

[11] G. Liu and S. S. Wang, "Multi-axial Yielding, Plastic Flow and Failure of PTFE/PEEK Composites," Paper No. 109, *Proceedings of the 29th Technical Conference*, American Society for Composites, September 8-10, 2014, La Jolla, CA.

[12] B. W. Cole, L. Li and S. S. Wang, "Strength and Failure Modes of Thick Adhesive-Bonded Joints of Glass Fabric/Vinyl Ester Composite Laminates", Paper No. 293, *Proceedings of the 29th Technical Conference,* American Society for Composites, September 8-10, 2014, La Jolla, CA.

[13] A. Miyase, L. Li and S. S. Wang, "Matrix-Dominated Deformation and Failure of VARIM Glass Fabric/Vinyl Ester Composites: In-plane Transverse and Interlaminar Damage Modes and Strengths," Paper No. 295, *Proceedings of the 29th Technical Conference,* American Society for Composites, September 8-10, 2014, La Jolla, CA.

[14] G. Liu and S. S. Wang, "Elevated Temperature Thermal Expansion Coefficients of PEEK/PTFE Composites: Experiment and Modeling," Paper No. 681, *Proceedings of the 29th Technical Conference,* American Society for Composites, September 8-10, 2014, La Jolla, CA.

[15] L. Yin, K. H. Lo and S. S. Wang, "Effect of Pile-Soil Interaction on Structural Dynamics of Large MW-Scale Offshore Wind Turbines in Shallow Water Western GOM," (ASME OMAE Paper No. OMAE2015-42320), *Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore and Artic Engineering*, American Society of Mechanical Engineers, St. John's, Newfoundland, Canada, May 28-31, 2015.

[16] L. Yin, K. Lo and S. S. Wang, "Rotor Pitching and Yawing, and Wind –wave Misalignment on Large Offshore Wind Turbine Dynamics in Western Gulf of Mexico Shallow Water during 100-year Return Hurricane," *ASME Journal of Offshore Mechanics and Artic Engineering*, No. 1, Vol 139, February 2017, pp. 011901-1

[17] King Him Lo, Akira Miyase and Su Su Wang, "Stiffness and Strength Models for Rigid PVC Structural Foams," (Paper No. 1575), *Proceedings of the American Society for Composites 2015 – The 30th Annual Technical Conference on Composite Materials,* Xinran Xiao, Alfred Loos and Dahsin Liu, Editors, Michigan State University, East Lancing, MI., September 28-30, 2015.

[18] Ethan Pedneau and Su Su Wang, "Permeability of Glass Fabric Reinforced Vinyl Ester Composite," (Paper No. 1583), *Proceedings of the American Society for Composites 2015*

– The 30th Annual Technical Conference on Composite Materials, Xinran Xiao, Alfred Loos and Dahsin Liu, Editors, Michigan State University, East Lancing, MI., September 28-30, 2015.

[19] Akira Miyase and Su Su Wang, "Test Method Development, Deformation and Failure Strength of Rigid PVC Structural Foams," (Paper No. 1584), *Proceedings of the American Society for Composites 2015 – The 30th Annual Technical Conference on Composite Materials,* Xinran Xiao, Alfred Loos and Dahsin Liu, Editors, Michigan State University, East Lancing, MI., September 28-30, 2015.

[20] Bill W. Cole, Akira Miyase, Tung-Pei Yu, King Him Lo and Su Su Wang, "Failure Modes and Strength of Composite Box Beam Structures," (Paper No. 1719), *Proceedings of the American Society for Composites 2015 – The 30th Annual Technical Conference on Composite Materials,* Xinran Xiao, Alfred Loos and Dahsin Liu, Editors, Michigan State University, East Lancing, MI., September 28-30, 2015

[21] Ling Ling Yin, King Him Lo and Su Su Wang, "Effect of Pile-Soil Interaction on Structural Dynamics of Large Megawatt-scale Offshore Wind Turbines in Shallow-water Western Gulf of Mexico," *ASME Journal of Offshore Mechanics and Arctic Engineering,* Vol. 137, December 2015, pp. 062001-1 – 062001-11.

[22] Lingling Yin, King Him Lo and Su Su Wang, "Blade Pitch and Rotor Yaw, and Wind-Wave Misalignment on Large Offshore Wind Turbine Dynamics in Western Gulf of Mexico Shallow Water in 100-Year Return Hurricane." *Journal of Offshore Mechanics and Arctic Engineering*, (Paper #: OMAE-15-1084) (Research Paper), Accepted for Publication, March 28, 2016

[23] Shuren Qu, Jonathan Penaranda Mora and Su Su Wang, "Tribological Behavior of PTFE/PEEK Composite," (Paper No. 4106), *Proceedings of the American Society for Composites 2016 – The 31st Annual Technical Conference on Composite Materials,* Barry Davidson, James Ratcliffe and Michael Czabaj, Editors, Williamsburg, VA., September 19-22, 2016.

[24] Akira Miyase, King Him Lo and Su Su Wang, "Effects of Density and Cell Rise Ratio on Compressive Stiffness and Strength of PVC Structural Foam," (Paper No. 3710), *Proceedings of the American Society for Composites 2016 – The 31st Annual Technical Conference on Composite Materials,* Barry Davidson, James Ratcliffe and Michael Czabaj, Editors, Williamsburg, VA., September 19-22, 2016.

[25] Ethan Pedneau and Su Su Wang, "3D Permeability of Thick-Section Off-Axis Glass Fabric/Vinyl Ester Composites by VARIM Processing," (Paper No. 1819), *Proceedings of the American Society for Composites 2016 – The 31st Annual Technical Conference on Composite Materials,* Barry Davidson, James Ratcliffe and Michael Czabaj, Editors, Williamsburg, VA., September 19-22, 2016.

[26] Tung-Pei Yu, Akira Miyase, King Him Lo and Su Su Wang, "Composite Box-Beam Failure Modes and Strength: 3D Modeling and Analysis, and Comparison with Experimental Results," (Paper No. 3209), *Proceedings of the American Society for*

Composites 2016 – The 31st Annual Technical Conference on Composite Materials, Barry Davidson, James Ratcliffe and Michael Czabaj, Editors, Williamsburg, VA., September 19-22, 2016.

[27] Su Su Wang, Tung-Pei Yu and King Him Lo, "Failure Initiation and Crack Growth in Thick Adhesive Bonded Composite Joints," (Paper No. 503), *Proceedings of the American Society for Composites 2016 – The 31st Annual Technical Conference on Composite Materials,* Barry Davidson, James Ratcliffe and Michael Czabaj, Editors, Williamsburg, VA., September 19-22, 2016.

[28] Haripriya Sundararaju, King Him Lo, Ralph Metcalfe and Su Su Wang, "Analysis of Dual- Rotor Wind Turbines with Combined Linear Momentum Theory and Computational Fluid Dynamics, Tribological Behavior of PTFE/PEEK Composite," submitted to *AIAA Journal*, August, 2016.

4.2 Technologies or techniques developed

In-situ Measurement in VARIM processing for manufacturing thermoset and thermoplastic matrix wind turbine composite laminates

Physical foaming methods for manufacturing high-strength low-density micro-cell structural foams for wind turbine core materials

4.3 Other products

Two graduate-level courses developed: Wind Energy I and Wind Energy II

Curing reaction kinetics models for optimum processing of thick-section thermoset composite laminates for wind turbine blades

Strength and stiffness models for prediction of integrity of structural foam-composite integrity

Video movies on processing development and manufacturing techniques for constructing thick-section wind-rotor thermoset composite laminates

Mechanical models and the associated data base of transverse and interlaminar strength and failure mechanisms in selected thick-section thermoset wind turbine composite systems.

12-ft and 6-ft composite load-bearing box beams (3) - internal stiffeners of scaled wind turbine blades

5. INTERNATIONAL AND NATIONAL COLLABORATIONS

5.1 Academic Institutions

Montana State University
University of Massachusetts - Amherst
University of Texas - Dallas
Texas A & M University
University of Minnesota
University of Colorado
Colorado School of Mines
University of Delaware
University of Puerto Rico-Mayaguez
University of Stuttgart, Germany
Technical University of Delft, the Netherlands
Technical University of Denmark - Riso National Lab.
University of Oldenburg, Germany

5.2 Wind Energy Industry

DeWind
Floating Wind Farms Corporation
GE Wind
Siemens Energy
TPI Composites
Wind Energy System Technology
Vestas
ABS
Bayer Material Science
Dow Chemical Company
PPG Industries
Owens Corning Corporation

5.3 Governmental Agencies

US Naval Research Laboratory
NASA Langley Research Center
National Renewable Energy Laboratory
Sandia National laboratory
Texas General Land Office
Texas State Energy Office
Massachusetts Executive Office – Energy and Environmental Affairs

6. Goals, Objectives and Actual Accomplishments

Task Number	Brief Task Description	Task Completion				Progress Notes
		Original Planned	Revised Planned	Actual	Percent Complete	
1	Basic research on science, engineering, and innovation of future wind energy systems, with focuses on innovative materials, design, advanced manufacturing technology and long-term turbine reliability.	Not specified	The activities associated with this task will occur throughout the entire project.		100%	
2	Applied research on advanced large wind turbines for deepwater offshore wind energy production	Not specified	The activities associated with this task will occur throughout the entire project.		100%	
3	Development of a NBRF at University of Houston with scaled wind turbine blade testing and advanced design capability for future wind power production systems.	Not specified	The activities associated with this task will occur throughout the entire project.		100%	Several design changes and modifications were made on the cooling systems for powering hydraulic actuators for the blade testing facility. .

4	Integration of innovative wind turbine blade design and manufacturing technology	Not specified	The activities associated with this task will occur throughout the entire project.		100%	
5	Offshore wind turbine long-term reliability and performance with scaled blade testing	Not specified	The activities associated with this task will occur throughout the entire project.		100%	We have developed very close and effective working relationships with several critical wind energy companies.
6	Education and Training of undergraduate and graduate students and post-doctoral researchers to support the US wind energy industry needs.	Not specified	The activities associated with this task will occur throughout the entire project.		100%	We have had many graduate students participating in this program on an ongoing basis. Several graduates with advanced degrees were hired by major engineering companies and national research laboratories