Trailing edge sub-component testing for wind turbine blades - Part A: Comparison of concepts

As a complement to the mandatory structural full-scale test for wind turbine blades, the method of subcomponent testing has recently been proposed by international standards and guidelines for the experimental investigation of design-critical full-scale parts. This work investigated different subcomponent test (SCT) concepts for a trailing edge of an outboard segment from a 34-m blade. Detailed analytical models to design the SCT concepts with regard to the boundary conditions were derived. Finite element analyses of the SCT's linear response were benchmarked against each other and against the full blade model in terms of displacements, rotations, in-plane strains, and energy consumption. All SCT concepts were in good agreement with the full-scale test with respect to the longitudinal strain response but showed deviations in the transverse and shear strain, as well as in the rotational and displacement response.

General information
State: Accepted/In press
Publication date: 2019
Peer-reviewed: Yes

Publication information
Journal: Wind Energy
ISSN (Print): 1095-4244
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.18 SJR 1.051 SNIP 1.834
Web of Science (2017): Impact factor 2.938
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.37 SJR 1.079 SNIP 2.316
Web of Science (2016): Impact factor 2.725
Assessment and propagation of mechanical property uncertainties in fatigue life prediction of composite laminates

A probabilistic model for estimating the fatigue life of laminated composite materials considering the uncertainty in their mechanical properties is developed. The uncertainty in the material properties is determined from fatigue coupon tests. Based on this uncertainty, probabilistic constant life diagrams are developed which can efficiently estimate probabilistic $E$-N curves at any load level and stress ratio. The probabilistic $E$-N curve information is used in a reliability analysis for fatigue limit state proposed for estimating the probability of failure of composite laminates under variable amplitude loading cycles. Fatigue life predictions of unidirectional and multi-directional glass/epoxy laminates are carried out to validate the proposed model against experimental data. The probabilistic fatigue behavior of laminates is analyzed under constant amplitude loading conditions as well as under both repeated block tests and spectral fatigue using the WISPER, WISPERX, and NEW WISPER load sequences for wind turbine blades.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbine Structures and Component Design
Contributors: Castro, O., Branner, K., Dimitrov, N. K.
Publication date: 2018
Peer-reviewed: Yes

Publication information
Journal: Journal of Composite Materials
Article number: 002199831876562
ISSN (Print): 0021-9983
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 1.57 SJR 0.555 SNIP 0.898
Web of Science (2017): Impact factor 1.613
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 1.42 SJR 0.528 SNIP 0.803
Web of Science (2016): Impact factor 1.494
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 1.4 SJR 0.573 SNIP 0.876
Web of Science (2015): Impact factor 1.242
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 1.44 SJR 0.612 SNIP 1.188
Web of Science (2014): Impact factor 1.173
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 1.45 SJR 0.625 SNIP 1.186
Web of Science (2013): Impact factor 1.257
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 1.21 SJR 0.599 SNIP 1.239
Web of Science (2012): Impact factor 0.936
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): CiteScore 1.23 SJR 0.649 SNIP 1.242
Web of Science (2011): Impact factor 1.068
BLATIGUE Project Report-Standard Static Tests of a 14.3 m Olsen Wing Blade

General information
State: Published
Organisations: Wind Turbine Structures and Component Design, Department of Wind Energy
Contributors: Chen, X., Trevisi, F., Berring, P., Yeniceli, S. C., Semenov, S., Madsen, S. H., Branner, K.
Publication date: 2018

Publication information
Original language: English
Electronic versions:
Blatigue_Project_Report_Standard_Static_Tests_of_a_14.3m_Olsen_Wing_Blade.pdf

Bibliographical note
Only abstract available for this report
Source: PublicationPreSubmission
Source-ID: 163304366
Research output: Research - peer-review » Report – Annual report year: 2018

Buckling and progressive failure of trailing edge subcomponent of wind turbine blade
Subcomponent tests offer promising opportunities for evaluating structural integrity of critical parts that could be difficult to load realistically during full-scale tests. As an important complement to the mandatory full-scale structural tests for certification of wind turbine blades, subcomponent testing has recently been proposed. Nevertheless, challenges still exist in reproducing structural behavior observed in fullscale structural tests by using subcomponent tests, especially when the nonlinear structural response associated with buckling and failure is under concern. This study presents an experimental investigation and numerical simulation on a trailing edge subcomponent cut from a 34 m full-scale composite rotor blade. A particular focus is placed on: 1) the development of an experimental method and test setup for the trailing edge subcomponent, 2) the development of a numerical model capable of capturing multiple structural nonlinearities, including different failure modes occurring at the trailing edge and 3) the buckling, post-buckling and progressive failure response of the trailing edge subcomponent. The trailing edge subcomponent under study was cut from the full-scale rotor blade in such a way that the cutting line passes through the zero-strain axis of the blade cross section for the leading towards
trailing edge (LTT) load case. The zero-strain axis was determined by a finite element analysis where the full-scale blade is subject to the LTT bending load case. A C-shape test rig was used to compress the trailing edge subcomponent to reproduce a strain field as close as possible to the one that the subcomponent would be subjected to if it was situated in the full blade. In order to avoid undesired premature failure at the specimen boundaries, overlamination and ply wood clamp were applied as local reinforcements and boundary constrains. Randomly distributed speckles were painted on the specimen for Digital Image Correlation (DIC) measurements. The actuator force and the crosshead displacement were recorded during the test, which was performed quasi-statically until collapse of the specimen. Postfailure observation was conducted to identify failure modes and their characteristics. Numerically, a nonlinear finite element (FE) model is developed using three-dimensional solid elements incorporated with progressive failure analysis techniques. Nonlinear buckling response of the trailing edge subcomponent is captured and multiple failure modes, i.e., adhesive joint debonding, sandwich core failure and composite fracture are predicted. Using the FE model, the failure process of the trailing edge subcomponent is reproduced and it is compared with experimental measurements and post-failure observation. The effect of different material properties and loading conditions are examined further to better understand the failure mechanisms of the trailing edge in question. It is found that the ultimate strength of the trailing edge is buckling-driven. The failure process after the peak load-carry capacity is of the chain-of-events nature. Different failure modes interact with each other and lead to the post-failure characteristics. Numerical results of failure analyses of trailing edge subcomponents showed a reasonably good agreement with experimental observation. Based on a parametric study, better structural designs of trailing edges are proposed in order to improve the structural integrity of wind turbine blades.
Integrated dynamic testing and analysis approach for model validation of an innovative wind turbine blade design

DTU Wind Energy continues the experimental investigation of the wind turbine blades to assess innovative designs of long and slender blades. This paper presents an experimental structural dynamics identification and structural model validation of the 14.3m long research blade. Unique feature of the blades is that its internal layup design has been highly optimized w.r.t. stretching the rotor and substantial mass reduction at the same time. As the result, the blade is more flexible than the traditional one. The results of the modal tests following analyses were performed: (i) Uncertainty Quantification of the experimental modal parameters for the blades, (ii) non-linearity assessment, (iii) numerical model correlation – frequencies and mode shapes of the experimental model comparison with those from Finite Element (FE). Finally, the outlook for the future experimental blade research activity is outlined.

General information
State: Published
Number of pages: 15
Publication date: 2018
Peer-reviewed: Yes
Electronic versions:
FINAL_revised_UPLOADED_Contribution_248_final_1_f.pdf
Source: PublicationPreSubmission
Source-ID: 158331885
Research output: Research - peer-review › Paper – Annual report year: 2018

RELIABLADE- Improved wind turbine blade reliability by using digital twins throughout the lifecycle

General information
State: Published
Organisations: Wind Turbine Structures and Component Design, Department of Wind Energy
Contributors: Branner, K.
Publication date: 2018
Peer-reviewed: Yes
Event: Abstract from Wind Energy Denmark 2018, Hedensted, Denmark.
URLs:
Research output: Research - peer-review › Conference abstract for conference – Annual report year: 2018

Report on probabilistic analysis method for blades Work Package 7.4: Structural reliability methods. Deliverable number 74.1

General information
Research sized wind turbine blade modal tests: comparison of the impact excitation with shaker excitation: Paper

Modern wind turbine blades are being tested for certification purposes in accordance to the IEC-64100 standard. Part 23 of the norm details the requirements for the full scale structural testing of rotor blades. As a minimum, it requires measurement of the first and second flap wise and first edge wise natural frequencies. It lists damping and mode shapes as other blade properties which may be of interest and optionally measured. The paper presents the modal model parameters estimation based on the experimental modal analysis. In two tests performed, the input force has been introduced through impact hammer and two electrodynamic shakers excitation. Several first modes had been identified for both excitation methods, including first torsional mode of the investigated blade. Results of the modal tests can be used to (a) provide more detailed information about the structural dynamics characteristics of the blade and (b) improve the design by adjusting the dynamic properties of the blade to some desired condition.
Materials for Wind Turbine Blades: An Overview
A short overview of composite materials for wind turbine applications is presented here. Requirements toward the wind turbine materials, loads, as well as available materials are reviewed. Apart from the traditional composites for wind turbine blades (glass fibers/epoxy matrix composites), natural composites, hybrid and nanoengineered composites are discussed. Manufacturing technologies for wind turbine composites, as well their testing and modelling approaches are reviewed.

General information
State: Published
Condensation of long-term wave climates for the fatigue design of hydrodynamically sensitive offshore wind turbine support structures

Cost-efficient and reliable fatigue designs of offshore wind turbine support structures require an adequate representation of the site-specific wind–wave joint distribution. Establishment of this wind–wave joint distribution for design load calculation purposes requires typically a correlation of the marginal wind and wave distribution. This is achieved by condensation of the site-specific wave climate in terms of wave period or wave height lumping, subsequently used as input for a correlation with the corresponding wind climate. The quality of this resulting wind–wave correlation is especially important for hydrodynamically sensitive structures since the applied met-ocean parameters have a non-linear influence on calculated fatigue design loads. The present article introduces a new wave lumping method for condensation of the wave climate. The novelty is predominantly based on refined equivalence criterions for fatigue loads aiming at preservation of the fatigue damage distribution over either the wave height or wave period distribution. This new method is assessed in comparison with different other traditional wave lumping methods on the basis of the site-specific wave climate for the offshore wind farm project Gemini which has kindly been made available by the developer Typhoon Offshore. It is shown that the new method allows for a significantly better preservation of the hydrodynamic fatigue in comparison to the traditional methods.
Initiation of trailing edge failure in full-scale wind turbine blade test
The reliability and accuracy of a numerical shell model simulation and its predictive capabilities with existing failure criteria are compared to experiments of a 34 m long blade tested to ultimate failure. Strengths and weaknesses of in-plane failure criteria are highlighted and the geometrical non-linear buckling effect of the trailing edge under combined loading, and how it affects the ultimate strength of a blade in a trailing-edge failure dominated load direction were investigated. The study details the interaction between trailing edge buckling on damage onset and sandwich panel failure. The numerically applied fracture mechanics approaches showed good agreement with the experimental results.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbine Structures and Component Design
Contributors: Haselbach, P. U., Branner, K.
Pages: 136–154
Publication date: 2016
Peer-reviewed: Yes

Publication information
Journal: Engineering Fracture Mechanics
Volume: 162
ISSN (Print): 0013-7944
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 2.8 SJR 1.244 SNIP 1.733
Web of Science (2017): Impact factor 2.58
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 2.39 SJR 1.262 SNIP 1.749
Web of Science (2016): Impact factor 2.151
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 2.44 SJR 1.334 SNIP 1.888
Web of Science (2015): Impact factor 2.024
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 2.28 SJR 1.561 SNIP 2.134
Web of Science (2014): Impact factor 1.767
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 2.25 SJR 1.426 SNIP 1.986
Web of Science (2013): Impact factor 1.662
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 1.82 SJR 1.329 SNIP 2.081
Web of Science (2012): Impact factor 1.413
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): CiteScore 1.92 SJR 1.718 SNIP 2.233
Web of Science (2011): Impact factor 1.353
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.447 SNIP 1.939
Web of Science (2010): Impact factor 1.576
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 1.709 SNIP 1.874
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 1.55 SNIP 2.185
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 1.343 SNIP 2.019
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 1.679 SNIP 2.226
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 2.147 SNIP 2.132
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 1.76 SNIP 2.279
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 1.547 SNIP 2.111
Web of Science (2003): Indexed yes
Scopus rating (2002): SJR 1.128 SNIP 1.58
Web of Science (2002): Indexed yes
Scopus rating (2001): SJR 0.9 SNIP 1.191
Scopus rating (2000): SJR 0.954 SNIP 1.1
Web of Science (2000): Indexed yes
Scopus rating (1999): SJR 0.733 SNIP 0.904
Original language: English
Keywords: Adhesive joints, Crack propagation, Fracture mechanics, Trailing edge damage, Wind turbine blade, Failure criteria, Local buckling
DOIs: 10.1016/j.engfracmech.2016.04.041
Source: FindIt
Source-ID: 2304361545
Research output: Research - peer-review › Journal article – Annual report year: 2016

Methodology for testing subcomponents; background and motivation for subcomponent testing of wind turbine rotor blades
This report aims to provide an overview of the design methodology followed by wind turbine blade structural designers, along with the testing procedure on full scale blades which are followed by testing laboratories for blade manufacturers as required by the relevant standards and certification bodies’ recommendations for design and manufacturing verification. The objective of the report is not to criticize the design methodology or testing procedure and the standards thereof followed in the wind energy community, but to identify those items offered by state of the art structural design tools that cannot be verified through the currently followed testing procedures and recommend ways to overcome these limitations. The work is performed within Work-Package WP7.1 entitled “Improved and validated wind turbine structural reliability - Efficient blade structure” of the IRPWINDEU programme. The numerical investigations performed are based on the INNWIND.EU reference 10MW horizontal axis wind turbine [1]. The structural properties and material and layout definition used within IRPWINDEU are defined in the INNWIND.EU report [2]. The layout of the report includes a review of the structural analysis models used for blade design, highlighting the current state of the art. The review of the full-scale blade testing procedure is performed under Section 3, followed by the discussion on the issues of verification of design and manufacture performed through testing. Finally, methodologies for testing blade subcomponents and/or blade parts are described in 5. The present report is complemented by all details of the comparison of blade test loads against design loads on the reference blade, as provided in Annex 1. These data will facilitate direct comparisons in fine points of interest along the reference blade for the load cases considered. The recommendations of this report are relevant for the design and testing of wind turbine subcomponents, in order to verify
the numerical analysis tools used in the structural design of wind turbine blades.

General information
State: Published
Contributors: Antoniou, A., Branner, K., Lekou, D., Nuin, I., Nijssen, R.
Number of pages: 94
Publication date: 2016

Publication information
Original language: English
Electronic versions:
D71_1_Review_blade_design_revised.pdf
Source: PublicationPreSubmission
Source-ID: 125463062
Research output: Research - peer-review; Report – Annual report year: 2016

Non-linear ultimate strength and stability limit state analysis of a wind turbine blade
According to the design codes for wind turbine blades, it is sufficient to evaluate the blade’s limit states using solely a linear analysis. This study, however, shows the need of non-linear analyses in blade design. Therefore, a geometrically non-linear structural response of a 34 m blade under flap-wise loading has been compared with a linear response to determine the blade’s resistance in the ultimate strength and stability limit states. The linear analysis revealed an unrealistic failure mechanism and failure mode. Further, it did not capture the highly non-linear response of the blade that was measured in an ultimate full-scale test to failure and determined by a geometrically non-linear analysis. A design evaluation in accordance with the least stringent Germanischer Lloyd (GL) requirements has been compared with non-linear approaches proposed by GL and Eurocode, which require the application of an imperfection. The more realistic non-linear approaches yielded more optimistic results than the mandatory linear bifurcation analysis. Consequently, the investigated blade designed after the lesser requirements was sufficient. Using the non-linear approaches, considering inter-fibre failure as the critical failure mode, yielded still a significant safety margin for the designer (7–28%). The non-linear response was significantly dependent on the scaling of the imperfection. Eurocode's method of applying an imperfection appeared more realistic than the GL method. Since the considered blade withstood 135% of the design load at a full-scale test to failure and the blade has operated successfully in the field, GL's safety factors combined with the imperfection size may be too conservative. Copyright © 2015 John Wiley & Sons, Ltd.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbines, Fraunhofer Institute for Wind Energy and Energy System Technology
Contributors: Rosemeier, M., Berring, P., Branner, K.
Number of pages: 22
Pages: 825–846
Publication date: 2016
Peer-reviewed: Yes

Publication information
Journal: Wind Energy
Volume: 19
Issue number: 5
ISSN (Print): 1095-4244
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 3.18 SJR 1.051 SNIP 1.834
Web of Science (2017): Impact factor 2.938
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.37 SJR 1.079 SNIP 2.316
Web of Science (2016): Impact factor 2.725
Subcomponent testing of trailing edge panels in wind turbine blades
This paper proposes a static subcomponent test method designed to check the compressive strength of the trailing edge region in wind turbine blades under a simplified loading. The paper presents numerical simulations using the proposed subcomponent test method and discusses its ability to be used for checking the compressive strength of the trailing edge region in wind turbine blades.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbine Structures and Component Design
Contributors: Branner, K., Berring, P., Haselbach, P. U.
Number of pages: 7
Publication date: 2016

A Critical Evaluation of Structural Analysis Tools used for the Design of Large Composite Wind Turbine Rotor Blades under Ultimate and Cycle Loading
Rotor blades for 10-20MW wind turbines may exceed 120m. To meet the demanding requirements of the blade design, structural analysis tools have been developed individually and combined with commercial available ones by blade designers. Due to the various available codes, understanding and estimating the uncertainty introduced in the design calculations by using these tools is needed to allow assessment of the effectiveness of any future design modification. For quantifying the introduced uncertainty a reference base was established within INNWIND.EU in which the several structural analysis concepts are evaluated. This paper shows the major findings of the comparative work performed by six organizations (universities and research institutes) participating in the benchmark exercise. The case concerns a 90m Glass/Epoxy blade of a horizontal axis 10MW wind turbine. The detailed blade geometry, the material properties of the constitutive layers and the aero-elastic loads formed the base by which global and local blade stiffness and strength are evaluated and compared. Static, modal, buckling and fatigue analysis of the blade were performed by each partner using their own tools; fully in-house developed or combined with commercially available ones, with its specific structural analysis approach (thin wall theory and finite element models using beam, shell or solid elements) and their preferable analysis type (linear or geometrical non-linear). Along with sectional mass and stiffness properties, the outcome is compared in terms of displacements, stresses, strains and failure indices at the ply level of the blade structure, eigen-frequencies and eigen-modes, critical buckling loads and Palmgren-Miner damage indices due to cycle loading. Results indicate that differences between estimations range from 0.5% to even 40%, depending on the property compared. Modelling details, e.g. load application on the numerical models and assumptions, e.g. type of analysis, lead to these differences. The paper covers these subjects, presenting the modelling uncertainty derived.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbines, Centre for Renewable Energy Sources, National Renewable Energy Center, Knowledge Centre Wind turbine Materials and Constructions, Polytechnic University of Milan, University of Patras
Number of pages: 12
Publication date: 2015

Committee III.2 Fatigue and Fracture
Concern for crack initiation and growth under cyclic loading as well as unstable crack propagation and tearing in ship and offshore structures. Due attention shall be paid to practical application and statistical description of fracture control methods in design, fabrication and service. Consideration is to be given to the suitability and uncertainty of physical models.
Comparing Fatigue Life Estimations of Composite Wind Turbine Blades using different Fatigue Analysis Tools

In this paper, fatigue lifetime prediction of NREL 5MW reference wind turbine is presented. The fatigue response of materials used in selected blade cross sections was obtained by applying macroscopic fatigue approaches and assuming uniaxial stress states. Power production and parked load cases suggested by the IEC 61400-1 standard were studied employing different load time intervals and by using two novel fatigue tools called ALBdeS and BECAS+F. The aeroelastic loads were defined through aeroelastic simulations performed with both FAST and HAWC2 tools. The stress spectra at each layer were calculated employing laminated composite theory and beam cross section methods. The Palmgren-Miner linear damage rule was used to calculate the accumulation damage. The theoretical results produced by both fatigue tools proved a prominent effect of analysed design load conditions on the estimated lifetime of the wind turbine blades and are good starting points for future fatigue analysis using other methods.

Damage tolerance and structural monitoring for wind turbine blades

The paper proposes a methodology for reliable design and maintenance of wind turbine rotor blades using a condition monitoring approach and a damage tolerance index coupling the material and structure. By improving the understanding of material properties that control damage propagation it will be possible to combine damage tolerant structural design, monitoring systems, inspection techniques and modelling to manage the life cycle of the structures. This will allow an efficient operation of the wind turbine in terms of load alleviation, limited maintenance and repair leading to a more effective exploitation of offshore wind.

Comparing Fatigue Life Estimations of Composite Wind Turbine Blades using different Fatigue Analysis Tools

In this paper, fatigue lifetime prediction of NREL 5MW reference wind turbine is presented. The fatigue response of materials used in selected blade cross sections was obtained by applying macroscopic fatigue approaches and assuming uniaxial stress states. Power production and parked load cases suggested by the IEC 61400-1 standard were studied employing different load time intervals and by using two novel fatigue tools called ALBdeS and BECAS+F. The aeroelastic loads were defined through aeroelastic simulations performed with both FAST and HAWC2 tools. The stress spectra at each layer were calculated employing laminated composite theory and beam cross section methods. The Palmgren-Miner linear damage rule was used to calculate the accumulation damage. The theoretical results produced by both fatigue tools proved a prominent effect of analysed design load conditions on the estimated lifetime of the wind turbine blades and are good starting points for future fatigue analysis using other methods.

Damage tolerance and structural monitoring for wind turbine blades

The paper proposes a methodology for reliable design and maintenance of wind turbine rotor blades using a condition monitoring approach and a damage tolerance index coupling the material and structure. By improving the understanding of material properties that control damage propagation it will be possible to combine damage tolerant structural design, monitoring systems, inspection techniques and modelling to manage the life cycle of the structures. This will allow an efficient operation of the wind turbine in terms of load alleviation, limited maintenance and repair leading to a more effective exploitation of offshore wind.
DTU-ESA millimeter-wave Validation STandard antenna (mm-VAST) - detailed design
A design of a well-characterized, mechanically and thermally stable multi-frequency Validation STandard antenna for mm-wave frequencies (mm-VAST) developed in an ESA project is presented. The antenna will facilitate inter-comparison and validation of antenna measurement ranges at K/Ka and Q/V bands in response to on-going deployment of satellite communication services at 20/30 GHz (K/Ka-band) as well as future commercial use of the 40/50 GHz bands (Q/V-band).

DTU-ESA millimeter-wave validation standard antenna (mm-vast) – performance verification
A new multi-frequency Validation Standard (VAST) antenna covering upper microwave (K/Ka) and millimeter wave (Q/V) bands, and thus called mmVAST, was developed in cooperation between DTU and TICRA under contract from the European Space Agency. In this paper, the mechanical and electrical requirements as well as the design and manufacturing of the mm-VAST antenna are briefly presented. The focus is then given to the details of conducted mechanical and electrical tests aimed at verifying the performance of the manufactured antenna and to the obtained measurement results.

Effect of Trailing Edge Damage on Full-Scale Wind Turbine Blade Failure
Modern wind turbine rotor blades are normally assembled from large parts bonded together by adhesive joints. The structural parts of wind turbine blades are usually made of composite materials, where sandwich core materials as well as
fibre composites are used. For most of the modern wind turbine blades the aerodynamically formed outer shell structure is manufactured as an upper and a lower part in separate moulds in order to simplify the production process. The aerodynamic shell structures are then bonded to internal load bearing structures during the production process. Adhesive joints exist where the load bearing structure is connected to the shells and at the joints of the upper and lower shells, usually at the leading and trailing edges. Maintenance inspections of wind turbines show that cracks in the vicinity of the trailing edge are typically occurring forms of damage. The cause of trailing edge failure is very complex and can arise from manufacturing flaws, damages during transportation and erection as well as under general and extreme operational conditions. The focus in this study is put on the geometrical nonlinear buckling effect of the trailing edge under combined loading and how it affects the ultimate strength of a holistic blade. For this reason a 34m long blade was studied experimentally and numerically under ultimate load until blade collapse. The interaction between trailing edge buckling on damage onset and sandwich panel failure was studied in detail. Numerically applied fracture mechanics approaches showed good agreement with the experimental results and helped to understand the relations between trailing edge buckling and blade collapse.

General Information
State: Published
Organisations: Department of Wind Energy, Wind Turbines
Contributors: Haselbach, P. U., Branner, K.
Number of pages: 12
Publication date: 2015

Host publication information
Title of host publication: Proceedings of the 20th International Conference on Composite Materials
Publisher: ICCM20 Secretariat
Keywords: Adhesive joints, Crack propagation, Fracture mechanics, Trailing edge damage, Wind turbine blade
Electronic versions:
Effect_of_Trailing_Edge_Damage.pdf
Research output: Research - peer-review › Article in proceedings – Annual report year: 2015

Electromechanical Drivetrain Simulation.
Wind turbines structures are exposed to inclement loading conditions varying from the turbulent wind field to fluctuations in the electric grid. The variation of these conditions, in addition to special events such as emergency stops, has a great impact of the life time of the components. In multi-MW wind turbines, it is common to find a geared drivetrain, which is the interface between the mechanical and electrical domain. Due to the varying conditions, the drivetrain can suffer accelerated damage reducing the target 20 years life of the turbine. This Ph.D. thesis focuses on the implementation of advanced models that consider the electromechanical interaction of the wind turbine structure, namely the main shaft and tower top, along with the gearbox and the generator. This is done with the purpose to advance the integrated analysis of wind turbines; something that is not common until recently. The state-of-the-art in wind turbine simulation is to consider the wind turbine structure with a simplified model of the drivetrain. Therefore, the main purpose of this Ph.D. is to develop a simulation tool capable of estimate the loading in the drivetrain internal components, with special attention to the planet bearings in the planetary stage. In brief, the tool is used for the dynamic analysis of the drive-train components under different loading conditions following certification guidelines. Several numerical simulations demonstrate the capabilities of the tool, and new results show how the lifetime of the bearings are affected by different load cases. The fatigue damage experienced by the planet bearings in the planetary stage is assessed for the normal operation of the wind turbine, by computing the damage equivalent loads for a 20 years period. Several operational modes are identified as the main contributors to the fatigue of the bearings. Second, the ultimate design loads obtained by extreme events such as Low-Voltage Ride through (LVRT), emergency stop and normal stop due to grid loss are investigated. A method to simulate the LVRT based on the grid code requirements from different countries is presented, along with results that highlight the importance of the voltage recovery and its relation to the effect on the bearing loads. Several recommendations are made for the three extreme events in terms of possible load reduction in the bearings. The main goal is to minimize the long-term damage that can be induced by the extreme cases. And finally, reliability analysis using FORM is performed based on two different types of bearing configurations. For this purpose, a bearing stiffness matrix corresponding to each configuration is used in the electromechanical drivetrain simulation tool. Thus, using a parametric study with different dynamic rating i values, it is found that this parameter has an important influence in the reliability, and hence, in the preliminary design of the components. Furthermore, the difference between the damage equivalent loads of both types of bearings is minimal. Therefore, the dynamic rating parameter is found to have higher influence on the bearings reliability. The methods presented in this dissertation can be used to model different drivetrain configurations for preliminary design, based on standard load cases used in wind turbine certification. In addition, it is possible to carry out reliability analysis, which ultimately, is one of the main focus areas when analyzing and designing such complex and costsensitive systems.
Experimental Blade Research - phase 2
This report is a summary of the results obtained in the project: Experimental Blade Research – phase 2 (EBR2). The project was supported by the Danish Energy Authority through the 2010 Energy Technology Development and Demonstration Program (EUDP 2010-II) and has journal no. 64011-0006. The project has been running from spring 2011 to the end of 2014.
Being a summary report, this report only contains a collection of the research topics and the major results. For more details, see the publications listed at the end of this report.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbines, LM Wind Power, DNV GL AS, Aalborg University
Contributors: Eder, M. A., Branner, K., Berring, P., Belloni, F., Stensgaard Toft, H., Sørensen, J. D., Corre, A., Lindby, T., Quispitupa, A., Petersen, T. K.
Number of pages: 108
Publication date: 2015

Millimeter wave VAilation STandard (mm-VAST) antenna. Final Report.

General information
State: Published
Organisations: Department of Electrical Engineering, Electromagnetic Systems, Department of Wind Energy, Wind Turbines, TICRA
Contributors: Kim, O. S., Jørgensen, R., Branner, K.
Publication date: 2015
New morphing blade section designs and structural solutions for smart blades

Within INNWIND.EU new concepts are investigated having the ultimate goal to reduce the cost per kilowatt-hour of the produced energy. With increasing size of wind turbines, new approaches to load control are required to reduce the stresses in blades. Experimental and numerical studies in the fields of helicopter and wind turbine blade research have shown the potential of shape morphing in reducing blade loads. Morphing technologies, along with other control concepts, are investigated under Task 2.3 of WP "Lightweight Rotor", against aerodynamic compliance and requirements of the complete wind turbine system. As these efforts mature from an aeroelastic and control point of view, in order to get to the next stage of applying the solutions on wind turbine systems evaluation of the structural needs of the various proposed solutions and quantification of their potential is required. The report includes the efforts performed within Task 2.2 “Lightweight structural design” of INNWIND.Eu work-package WP2 “Lightweight Rotor” regarding the structural solutions necessary to accommodate the requirements of smart blades developed within work-package WP2 Task 2.3 “Active and passive loads control and alleviation (smart blades) design”. The research performed within Task 2.2 and reported herein does not cover investigations for the complete set of design requirements of smart blades, such as aerodynamic control surface size. Rather it focuses on answers relevant to integration within the blade structure, i.e. no loss of local/global stiffness or strength and/or fatigue life. The purpose is to report efforts towards the use of new morphing blade section designs and the structural solutions for smart blades (developed in Task 2.3). The objective is to define, assess and demonstrate innovative concepts for lightweight rotor blades through the synergistic combination of adaptive characteristics from passive built-in geometrical couplings and active control. The investigations performed on the blade sections with variable geometry airfoils were designed and assessed towards compliance with structural constraints and manufacturing processes constraints. Down selection of design based on results of analysis (for input to Task 2.3) was also performed. Following solutions were investigated: Morphing blade sections with Shape Memory Alloys (SMA) by University of Patras Morphing blade sections using an elastomer of zero Poisson ratio by University of Bristol Morphing blade sections involving an innovative mechanism by Denmarks University of Technology The work performed on these three concepts is described in individual chapters of the present report. Section 2 discusses the concept using shape memory alloys, section 3 the concept using the special properties elastomer and section 4 the structural investigations on the blade that should support the innovative mechanism. The advantages and disadvantages of these concepts are discussed in the individual sections, while an overall assessment is performed in the last section of the present report. The solutions using Shape Memory Alloys, as well as an elastomer of zero Poisson ratio have a quite low technological readiness level (TRL). Both are inspired through the aeronautics sector, yet there are different challenges to address when designing for wind turbine blades. The size in addition with the loading on the component combined with low (or even no) maintenance during the 20-30 years of the blade service life makes fatigue of special importance for these solutions. Relevant to the morphing blade comprising an innovative mechanism, the focus lays into the elastic stability (buckling) of the supporting structure, i.e. the blade, which needs to be modified to accommodate the mechanism. INNWIND.EU, Deliverable 2.23, New morphing blade section designs & structural solutions for smart blades The technology readiness level (TRL) of the three solutions ranges from 4-6 for wind turbine system applications. Feasibility studies have been undertaken by looking at the complete system by numerical applications and at details of the concepts through dedicated experiments. Through the efforts performed and presented in this report an advance of this level has been achieved. For all cases the investigations have been conducted with reference to the DTU 10MW reference wind turbine used as the baseline for research activities performed within INNWIND.EU. Due to the initial stages of the concept development, several configurations and several sensitivity studies have been performed to support the results. These are all described within the present report.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbine Structures and Component Design, University of Patras, University of Bristol, Centre for Renewable Energy Sources
Number of pages: 165
Publication date: 2015

Publication information
Original language: English
Electronic versions:
Deliverable_D2_23_structural_issues_smart_blades_v4.pdf
Source: PublicationPreSubmission
Source-ID: 125463729
Research output: Research - peer-review ; Report – Annual report year: 2016

Offshore Wind Turbine Foundation Design
Offshore wind energy has greatly matured during the last decade with an annually installed energy capacity exceeding 1 GW. A key factor for further large-scale development of offshore wind energy is a cost of energy reduction. Given for example the drop in oil price since summer 2014, which has continued into 2015 it is even more important to drive down the costs of energy for renewable energy sources such as offshore wind energy in order to arrive at a sustainable future on a global level. Cost of energy reductions for offshore wind turbines (OWTs) can be achieved by optimizations on
different disciplines such as the structural design, fabrication and installation. In all cases it is very important to carefully assess the mutual influences of the different disciplines and the overall costs of energy. Different subsystems of the OWT such as the foundation or control system require on one hand the involvement of specialists with different technical backgrounds and on the other hand considerations of the whole OWT system and the mutual influences of the subsystems. For example, accurate design loads are essential for cost-efficient and safe foundation designs. However, such accurate loads can only be established under proper consideration of the dynamics of the whole system requiring adequate models of the individual subsystems and environment. This is due to the fact that OWTs introduce complex interactions between individual subsystems and the environment. Hence, a thorough understanding of the overall OWT system is essential for the establishment of accurate design loads and the subsequent optimization of individual subsystems as part of an overall optimization. In the present thesis, the design of OWT foundations is approached from the perspective of a foundation designer starting with a general introduction of the design process. The complexity of this particular field is emphasized by consideration of a variety of topics covering different foundations types and aspects throughout the design process. Focus is on structural modelling, environmental modelling and load calculations as already established in literature and design practice. Methods and approaches of the selected topics are assessed with respect to their influences on the dynamics of the system and design loads in order to evaluate their applicability in the design process. The investigations comprise new as well as existing methods and approaches. In design practice, the modelling of the structure as well as of the environment is often based on simplifications. For the environmental conditions, this is e.g. due to the fact that the combined, directional wind and wave climate consists of an impractically large amount of combinations of met-ocean parameters for load calculations purposes, which is consequently handled by application of condensed wind-wave correlations. A new damage equivalent wind-wave correlation method is introduced in the present thesis and assessed against alternative methods. It is shown that only the new method allows for a damage equivalent preservation of long-term, full wave climates throughout the entire support structure, while the alternative methods may introduce severe errors due to an insufficient consideration of the dynamics throughout the whole system. In the detailed design process, condensed wind-wave correlations are typically subjected to sequential load calculation approaches in an iterative and collaborative process between foundation designer and wind turbine manufacturer. Involvement of these different design parties may be motivated by various aspects such as introduction of state-of-the-art design expertise and tools from individual fields of technology. However, the collaboration requires special load calculation methods and simplifications of individual subsystem models in the design process due to different tools, expertise and design responsibilities of both parties. It is shown in the present thesis, how various aspects, such as the load calculation approach or the foundation model in the aeroelastic analysis, influence the dynamics and may thereby potentially introduce design load errors on the conservative or non-conservative side if not considered adequately. Different types of OWT foundations have individual characteristics and show differences in the interactions with other subsystems leading to varying requirements regarding structural modelling, environmental modelling and load calculations in the design process. Hence, it is important to carefully assess particular aspects in the specific context of OWTs and individual foundation type characteristics. For example, modelling and load calculation approaches for jacket type foundations of OWTs are often inherited from existing experiences of monopile type foundations or from their counterparts in the offshore oil & gas industry. However, severe errors may be introduced due to different dynamic characteristics and loading conditions in case the inherited approaches are not adjusted adequately for the individual requirements of jacket type foundations for OWTs. For example, quasi-static foundation load calculation approaches as often applied for jacket foundations of substations or jackets from the offshore oil & gas industry may introduce severe errors when applied to jacket foundations for OWTs e.g. due to differences in the loading conditions. However, in case of monopiles for OWTs quasi-static foundation load calculation approaches are applicable despite the fact that loading conditions are similar to their jacket counterparts. This is due to differences in the structural dynamic characteristics, e.g. the pronounced coupling of local foundation modes with higher global modes for jacket foundations of OWTs do not occur for monopiles. In the present thesis, the investigations cover monopile and jacket type foundations as representatives of individual characteristics and individual requirements of different bottom-mounted foundation types for OWTs. The present thesis is complemented by various aspects from the industrial work of the author emphasizing the industrial character of the PhD project.

**General information**

State: Published
Contributors: Passon, P., Branner, K., Larsen, S. E., Hvenekær Rasmussen, J.
Number of pages: 301
Publication date: 2015

**Publication information**

Publisher: DTU Wind Energy
ISBN (Electronic): 978-87-93278-23-3
Original language: English
(DTU Wind Energy PhD: No. 0044(EN)).
Electronic versions: Offshore_Wind_Turbine_Foundation_Design.pdf
Structural Design of the DTU-ESA MM-Wave Validation Standard Antenna

A new specially designed antenna to be used for inter-comparisons and validation of antenna test facilities is under development in cooperation between DTU and TICRA under a contract from the European Space Agency. The antenna is designed to be extremely thermally and mechanically stable in the range of temperatures 20±5°C under arbitrary orientation in the gravity field. The antenna has a characteristic length of approximately 500mm. And in order to obtain very low measuring error, the allowable deformations of the reflector and feeds are down to 2.5μm. The antenna is modelled structurally using the commercial finite element package MSC.Patran with MSC.MARC as solver. The solid parts of the antenna are meshed with 10-noded tetrahedral elements, which have quadratic shape functions and the entire model has approximately 325,000 elements. The individual solid part of the antenna is connected via a glued contact formulation in MSC.MARC. Because of the size and the complexity of the model a computer cluster is applied to solve the analyses. This paper describes the structural solution to meet these extremely strict stability requirements and the structural analyses done in order to verify that they can be met. The paper also discusses the challenges of integrating an aluminum feed cluster with high thermal expansion coefficient in a CFRP support frame with very low thermal expansion coefficient.

General information
State: Published
Contributors: Branner, K., Berring, P., Markussen, C. M., Kim, O. S., Jørgensen, R., Pivnenko, S., Breinbjerg, O.
Number of pages: 10
Publication date: 2015

Host publication information
Title of host publication: Proceedings of the 20th International Conference on Composite Materials
Publisher: ICCM20 Secretariat
Keywords: Structural design, Antenna, CFRP, Thermally stable, Mechanically stable, Finite element analysis
Electronic versions: Structural_Design_of_the_DTU_ESA.pdf
Source: PublicationPreSubmission
Source-ID: 117498499
Research output: Research - peer-review › Article in proceedings – Annual report year: 2015

The DTU-ESA Millimeter-Wave Validation Standard Antenna – Manufacturing and Testing

A new precision tool for antenna test range qualification and inter-comparisons at mm-waves – the mm-VAST antenna – is under development at the Technical University of Denmark (DTU) in collaboration with TICRA under a European Space Agency (ESA) contract. The DTU-ESA mm-VAST antenna will facilitate accurate measurements of the next generation satellite communication antennas at K-, Ka-, Q-, and V-bands. The development is focused in particular on the mechanical and temperature stability of the antenna under various operational conditions. In this contribution, we present the details of the antenna mechanical design, fabrication and assembling procedures. The performance verification test plan as well as first measurement results are also discussed.

General information
State: Published
Contributors: Kim, O. S., Pivnenko, S., Breinbjerg, O., Branner, K., Berring, P., Markussen, C. M.
Pages: 347-351
Publication date: 2015

Host publication information
Title of host publication: Proceedings of the AMTA 37th Annual Meeting & Symposium
Source: PublicationPreSubmission
Source-ID: 117989931
Research output: Research - peer-review › Article in proceedings – Annual report year: 2015

The effect of delaminations on local buckling in wind turbine blades

In this article the effect of delaminations on the load carrying capacity of a large wind turbine blade is studied numerically. For this purpose an 8.65 m long blade section with different initial delaminations in the main spar was subjected to a flapwise dominated bending moment. The model was setup in Abaqus and cohesive elements were chosen for modelling delamination growth.

For initial delaminations with a width of 30–50% of the cap width the study showed that delamination close to the surface started to grow in load ranges of normal operation conditions and led to local buckling modes. The local buckling caused high strains and stresses in the surrounding of the delamination, which exceeded the material design properties and therefore should be considered as dangerous.
Delaminations placed near the mid-surface of the cap did not have a significant effect on the blade response under normal operation conditions. In the simulations the static load exceeded the design load by more than 40% before delamination growth or cap buckling occurred.

It could be concluded that delamination induced near-surface buckling modes have to be considered critical due to an onset of local sublaminate buckling below the design load level.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbines
Contributors: Haselbach, P. U., Bitsche, R., Branner, K.
Pages: 295-305
Publication date: 2015
Peer-reviewed: Yes

Publication information
Journal: Renewable Energy
Volume: 85
ISSN (Print): 0960-1481
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 5.38 SJR 1.847 SNIP 2.008
Web of Science (2017): Impact factor 4.9
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 4.83 SJR 1.661 SNIP 2.05
Web of Science (2016): Impact factor 4.357
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 4.51 SJR 1.767 SNIP 2.085
Web of Science (2015): Impact factor 3.404
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 4.51 SJR 1.925 SNIP 2.621
Web of Science (2014): Impact factor 3.476
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 4.63 SJR 1.989 SNIP 2.719
Web of Science (2013): Impact factor 3.361
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 3.97 SJR 1.787 SNIP 2.699
Web of Science (2012): Impact factor 2.989
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): CiteScore 3.9 SJR 1.634 SNIP 2.349
Web of Science (2011): Impact factor 2.978
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 1
Ultimate Strength of Wind Turbine Blades under Multiaxial Loading

Modern wind turbine rotor blades are sophisticated lightweight structures, optimised towards achieving the best compromise between aerodynamic and structural design as well as a cost efficient manufacturing processes. They are usually designed for a lifetime of minimum 20 years, where they must endure a variety of weather conditions including uncontrollable, extreme winds without developing damage and fracture.

The trend in the development of wind turbines is towards larger, more efficient wind turbines, placed offshore, where access is difficult and repairs costly. In consequence, failures in the rotor blade usually lead to long downtimes. Therefore, it is of great importance that the turbines operate reliably and that robust methods are available to predict damage initiation and growth under multiaxial loading conditions. The purpose of this PhD project is the investigation of multiaxial loading effects and its influence on the ultimate strength of typical wind turbine rotor blade structures and to develop methods to perform reliable prediction of failure. For this purpose, origin and consequence of some of the typically occurring failure types in wind turbine rotor blades are investigated. The research aims on predicting more accurately when and how blades fail under complex loading. The main contribution from this PhD study towards more reliable and robust operating wind turbine systems can be divided into two fields. One part covers numerical modelling approaches and the other part deals with failure origin and effects. The research, covering the numerical part, is done with the purpose to investigate the limitation of state-of-the-art numerical prediction methods and to improve existing simulation methods by combining different existing techniques, capable to predict the ultimate strength of wind turbine rotor blades under multiaxial loadings. The purpose of this PhD project is the investigation of multiaxial loading effects and its influence on the ultimate strength of typical wind turbine rotor blade structures and to develop methods to perform reliable prediction of failure. For this purpose, origin and consequence of some of the typically occurring failure types in wind turbine rotor blades are investigated. The research aims on predicting more accurately when and how blades fail under complex loading. The main contribution from this PhD study towards more reliable and robust operating wind turbine systems can be divided into two fields. One part covers numerical modelling approaches and the other part deals with failure origin and effects. The research, covering the numerical part, is done with the purpose to investigate the limitation of state-of-the-art numerical prediction methods and to improve existing simulation methods by combining different existing techniques, capable to predict the ultimate strength of wind turbine rotor blades under multiaxial loadings. Failure origin and effects are studied numerically and experimentally with the purpose to investigate root causes of blade failure and to find generalities for their origin. The main contributions from this PhD study covering the numerical part are the demonstration of a subset simulation approach for large scale delamination in the cap of a wind turbine rotor blade, making it possible to determine more precisely critical delamination sizes and load levels for delamination growth onset and propagation in dependency of the through the thickness location. Another modelling approach shows a modelling strategy, where shell and solid elements were combined with the purpose to estimate the strain energy release rate of transversely orientated crack in the trailing edge for different loading conditions. Furthermore, state-of-the-art failure criteria are studied and their limitations demonstrated by comparing numerical and experimental results of a full scale blade loaded to ultimate failure. The main contributions from this PhD thesis dealing with failure origin and effects are the determination of generalities of failure. For buckling driven delaminations, delamination onset and propagation could be determined. For trailing-edge failure, a characterisation of effects of geometrical non-linear cross section deformation and trailing-edge wave formation on the energy release rate was shown. Furthermore, a sequence of
trailing edge buckling leading to sandwich failure and finally causing ultimate blade failure were demonstrated.

Very large wind turbine rotor blades require damage tolerance and damage monitoring

Advanced topics on rotor blade full-scale structural fatigue testing and requirements

Advanced on rotor blade full-scale structural fatigue testing and requirements

Full scale fatigue test is an important part of the development and design of wind turbine blades. Testing is also needed for the approval of the blades in order for them to be used on large wind turbines. Fatigue test of wind turbine blades was started in the beginning of the 1980s and has been further developed since then. Structures in composite materials are generally difficult and time consuming to test for fatigue resistance. Therefore, several methods for testing of blades have been developed and exist today. Those methods are presented in [1].

This report deals with more advanced topics for fatigue testing of wind turbine blades. One challenge is how to fatigue test blades under realistic conditions. In order to study this topic a finite element based multibody formulation using the floating frame of reference approach is used to study fatigue loading under different external conditions.

An important purpose of full scale testing is to give valuable information to the designers on how the blade behaves in the test situation and which structural details that are important and should be included in the structural models for design. In order to be able to see the blade behaviour advanced measuring methods are needed.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbines
Contributors: Berring, P., Fedorov, V., Belloni, F., Branner, K.
Number of pages: 50
Publication date: 2014

Publication information
Publisher: DTU Wind Energy
ISBN (Electronic): 978-87-93278-10-3
Original language: English
(Keywords: DTU Wind Energy E-0068, DTU Wind Energy E-68
Electronic versions:
Advanced_topics_on_rotor_blade.pdf
Source: PublicationPreSubmission
Source-ID: 118026995
Research output: Research › Report – Annual report year: 2015
An high order Mixed Interpolation Tensorial Components (MITC) shell element approach for modeling the buckling behavior of delaminated composites

This paper describes the experimental and numerical studies carried out on delaminated fiberglass epoxy resin laminates made-up by different fabrication methods, namely by vacuum infusion and prepreg. While the tested specimens were originally intended for the assessment of buckling behavior of composite laminates of wind turbine blades, results were found valuable for the marine industry as well, because similar laminates are used for the hull shell and stiffeners. Systematic calculations were carried out to assess the effects of an embedded delamination on the buckling load, varying the size and through thickness position of the delamination. Different finite element modeling strategies were considered and validated against the experimental results. The one applying the 9 nodes MITC shell elements was found matching the experimental data despite failure modes were different for the two fabrication methods. © 2013 Elsevier Ltd. All rights reserved.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbines, University of Genoa
Contributors: Gaiotti, M., Rizzo, C. M., Branner, K., Berring, P.
Number of pages: 10
Pages: 657-666
Publication date: 2014
Peer-reviewed: Yes

Publication information
Journal: Composite Structures
Volume: 108
Issue number: 1
ISSN (Print): 0263-8223
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 2
Scopus rating (2017): CiteScore 4.52 SJR 1.905 SNIP 1.939
Web of Science (2017): Impact factor 4.101
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 4.45 SJR 2.162 SNIP 2.044
Web of Science (2016): Impact factor 3.858
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): CiteScore 4.25 SJR 2.157 SNIP 2.208
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 4.03 SJR 2.294 SNIP 2.483
Web of Science (2014): Impact factor 3.318
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): CiteScore 3.7 SJR 1.964 SNIP 2.878
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): CiteScore 2.85 SJR 1.779 SNIP 2.77
Web of Science (2012): Impact factor 2.231
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
A practical approach to fracture analysis at the trailing edge of wind turbine rotor blades

Wind turbine rotor blades are commonly manufactured from composite materials by a moulding process. Typically, the wind turbine blade is produced in two halves, which are eventually adhesively joined along their edges. Investigations of operating wind turbine blades show that debonding of the trailing edge joint is a common failure type, and information on specific reasons is scarce. This paper is concerned with the estimation of the strain energy release rates (SERRs) in trailing edges of wind turbine blades in order to gain insight into the driving failure mechanisms. A method based on the virtual crack closure technique (VCCT) is proposed, which can be used to identify critical areas in the adhesive joint of a trailing edge. The paper gives an overview of methods applicable for fracture cases comprising non-parallel crack faces in the realm of linear fracture mechanics. Furthermore, the VCCT is discussed in detail and validated against numerical analyses in 2D and 3D. Finally, the SERR of a typical blade section subjected to various loading conditions is investigated and assessed in order to identify potential design drivers for trailing edge details. Analysis of the blade section model suggests that mode III action is governing and accordingly that flapwise shear and torsion are the most important load cases.

Copyright © 2013 John Wiley & Sons, Ltd.
Damage detection methods on wind turbine blade testing with wired and wireless accelerometer sensors

Testing was performed on a 34 meter blade at a facility in DTU Risø Campus, featuring both wired accelerometers and low-power MEMs-based wireless accelerometers. Testing was focused on an induced delamination area on the trailing edge of the blade, which was subject to various configurations in order to simulate different degrees of damage. Excitation was performed in two ways: near the delamination zone in a simulation of operational wind excitations, and with a bar designed to excite torsional modes of the wind turbine blade.

We compare the data collected from the wireless sensors against wired sensors to demonstrate their performance. We explore methods for determining damage. We first explore results of autoregressive coefficients for indicating damage levels. Finally, we demonstrate the use of damage sensitive features from the wavelet transforms of input and output signals to provide a method suitable for non-stationary blade excitations.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbines, Stanford University
Contributors: Mollineaux, M., Balafas, K., Branner, K., Nielsen, P. H., Tesauro, A., Kiremidjian, A., Ramesh, R.
Number of pages: 8
Pages: 1863-1870
Publication date: 2014

Host publication information
Title of host publication: Proceedings of the 7th European Workshop on Structural Health Monitoring
Keywords: Structural Health Monitoring, Damage Detection, Wind Turbine, Wireless sensing, Wavelets
Source: PublicationPreSubmission
Source-ID: 125466309
Research output: Research - peer-review › Article in proceedings – Annual report year: 2014

Database about blade faults
This report deals with the importance of measuring the reliability of the rotor blades and describing how they can fail. The Challenge is that very little non-confidential data is available and that the quality and detail in the data is limited.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbines, Fluid Mechanics
Contributors: Branner, K., Ghadirian, A.
Number of pages: 16
Publication date: 2014

Publication information
Publisher: DTU Wind Energy
ISBN (Electronic): 978-87-93278-09-7
Original language: English
(Keywords: DTU Wind Energy E: No. 0067).
DTU-ESA millimeter-wave validation standard antenna – requirements and design
Inter-comparisons and validations of antenna measurement ranges are useful tools allowing the detection of various problems in the measurement procedures, thus leading to improvements of the measurement accuracy and facilitating better understanding of the measurement techniques. The maximum value from a validation campaign is achieved when a dedicated Validation Standard (VAST) antenna specifically designed for this purpose is available. The driving requirements to VAST antennas are their mechanical stability with respect to any orientation of the antenna in the gravity field and thermal stability over a given operational temperature range. In addition, VAST antennas must possess electrical characteristics that are typical for satellite antennas and challenging to measure. A multi-band millimeter-wave VAST (mm-VAST) antenna for the K/Ka-bands and Q/V bands is currently under development in collaboration between the Technical University of Denmark (DTU) and TICRA under contract from the European Space Agency. In this paper, the electrical and mechanical requirements of the DTU-ESA mm-VAST antenna are discussed and presented. Potential antenna types fulfilling the electrical requirements are briefly reviewed and the baseline design is described. The emphasis is given to definition of the requirements for the mechanical and thermal stability of the antenna, which satisfy the stringent stability requirement for the mm-VAST electrical characteristics.

General information
State: Published
Contributors: Pivnenko, S., Kim, O. S., Breinbjerg, O., Branner, K., Markussen, C. M., Jørgensen, R., Larsen, N. V., Paquay, M.
Number of pages: 6
Publication date: 2014

Host publication information
Title of host publication: Proceedings of the 36th Annual Symposium of the Antenna Measurement Techniques Association (AMTA)
Publisher: IEEE
Electronic versions: Paper_DTU_ESA_mmVAST_antenna_final.pdf
Source: PublicationPreSubmission
Source-ID: 102421380
Research output: Research - peer-review » Article in proceedings – Annual report year: 2014

Effect of a Damage to Modal Parameters of a Wind Turbine Blade
This study reports structural dynamic characteristics obtained experimentally from an extensive testing campaign on a 34m long wind turbine blade mounted on a test-rig under laboratory conditions. Further, these experimental results have been compared with analog numerical results obtained from a very detailed FE model of the same blade using 3D solid elements. Both an undamaged and a damaged blade are investigated, and it is observed that the natural frequencies of the first few modes of the blade change very little due to a significant artificial damage imposed in trailing edge, whereas the mode shapes - especially if decomposed into the flapwise, edgewise and torsional components - contain information which might be helpful for detecting and localizing wind turbine blade damages.

General information
State: Published
Contributors: Larsen, G. C., Berring, P., Tchemiak, D., Nielsen, P. H., Branner, K.
Number of pages: 9
Publication date: 2014

Host publication information
Title of host publication: Proceedings of the 7th European Workshop on Structural Health Monitoring
Publisher: INRIA
Keywords: Dynamic characteristics, FE modeling, OMA, Structural damages, Wind turbine blade
Electronic versions: Effect_of_a_Damage_to_Modal_Parameters.pdf
URLs: https://hal.inria.fr/EWSHM2014
Load calculation methods for offshore wind turbine foundations

Calculation of design loads for offshore wind turbine (OWT) foundations is typically performed in a joint effort between wind turbine manufactures and foundation designers (FDs). Ideally, both parties would apply the same fully integrated design tool and model for that purpose. However, such solutions are rather limited as it would require exchanging confidential data and the need of sophisticated modelling capabilities for all subsystems of the OWT. In practice, this leads to an iterative and sequential load calculation process involving different design tools. In this process, the wind turbine manufacturer provides the FD with dynamic responses obtained from aeroelastic simulations at a predefined interface. These responses are subsequently expanded to the corresponding dynamic responses in all structural parts of the foundation. In this article, a novel load calculation method, for the expansion to dynamic foundation responses based on an inverse dynamics algorithm, is introduced and described in detail. Furthermore, a summary of load calculation methods currently applied for the design of bottom-mounted OWTs foundations is provided and compared with the proposed method. While emphasis is given to jacket-type foundations, the methods are considered applicable for other bottom-mounted foundation types as well. All load calculation methods are applied and evaluated for an exemplarily fatigue design scenario from the perspective of an FD in order to establish more confidence in these methods. The article concludes with an assessment and recommendation for all presented load calculation methods.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbines, Ramboll Group AS
Contributors: Passon, P., Branner, K.
Pages: 433–449
Publication date: 2014
Peer-reviewed: Yes

Publication information
Journal: Ships and Offshore Structures
Volume: 9
Issue number: 4
ISSN (Print): 1744-5302
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 1.55 SJR 0.79 SNIP 1.541
Web of Science (2017): Impact factor 1.685
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 1.34 SJR 0.985 SNIP 1.524
Web of Science (2016): Impact factor 1.387
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 0.89 SJR 0.894 SNIP 0.971
Web of Science (2015): Impact factor 0.79
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 0.69 SJR 0.483 SNIP 1.142
Web of Science (2014): Impact factor 0.583
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 0.91 SJR 0.598 SNIP 1.107
Web of Science (2013): Impact factor 0.817
ISI indexed (2013): ISI indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 0.41 SJR 0.287 SNIP 0.562
Web of Science (2012): Impact factor 0.286
Methods for testing of geometrical down-scaled rotor blades

Full scale fatigue test is an important part of the development and design of wind turbine blades. Testing is also needed for the approval of the blades in order for them to be used on large wind turbines. Fatigue test of wind turbine blades was started in the beginning of the 1980s and has been further developed since then. Structures in composite materials are generally difficult and time consuming to test for fatigue resistance. Therefore, several methods for testing of blades have been developed and exist today. Those methods are presented in [1].

Current experimental test performed on full scale MW wind turbine blade are very time consuming and expensive. For the industry that means that the tests, both static and fatigue, are not a tool in or a part of the design process. In the academic community, full scale testing of modern and future wind turbine blades are even more challenging as requirements for experimental facilities are very demanding and furthermore the time for performing the experimental test campaign and the cost are not well suitable for most research projects.

This report deals with the advantages, disadvantages and open questions of using down-scaled testing on wind turbine blades.

General information

State: Published
Organisations: Department of Wind Energy, Wind Turbines
Contributors: Branner, K., Berring, P.
Number of pages: 15
Publication date: 2014

Publication information

Publisher: DTU Wind Energy
ISBN (Electronic): 978-87-93278-11-0
Original language: English
Keywords: DTU Wind Energy E-0069
Electronic versions:
Methods_for_testing.pdf
Source: PublicationPreSubmission
Source-ID: 118027008
Research output: Research - peer-review › Journal article – Annual report year: 2014

Quick Method for Aeroelastic and Finite Element Modeling of Wind Turbine Blades

In this paper a quick method for modeling composite wind turbine blades is developed for aeroelastic simulations and finite element analyses. The method reduces the time to model a wind turbine blade by automating the creation of a shell finite element model and running it through a cross-sectional analysis tool in order to obtain cross-sectional properties for the aeroelastic simulations. The method utilizes detailed user inputs of the structural layup and aerodynamic profile including ply thickness, orientation, material properties and airfoils to create the models. After the process is complete the user has two models of the same blade, one for performing a structural finite element model analysis and one for aeroelastic simulations. Here, the method is implemented and applied to reverse engineer a structural layup for the NREL 5MW reference blade. The model is verified by comparing natural frequencies to the reference blade. Further, the application to aeroelastic and structural evaluations is demonstrated. Aeroelastic analyses
are performed, and predicted fatigue loads are presented. Extreme loads from the aeroelastic simulations are extracted and applied onto the blade for a structural evaluation of the blade strength. Results show that the structural properties and natural frequencies of the developed 5MW blade match well with the reference blade, however the structural analysis found excessive strain at 16% span in the spar caps that would cause the blade to fail.

Rotor blade online monitoring and fault diagnosis technology research
Rotor blade online monitoring and fault diagnosis technology is an important way to find blade failure mechanisms and thereby improve the blade design. Condition monitoring of rotor blades is necessary in order to ensure the safe operation of the wind turbine, make the maintenance more economical, and accumulate data for evaluation of the blade design. In this report the implementation of condition monitoring methods is described focusing on the kind of sensors that have to be mounted on the blades in order to detect different changes to the blades. These changes are damage progression, unbalancing of the rotor, icing and lightning. Research is done throughout the world in order to develop and improve such measurement systems. Commercial hardware and software available for the described purpose is presented in the report.

Statistical approach for uncertainty quantification of experimental modal model parameters
Composite materials are widely used in manufacture of aerospace and wind energy structural components. These load carrying structures are subjected to dynamic time-varying loading conditions. Robust structural dynamics identification procedure impose tight constraints on the quality of modal models estimates obtained from vibration experiments. Modal testing results are influenced by numerous factors introducing uncertainty to the measurement results. Different experimental techniques applied to the same test item or testing numerous nominally identical specimens yields different test results. This paper aims at a systematic approach for uncertainty quantification of the parameters of the modal models estimated from experimentally obtained data. Statistical analysis of modal parameters is implemented to derive an assessment of the entire modal model uncertainty measure. Investigated structures represent different complexity levels ranging from coupon, through sub-component up to fully assembled aerospace and wind energy structural components made of composite materials. The proposed method is demonstrated on two application cases of a small and large wind turbine blade.
Strain and displacement controls by fibre Bragg grating and digital image correlation

Test control is traditionally performed by a feedback signal from a displacement transducer or force gauge positioned inside the actuator of a test machine. For highly compliant test rigs, this is a problem since the response of the rig influences the results. It is therefore beneficial to control the test based on measurements performed directly on the test specimen. In this paper, fibre Bragg grating (FBG) and Digital Image Correlation (DIC) are used to control a test. The FBG sensors offer the possibility of measuring strains inside the specimen, while the DIC system measures strains and displacement on the surface of the specimen. In this paper, a three-point bending test is used to demonstrate the functionality of a control loop, where the FBG and DIC signals are used as control channels. The FBG strain control was capable of controlling the test within an error tolerance of 20 μm m⁻¹. However, the measurement uncertainty offered by the FBG system allowed a tolerance of 8.3 μm m⁻¹. The DIC displacement control proved capable of controlling the displacement within an accuracy of 0.01 mm. © 2014 Wiley Publishing Ltd.

General information

State: Published
Organisations: Department of Civil Engineering, Section for Structural Engineering, Department of Mechanical Engineering, Solid Mechanics, Section for Building Design, Department of Wind Energy, Wind Turbines
Pages: 262-273
Publication date: 2014
Peer-reviewed: Yes

Publication information

Journal: Strain
Volume: 50
Issue number: 3
ISSN (Print): 0039-2103
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 1.84 SJR 0.805 SNIP 1.274
Web of Science (2017): Impact factor 1.605
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 1.82 SJR 0.646 SNIP 1.139
Web of Science (2016): Impact factor 1.694
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 1.54 SJR 0.649 SNIP 1.263
Web of Science (2015): Impact factor 1.522
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 1.34 SJR 0.691 SNIP 1.234
Uncertainty Quantification in Experimental Structural Dynamics Identification of Composite Material Structures

Aerospace and wind energy structures are extensively using components made of composite materials. Since these structures are subjected to dynamic environments with time-varying loading conditions, it is important to model their dynamic behavior and validate these models by means of vibration experiments. Modal testing results depend on numerous factors introducing uncertainty to the measurement results. Different experimental techniques applied to the same test item or testing numerous nominally identical specimens yields different test results. This paper presents a systematic approach for uncertainty evaluation in experimentally estimated models. Investigated structures are plates, fuselage panels and helicopter main rotor blades as they represent different complexity levels ranging from coupon, through sub-component up to fully assembled structures made of composite materials. To evaluate the variability of the identified parameters, a statistical method is implemented for processing an extensive collection of experimental data.

General information
State: Published
Updating Finite Element Model of a Wind Turbine Blade Section Using Experimental Modal Analysis Results

This paper presents selected results and aspects of the multidisciplinary and interdisciplinary research oriented for the experimental and numerical study of the structural dynamics of a bend-twist coupled full scale section of a wind turbine blade structure. The main goal of the conducted research is to validate finite element model of the modified wind turbine blade section mounted in the flexible support structure accordingly to the experimental results. Bend-twist coupling was implemented by adding angled unidirectional layers on the suction and pressure side of the blade. Dynamic test and simulations were performed on a section of a full scale wind turbine blade provided by Vestas Wind Systems A/S. The numerical results are compared to the experimental measurements and the discrepancies are assessed by natural frequency difference and modal assurance criterion. Based on sensitivity analysis, set of model parameters was selected for the model updating process. Design of experiment and response surface method was implemented to find values of model parameters yielding results closest to the experimental. The updated finite element model is producing results more consistent with the measurement outcomes.
Validated Loads Prediction Models for Offshore Wind Turbines for Enhanced Component Reliability

To improve the reliability of offshore wind turbines, accurate prediction of their response is required. Therefore, validation of models with site measurements is imperative. In the present thesis a 3.6MW pitch regulated-variable speed offshore wind turbine on a monopole foundation is built in the aero-servo-hydro-elastic code HAWC2. The results are validated with full scale measurements from a 3.6MW Siemens offshore wind turbine installed in the Walney Offshore Wind Farm 1 at the west coast of England. Damping estimation, wind-wave misalignment cases and storm loads are analyzed. The findings are used for the modification of the sub-structure/foundation design for possible material savings.

First, the background of offshore wind engineering, including wind-wave conditions, support structure, blade loading and wind turbine dynamics are presented. Second, a detailed description of the site is given and the metocean conditions are analyzed. The joint wind-wave distribution and the probability of the misalignment angles are estimated. Third, the calibration process of the different components is thoroughly depicted. The turbulence intensity implemented in the simulations is extracted from a nacelle mounted cup-anemometer.

The model setup is based on the downscaled 5MW NREL reference wind turbine. Modifications on the downscaled model to match the actual full-scale wind turbine (mass and natural frequency) are applied. Extreme and mean measured loads from the free wind and the wake sectors, as well as 1Hz equivalent loads are used for the validation of the model.
uncertainties both in the model and full-scale wind turbine are quantified. The main contribution of the current thesis is presented in the final three chapters. The support structure net damping is estimated from the impulse response of a boat impact. The first and second modal damping of the system during normal operation both from measurements and simulations are identified with the implementation of the Enhanced Frequency Domain Decomposition technique. The effect of damping on the side-side fatigue of the support structure due to wind-wave misalignment cases is examined. The higher measured net damping is then used in the design process of the sub-structure/foundation for material savings. A detailed ultimate strength, stability strength and fatigue analysis are performed in the baseline and the modified designs to ensure structural integrity of the system.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbines
Contributors: Koukoura, C., Natarajan, A., Branner, K.
Number of pages: 198
Publication date: 2014

Publication information
Place of publication: Kgs. Lyngby
Publisher: Technical University of Denmark (DTU)
ISBN (Print): 978-87-92896-88-9
Original language: English
Electronic versions:
PhD_Thesis_kouk..PDF
Research output: Research › Ph.D. thesis – Annual report year: 2015

Calibration of a finite element composite delamination model by experiments
This paper deals with the mechanical behavior under in plane compressive loading of thick and mostly unidirectional glass fiber composite plates made with an initial embedded delamination. The delamination is rectangular in shape, causing the separation of the central part of the plate into two distinct sub-laminates. The work focuses on experimental validation of a finite element model built using the 9-noded MITC9 shell elements, which prevent locking effects and aiming to capture the highly non linear buckling features involved in the problem. The geometry has been numerically defined by a previously established modeling strategy (Branner et al., 2011; Gaiotti & Rizzo, 2011), using a pure shell model where the delamination is accounted for by properly offsetting its surfaces and connecting them to the intact plate via rigid link constraining algorithms. The numerical model developed by the University of Genova is compared with the experimental results provided by an extensive experimental campaign conducted by the Department of Wind Energy at the Technical University of Denmark (Branner & Berring, 2011). Along with the experimental/numerical comparison, an attempt to identify the fracture modes related to the production methods is presented in this paper. A microscopic analysis of the fracture surfaces was carried out in order to better understand the failure mechanisms. © 2013 Taylor & Francis Group.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbines, University of Genoa
Contributors: Gaiotti, M., Rizzo, C., Branner, K., Berring, P.
Pages: 389-396
Publication date: 2013

Host publication information
Title of host publication: Analysis and Design of Marine Structures - Proceedings of the 4th International Conference on Marine Structures, MARSTRUCT 2013
Publisher: Taylor & Francis
Editors: Guedes Soares, C., Romanoff, J.
Keywords: Delamination, Glass fibers, Ocean structures, Wind power, Finite element method
Source: dtu
Source-ID: n::oai:DTIC-ART:compendex/383256522::34761
Research output: Research - peer-review › Article in proceedings – Annual report year: 2013

Comparison of coupled and uncoupled load simulations on a jacket support structure
In this article, a comparison of the moments and forces at the joints of a jacket structure is made between fully coupled aerohydroelastic simulations in HAWC2 and uncoupled load predictions in the finite element software Abaqus. The jacket sub structure is modelled in moderate deep waters of 50m and designed for the 5MW NREL baseline wind turbine. External conditions are based on wind and wave joint distribution for a site in the North Sea. The turbulent wind field in HAWC2 is generated by random values, defined by the Mann Turbulence model, for each operational mean wind speed. A four-legged jacket structure similar to the Upwind reference jacket is developed in the Abaqus environment, to which is added the transition piece and tower. The aeroelastic loads determined in normal operating conditions of the turbine is
integrated and centralized as nodal forces and moments acting at the tower top of the finite element model. Hydrodynamic loads from the incoming waves are computed using the Morison equation and based on a nonlinear irregular wave field. Velocities, accelerations and amplitudes of the wave field as well as tower top forces and moments are used as inputs for the structural analysis in Abaqus. The fully coupled simulation is implemented and performed in HAWC2. In the uncoupled case, the loads (wave loads and tower base loads) are analysed by an implicit structural Finite Element Analysis (Abaqus 6.11-1). A subroutine is used as a preprocessor generating a beam element model and linking the loads to the components as nodal forces. In both simulation cases, the integrated loads acting on the jacket legs are computed as time series and as damage equivalent loading. The analysis and comparison of the fully coupled and decoupled simulation method show that the results vary depending on the structural stiffness and the applied wave loads. Variation in the amplitudes of the moments and forces on the jacket legs up to 25% was observed between the results obtained from coupled and uncoupled simulations.

© 2013 The Authors. Published by Elsevier Ltd.
Development of an anisotropic beam finite element for composite wind turbine blades in multibody system

In this paper a new anisotropic beam finite element for composite wind turbine blades is developed and implemented into the aeroelastic nonlinear multibody code, HAWC2, intended to be used to investigate if use of anisotropic material layups in wind turbine blades can be tailored for improved performance such as reduction of loads and/or increased power capture. The element stiffness and mass matrices are first derived based on pre-calculated anisotropic beam properties, and the beam element is subsequently put into a floating frame of reference to enable full rigid body displacement and rotation of the beam. This derivation provides the mass and stiffness properties and the fictitious forces needed for implementation into HAWC2. The implementation is subsequently validated by running three validation cases which all show good agreement with results obtained by other authors. Further, a parametric study is conducted in order to investigate if the given anisotropic effect of the composite blade, bend-twist coupling effect, is able to be examined by the developed beam element in a multibody system or not. Two different coupled examples of bend-twist coupling for the blade of a 5 MW fictitious wind turbine are considered. The two cases differ in the amount of bend-twist coupling introduced into the blade so that they produce 0.3 and 1 twist at the blade tip (toward feather), respectively, for a 1m flapwise tip deflection toward the tower. It is examined if the current structural model is able to capture the anisotropic effects in a multibody system. © 2013 Elsevier Ltd. All rights reserved.

General information
State: Published
Organisations: Department of Wind Energy, Aeroelastic Design, Wind Turbines
Contributors: Kim, T., Hansen, A. M., Branner, K.
Pages: 172-183
Publication date: 2013
Peer-reviewed: Yes

Publication information
Journal: Renewable Energy
Volume: 59
ISSN (Print): 0960-1481
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 5.38 SJR 1.847 SNIP 2.008
Web of Science (2017): Impact factor 4.9
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 4.83 SJR 1.661 SNIP 2.05
Web of Science (2016): Impact factor 4.357
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 4.51 SJR 1.767 SNIP 2.085
Web of Science (2015): Impact factor 3.404
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 4.51 SJR 1.925 SNIP 2.621
Web of Science (2014): Impact factor 3.476
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): CiteScore 4.63 SJR 1.989 SNIP 2.719
Web of Science (2013): Impact factor 3.361
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): CiteScore 3.97 SJR 1.787 SNIP 2.699
Web of Science (2012): Impact factor 2.989
Electromechanical Drivetrain Simulation

The work presented in this paper is another step from the DTU Wind Energy efforts to advance understanding of the electromechanical drive-train loads and its interaction with the rest of the components in the wind turbine. The main objective of the PhD is to investigate the modelling and simulation of a wind turbine’s drivetrain using an integrated simulation approach where different simulation tools are interconnected. Matlab and HAWC2 are used for this purpose. A contribution is expected to be in the study of the interaction between the mechanical loads in the gearbox due to gear mesh and bearing flexibilities, the generator dynamics and the grid, along with the structural loads in the wind turbine. In this paper, two simulation approaches are presented and conclusions are made according to their advantages and disadvantages. The drive-train is described by means of a torsional model composed of the main shaft, gearbox and generator. Special attention is given to the modelling of the gearbox and the generator in order to study the mechanical vibrations caused by turbulent wind and grid dynamics.

General information

State: Published
Organisations: Department of Wind Energy, Wind Turbines, Wind Energy Systems
Contributors: Gallego-Calderon, J., Branner, K., Natarajan, A., Cutululis, N. A., Hansen, J. C.
Number of pages: 5
Publication date: 2013
Hybrid Testing of Composite Structures with Single-Axis Control

Hybrid testing is a substructuring technique where a structure is emulated by modelling a part of it in a numerical model while testing the remainder experimentally. Previous research in hybrid testing has been performed on multi-component structures e.g. damping fixtures, however in this paper a hybrid testing platform is introduced for single-component hybrid testing. In this case, the boundary between the numerical model and experimental setup is defined by multiple Degrees-Of-Freedoms (DOFs) which highly complicate the transferring of response between the two substructures. Digital Image Correlation (DIC) is therefore implemented for displacement control of the experimental setup. The hybrid testing setup was verified on a multicomponent structure consisting of a beam loaded in three point bending and a numerical structure of a frame. Furthermore, the stability of the hybrid testing loop was investigated for different ratios of stiffness between the numerical model and test specimen. It was found that when deformations were transferred from the numerical model to the experimental setup, the hybrid test was only stable when the stiffness of the numerical model was higher than the test specimen. The hybrid test gave similar results as a numerical simulation of the full structure. The deviation between the two was primarily due to the response of the specimen in the hybrid test being one load step behind the numerical model.
Reliability assessment of fatigue critical welded details in wind turbine jacket support structures

This paper describes a probabilistic approach to reliability assessment of fatigue critical welded details in jacket support structures for offshore wind turbines. The analysis of the jacket response to the operational loads is performed using Finite Element Method (FEM) simulations in SIMULIA Abaqus. Fatigue stress cycles are computed on the jacket members by applying tower top loads from an aeroelastic simulation with superimposed marine loads and in accordance to the IEC-61400-3 guidelines for operational conditions. The combined effect of the hydrodynamic loads and the rotor loads on the jacket structure is analyzed in a de-coupled scheme, but including the structural dynamics of the support structure. The failure prediction of the welded joints, connecting the individual members of the support structure is based on SN-curves and Miner's rule according to ISO 19902 and DNV-RP-C203/DNV-OS-J101. Probabilistic SN-curves and a stochastic model for Miner's rule is used to estimate the reliability of selected critical welded details in the jacket structure taken into account the uncertainty in the fatigue stresses.
Results of the benchmark for blade structural models, part A

A benchmark on structural design methods for blades was performed within the InnWind.Eu project under WP2 “Lightweight Rotor” Task 2.2 “Lightweight structural design”. The present document is describes the results of the comparison simulation runs that were performed by the partners involved within Task 2.2 of the InnWind.Eu project. The benchmark is based on the reference wind turbine and the reference blade provided by DTU [1]. “Structural Concept developers/modelers” of WP2 were provided with the necessary input for a comparison numerical simulation run, upon definition of the reference blade [2]. Output is compared in here in terms of weight, stiffness, natural frequencies, deflection (extreme load) and strength & stability (extreme load).

General information
State: Published
Organisations: Department of Wind Energy, Wind turbine loads & control, Centre for Renewable Energy Sources, National Renewable Energy Center, University of Patras, Knowledge Centre Wind turbine Materials and Constructions, Politecnich University of Milan
Number of pages: 138
Publication date: 2013

Publication information
Original language: English
Electronic versions:
DeliverableD2.21_PartA_INNWIND.EU.pdf
Source: PublicationPreSubmission
Source-ID: 125463709
Research output: Research - peer-review › Report – Annual report year: 2013

Rotor blade full-scale fatigue testing technology and research

Full scale fatigue test is an important part of the development and design of wind turbine blades. Testing is also needed for the approval of the blades in order for them to be used on large wind turbines. However, usually only one prototype blade is tested. Fatigue test of wind turbine blades was started in the beginning of the 1980’s and has been further developed since then. Structures in composite materials are generally difficult and time consuming to test for fatigue resistance. Therefore, several methods for testing of blades have been developed and exist today. These methods will be presented in this report giving the blade test facility operator a guide to choose the method that best fit the needs and economic constraints. The state of the art method is currently dual axis mass resonance, where the purpose of the test is to emulate the loads the blades encounter in operation.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbines, Aeroelastic Design
Contributors: Nielsen, P. H., Berring, P., Pavese, C., Branner, K.
Number of pages: 28
Publication date: 2013

Publication information
Publisher: DTU Wind Energy
ISBN (Electronic): 978-87-92896-71-1
Original language: English
Keywords: DTU Wind Energy E-0041, DTU Wind Energy E-41
Electronic versions:
Rotor_blade_full_scale_fatigue.pdf
Source: PublicationPreSubmission
Source-ID: 118026971
Research output: Research - peer-review › Report – Annual report year: 2013

Static strain and deformation controlled testing of composite beams

General information
State: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics, Department of Civil Engineering, Section for Structural Engineering, Section for Building Design, Department of Wind Energy, Wind Turbines
Uncertainty modelling and code calibration for composite materials

Uncertainties related to the material properties of a composite material can be determined from the micro-, meso- or macro-scales. These three starting points for a stochastic modelling of the material properties are investigated. The uncertainties are divided into physical, model, statistical and measurement uncertainties which are introduced on the different scales. Typically, these uncertainties are taken into account in the design process using characteristic values and partial safety factors specified in a design standard. The value of the partial safety factors should reflect a reasonable balance between risk of failure and cost of the structure. Consideration related to calibration of partial safety factors for composite material is described, including the probability of failure, format for the partial safety factor method and weight factors for different load cases. In a numerical example, it is demonstrated how probabilistic models for the material properties formulated on micro-scale can be calibrated using tests on the meso- and macro-scales. The results are compared to probabilistic models estimated directly from tests on the macro-scale. In another example, partial safety factors for application to wind turbine blades are calibrated for two typical lay-ups using a large number of load cases and ratios between the aerodynamic forces and the inertia forces.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbines, Composites Mechanics and Materials Mechanics, Aalborg University
Contributors: Toft, H. S., Branner, K., Mishnaevsky, L. J., Sørensen, J. D.
Pages: 1729-1747
Publication date: 2013
Peer-reviewed: Yes

Publication information
Journal: Journal of Composite Materials
Volume: 47
Issue number: 14
ISSN (Print): 0021-9983
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 1.57 SJR 0.555 SNIP 0.898
Web of Science (2017): Impact factor 1.613
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 1.42 SJR 0.528 SNIP 0.803
Web of Science (2016): Impact factor 1.494
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 1.4 SJR 0.573 SNIP 0.876
Web of Science (2015): Impact factor 1.242
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): CiteScore 1.44 SJR 0.612 SNIP 1.188
Web of Science (2014): Impact factor 1.173
Anisotropic beam model for analysis and design of passive controlled wind turbine blades

The main objective of the project was, through theoretical and experimental research, to develop and validate a fully coupled, general beam element that can be used for advanced and rapid analysis of wind turbine blades. This is fully achieved in the project and the beam element has even been implemented in the aeroelastic code HAWC2. It has also been demonstrated through a parametric study in the project that a promising possibility with the tool is to reduce fatigue loads through structural couplings. More work is needed before these possibilities are fully explored and blades with structural couplings can be put into production.

A cross section analysis tool BECAS (BEam Cross section Analysis Software) has been developed and validated in the project. BECAS is able to predict all geometrical and material induced couplings. This tool has obtained great interest from both industry and
The developed fully coupled beam element and cross section analysis tool has been validated against both numerical calculations and experimental measurements. Numerical validation has been performed against beam type calculations including Variational Asymptotical Beam Section Analysis (VABS) and detailed shell and solid finite element analyses. Experimental validation included specially designed beams with built-in couplings, a full-scale blade section originally without couplings, which subsequently was modified with extra composite layers in order to obtain measurable couplings. Both static testing and dynamic modal analysis tests have been performed.

The results from the project now make it possible to use structural couplings in an intelligent manner for the design of future wind turbine blades. The developed beam element is especially developed for wind turbine blades and can be used for modeling blades with initial curvature (pre-bending), initial twist and taper. Finally, it has been studied what size of structural couplings can be obtained in current and future blade designs.
test performed on the box girder. During the final test the box girder failed at 58% of the expected ultimate load. Unfortunately, no definite conclusion could be made concerning the failure mechanism.

General information
State: Published
Organisations: Department of Wind Energy, Wind Turbines, Composites Mechanics and Materials Mechanics
Number of pages: 221
Publication date: 2012

Publication information
Publisher: DTU Wind Energy
Original language: English
(DTU Wind Energy E; No. 0010(EN)).
Keywords: DTU Wind Energy E-0010 (EN), DTU Wind Energy E-0010, DTU Wind Energy E report 0010
Electronic versions:
Design_and_test_of_box.pdf
Research output: Research › Report – Annual report year: 2013

Experimental Determination and Numerical Modelling of Process Induced Strains and Residual Stresses in Thick Glass/Epoxy Laminate
In this work, a cure hardening instantaneous linear elastic (CHILE) model and a path dependent (PD) constitutive approach are compared, for the case of modelling strain build-up during curing of a thick composite laminate part. The PD approach is a limiting case of viscoelasticity with path dependency on temperature and cure degree. Model predictions are compared to experimentally determined in-situ strains, determined using FBG sensors. It was found that both models offer good approximations of internal strain build-up. A general shortcoming is the lack of capturing rate-dependent effects such as creep.

General information
State: Published
Organisations: Department of Mechanical Engineering, Manufacturing Engineering, Department of Wind Energy, Composites Mechanics and Materials Mechanics, Wind Turbines
Contributors: Nielsen, M. W., Hattel, J. H., Løgstrup Andersen, T., Branner, K., Nielsen, P. H.
Number of pages: 8
Publication date: 2012

Host publication information
Title of host publication: ECCM15 - 15th European Conference On Composite Materials
Keywords: Numerical modeling, Shape distortions, FBG sensoring, Curing
Research output: Research - peer-review › Article in proceedings – Annual report year: 2012

A 1d Coupled Curing and Visco-Mechanical Void Growth Model of Thick Thermosetting Composite Laminates

General information
State: Published
Organisations: Manufacturing Engineering, Department of Mechanical Engineering, Composites and Materials Mechanics, Materials Research Division, Risø National Laboratory for Sustainable Energy, Wind Turbines, Wind Energy Division
Contributors: Nielsen, M. W., Hattel, J. H., Løgstrup Andersen, T., Branner, K., Nielsen, P. H.
Publication date: 2011

Host publication information
Title of host publication: ICCM18
Keywords: Voids, Numerical modelling, Curing, Laminate
Electronic versions:
ge_nielsenm_ICCM18.pdf
URLs:
http://www.iccm18.org/

Bibliographical note
The project is supported by Danish Energy Agency through the Energy Technology Development and Demonstration Program (EUDP). The supported EUDP-project is titled “Demonstration of new blade design using manufacturing process simulations” and has journal no. 64009-0094. The support is gratefully acknowledged.
**Anisotropic beam element for modeling of the wind turbine blades**

**General information**
- **State:** Published
- **Organisations:** Aeroelastic Design, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Wind Turbines
- **Contributors:** Kim, T., Branner, K.
- **Publication date:** 2011
- **Event:** Poster session presented at EWEA Annual Event 2011, Brussels, Belgium.
- **Keywords:** Aeroelastic design methods

**Electronic versions:**
- **Kim_poster_EWEA2011presentation.pdf**

**Comparison of two finite element methods with experiments of delaminated composite panels**

**General information**
- **State:** Published
- **Organisations:** Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy, University of Genoa
- **Contributors:** Branner, K., Berring, P., Gaiotti, M., Rizzo, C.
- **Publication date:** 2011

**Host publication information**
- **Title of host publication:** Proceedings
- **Keywords:** Wind turbine structures

**Electronic versions:**
- **COMPARISON OF TWO FINITE ELEMENT.pdf**

**Compressive strength of thick composite panels**

The aim of this study is to investigate how much the compressive strength of thick composite panels is reduced due to delaminations and to investigate under which conditions a delamination will grow. Understanding of this is essential in order to move forward the design limits used in the structural design process.

Results obtained from finite element modeling analyses are compared with an experimental test campaign performed on flat composite panels with and without delaminations.

**General information**
- **State:** Published
- **Organisations:** Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy
- **Contributors:** Branner, K., Berring, P.
- **Pages:** 221-228
- **Publication date:** 2011
- **Peer-reviewed:** Yes

**Publication information**
- **Journal:** Proceedings of the Risø International Symposium on Materials Science
- **Volume:** 32
- **ISSN (Print):** 0907-0079
- **Ratings:**
  - BFI (2019): BFI-level 1
  - BFI (2018): BFI-level 1
  - BFI (2017): BFI-level 1
Damage Detection in Wind Turbine Blade Panels Using Three Different SHM Techniques

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy, Wind Energy Division, Wind Turbines
Contributors: Luczak, M., Peeters, B., Mevel, L., Döhler, M., Ostachowicz, W., Malinowski, P., Wandowski, T., Branner, K.
Pages: 125-134
Publication date: 2011

Host publication information
Title of host publication: Structural Dynamics and Renewable Energy
Volume: 1
Publisher: Society for Experimental Mechanics
ISBN (Print): 978-1-4419-9715-9
(Conference Proceedings of the Society for Experimental Mechanics Series; No. 10).
Keywords: Wind turbine structures, Wind Energy
DOIs:
10.1007/978-1-4419-9716-6_12
Source: orbit
Source-ID: 270561
Research output: Research - peer-review › Article in proceedings – Annual report year: 2010

Defect distribution and reliability assessment of wind turbine blades
In this paper, two stochastic models for the distribution of defects in wind turbine blades are proposed. The first model assumes that the individual defects are completely randomly distributed in the blade. The second model assumes that the defects occur in clusters of different size, based on the assumption that one error in the production process tends to trigger several defects. For both models, additional information, such as number, type, and size of the defects, is included as stochastic variables. In a numerical example, the reliability is estimated for a generic wind turbine blade model both with and without defects in terms of delaminations. The reliability of the blade decreases when defects are included. However, the distribution of the defects influences how much the reliability is decreased. It is also shown how non-destructive inspection (NDI) after production can be used to update the reliability for the wind turbine blade using Bayesian statistics.

General information
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Aalborg University
Contributors: Stensgaard Toft, H., Branner, K., Berring, P., Sørensen, J. D.
Pages: 171-180
Publication date: 2011
Peer-reviewed: Yes
Developing Anisotropic Beam Element for Design of Composite Wind Turbine Blades

General information
State: Published
Organisations: Aeroelastic Design, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Wind Turbines
Contributors: Kim, T., Branner, K., Hansen, A. M.
Publication date: 2011

Host publication information
Title of host publication: Proceedings
Keywords: Aeroelastic design methods
Source: orbit
Source-ID: 284729
Research output: Research › Article in proceedings – Annual report year: 2011

Dynamic investigation of twist-bend coupling in a wind turbine blade
This paper presents some results and aspects of the multidisciplinary and interdisciplinary research oriented for the experimental and numerical study in static and dynamic domains on the bend-twist coupling in the full scale section of a wind turbine blade structure. The main goal of the conducted research is to confirm experimentally the numerical prediction of modification of the dynamic and static properties of a wind turbine blade. The bend-twist coupling was implemented by adding angled UD (UniDirectional) layers on the suction and pressure side of the blade. Static and dynamic tests were performed on a section of the full scale wind turbine blade provided by VestasWind Systems A/S. The results are presented and compared with the measurements of the original and modified blade. Comparison analysis confirmed that UD layers introduce measurable bend-twist couplings, which was not present in the original blade.

General information
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Polish Academy of Sciences, LMS International, Gdansk University of Technology
Contributors: Luczak, M., Manzato, S., Peeters, B., Branner, K., Berring, P., Kahsin, M.
Pages: 765-789
Publication date: 2011
Peer-reviewed: Yes

Publication information
Journal: Journal of Theoretical and Applied Mechanics
Volume: 49
Issue number: 3
ISSN (Print): 1429-2955
Ratings:
BFI (2019): BFI-level 1
Web of Science (2019): Indexed yes
BFI (2018): BFI-level 1
Web of Science (2018): Indexed yes
BFI (2017): BFI-level 1
Scopus rating (2017): CiteScore 0.87 SJR 0.321 SNIP 0.651
Web of Science (2017): Impact factor 0.783
Experimental Verification of the Implementation of Bend-Twist Coupling in a Wind Turbine Blade

General information
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy, LMS International
Contributors: Luczak, M., Manzato, S., Peeters, B., Branner, K., Berring, P., Haselbach, P. U.
Publication date: 2011

Host publication information
Title of host publication: Proceedings
Publisher: European Wind Energy Association (EWEA)
Keywords: Wind turbine structures
Electronic versions:
Experimental Verification.pdf
Source: orbit
Source-ID: 312471
Research output: Research › Article in proceedings – Annual report year: 2011

Finite elements modeling of delaminations in composite laminates
The application of composite materials in many structures poses to engineers the problem to create reliable and relatively simple methods, able to estimate the strength of multilayer composite structures. Multilayer composites, like other laminated materials, suffer from layer separation, i.e., delaminations, which may affect the stiffness and stability of structural components. Especially deep delaminations in the mid surface of laminates are expected to reduce the effective flexural stiffness and lead to collapse, often due to buckling behaviour. This paper deals with the numerical modelling of the buckling strength of composite laminates containing delaminations. Namely, non-linear buckling and post-buckling analyses are carried out to predict the critical buckling load of elementary composite laminates affected by rectangular delaminations of different sizes and locations, which are modelled by finite elements using different techniques. Results
obtained with different finite element models are compared and discussed.

**General information**

State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy, University of Genoa
Contributors: Gaiotti, M., Rizzo, C., Branner, K., Berring, P.
Pages: 133-139
Publication date: 2011

**Host publication information**

Title of host publication: Advances in Marine Structures
Place of publication: London
Publisher: Taylor & Francis
Editor: Fricke, W.
ISBN (Print): 978-0-415-67771-4
Keywords: Wind turbine structures
DOIs:
10.1201/b10771-1
Source: orbit
Source-ID: 312469
Research output: Research - peer-review › Article in proceedings – Annual report year: 2011

**Full Scale Test SSP 34m blade, Combined load, Data report**

This report is part of the research project entitled "Eksperimentel vingeforskning: Strukturelle mekanismer i nutidens og fremtidens store vinger under kombineret last" where a 34m wind turbine blade from SSP-Technology A/S was tested in combined flap and edgewise load. The applied load is 55% of an imaginary extreme event based on the certification load of the blade. This report describes the reason for choosing the loads and the load direction and the method of applying the loads to the blade. A novel load introduction allows the blade to deform in a more realistic manner, allowing the observation of e.g. transverse shear distortion. The global and local deformation of the blade as well as the blades’ respond to repeated tests has been studied and the result from these investigations are presented, including the measurements performed.

**General information**

State: Published
Number of pages: 183
Publication date: 2011

**Publication information**

Place of publication: Roskilde
Publisher: Danmarks Tekniske Universitet, Risø Nationallaboratoriet for Bæredygtig Energi
ISBN (Print): 978-87-550-3847-9
Original language: English
Keywords: Wind turbine structures, Risø-R-1749, Risø-R-1749(EN)
Electronic versions:
ris-r-1749.pdf
Source: orbit
Source-ID: 276273
Research output: Research › Report – Annual report year: 2011

**Investigating the impact of non-linear geometrical effects on wind turbine blades—Part 1: Current status of design and test methods and future challenges in design optimization**

This article is the first part of a three-article series and it deals with full-scale tests of a load-carrying box girder. The two other articles present more details on smaller sub-component levels as well as cap specimens (article 2) and shear webs (article 3). This article also links to the two other articles and brings the main results from them into relevance for a wind turbine blade designer. The investigated failure modes in all three articles relate to the Brazier effect, which is expected to be the key dominating failure mechanism in future wind turbine blade designs. The Brazier effect may also have a significant impact on present wind turbine blades. In this article, a 34m long load-carrying box girder has been tested in
static flap-wise bending, and it has been demonstrated that, for this design, the Brazier effect is a critical phenomenon of great relevance for the ultimate failure strength. The box girder has been evaluated with and without a cap (wire) reinforcement. The cap reinforcement is one out of seven inventions Risø DTU published in 2008, which are all intended to result in a lighter and more reliable blade design. Copyright © 2010 John Wiley & Sons, Ltd.
On innovative concepts of wind turbine blade design

General information
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy
Contributors: Jensen, F. M., Nielsen, P. H., Roczek-Sieradzan, A., Sieradzan, T., Branner, K., Bitsche, R.
Pages: 275-279
Publication date: 2011

Host publication information
Title of host publication: Scientific Proceedings
Publisher: European Wind Energy Association (EWEA)
Keywords: Wind turbine structures
Electronic versions:
Jensen_EWEA2011presentation.pdf
Jensen_poster_EWEA2011presentation.pdf

Bibliographical note
paper + poster
Source: orbit
Source-ID: 275637
Research output: Research - peer-review › Article in proceedings – Annual report year: 2011

Optimal Design of Laminated Composite Beams
This thesis presents an optimal design framework for the structural design of laminated composite beams. The possibility of improving the static and dynamic performance of laminated composite beam through the use of optimal design techniques motivates the investigation presented here. A structural model for the analysis of laminated composite beams is proposed. The structural analysis is performed in a beam finite element context. The development of a finite element based tool for the analysis of the cross section stiffness properties is described. The resulting beam finite element formulation is able to account for the effects of material anisotropy and inhomogeneity in the global response of the beam. Beam finite element models allow for a significant reduction in problem size and are therefore an efficient alternative in computationally intensive applications like optimization frameworks. Furthermore, the devised beam model is able account
for the different levels of anisotropic elastic couplings which depend on the laminate lay-up. An optimization model based on multi-material topology optimization techniques is described. The design variables represent the volume fractions of the different candidate materials. Existing material interpolation, penalization, and filtering techniques have been extended to accommodate any number of anisotropic materials. The resulting optimization model is suitable for the simultaneous optimization of cross section topology and laminate properties in the optimal design of laminated composite beams. The devised framework is applied in the optimal design of laminated composite beams with different cross section geometries and subjected to different load cases. Design criteria such as beam stiffness, weight, magnitude of the natural frequencies of vibration, and the position of the cross section shear and mass center, are considered. The proposed optimal design framework can be applied to tailor the static and dynamic properties of laminated composite structures like wind turbine blades.

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy, Wind Turbines, Wind Energy Division, Applied functional analysis, Department of Mathematics, Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering
Contributors: Blasques, J. P. A. A., Stolpe, M., Berggreen, C., Branner, K.
Number of pages: 249
Publication date: 2011

Publication information
Place of publication: Kgs. Lyngby, Denmark
Publisher: Technical University of Denmark (DTU)
Original language: English
(DCAMM Special Report; No. S134).
Keywords: Wind turbine structures
Electronic versions:
S134 José Pedro Blasques.pdf
Source: orbit
Source-ID: 312644
Research output: Research › Ph.D. thesis – Annual report year: 2011

Parametric study of composite wind turbine blades
In this paper an anisotropic beam element for a composite wind turbine blades is developed. Eigenvalue analysis with the new beam element is conducted in order to understand its responses associated with the wind turbine performances. From the results of natural frequencies and mode shapes it is obvious that the anisotropic characteristics should not be ignored to obtain accurate results.

General information
State: Published
Organisations: Aeroelastic Design, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Wind Turbines
Contributors: Kim, T., Branner, K., Hansen, A. M.
Pages: 339-350
Publication date: 2011
Peer-reviewed: Yes

Publication information
Volume: 32
ISSN (Print): 0907-0079
Ratings:
BFI (2019): BFI-level 1
BFI (2018): BFI-level 1
BFI (2017): BFI-level 1
BFI (2016): BFI-level 1
BFI (2015): BFI-level 1
BFI (2014): BFI-level 1
BFI (2013): BFI-level 1
ISI indexed (2013): ISI indexed no
BFI (2012): BFI-level 1
ISI indexed (2012): ISI indexed no
BFI (2011): BFI-level 1
Reliability-based Calibration of Partial Safety Factors for Wind Turbine Blades

**General information**
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Aalborg University
Contributors: Stensgaard Toft, H., Branner, K., Sørensen, J. D., Berring, P.
Pages: 124-128
Publication date: 2011

**Host publication information**
Title of host publication: Scientific Proceedings
Publisher: European Wind Energy Association (EWEA)
Keywords: Wind turbine structures
Source: orbit
Source-ID: 275837
Research output: Research - peer-review › Article in proceedings – Annual report year: 2011

**Wind turbine blade testing under combined loading**
The paper presents full-scale blade tests under a combined flap- and edgewise loading. The main aim of this paper is to present the results from testing a wind turbine blade under such conditions and to study the structural behavior of the blade subjected to combined loading. A loading method using anchor plates was applied, allowing transverse shear distortion. The global and local deformation of the blade as well as the reproducibility of the test was studied and the results from the investigations are presented.

**General information**
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy
Contributors: Roczek-Sieradzan, A., Nielsen, M., Branner, K., Jensen, F. M., Bitsche, R.
Pages: 449-456
Publication date: 2011
Peer-reviewed: Yes

**Publication information**
Volume: 32
ISSN (Print): 0907-0079
Ratings:
BFI (2019): BFI-level 1
BFI (2018): BFI-level 1
BFI (2017): BFI-level 1
BFI (2016): BFI-level 1
BFI (2015): BFI-level 1
BFI (2014): BFI-level 1
BFI (2013): BFI-level 1
ISI indexed (2013): ISI indexed no
BFI (2012): BFI-level 1
ISI indexed (2012): ISI indexed no
BFI (2011): BFI-level 1
Applying static and dynamic test responses for defect prediction in wind turbine blades using a probabilistic approach

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy, Wind Energy Division, Wind Turbines, Materials Research Division, Composites and Materials Mechanics, LMS International, Polish Academy of Sciences
Contributors: Luczak, M., Branner, K., Kahsin, M., Martyniuk, K., Peeters, B., Ostachowicz, W., Wandowski, T., Malinowski, P.
Publication date: 2010

Host publication information
Title of host publication: EWEC 2010 Proceedings online
Publisher: European Wind Energy Association (EWEA)
Keywords: Wind turbine structures, Wind energy
Electronic versions:
Applying static.pdf
Source: orbit
Source-ID: 270559
Research output: Research - peer-review › Article in proceedings – Annual report year: 2010

Blade materials, testing methods and structural design

General information
State: Published
Organisations: Composites and Materials Mechanics, Materials Research Division, Risø National Laboratory for Sustainable Energy, Wind Turbines, Wind Energy Division
Contributors: Sørensen, B. F., Holmes, J. W., Brøndsted, P., Branner, K.
Number of pages: 720
Pages: 417-466
Publication date: 2010

Host publication information
Title of host publication: Wind Power Generation and Wind Turbine Design
Publisher: WIT Press
ISBN (Print): 978-1-84564-205-1
Keywords: Light strong materials for energy purposes, Wind Energy
Source: orbit
Source-ID: 269374
Research output: Research - peer-review › Book chapter – Annual report year: 2010

Effect of Strain Rate on Sandwich Web Failure in the Load Carrying Girder of a Wind Turbine Blade

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy, Wind Energy Division, Wind Turbines
Contributors: Branner, K., Bitsche, R., Jensen, F. M.
Publication date: 2010

Host publication information
Title of host publication: Proceedings
Publisher: California Institute of Technology
Full Scale Test of SSP 34m blade, edgewise loading LTT: Data Report 1
This report is a part of the research project "Eksperimentel vingeforskning: Strukturelle mekaniser i nutidens og fremtidens store vinger under kombineret last" where a 34m wind turbine blade from SSP-Technology A/S has been tested in edgewise direction (LTT). The applied load is 60% of an unrealistic extreme event, corresponding to 75% of a certificated extreme load. This report describes the background, the test set up, the tests and the results. For this project, a new solution has been used for the load application and the solution for the load application is described in this report as well. The blade has been submitted to thorough examination. More areas have been examined with DIC, both global and local deflections have been measured, and also 378 strain gauge measurements have been performed. Furthermore Acoustic Emission has been used in order to detect damage while testing new load areas. The global deflection is compared with results from a previous test and results from FEM analyses in order to validate the solution as to how the gravity load on the blade was handled. Furthermore, the DIC measurement and the displacement sensors measurements are compared in order to validate the results from the DIC measurements. The report includes the results from the test and a description of the measurement equipment and the data acquisition.

General information
State: Published
Number of pages: 158
Publication date: 2010

Publication information
Place of publication: Roskilde
Publisher: Danmarks Tekniske Universitet, Riso Nationallaboratoriet for Bæredygtig Energi
ISBN (Print): 978-87-550-3794-6
Original language: English
(University. Forskningscenter Risoe. Risoe-R; No. 1718(EN)),
Keywords: Wind turbine structures, Wind energy, Risø-R-1718, Risø-R-1718(EN)
Electronic versions:
ris-r-1718.pdf
Source: orbit
Source-ID: 263769
Research output: Research › Report – Annual report year: 2010

Full Scale Test SSP 34m blade, edgewise loading LTT. Extreme load and PoC_InvE Data report
This report is the second report covering the research and demonstration project "Eksperimentel vingeforskning: Strukturelle mekaniser i nutidens og fremtidens store vinger under kombineret last", supported by the EUDP program. A 34m wind turbine blade from SSP-Technology A/S has been tested in edgewise direction (LTT). The blade has been submitted to thorough examination by means of strain gauges, displacement transducers and a 3D optical measuring system. This data report presents results obtained during full scale testing of the blade up to 80% Risø load, where 80% Risø load corresponds to 100% certification load. These pulls at 80% Risø load were repeated and the results from these pulls were compared. The blade was reinforced according to a Risø DTU invention, where the trailing edge panels are coupled. The coupling is implemented to prevent the out of plane deformations and to reduce peeling stresses in the adhesive joints. Test results from measurements with the reinforcement have been compared to results without the coupling. The report presents only the relevant results for the 80% Risø load and the results applicable for the investigation of the influence of the invention on the profile deformation.

General information
State: Published
Improved design for large wind turbine blades of fibre composites (Phase 4) - Summary report

Results are summarised for the project "Improved design for large wind turbine blades (Phase 4)", partially supported by the Danish Energy Agency under the Ministry of Climate and Energy through the EUDP journal no.: 33033-0267. The aim of the project was to develop new and better design methods for wind turbine blades, so that uncertainties associated with damage and defects can be reduced. The topics that are studied include buckling-driven delamination of flat load-carrying laminates, cracking along interfaces in material joints (fracture mechanical characterisation and modelling), cyclic crack growth with large scale bridging and the use of cohesive laws in finite element programmes for simulating wind turbine blade failure. An overview is given of the methods and the major research results of the project. The implementation of the knowledge in the industry is discussed. Finally, some ideas for future research activities are considered.

Investigation of Structural Behavior due to Bend-Twist Couplings in Wind Turbine Blades

One of the problematic issues concerning the design of future large composite wind turbine blades is the prediction of bend-twist couplings and torsion behaviour. The current work is a continuation of a previous work [1,2], and it examines different finite element modelling approaches for predicting the torsional response of the wind turbine blades with built-in bend-twist couplings. Additionally, a number of improved full-scale tests using an advanced bi-axial servo-hydraulic load control have been performed on a wind turbine blade section provided by Vestas Wind Systems A/S. In the present work attention was aimed specifically at shell element based FEA models for predicting torsional behaviour of the blade. Three models were developed in different codes: An ANSYS and ABAQUS model with standard section input and an ANSYS model with matrix input. All models employed the outer surface of the blade cross section as the defining surface, offset-setting the location of the shell elements according to the specified thickness. The experimental full-scale tests were carried out on an 8 m section of a 23 m wind turbine blade with specially implemented bend-twist coupling. The blade was tested under considerably larger load levels compared to earlier tests and showed linear-elastic response during flap-wise bending and combined bending-torsion tests which made it possible to employ the principle of superposition to extract the torsional characteristics of the blade from these tests. Additionally, pure torsion tests were carried out on the blade employing a more advanced bi-axial servo-hydraulic load application control. The use of shell-solid models for the prediction of torsional response was recommended based on earlier investigations.
However as these models in practice are cumbersome to apply in design, the numerical models mentioned above were compared with previous experiments and the new experiments presented in this paper. Additionally, the models were verified against two older MSC.Nastran models developed in. All shell models performed well for flap-wise bending, but performed poorly in torsion with deviations in the range of 15 to 35%, when employing the section input for the off-set definition. However, the ANSYS model generated using matrix input for the off-set definition was found to perform adequately.
Upscaling of Sandwich Panels for 120 m Wind Turbine Blades

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy, Wind Energy Division, Wind Energy Educational Programme, Wind Turbines, Department of Mechanical Engineering, Coastal, Maritime and Structural Engineering
Contributors: Andrlová, Z., Branner, K., Jensen, F. M., Berggreen, C.
Publication date: 2010

Host publication information
Title of host publication: Proceedings
Publisher: California Institute of Technology
Keywords: Wind turbine structures, Wind Energy

A Hierarchical FEM approach for Simulation of Geometrical and Material induced Instability of Composite Structures

In this paper a hierarchical FE approach is utilized to simulate delamination in a composite plate loaded in uni-axial compression. Progressive delamination is modelled by use of cohesive interface elements that are automatically embedded. The non-linear problem is solved quasi-statically in which the interaction between material degradation and structural instability is solved iteratively. The effect of fibre bridging is studied numerically and in-plane failure is predicted using physically based failure criteria.

General information
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Aalborg University, Imperial College London
Number of pages: 6
Publication date: 2009

Host publication information
Title of host publication: Proceedings of Composites 2009

Committee III.1 Ultimate strength

General information
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy
Pages: 95-125
Publication date: 2009

Host publication information
Title of host publication: Proceedings of the 17th International Ship and Offshore Structures Congress
Volume: 3

Comparison of the three different approaches for damage detection in the part of the composite wind turbine blade

General information
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Composites and Materials Mechanics, Materials Research Division
**Investigation of structural behaviour due to bend-twist couplings in wind turbine blades**

The structural behaviour of a composite wind turbine blade with implemented bend-twist coupling is examined in this paper. Several shell finite element models of the blade have been developed and validated against full-scale tests. All shell models performed well for flap-wise bending, but performed poorly in torsion, when employing material off-sets.
Reducing Cross-Sectional Deformations in a Wind Turbine Blade

Structural Design of Large Future Wind Turbine Blades under Combined Loading

Ultimate strength
Ultimate Strength of Wind Turbine Blades

General information
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy
Contributors: Branner, K.
Pages: 38-39
Publication date: 2009

Host publication information
Title of host publication: Program, list of participants and abstracts
Publisher: DCAMM, Technical University of Denmark
Keywords: Wind turbines, Wind energy
URLs:
http://www.fam.web.mek.dtu.dk/dcamm05/Program-09-03-19.pdf
Source: orbit
Source-ID: 253834
Research output: Research › Conference abstract in proceedings – Annual report year: 2009

Vibration-Based Damage Detection in Multilayer Composite Material

General information
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Composites and Materials Mechanics, Materials Research Division
Contributors: Szkudlarek, W., Kahsin, M., Luczak, M., Peeters, B., Kurowski, M., Branner, K., Martyniuk, K., Wasilczuk, M.
Publication date: 2009

Host publication information
Title of host publication: Proceedings
Source: orbit
Source-ID: 280456
Research output: Research › Article in proceedings – Annual report year: 2009

Buckling Strength of Thick Composite Panels in Wind Turbine Blades: Part I: Effect of Geometrical Imperfections

General information
State: Published
Organisations: Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering, Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy, National Technical University of Athens, Det Norske Veritas
Contributors: Berggreen, C., Tsouvalis, N. G., Hayman, B., Branner, K.
Publication date: 2008
Peer-reviewed: Yes
Event: Abstract from 4th International Conference of Composites Testing & Model Identification, Dayton, OH, United States.
Source: orbit
Source-ID: 233116
Research output: Research › peer-review › Conference abstract for conference – Annual report year: 2008
Buckling Strength of Thick Composite Panels in Wind Turbine Blades: Part II: Effect of Delaminations

General information
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering
Contributors: Branner, K., Berring, P., Berggreen, C.
Publication date: 2008
Peer-reviewed: Yes
Event: Abstract from 4th International Conference of Composites Testing & Model Identification, Dayton, OH, United States.
Source: orbit
Source-ID: 233121
Research output: Research - peer-review › Conference abstract for conference – Annual report year: 2008

Digital image correlation based failure examination of sandwich structures for wind turbine blades

General information
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy
Contributors: Dear, J., Puri, A., Fergusson, A., Morris, A., Dear, I., Branner, K., Jensen, F. M.
Pages: 212-223
Publication date: 2008

Host publication information
Title of host publication: Proceedings. Vol. 1
Publisher: SAGE Publications
Source: orbit
Source-ID: 231891
Research output: Research › Article in proceedings – Annual report year: 2008

Effect of sandwich core properties on ultimate strength of a wind turbine blade

General information
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy
Contributors: Branner, K., Jensen, F. M., Berring, P., Puri, A., Morris, A., Dear, J.
Pages: 523-533
Publication date: 2008

Host publication information
Title of host publication: Proceedings. Vol. 1
Publisher: SAGE Publications
Source: orbit
Source-ID: 231890
Research output: Research › Article in proceedings – Annual report year: 2008

Full Scale Test of a SSP 34m box girder 1. Data report
This report presents the setup and result of a full-scale test of a reinforced glass fibre/epoxy box girder used in 34m wind turbine blade. The tests were performed at the Blaest test facility in August 2006. The test is an important part of a research project established in cooperation between Risø DTU, the National Laboratory for Sustainable Energy at the Technical University of Denmark –, SSP-Technology A/S and Blaest (Blade test centre A/S) and it has been performed as a part of Find Melholt Jensen”s PhD study. This report contains the complete test data for the final test, in which the box girder was loaded until failure. A comprehensive description of the test setup is given. This report deals only with tests and results. There are no conclusions on the data in this report, but references are given to publications, where the data are used and compared with FEM etc. Various kinds of measuring equipment have been used during these tests: acoustic emission, 330 strain gauges, 24 mechanical displacement devices and two optical deformation measuring systems. The mechanical displacement devices measured both global (absolute) and local (relative) deflection and the optical systems measured surface deformation. A prediction was made on the location of the failure of the girder. At this location the majority of the measuring equipment was concentrated. The prediction was proved to be correct and valuable information of the behaviour of the box girder prior to failure was obtained. The experimental investigation consisted of the following load configurations: -Flapwise bending -Torsion Ultrasonic scanning of the box girder was performed before, during and after the test the box girder. This was done to investigate whether the girder was damaged by the load or imperfection
Full Scale Test of a SSP 34m box girder 2: Data report

This report presents the setup and result from three static full-scale tests of the reinforced glass fiber/epoxy box girder used in a 34m wind turbine blade. One test was without reinforcement one with cap reinforcement and the final test was with rib reinforcement. The cap reinforcement test was part of a proof of concept investigation for a patent. The tests were performed at the Blaest test facility in August 2007. The tests are an important part of a research project established in cooperation between Risø National Laboratory for sustainable energy – Technical university of Denmark, SSP-Technology A/S and Blaest (Blade test centre A/S) and it has been performed as a part of Find Mølholt Jensen's PhD thesis. This report is the second data report containing the complete test data for the three full-scale tests. This report deals only with the test methods and the obtained results, no conclusions are drawn. These can be found in papers and patent referenced in the data report. Various kinds of measuring equipment have been used during these tests: acoustic emission, force transducers, strain gauges and optical deformation measuring system (DIC). The experimental investigation consisted of the following tests: 1) Flapwise bending with no reinforcement 2) Flapwise bending with wire reinforcements 3) Flapwise bending with rib reinforcements
On the Effect of Curvature in Debonded Sandwich Panels Subjected to Compressive Loading

The aim of this study is to obtain an understanding of the effect of panel curvature on residual compressive strength in debond damaged sandwich panels. Finite element analysis and linear elastic fracture mechanics are employed to analyze the residual compressive strength of curved panels with a circular debond. The Crack Surface Displacement Extrapolation (CSDE) method is used to calculate fracture parameters in the interface. Compression tests were carried out on two types of debonded curved panels with different curvature using Digital Image Correlation (DIC) measurements to determine the full-field distribution of strain. The failure and buckling loads predicted from finite element analyses are in good agreement with experimental results.

Application and Analysis of Sandwich Elements in the Primary Structure of Large Wind Turbine Blades

The present work studies the advantages of applying a sandwich construction as opposed to traditional single skin composites in the flanges of a load carrying spar in a future 180 m wind turbine rotor. A parametric finite element model is used to analyze two basic designs with single skin and sandwich flanges, respectively. Buckling is by far the governing criterion for the single skin design. Introducing a sandwich construction results in a globally more flexible structure making tower clearance the critical criterion. Significant weight reduction up to 22.3% and increased buckling capacity is obtained. Moreover, the study showed that proper choice of core material is important to prevent face wrinkling. Geometric nonlinear analysis showed sensitivity to imperfections. A consistent submodeling technique is presented for verifying the response from the global model in any section of interest.
Torsional Performance of Wind Turbine Blades: Part I: Experimental Investigation

The complete 3D static responses of two different eight meter long wind turbine blade sections were tested. To experimentally investigate the 3D response, an advanced 3D digital optical deformation measuring system (ARAMIS 2M and 4M) was applied in this work. This system measures the full-field displacements (ux, uy and uz) of the blade surface. A least squares algorithm was developed, which fits a plane through each deformed cross section, and defines a single set of displacements and rotations (three displacements and rotations) per cross section. This least squares algorithm was also used to accommodate problems with a flexible boundary condition by determining the displacements and rotations for a cross section near the boundary. These displacements and rotations are subtracted from all other cross sections along the blade and thereby making the blade section fully fixed at the chosen cross section near the boundary.

General information
State: Published
Organisations: Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering, Technical University of Denmark
Contributors: Berring, P., Branner, K., Berggreen, C., Knudsen, H. W.
Number of pages: 1,432
Publication date: 2007

Host publication information
Title of host publication: Sixteenth International Conference on Composite Materials: A Giant Step towards Environmental Awareness: From Green Composites to Aerospace
Volume: 2
Place of publication: Tokyo, Japan
Publisher: Japan Society for Composite Materials
Editors: Kageyama, K., Ishikawa, T., Takeda, N., Hojo, M., Sugimoto, S., Ogasawara, T.
ISBN (Print): 978-4-931136-06-9
Source: orbit
Source-ID: 201947
Research output: Research - peer-review › Article in proceedings – Annual report year: 2007

Torsional performance of wind turbine blades - Part 1: Experimental investigation

General information
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering
Contributors: Berring, P., Branner, K., Berggreen, C., Knudsen, H.
Pages: 1118-1119
Publication date: 2007

Host publication information
Title of host publication: Proceedings of the 16th International conference on composite materials : Book of abstracts. Vol. 2
Publisher: Japan Society for Composite Materials
Editors: Kageyama, K., Ishikawa, T., Takeda, N., Hojo, M., Sugimoto, S., Ogasawara, T.
ISBN (Print): 978-4-931136-06-9
Source: orbit
Source-ID: 231971
Research output: Research › Conference abstract in proceedings – Annual report year: 2007
Torsional performance of wind turbine blades - Part 2: Numerical validation

General information
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy, Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering
Contributors: Branner, K., Berring, P., Berggreen, C., Knudsen, H.
Pages: 1120-1121
Publication date: 2007

Host publication information
Title of host publication: Proceedings of the 16th International conference on composite materials : Book of abstracts
Volume: vol. 2
Publisher: Japan Society for Composite Materials
Editors: Kageyama, K., Ishikawa, T., Takeda, N., Hojo, M., Sugimoto, S., Ogasawara, T.
ISBN (Print): 978-4-931136-06-9
Source: orbit
Source-ID: 231972
Research output: Research › Conference abstract in proceedings – Annual report year: 2007

Improved design basis for large wind turbine blades

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Contributors: Branner, K.
Publication date: 2006
Peer-reviewed: No
Source: orbit
Source-ID: 309978
Research output: Research › Conference abstract for conference – Annual report year: 2006

Modeling failure in cross-section of wind turbine blade

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Contributors: Branner, K.
Publication date: 2006

Host publication information
Title of host publication: Proceedings
Source: orbit
Source-ID: 309291
Research output: Research › Article in proceedings – Annual report year: 2006

Static testing of cross-section of wind turbine blade (poster)

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Contributors: Branner, K.
Pages: 46-47
Publication date: 2006

Host publication information
Title of host publication: Book of abstracts (online)
Place of publication: Porto
Publisher: Universidade de Porto, Faculdade de Engenharia
URLs:
**Strukturel design af vindmøllevinger**

**General information**
- **State:** Published
- **Organisations:** Risø National Laboratory for Sustainable Energy
- **Contributors:** Branner, K., Berggren, C.
- **Publication date:** 2006
- **Peer-reviewed:** No
- **Event:** Abstract from Vinddag 2006, Dansk Forskningskonsortium for Vindenergi, Risø, Denmark.

**Torsional properties of large wind turbine blades**

**General information**
- **State:** Published
- **Organisations:** Risø National Laboratory for Sustainable Energy
- **Contributors:** Hansen, A., Branner, K., Berring, P., Knudsen, H., Capellaro, M.
- **Pages:** 99-105
- **Publication date:** 2006

**Host publication information**
- **Title of host publication:** Research in aeroelasticity EFP-2005
- **Volume:** Risø-R-1559(EN)
- **Editor:** Bak, C.
- **ISBN (Print):** 87-550-3521-3
- **URLs:**
- **Source:** orbit
- **Source-ID:** 309593

**Application of load carrying sandwich elements in large wind turbine blades**

**General information**
- **State:** Published
- **Organisations:** Risø National Laboratory for Sustainable Energy
- **Contributors:** Jensen, J., Schultz, J., Branner, K., Berggreen, C.
- **Pages:** 947-956
- **Publication date:** 2005

**Host publication information**
- **Title of host publication:** Sandwich structures 7: Advancing with sandwich structures and materials
- **Place of publication:** Berlin
- **Publisher:** Springer
- **Editors:** Thomsen, O., Bozhevolnaya, E., Lyckegaard, A.
- **Source:** orbit
- **Source-ID:** 308774

**Finite element analysis of the cross-section of wind turbine blades: a comparison between shell and 2D-solid models**

A very detailed 2D-solid finite element model is developed representing the load carrying box girder of a wind turbine blade. Using typical geometrical values for the girder dimensions and public available material data, the overall cross-sectional behaviour is analysed for a simple compressive line load. The results are compared with result from similar shell models, which typically are used for practical design. Usually, good agreement between the shell models and the detailed 2D-solid model is found for the deflections, strains and stresses in regions with loads from pure bending. However, large differences can exist in regions where the loading is dominated by shear. It is found that geometrical non-linearity starts to become important.
when deflections are of the same order as the laminate thickness.
Perspektiver med udnyttelse af nanoteknologi

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Contributors: Branner, K., Sørensen, B.
Publication date: 2004
Peer-reviewed: No
URLs:
Source: orbit
Source-ID: 307641
Research output: Research › Conference abstract for conference – Annual report year: 2004

Fatigue loading

General information
State: Published
Organisations: Risø National Laboratory for Sustainable Energy
Contributors: Watenabe, I., Branner, K., Cariou, A., Fukasawa, T., Gu, X., Kapsenberg, G.
Pages: 235-284
Publication date: 2003

Host publication information
Title of host publication: Proceedings. Vol. 2
Place of publication: London
Publisher: Elsevier Science & Technology Books
Editors: Ertekin, R., Mansour, A.
Source: orbit
Source-ID: 306327
Research output: Research › Article in proceedings – Annual report year: 2003

Future Challenges for the Structural Design of Marine High Speed Vessels

General information
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy
Contributors: Branner, K., Sangberg, B., Groes-Petersen, P.
Publication date: 1998

Host publication information
Title of host publication: Proceedings
Source: orbit
Source-ID: 280427
Research output: Research › Article in proceedings – Annual report year: 1998

Hydrodynamic Behavior, Comparison and Load Application Concerning a Transatlantic High-speed Container Vessel

General information
State: Published
Organisations: Wind Turbines, Wind Energy Division, Risø National Laboratory for Sustainable Energy
Contributors: Branner, K., Sangberg, B.
State-of-the-Art Report on Computer Systems for Design

Although the shipbuilding industry is among the oldest and most traditional heavy industries in the world, it was also among the first to recognise the advantages of computers in the design and production processes. Today the computer is an indispensable tool in the total design phase ranging from the feasibility study to the final working drawings.

Capacity and Lifetime of Foam Core Sandwich Structures

Projects:

Structural Damage Prediction of Full-Scale Wind Turbine Blades Under Fatigue Loading
Anchondo, R. I. E., PhD Student, Department of Wind Energy
Branner, K., Main Supervisor, Department of Wind Energy
Castro Ardila, O. G., Supervisor, Department of Wind Energy
15/01/2019 → 14/01/2022
Project: PhD
**Advanced methods for blade Monitoring Under full-scale Testing (AMOUNT)**
Belloni, F., PhD Student, Department of Wind Energy
Branner, K., Main Supervisor, Department of Wind Energy
Kann, J., Supervisor
Chen, X., Supervisor, Department of Wind Energy
01/09/2018 → 31/08/2021
Project: PhD

**Verification of Structural Properties for Bend-Twist Coupled Wind Turbine Blades**
Tiedemann, M. M., PhD Student, Department of Wind Energy
Branner, K., Main Supervisor, Department of Wind Energy
Bode, J., Supervisor
Chen, X., Supervisor, Department of Wind Energy
Industrial PhD
01/03/2018 → 28/02/2021
Award relations: Verification of Structural Properties for Bend-Twist Coupled Wind Turbine Blades
Project: PhD

**CASMaT: Villum Center for Advanced Structural and Material Testing**
Stang, H., Project Manager, Department of Civil Engineering, Section for Structural Engineering
Klems, C., Project Participant, Department of Civil Engineering
Mikkelsen, L. P., Project Participant, Department of Wind Energy
Serensen, B. F., Project Participant, Department of Wind Energy, Composites Mechanics and Materials Mechanics
Toftegaard, H. L., Project Participant, Department of Wind Energy, Composites Mechanics and Materials Mechanics
Berggreen, C., Project Participant, Department of Mechanical Engineering, Solid Mechanics
Branner, K., Project Participant, Department of Wind Energy, Wind Turbine Structures and Component Design
Michel, A., Project Participant, Department of Civil Engineering, Section for Structural Engineering
Andreassen, M. J., Project Participant, Department of Civil Engineering, Section for Structural Engineering
Luczak, M., Project Participant, Department of Wind Energy, Wind Turbine Structures and Component Design
Chen, X., Project Participant, Department of Wind Energy, Wind Turbine Structures and Component Design
Bjørnbak-Hansen, J., Project Participant, Department of Civil Engineering, Section for Structural Engineering
Legarth, B. N., Project Participant, Department of Mechanical Engineering, Solid Mechanics
Waldbjørn, J. P., Project Participant, Department of Mechanical Engineering, Solid Mechanics
Bangaru, A. K., PhD Student, Department of Wind Energy, Composites Mechanics and Materials Mechanics
Moncy, A., PhD Student, Department of Mechanical Engineering, Solid Mechanics
Quinlan, A., PhD Student, Department of Civil Engineering, Section for Structural Engineering
07/11/2017 → …
Project: Research

**Multi-axial fatigue damage laws for composite materials at the macro-scale**
Moncy, A., PhD Student, Department of Mechanical Engineering
Berggreen, C., Main Supervisor, Department of Mechanical Engineering
Branner, K., Supervisor, Department of Wind Energy
Stang, H., Supervisor, Department of Civil Engineering
Serensen, B. F., Supervisor, Department of Wind Energy
Institut stipendie (DTU)
01/11/2017 → 31/10/2020
Award relations: Multi-axial fatigue damage laws for composite materials at the macro-scale
Project: PhD

**Fatigue behaviour of polymer composite materials at the sub-structural and structural scale**
Quinlan, A., PhD Student, Department of Civil Engineering
Stang, H., Main Supervisor, Department of Civil Engineering
Berggreen, C., Supervisor, Department of Mechanical Engineering
Branner, K., Supervisor, Department of Wind Energy
Waldbjørn, J. P., Supervisor, Department of Mechanical Engineering
Institut stipendie (DTU)
01/08/2017 → 31/07/2020
Award relations: Fatigue behaviour of polymer composite materials at the sub-structural and structural scale
Project: PhD
**Strukturel modellering af vindmølleblade med passiv kontrol**
Fedorov, V., PhD Student, Department of Mechanical Engineering
Berggreen, C., Main Supervisor, Department of Mechanical Engineering
Branner, K., Supervisor, Department of Naval Architecture and Offshore Engineering
Krenk, S., Supervisor, Department of Mechanical Engineering
Jensen, J. J., Examiner, Department of Mechanical Engineering
Hayman, B., Examiner, Department of Mechanical Engineering
Thybo Thomsen, O., Examiner
Institut stipendie (DTU) Samf.
01/03/2008 → 23/11/2012
Award relations: Strukturel modellering af vindmølleblade med passiv kontrol
Project: PhD

**Kapacitet og levetid for højtbelastede maritime FRP-sandwich konstruktioner**
Branner, K., PhD Student, Department of Wind Energy
Pedersen, P. T., Main Supervisor, Department of Mechanical Engineering
Jensen, J. J., Supervisor, Department of Mechanical Engineering
Kildegaard, A., Examiner
DTU-stipendium
01/02/1992 → 29/01/1996
Award relations: Kapacitet og levetid for højtbelastede maritime FRP-sandwich konstruktioner
Project: PhD

**Fatigue strength of composite wind turbine blade structures**
Castro Ardila, O. G., PhD Student, Department of Wind Energy
Branner, K., Main Supervisor, Department of Wind Energy
Brøndsted, P., Supervisor, Department of Wind Energy
Mikkelsen, L. P., Examiner, Department of Wind Energy
Burchardt, C., Examiner
Varna, J., Examiner
Burchardt, C., Examiner
Varna, J., Examiner
Forskningsrådsfinansiering
01/01/2015 → 08/06/2018
Award relations: Fatigue strength of composite wind turbine blade structures
Project: PhD

**Offshore Wind Turbine Foundation Design**
Passon, P. A., PhD Student
Branner, K., Main Supervisor, Department of Wind Energy
Larsen, S. E., Supervisor, Department of Wind Energy
Rasmussen, J. H., Supervisor
Bredmose, H., Examiner, Department of Wind Energy
Musculus, M., Examiner
Tarp-Johansen, N. J., Examiner
ErhvervsPhD-ordningen VTU
01/10/2011 → 22/06/2015
Award relations: Offshore Wind Turbine Foundation Design
Project: PhD

**Ultimativ styrke af Vestas' vingeboksdesign**
Jensen, F. M., PhD Student, Department of Civil Engineering
Stang, H., Main Supervisor, Department of Civil Engineering
Branner, K., Supervisor, Department of Wind Energy
Wedel-Heinen, J. J., Supervisor
Berggreen, C., Examiner, Department of Mechanical Engineering
Fuglsang, L., Examiner
Lasæ, J. M., Examiner
Risa (Løn)
01/07/2003 → 22/04/2009
Award relations: Ultimativ styrke af Vestas' vingeboksdesign
Project: PhD
Optimal design of adaptive wind turbine blades
Stäblein, A., PhD Student, Department of Wind Energy
Hansen, M. H., Main Supervisor, Department of Wind Energy
Branner, K., Supervisor, Department of Wind Energy
Kim, T., Supervisor, Department of Wind Energy
Hansen, M. O. L., Examiner, Department of Wind Energy
Nielsen, S. R., Examiner
Riziotis, V. A., Examiner
Marie Curie (EU-stipendium)
15/05/2013 → 16/02/2017
Award relations: Optimal design of adaptive wind turbine blades
Project: PhD

Validated loads prediction models for offshore wind turbines for enhanced component reliability
Koukoura, C., PhD Student, Department of Wind Energy
Natarajan, A., Main Supervisor, Department of Wind Energy
Branner, K., Supervisor, Department of Wind Energy
Hansen, K. S., Examiner, Department of Wind Energy
Bossanyi, E. A., Examiner
Ibsen, L. B., Examiner
Offentlig finansiering
15/09/2011 → 19/12/2014
Award relations: Validated loads prediction models for offshore wind turbines for enhanced component reliability
Project: PhD

Electromechanical Drivetrain Simulation
Gallego Calderon, J. F., PhD Student, Department of Wind Energy
Natarajan, A., Main Supervisor, Department of Wind Energy
Branner, K., Supervisor, Department of Wind Energy
Cutululis, N. A., Supervisor, Department of Wind Energy
Hansen, J. M., Supervisor, Department of Wind Energy
Juul Jensen, D., Examiner, Materials science and characterization
Bottasso, C. L., Examiner
Muljadi, E., Examiner
Bottasso, C. L., Examiner
Bottasso, C. L., Examiner
Forskningsrådsfinansiering
15/03/2012 → 24/08/2015
Award relations: Electromechanical Drivetrain Simulation
Project: PhD

Optimal Design of Composite Structures under Manufacturing Constraints
Marmaras, K., PhD Student, Department of Applied Mathematics and Computer Science
Stolpe, M., Main Supervisor, Department of Applied Mathematics and Computer Science
Lund, E., Supervisor
Mikkelsen, L. P., Supervisor, Department of Solid Mechanics
Branner, K., Examiner, Department of Naval Architecture and Offshore Engineering
Duysinx, P., Examiner, Department of Applied Mathematics and Computer Science
Klarbring, A., Examiner
Klarbring, A., Examiner
Forskningsrådsfinansiering
01/08/2011 → 05/11/2014
Award relations: Optimal Design of Composite Structures under Manufacturing Constraints
Project: PhD

Hybrid Testing of Wind Turbine Blades
Haght, J. H., PhD Student, Department of Mechanical Engineering
Berggreen, C., Main Supervisor, Department of Mechanical Engineering
Branner, K., Supervisor, Department of Wind Energy
Schmidt, J. W., Supervisor, Department of Civil Engineering
Stang, H., Supervisor, Department of Civil Engineering
Høgsberg, J. B., Examiner, Department of Mechanical Engineering
Barton, J., Examiner
Lund, E., Examiner
Barton, J., Examiner
Lund, E., Examiner
1/3 FU, 1/3 inst 1/3 Andet
01/12/2011 → 04/07/2016
Award relations: Hybrid Testing of Wind Turbine Blades
Project: PhD

Optimal Design of Smart Composite Structures
Blasques, J. P. A. A., PhD Student, Department of Mechanical Engineering
Stolpe, M., Main Supervisor, Department of Applied Mathematics and Computer Science
Berggreen, C., Supervisor, Department of Mechanical Engineering
Branner, K., Supervisor, Department of Naval Architecture and Offshore Engineering
Buhl, T., Examiner, Department of Solid Mechanics
Duysinx, P., Examiner, Department of Applied Mathematics and Computer Science
Lund, E., Examiner
DTU-lønnet stipendie
01/10/2007 → 30/11/2011
Award relations: Optimal Design of Smart Composite Structures
Project: PhD

Ultimate strength of wind turbine blade structures under multi axial loading
Haselbach, P. U., PhD Student, Department of Wind Energy
Branner, K., Main Supervisor, Department of Wind Energy
Berggreen, C., Supervisor, Department of Mechanical Engineering
Bitsche, R., Supervisor, Department of Wind Energy
Mikkelsen, L. P., Examiner, Department of Wind Energy
Lindgaard, E., Examiner
Nijsen, R., Examiner
1/3 FU, 1/3 inst 1/3 Andet
01/05/2012 → 25/02/2016
Award relations: Ultimate strength of wind turbine blade structures under multi axial loading
Project: PhD

Modeling the manufacturing process of wind turbine blades
Nielsen, M. W., PhD Student, Department of Mechanical Engineering
Hattel, J. H., Main Supervisor, Department of Mechanical Engineering
Legstrup Andersen, T., Supervisor
Branner, K., Supervisor
Nielsen, P. H., Supervisor
Thybo Thomsen, O., Examiner
Svanberg, M., Examiner
Talreja, R., Examiner
Institut stipendie (DTU) Samf.
01/01/2010 → 25/06/2013
Award relations: Modeling the manufacturing process of wind turbine blades
Project: PhD

Damage Tolerance of Curved Sandwich Structures in Wind Turbine Blades
Moslemian, R., PhD Student, Department of Mechanical Engineering
Berggreen, C., Main Supervisor, Department of Mechanical Engineering
Branner, K., Supervisor, Risø National Laboratory for Sustainable Energy
Carlsson, L. A., Supervisor, Department of Mechanical Engineering
Serensen, B. F., Supervisor, Department of Electrical Engineering
Legarth, B. N., Examiner, Department of Mechanical Engineering
Dear, J. P., Examiner
Zenkert, D., Examiner
Institut stipendie (DTU) Samf.
15/01/2008 → 30/11/2011
Award relations: Damage Tolerance of Curved Sandwich Structures in Wind Turbine Blades
Project: PhD
**DCCSM: Danish Centre for Composites Structures and Materials for Wind Turbines**

Some of the most critical components of a wind turbine are the rotor blades, which are usually made of polymer matrix composites and are the largest rotating components of a wind turbine. Different types of damage can develop at different length scales in wind turbine rotor blades. Therefore, the Danish Centre for Composite Structures and Materials for Wind Turbines (DCCSM) aims to develop a coherent, multiscale-based understanding of the mechanical behaviour of composite materials and structures for wind turbine blades. The length scale goes from nano- and microscale (materials) to product scale (the whole blade, which currently can be more than 60 meters in length), and covers manufacturing, materials design, damage detection, modelling and prediction of damage evolution in wind turbine blades. A coherent multiscale understanding of composite materials and structures will enable full optimisation, viz., optimisation at all length scales. The Centre aims for the creation of new knowledge (e.g. material models), new experimental methods and new modeling methods. The Centre spans wide thematically and disciplinarily. The specific PhD, Post Doc and research projects funded by DCCSM (Core and Shell activities) are focused at smaller, well-defined topics. Therefore, the Centre will coordinate the research activities in Denmark in the area of composite structures and materials for wind turbines. That includes the Core and Shell activities of DCCSM and research projects that are not funded by the DSF funds but are thematically covered by the Centre. Such projects are called "Crust" projects. DSF Strategic Research Centre (sags. nr. 09-067212).

**Sørensen, B. F., Approving Authority, Department of Wind Energy, Composites Mechanics and Materials Mechanics**

**Almdal, K., Project Participant, Department of Micro- and Nanotechnology, Amphiphilic Polymers in Biological Sensing**

**Mikkelsen, L. P., Project Participant, Department of Wind Energy, Composites Mechanics and Materials Mechanics**

**Branner, K., Project Participant, Department of Wind Energy, Wind Turbines**

**Mishnaevsky, L., Project Participant, Department of Wind Energy, Composites Mechanics and Materials Mechanics**

**Zike, S., PhD Student, Department of Wind Energy, Composites Mechanics and Materials Mechanics**

**Hansen, J. Z., PhD Student**

**Ashouri Vajari, D., PhD Student, Solid Mechanics, Department of Wind Energy**

**Legarth, B. N., Project Participant, Department of Mechanical Engineering, Solid Mechanics**

**Berggreen, C., Project Participant, Department of Mechanical Engineering, Solid Mechanics**

**Storgaard, H., Project Participant, Department of Civil Engineering, Section for Structural Engineering**

**External Project ID: 09-067212**

01/04/2010 → 31/03/2017

Project: Research

**Marine Structures**

STVF funded Frame Programme. The purpose of the programme is to carry out technical and scientific research of fundamental importance for the analysis of ships and offshore structures.

**Pedersen, P. T., Project Manager, Department of Naval Architecture and Offshore Engineering**

**Andersen, M. R., Project Participant, Department of Naval Architecture and Offshore Engineering**

**Andersen, P., Project Participant, Department of Naval Architecture and Offshore Engineering**

**Baattrup, J., Project Participant, Department of Naval Architecture and Offshore Engineering**

**Friis-Hansen, P., Project Participant, Department of Naval Architecture and Offshore Engineering**

**Jensen, J. J., Project Participant, Department of Naval Architecture and Offshore Engineering**

**Nielsen, L. P., Project Participant, Department of Naval Architecture and Offshore Engineering**

**Pedersen, T., Project Participant, Department of Naval Architecture and Offshore Engineering**

**Cerup-Simonsen, B., Project Participant, Department of Naval Architecture and Offshore Engineering**

**Wang, Z., Project Participant, Department of Naval Architecture and Offshore Engineering**

**Zhang, S., Project Participant, Department of Naval Architecture and Offshore Engineering**

**Branner, K., Project Participant, Department of Naval Architecture and Offshore Engineering**

**Riber, H. J., Project Participant, Department of Naval Architecture and Offshore Engineering**

**Pawlowski, M., Project Participant, Department of Naval Architecture and Offshore Engineering**

**Verdier, G. H. C., Project Participant, Department of Naval Architecture and Offshore Engineering**

**Xia, J., Project Participant, Department of Naval Architecture and Offshore Engineering**

Ukendt: DKK14,000,000.00

01/01/1993 → 31/12/1997

Collaborators: Danish Maritime Institute, Aalborg University

Award relations: Marine Structures

Project: Research

**Dynamically Loaded Sandwich Structures**

Nordic Research project (NoKoS) on composite sandwich structures for marine use.

**Pedersen, P. T., Project Manager, Department of Naval Architecture and Offshore Engineering**

**Riber, H. J., Project Participant, Department of Naval Architecture and Offshore Engineering**

**Branner, K., Project Participant, Department of Naval Architecture and Offshore Engineering**

Ukendt: DKK625,000.00

01/01/1993 → 31/12/1997
Activities:

An Advanced Blade Modelling Approach
Period: 26 Jun 2017 → 29 Jun 2017
Philipp Ulrich Haselbach (Other)
Kim Branner (Other)
Department of Wind Energy
Wind Turbine Structures and Component Design
Degree of recognition: International

Related event
Wind Energy Science Conference 2017
26/06/2017 → 29/06/2017
Lyngby, Denmark
Activity: Talks and presentations › Conference presentations