Template for Industrial PhD project description

Basic information

Project title	Advanced Accurate and Computationally Efficient Numerical Methods for Wind Turbine Rotor Blade Design
Industrial PhD candidate	Paola Bertolini
Company	LM Wind Power A/S
University, centre/institute	DTU Wind Energy/ Wind Turbine Structures and Component Design (SAC)
Any first third party	none
Any second third party	none

A. Objectives and success criteria (max. ½ page)

The project's objectives | The aim of this project is to develop, implement and validate advanced computational models and methods suitable for structural optimization based large utility wind turbine rotor blade analysis. The models and methods are implemented into LM Wind Power's in-house developed cross sectional analysis tool LMBlades, and hence become an integrated part of the blade design workflow at LM Wind Power. The intended outcome of this project is to demonstrate that the gain in accuracy and computational efficiency to predict complex blade design features leads to increased reliability, lower manufacturing costs and eventually lower costs of energy when compared to classic state-of-the-art design approaches. This will be demonstrated by application of the advanced numerical capabilities on redesign of an existing LM wind turbine blade. The added value of the advanced numerical capabilities will be measured in terms of optimization based reduction of material usage through enhanced accuracy and in terms of design time savings enabled by computational efficiency.

The project's success criteria |

1. Successfully implemented the advanced numerical capabilities into LMBlades, fully validated and delivered on time.
2. Qualitative demonstration of improved accuracy and computational efficiency of numerical prediction capabilities of LMBlades according to LM's performance requirements.
3. New blade design and improved manufacturing process/technology for large utility wind turbine blades in small series, with a 20% decrease in total blade cost while upholding high performance.

B. Commercial potential (max. 1 page)

The wind energy business faces fierce competition owing to the appearance of numerous Chinese blade manufacturers on the market. According to the annual 2014 Global Wind Energy Council (GWEC) report more than 51GW of new wind power capacity was installed with 23GW in China alone which represents 45% of the market. Forecasts for 2019 by GWEC predict an annual new installation of 66.5GW in order to cover global demands. LM Wind Power aims at reaching a targeted increase of approx. 4% of the Chinese/Pacific market share which inevitably requires a significant reduction of blade costs.

LM Wind Power is the world's largest supplier of wind turbine rotor blades and in the squad of the world elite amongst a handful of European competitors. The competitive advantage for the world elite is their pole position at the forefront of development and quality assurance where today's major challenge is reduction of Cost of Energy (CoE). LM Wind Power strives for a reduction of warranty provisions and blade wrecks which ultimately increases the annual energy production and decreases service expenditure. This project contributes to the strategic goals of LM Wind Power to outperform its competitors and to prevail as the world elite of blade manufacturers whilst continuously facing demands for length upscaling and the production of even lighter blades with increased reliability.

The advanced computational capabilities developed in this project benefit the wind energy sector by lowering CoE in general and in particular are helping LM Wind Power to decisively maintain its leading position at the forefront of research and development. The key competitive advantages LM Wind Power provides for today's wind turbine blade market are reliability and up-scalability where this project contributes to both. In order to remain competitive against Vestas, Siemens and SSP, weight savings are of crucial importance which requires advanced computational capabilities which are capable of incorporating high-tech carbon fibre reinforced blade designs. The novel computational analysis capabilities developed in this project allow LM Wind Power to efficiently predict the fatigue life and therefore the reliability of their blades with unprecedented accuracy by considering important effects which are usually neglected. As a consequence safety factors can be made less conservative adding value through direct cost savings by significantly reducing material usage which clearly poses a competitive advantage. This not only leads to more cost efficient blades but also paves the way for lighter blade designs which represent an immediate tactical advantage in the upscaling battle pushing towards the 100-meter length mark.

C. State-of-the-art and theoretical background (max. 1 page excl. references)

In order to meet the vigorous demands of blade designs on reliability and optimal material usage requires numerical analysis and design models and methods which provide a high level of accuracy along with computational efficiency suitable for structural design optimization procedures. Modern large utility wind turbine rotor blades exhibit complex geometries dictated by the lift generating surfaces. Therefore, wind turbine rotor blades feature lengthwise geometrical variations (LGVs) such as taper i.e. change of cross-section height, twist i.e. cross-section rotation and pre-curvature (pre bending). Rapid local LGVs can typically be found in the root-to-airfoil transition (see Figure1).

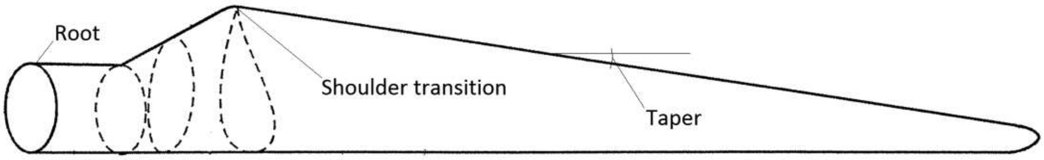


Figure 1 Typical LGVs in turbine blades such as taper (smooth) and the 'shoulder transition' (non-smooth).

For reasons of shape manufacturability and because of their desirable high strength-to-low-mass ratios usually adhesively connected fibre reinforced polymers are employed. The high stiffness-to-low-mass utilisation results in thin-walled multi cellular (see Figure2) beam type structures which can undergo large deformations with tip deflections up to 20% of the span. This causes severe distortion of the cross-section leading to deformations which progressively increase with load in a non-linear manner [1, 2]. An accurate numerical prediction of these geometrically non-linear deformations as depicted in Figure2 is therefore highly important.

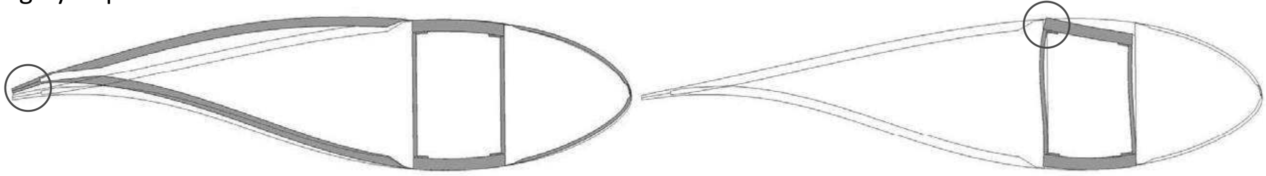


Figure 2 Geometrically non-linear cross-section deformations (solid grey) severely affects the trailing edge joint (left) and web-to-cap joint (right) by inducing prying-forces into blade components having the tendency to rip bond lines apart.

To date the most accurate computational methods are 3D finite element models. However, blades are subject to highly dynamic operational conditions leading to extensive multiaxial load time histories. The major drawback of full 3D finite element models is their high computational demand. It renders them highly impractical when used for structural optimisation based on time history analysis in which the model is subsequently analysed for several hundred thousand time steps. Literature provides different computationally efficient approaches: Sub-modelling techniques foresee the partition of the entire model into smaller sub-models which are separately analysed. The method follows 3D modelling approaches and is therefore capable of considering aforementioned effects whilst preserving computational efficiency through reduction of model size. Sub-modelling can also be used for static condensation techniques [3] where the problem size of the full model is reduced by condensation techniques. Nevertheless, the biggest drawback of sub-modelling and condensation approaches is dissenting boundary conditions which can induce significant deviations from the real blade. Cross section analysis techniques based on analysis of blade slices are considered the most promising way forward. The state-of-the-art DTU Wind Energy owned finite element based cross section analysis tool BECAS [4] produces high fidelity results in terms of complete sets of 3D stress and strain components for slender, predominantly prismatic beams considering all six cross section forces and moments. The cross section analysis formulation of BECAS allows ultra-high mesh discretization levels proven suitable for detailed multi axial stress based [5] and fracture based [6] high cycle fatigue analysis without compromising computational efficiency. The current formulation of BECAS assumes a sequential distribution of infinitesimally small prismatic cross sections along the beam axis disregarding LGV effects. On the other hand, analytical solutions of linearly tapered beams [7, 8, 9, 10] indicate shear stresses being significantly at variance with classic shear stress distributions which neglect taper effects as illustrated in Figure3.

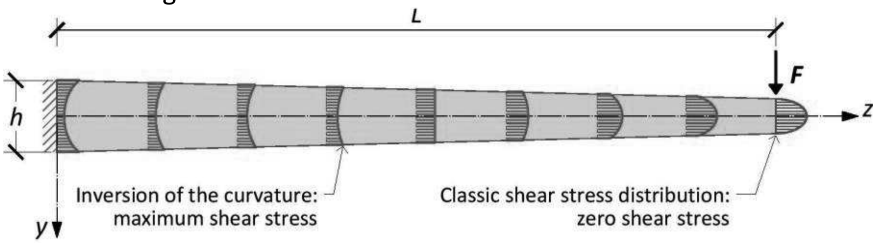


Figure 3 Shear stress distributions (red hatch) in a tapered beam differ in different cross-sections and can be significantly at variance with prismatic cases depending on the taper angle and the loading conditions.

A recent investigation of taper effects in thin walled box beams [11] showed that taper affects all stress components which are otherwise not present under prismatic conditions. Literature provides several numerical approaches for approximate solutions of piecewise linearly tapered Timoshenko type beams [12, 13] and more recently for continuously non-linearly tapered beams [14] with the ability to provide stress and strain solutions with various degrees of accuracy. An energy-based variational asymptotic method capable of considering piecewise linear taper was instigated by [15] for the commercially available cross sectional analysis tool VABS [16] but has not reached application maturity. It is deemed that the implementation of LGV correction approaches in conjunction with geometric nonlinearity solution strategies leads to a computational blade analysis method with unprecedented accuracy.

[1] M. Eder, R. Bitsche and F. Belloni, "Effects of geometric non-linearity on energy release rates in a realistic wind turbine blade cross section," Composite Structures, vol. 132, pp. 1075-1084, 2015.

[2] P. Haselbach, M. Eder and F. Belloni, "A comprehensive investigation of trailing edge damage in a wind turbine rotor blade," Wind Energy, p. 18, 2016.

[3] M. Paz and W. Leigh, "Static Condensation and Substructuring," in *Integrated Matrix Analysis of Structures*, Springer US, 2001, pp. 239-260.

[4] J. Blasques, "BECAS," DTU Wind Energy, [Online]. Available: http://www.becas.dtu.dk.

[5] H. Pörtner, "Multi-axial Fatigue Models for Composite Lightweight Structures," MSc Thesis, Chalmers University of Technology, Göteborg, Sweden, 2013.

[6] J. Blasques and R. Bitsche, "An efficient and accurate method for computation of energy release rates in beam structures with longitudinal cracks," *Engineering Fracture Mechanics,* vol. 133, pp. 56-69, 2015.

[7] F. Bleich, "Stahlhochbauten," Berlin, Germany, Springer, 1932.

[8] A. Paglietti and G. Carta, "Remarks on the current theory of shear strength of variable depth beams," *Open Civil Engineering Journal,* vol. 3, pp. 28-33, 2009.

[9] N. Trahair and P. Ansourian, "In-plane behaviour of web-tapered beams," *Eng. Struct,* vol. 108, pp. 47-52, 2016.

[10] S. Bennati, P. Bertolini, L. Taglialegne and P. Valvo, "On shear stresses in tapered beams," in *GIMC-GMA 2016 - 21st Italian Conference on Computational Mechanics and 8th Meeting of the AIMETA Materials Group*, Lucca, Italy, 2016.

[11] P. Bertolini, "Structural analysis of wind turbine blades: A study of the effects of tapering on shear stresses," MSc Thesis, University of Pisa, Pisa, Italy, 2015.

[12] D. Hodges, J. Ho and W. Yu, "The effect of taper on section constants for in-plane deformation of an isotropic strip," *J. Mech. Mater. Struct.,* vol. 3, pp. 425-440, 2008.

[13] D. Hodges, A. Rajagopal, J. Ho and W. Yu, "Stress and strain recovery for the in plane deformation of an isotropic tapered strip-beam," *J. Mech. Mater. Struct,* vol. 5, pp. 963-975, 2010.

[14] G. Balduzzi, M. Aminbaghai, E. Sacco, J. Füssl, J. Eberhardsteiner and F. Auriccio, "Non-prismatic beams: A simple and effective Timoshenko-like model," *Int J Solids Struct.,* vol. 90, pp. 236-250, 2016.

[15] A. Rajagopal, "Advancements in rotor blade cross sectional analysis using the variational-asymptotic method," PhD Thesis, Georgia Institute of Technology, 2014.

[16] "VABS," Analy Swift, [Online]. Available: http://analyswift.com/.

D. Project description (max. 4 pages excl. references)

This project develops numerical models and methods capable of accurately and computationally efficiently predicting the reliability of large utility wind turbine rotor blades. These improved models and methods are integrated in LM Wind Power's blade design process and enable a more accurate prediction of deformations, cross sectional stresses and strains. The enhanced predictive capabilities ultimately lead to a more accurate prediction of the fatigue life of blade components as well as the adhesive bondlines. The novelty in this project is the development of numerically robust and reliable structural analysis models and methods which accurately consider the effects of LGV and geometrical non-linearity. During the development of these novel models and methods strong emphasis will simultaneously be put on computational efficiency in order to make them suitable for time history analysis and structural optimization – both of which requires a fast repeatedly computation which must outperform conventional full 3D finite element models. The intended outcome of this project is to provide novel computationally aided rotor blade design capabilities which enable LM Wind Power to produce larger blades without compromising reliability or to reduce weight and cost of blades of existing sizes.

The following activities (described as Work Packages (WPs)) are planned to obtain these goals:

WP1: Review of state-of-the-art.
WP2: Analytical LGV models.
WP3: Implementation of LGV correction.
WP4: Implementation of geometrical non-linearity.
WP5: Application of numerical methods.
WP6: PhD thesis.

Hypothesis | Improved analysis capabilities lead to better design processes. This holds especially true for design processes which are supported by numerical structural optimization. By improving the analysis models and methods, safety factors can be reduced resulting in (i) lower weight and increased strength through better material utilisation (ii) lower manufacturing costs due to material savings (iii) lower maintenance and operation and provision costs due to increased blade reliability (iv) reduced levelized cost of electricity (LCOE).

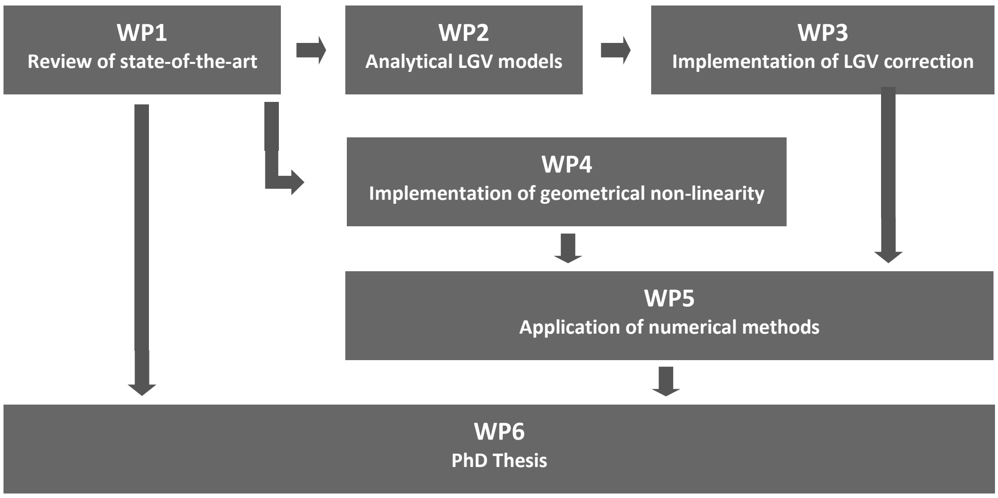
Research Questions

- How to implement LGV into cross-sectional analysis approaches?
- How to implement geometrically nonlinear procedures into cross sectional analysis approaches?
- How to improve computational efficiency of these approaches?
- How does taper affect the stress distribution in blades and how are stresses redistributed within blade different blade components?
- How does taper and geometric nonlinearity affect cross-section deformation and the integrity of bond lines?

Industrial questions

- How much can the weight of the blade be decreased when these advanced analysis techniques are used in the design process?
- How much can the manufacturing costs be decreased when these advanced analysis techniques are used in the design process?

The methods applied in the project comprise application of continuum mechanics and elasticity theory, non-linear finite element method, development and implementation of numerical structural analysis methods, blade design through optimization techniques and assessment of wind turbine blades through structural analysis.
DTU Wind Energy contributes with knowledge on models and methods for blade design, structural analysis and structural and multidisciplinary optimization. LM Wind Power contributes with knowledge on blade design, production technologies and material properties.
The PhD project is divided into six Work Packages (WPs). These WPs are interlinked as illustrated below:



__**WP1 Review of the state-of-the-art.**__

Objectives The objectives of this WP are to broaden the current knowledge pool on the main areas of the project and provide this as input to the other WPs.

Work Conduct a detailed literature review of cross-sectional analysis methods (T1.1) as well as sub-modelling and static condensation techniques (T1.2). Examine computationally efficient iterative solvers e.g. Newton-Raphson, modified Newton-Raphson, Arc Length Method, etc. suitable for geometric non-linear time history analysis in the framework of cross-section analysis (T1.3).

Results An extensive review report with a collection of relevant literature of these fields including a thorough discussion and assessment of the most suitable method for this project.

Deliverable

D1 @ month 3: A review of state-of-the-art containing a detailed discussion of pros and cons of all the available methods.

Milestone

M1 @ month 3: Technical report completed.

WP2 Analytical LGV models.

Objectives The objective of this WP is to derive analytical (closed form) solutions for structural analysis of simplified load carrying box girders of wind turbine blades. The aim is to use these solutions in order to gain deep insights into the theory of LGV which ultimately serves as an essential basis for **WP4**.

Work Use linear elasticity theory to derive complete continuum mechanics based analytical solutions in terms of stresses, strains and displacements for tapered thin-walled non-symmetric multi-cellular cantilever beams. Obtain Cauchy stresses by solving the relevant partial differential equilibrium equations for specific wind turbine blade relevant boundary conditions. Derive displacement fields by integration of first order strain equations using constitutive equations and compatibility conditions (T2.1). Validate analytical solutions against 3D finite element models (T2.2). Investigate the role of different model parameters on transverse shear distortion and prying forces (T2.3).

Results The WP provides a collection of relevant parameters influencing transverse shear distortion and the resulting prying forces and prying moments acting on cross section members such as shear webs and caps. Quantifiable sensitivities of cross sectional stresses and deformations as a function of cross section forces. Availability of fully established continuum mechanics framework for tapered beams.

Deliverable

D2 @ month 10: A collection of numerically validated analytical solutions including fundamental sensitivity studies of relevant parameters (Report). Poster presented at the DCAMM internal symposium.

Milestone

M2 @ month 10: Journal paper submitted to Thin-Walled Structures.

WP3 Implementation of LGV correction.

Objectives Generalisation of the underlying theory of the existing stress analysis tool LMBlades in order to accurately consider the effects of LGV. Implementation of the new method into LMBlades and subsequent validation of the numerical results against previously developed analytical solutions obtained in **WP2**.

Work Exploit the knowledge obtained in **WP1** and **WP2** and modify the existing stepwise prismatic theory in such a way that LGV effects can be accurately predicted. This will be done by making the cross section geometry coordinates a function of the lengthwise beam coordinate (T4.1). Develop the theory along the lines of efficient finite element based solution strategies by formulating the problem along the lines of fast numerical algorithms. Implement the theory into LMBlades (T4.2) and validate the results against both analytical solutions (**WP2**) and 3D finite element models for different multiaxial loading conditions (T4.3).

Results Complete mathematical formulations of the modified theory. Computationally efficient numerical high fidelity tool ready to use for optimisation based blade design procedures in conjunction with time history analysis.

Deliverable

D3 @ month 14: Journal paper Computational Mechanics comprising of a mathematical description of the extended theory, its assumptions and application to a selection of special benchmark cases. Posters presented at TORQUE internal conference and at NSCM seminar.

Milestone

M3 @ month 14: Development, implementation and validation of LGV correction into LMBlades (Software code ready for use and documentation report completed).

WP4 Implementation of geometrical non-linearity.

Objectives Extend the current first order small deformation based cross section analysis theory to iterative Green-Lagrange based large deformation analysis and implement it into LMBlades.

Work Implement iterative and fast converging numerical procedures for geometric nonlinear formulations identified in **WP1** into the industrial cross section analysis tool LMBlades by extending the first order strain based formulation to second order Green-Lagrange formulation (T3.1). Maximize computational efficiency and numerical robustness towards use for time history analysis for the adopted iterative solution strategy (T3.2). Validate numerical results against classic readily available analytical solutions for non-linear cross-section deformations from the literature e.g. circular tube under pure bending and against more complex non-linear full 3D finite element models. Benchmark computation times against other efficient structural analysis software such as Abaqus (T3.3).

Results Computationally efficient numerical algorithm ready to use for blade analysis in combination with developments of **WP4**

Deliverable

D4 @ month 24: Journal paper Computational Mechanics and oral presentation at the ICCM conference.

Milestone

M4 @ month 24: Reached the level of advanced numerical analysis techniques. (Software code ready for use and documentation report completed).

WP5 Application of numerical methods.

Objectives Application of the new numerical analysis capabilities to an LM wind turbine rotor blade. Show quantitatively that improved accuracy in combination with structural optimization results in a reduction of material usage and an increase in blade reliability.

Work Apply the new methods developed and implemented in **WP4** to LM blade designs and benchmark against 3D finite element blade models and experimental measurement data provided by LM Wind Power (T5.1). Conduct comprehensive parametric studies of prying forces and moments in the bond lines of adhesive joints and stresses and strains in laminates by changing design parameters identified in **WP2**. Study both linear and non-linear transverse shear distortion in conjunction with torsion and shear loading and qualitatively compare with analytical solutions developed in **WP2** (T5.2). Use parametric studies to investigate the effect of LGV on loads acting on blade components and consequently on the fatigue life of adhesive bond lines. Use parametric studies to investigate the effect of LGV on the (shear) stress distribution in the load carrying girder. Develop simplified design models used to estimate LGV effects on prying forces (T5.3).

Results Implementation of improved cross section analysis tool into the LM design work flow. Catalogue of 'design curves' for different key design parameters e.g. prying forces and moments or shear correction factors for different blades, based cross-section types (e.g. flat-back) on extensive numerical parametric studies. A compendium of simplified design approaches for LGV effects.

Deliverable

D5 @ month 30: A detailed technical report completed. Journal paper Wind Energy. Oral Presentation at the EWEA conference.

Milestone

M5 @ month 30: Software capable of supporting an industrial blade design process.

WP6 PhD thesis.

(Objectives, work, results) The candidate dedicates this WP to the writing up and finalization of the PhD thesis.
M6 @ month 36: Thesis complete and handed in.

E. Publication plan (max. ½ page)

Proposed title and date of publication	**Proposals for one or more acknowledged research journals as desired place of publication**
Analytical elasticity theory based solutions for thin walled tapered hollow sections. *To be submitted in February 2018*	Thin-Walled Structures http://www.journals.elsevier.com/thin-walled-structures Impact Factor: 2.063
A novel approach for considering lengthwise geometrical variation effects in cross-section analysis methods. *To be submitted in September 2018*	Computational Mechanics http://link.springer.com/journal/466 Impact Factor: 2.639
A computationally efficient solver for geometric non-linear problems in cross-section analysis methods. *To be submitted in February 2019*	Computational Mechanics http://link.springer.com/journal/466 Impact Factor: 2.639
Efficient and more reliable blade designs enabled by advanced cross-section analysis procedures. *To be submitted in September 2019*	Wind Energy http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1099-1824 Impact Factor: 2.891

F. Courses, conferences and stays abroad (max. ½ page)

PhD courses | The PhD students attends the following MSc and PhD courses as part of the requirements for the PhD degree:

- 46910 Advanced Finite Element Simulations Using Abaqus (PhD, 5 ECTS)
- 12925 Principle of programming and implementation (PhD, 5 ECTS)
- 46411 Design of large composite structures (MSc, 5 ECTS)
- 46415 Structural analysis and design optimization of wind turbine blades (MSc, 5 ECTS)
- Analysis and Gradient Based Optimization of Laminated Composite Structures (PhD, 5 ECTS, Aalborg University)

The missing 5 ECTS will be decided on a later date. The objective is to attend an international PhD course.

Conferences | The PhD student attends some of the following scientific conferences/workshops:

- The Danish Center for Mathematics and Mechanics (DCAMM) Internal Symposium in 2017 (poster presentation) and 2019 (oral presentation)
- The International Conference on Composite Materials ICCM (oral presentation)
- Science of Making Torque from Wind (TORQUE) (poster presentation)
- The European Wind Energy Association EWEA Annual Event (oral presentation)
- Nordic Seminar on Computational Mechanics NSCM (poster presentation)

Stays abroad | Several possible destinations for the research stays abroad are envisaged. Shorter (a few weeks) or longer stays (months) are intended. The list of relevant research groups for an external stay are led by the following professors:

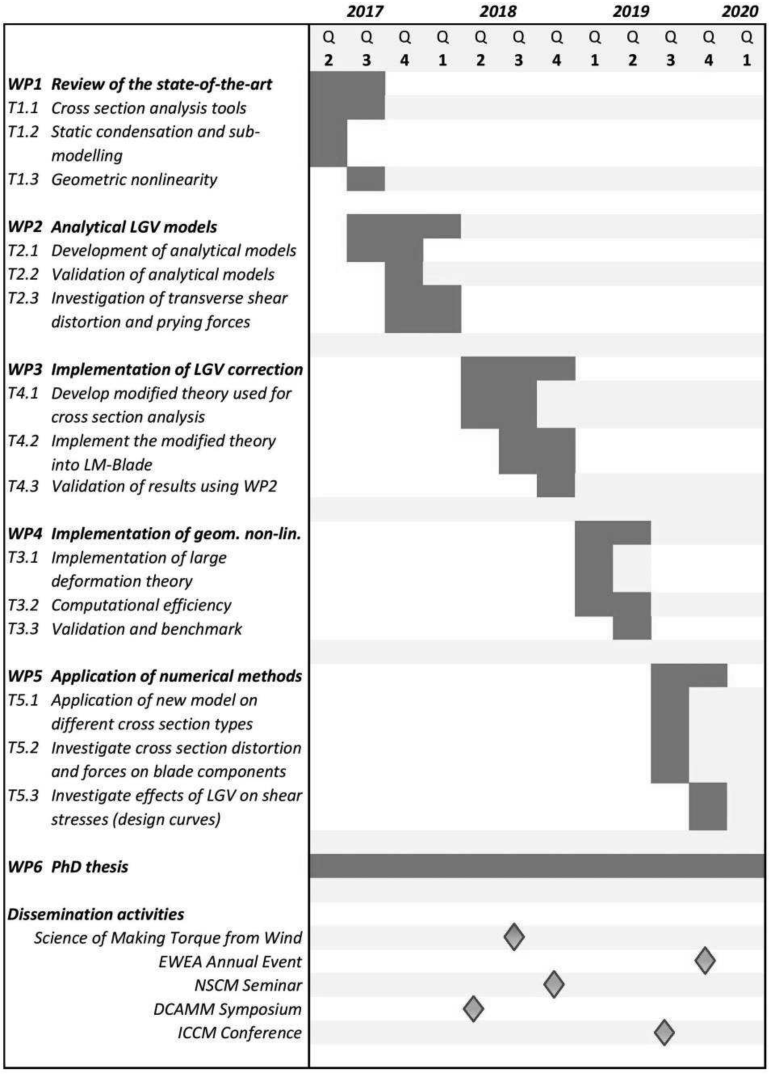
Professor Dewey H. Hodges, *The Daniel Guggenheim School of Aerospace Engineering*, Georgia Institute of Technology, Georgia, USA. Professor Hodges is a wold leading expert in aeroelasticity, classic and multibody dynamics, structural mechanics. Professor Hodges is one of the founders of the cross section analysis software VABS which is the main commercial competitor to BECAS and similar software.

Professor Wenbin Yu, *School of Aeronautics and Astronautics, Purdue University*, Indiana, USA. Professor Yu is a wold leading expert in multiscale modelling, structural mechanics, micromechanics, computational mechanics, multiphysics modelling and advanced materials/structures.

G. Dissemination plan (max. ½ page)

- Four articles submitted to international scientific journals during the PhD program (estimated time: 400 hours). The targeted journals are listed under Section E and include the leading journals in wind Energy and computational mechanics.
- Presentations at four national/international scientific/industrial conferences (estimated time: 240 hours). This includes submission of abstract and poster/oral presentation at the conference. The conferences are listed above under Section F.
- Presentations at DTU Wind Energy section meetings once per year (estimated time: 60 hours).
- Presentations at LM Wind Power once per year (estimated time: 60 hours).
- Total estimated time for dissemination is thus 760 hours.

H. Structure and time schedule (max. 1 page)



Milestones and success criteria:

M	Mo.	Definition	Success criterion
M1	3	Technical report completed	Delivered report is high quality and meets or exceeds the intended scientific value.
M2	10	Journal paper submitted to Thin-Walled Structures	Paper accepted with high citation number.
M3	14	Development, implementation and validation of LGV correction into LMBlades (Software code ready for use and documentation report completed).	Software part fully functional and validated within time-frame and budget meeting or exceeding LM Wind Power's expectations.
M4	24	Reached the level of advanced numerical	Software part fully functional and

		analysis techniques. (Software code ready for use and documentation report completed).	validated within time-frame and budget meeting or exceeding LM Wind Power's expectations.
M5	30	Software capable of supporting an industrial blade design process.	Software recognized as strategic asset by LM Wind Power throughout all management levels.
M6	36	Thesis complete and handed in.	Thesis internationally recognized as important scientific contribution in both academia and industry.

I. Time allocation

Allocation of the Industrial PhD candidate's time	in months	in % of project time
In Danish division of host company	12	33.3 %
In non-Danish divisions of host company	0	0.0 %
At other companies or organisations	0	0.0 %
At the host university	18	50 %
At other universities and research institutions	6	16.7 %

J. Company (max. 2 pages)

- **The company and its activities |**

LM Wind Power (formerly **LM Glasfiber**) is the world's largest independent supplier of rotor blades to the wind industry. The company is headquartered in Kolding, Denmark and has a global business office in Amsterdam, the Netherlands. The principal shareholders of LM Wind Power are the partnerships by Doughty Hanson & Co. Ltd.

LM Wind Power has produced more than 185,000 blades since 1978, corresponding to approximately 77 GW installed wind power capacity which each year effectively saves approximately 147 million tons of CO_2. This corresponds to the annual CO_2 emissions from electricity used in 20 million (US) homes. LM Wind Power has built production facilities in the major wind energy markets – 14 locations in 8 countries (Denmark, Spain, USA, Canada, India, China, Poland, and Brazil). In addition to this, the company has a global network of R&D centers in Denmark, the Netherlands and India.

LM Wind Power was founded in 1940 as **Lunderskov Møbelfabrik** (**Lunderskov furniture factory**) in the small town Lunderskov, Denmark. In 1952 LM investigated the possibilities of commercial exploitation of glass fiber technology, which was the reason to change the company name to LM Glasfiber and abandon the manufacturing of wooden furniture. It wasn't until 1978 that LM started making wind turbine blades. In 2010, the company name was changed from LM Glasfiber to LM Wind Power, to better reflect the industry in which it operates. Since the establishment of LM Wind Power in 1940 as Lunderskov Møbelfabrik in Lunderskov, Denmark the company has expanded to locations worldwide, while remaining headquartered in Denmark. LM Wind Power established its first factory in the Americas region in Grand Forks, North Dakota in 1998. This investment was followed by two other factories in Gaspé, Quebec, Canada in 2006 and Little Rock, Arkansas in 2008. Built in 2002, LM Wind Power's factory in Goleniów, Poland was the company's largest factory at that time. In the same year, the company also expanded its operations in China and increased its production capacity in Denmark. The 2007 opening of LM Wind Power's Dobespet factory marked the company's second blade manufacturing facility in India and 11th worldwide at the time. Earlier that year, the company also opened new factories in Spain and China. In October 2012, LM Wind Power confirmed its plans to construct its first blade manufacturing facility in Brazil, in conjunction with the company's joint venture partner Eólice. The factory was built in the port of Suape, to serve major wind farms in the North East of Brazil and beyond. In September 2015 LM Wind Power announced the signing of an agreement with its joint venture partner to purchase the remaining interest in LM Wind Power do Brazil

S.A. In April 2016 LM Wind Power announced the inauguration of its second Indian plant, located in Vadodara, Gujarat. Customers, business partners and local dignitaries joined in on the event which is a strong signal of the company's growth in the important Indian market as well as a celebration of a highly efficient ramp up to production. The plant, which was announced in November 2015, began producing wind turbine blades a full month ahead of schedule.

In June 2016, LM Wind Power announced the Launch of the world's largest wind turbine blade, the LM 88.4 P (see Figure1) the blade demonstrates new material technologies positioning the company well for the future of very large blades. LM Wind Power has produced more than 185,000 blades corresponding to a capacity of approximately 77 GW. LM Wind Power blades are currently mounted on more than one in three wind turbines worldwide. LM Wind Power is accredited to test wind turbine rotor blades by DANAK, the "Danish Accreditation and Metrology Fund". LM Wind Power conducts research in its own R&D department and is involved in several research projects together with DTU Wind Energy.

Figure 1 Since the establishment of LM Wind Power in 1940 as Lunderskov Møbelfabrik in Lunderskov, Denmark the company has expanded to locations worldwide, while remaining headquartered in Denmark.

- **The candidate's placement in the company |**

The candidate will be embedded in the *Stress Engineering group* in the department *Produce Design & Engineering*, and will be placed in the LM office located in Kolding. The group comprises a total of 26 employees in Denmark, Netherlands and India where hereof 9 employees are placed in Kolding (Denmark). This group performs the structural design of all new blades of LM Wind Power. The key competences of this group are general stress engineering, finite element analysis, fracture mechanics and C++ programming.

K. University (max. 1 page)

DTU Wind Energy | On 1 January 2012, the Technical University of Denmark (DTU) brought together all groups with activities within wind energy into the new department, DTU Wind Energy. It has more than 230 employees, including 150 academic staff members and approximately 40 PhD students. Research is conducted within the three main programs: Offshore Wind Energy, Wind Turbine Technology, and Siting and Integration. DTU Wind Energy is today one of the largest and most prominent research institutions within wind energy.

The collaborative research environment at DTU Wind Energy ensures that PhD student has access to expertise within many relevant fields such as wind turbine design and analysis, composite structure and material testing, models of future wind turbines, etc. DTU Wind Energy develops relevant analysis software such as the time-domain simulation tool HAWC2 which is used to simulate wind loads. For the project the software BECAS is of special importance. BECAS, the BEam Cross section Analysis Software, is used to create highly accurate beam models of wind turbine blades to be used in aeroelastic simulations. BECAS determines cross section stiffness properties using a finite element based approach. BECAS handles arbitrary cross section geometries, any number of arbitrarily oriented anisotropic materials, and correctly accounts for all geometrical and material induced couplings (e.g. bend-twist coupling). BECAS is used to correctly predict, e.g., torsional deformation and analyze the ultimate strength and fatigue damage with very high accuracy. BECAS serves as a starting point for the further developments in LMBlades.

The section | The PhD project is placed in the section Wind Turbine Structures and Component Design (SAC) at DTU Wind Energy. The section is (among other things) responsible for the development of BECAS. The research in the section focuses on design and prediction of structural response of wind turbines and their components. The research deals with loads and their dependence on environmental conditions, (optimal) structural design, and testing to quantify reliability and operational lifetime. The research includes development of advanced mathematical models, testing methods, and efficient numerical optimization methods for reliable structural design of wind turbine components.

The teams | Within the section the project falls within the expertise of two of the main research themes. The focus in the Structural and Multidisciplinary Optimization team is on development and implementation of models and efficient and numerical methods for robust structural optimization of parts and entire structures. The work in the team focuses on optimal design of laminated composite structures (such as wind turbine blades), optimal design of steel structures (such as offshore wind energy support structures), and development of general techniques for structural optimization. The team currently consists of one professor, one scientist, three post doctoral fellows, and three PhD students.

The Structural Design & Testing team is doing research in the areas of experimental, numerical and analytical design in order to develop more reliable and precise methods for structural design of wind turbine blades and other large composite structures. The team develops methods to predict the structural response of large structures subjected to complex loading. The team develops testing methods and measuring equipment for testing full-scale and parts of structures.

L. Third parties (max. 1 page per third party)

N/A