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STRUCTURAL OPTIMIZATION OF WIND TURBINE BLADES

BY
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Structural Optimization of Wind Turbine Blades

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Preface

This thesis has been submitted to the Faculty of Engineering and Science at Aalborg University in fulfillment of the requirements for the degree of Doctor of Philosophy in Mechanical Engineering. The work has been carried out at the Department of Materials and Production at Aalborg University in the period from November 2015 to November 2018. The work is part of the research project entitled *OPTI_MADE_BLADE* which has been funded by the Innovation Fund, grant no. 75-2014-3. This support is gratefully acknowledged.

The project was supervised by Professor Erik Lund, Department of Materials and Production, Aalborg university. I would like to express my sincere gratitude to my supervisor who throughout the project provided not only competent guidance and support, but also a pleasant and inspiring work environment. During the PhD project I visited Daniël Peeters at University of Limerick. The three months in Limerick were very valuable to me both with regard to academic output and personal memories, and I am very grateful for the opportunity to stay there.

My friends, family, and especially my girlfriend Caroline, have all provided invaluable support throughout the project for which I am very thankful.

Aalborg, February 2019

Jonas Heidemann Sjølund

Abstract

Wind turbines play an important role in the transition from fossil fuels to renewable energy. The overall purpose of this thesis is to explore new or improved structural design methods for offshore wind turbine blades, leading to reduced costs of energy. In general, in this thesis, the cost of energy is reduced by minimizing the wind turbine blade mass. Mass savings means a reduced cost of materials, but also lower gravity induced loads in the drive train and tower. The outcome of this work is described in three journal papers, herein denoted paper A, B, and C, of which two have been published and one is submitted.

In Paper A, structural gradient-based sizing optimization is used to minimize the mass of a modern 73.5 m offshore wind turbine blade. The optimization is performed while including 12 load cases and multiple structural constraints. The constraints include a maximum strain failure criterion, tip deflection, buckling, and manufacturing considerations. The sizing optimization is based on a high-fidelity solid-shell finite element model with no inherent restrictions. Since solid-shell elements are used, the sizing optimization also involves shape optimization as the nodes must move when changing a thickness. Ply-group thicknesses (groups of plies with the same material and fiber angle) are used as design variables. With this approach 406 design variables are required to parameterize the uni-directional and balsa parts of the blade layup. During the optimization the blade mass is significantly reduced, while multiple criteria become active. Finally, the optimized design is post-processed in order to achieve a manufacturable design. The post-processing yields a slightly heavier design, but also improves the margin of safety of all criteria.

Paper B takes offset in the Discrete Material and Thickness Optimization (DMTO) method. This method can be used for structural optimization of composite structures on a ply-basis. Design variables exist not only to determine the local thickness of the structure (how many plies), but also, for each ply, to determine the optimal fiber angle among a discrete set of candidates. In this paper an extension to the DMTO method is suggested. This extension modifies the thickness design variable parameterization, so that design variables affect ply-thicknesses rather than constitutive properties. This modification allows for having internal ply-drops, and hence more realistic designs can be obtained. Furthermore, the design sensitivities are affected, and it is shown how convergence properties are in some cases improved.

Paper C continues to explore how the new thickness parameterization can be applied to sandwich structures. With the new thickness parameterization, which affects ply-thicknesses rather than constitutive properties, internal plies can be removed without causing intermediate voids. This in turn means that multiple groups of layers can be sized simultaneously. More specifically, the layer-wise thickness and material candidate choice for both sandwich core and face sheet plies can be optimized simultaneously. This is utilized to optimize composite structures with a number of thick balsa plates in the middle, and a number of relatively thin glass-fiber reinforced plastic (GFRP) plies as face sheets. The optimization use conflicting criteria to demonstrate how a non-intuitive composite variable thickness lay-ups can be found.

This thesis serves to provide motivation to the research area, and to provide an introduction to state-of-the-art of structural optimization of wind turbine blades, before presenting papers A, B, and C.

Resumé

Vindmøller spiller en vigtig rolle i forbindelse med overgangen til grøn energi. Det overordnede formål i denne afhandling er at udforske nye eller forbedrede metoder til strukturelt design af vindmøllevinger, hvilket kan skabe billigere vindenergi. De forbedrede designmetoder tager udgangspunkt i at minimere massen af vindmøllevinger. En reduceret masse kan både give materialebesparelser, men også reducere de tyngdekraftsinducerede laster i resten af møllen. Resultatet af arbejdet i dette PhD projekt er beskrevet i tre artikler, heri kaldt artikel A, B, og C, hvoraf to er udgivne og én er indsendt.

I artikel A bliver strukturel gradient-baseret tykkelsesoptimering brugt til at minimere massen af en moderne 73.5 m offshore vindmøllevinge. Optimeringen inkluderer 12 lasttilfælde og flere strukturelle kriterier. De anvendte grænser i optimeringen indeholder maks. tøjning fejlkriteriet, tipudbøjning, buling samt produktionshensyn. Tykkelsesoptimeringen er baseret på en nøjagtig solid-skal element model uden indbyggede begrænsninger. Da optimeringen baseres på solid-skalelementer, involverer tykkelsesoptimeringen også flytning af knuder. Designvariablene vælges som tykkelser af grupper af UD lag eller balsa. Kombineret med en parametrisering af vingen i både tværsnittet og i længden resulterer dette i 406 designvariable. Under optimeringen reduceres vingemassen betydeligt, mens flere kriterier bliver aktive. Endelig post-processeres det optimerede design for at opnå et producerbart resultat. Det post-processerede resultat giver en marginalt tungere vinge, men resulterer også i højere sikkerhedsmarginer på alle kriterier samt et mere produktionsvenligt design.

I artikel B tages der udgangspunkt i den såkaldte DMTO-metode (Diskret Materiale og Tykkelses Optimering). Denne metode kan anvendes til strukturelt at optimere kompositkonstruktioner på en lagvis basis. I denne metode anvendes der designvariable til både at repræsentere den lokale tykkelse (antal lag), men også, for hver enkelt lag, fibervinklen. Fibervinklen er også en diskret variabel idet der kun kan vælges imellem et forudbestemt antal kandidater. I denne artikel foreslås en udvidelse til DMTO-metoden. Udvidelsen ændrer formuleringen således at tykkelsesvariable påvirker lagtykkelsen fremfor de konstitutive egenskaber. Denne ændring tillader indre materialeaftrapninger og dermed mere realistiske designs. Denne ændring påvirker også designsensitiviteterne, og det vises hvordan konvergenskarakteristika i nogle tilfælde forbedres.

I artikel C udforskes denne udvidelse til DMTO-metoden ift. anvendelse til optimering af sandwichkonstruktioner. Med den nye tykkelsesformulering, som påvirker lagtykkelser fremfor konstitutive egenskaber, kan interne lag fjernes uden at der fremkommer indre hulrum. Dette betyder at flere grupper af lag kan optimeres samtidig. Mere specifikt betyder det at lagvise tykkelser af de indre kernelag og de ydre dæklag kan optimeres samtidigt. Dette udnyttes til at optimere kompositkonstruktioner med relativt tykke balsaplader som kernemateriale, og tynde glasfiberforstærkede dæklag. I optimeringen anvendes der modstridende kriterier til at demonstrere hvordan ikke-intuitive sammensætninger af fibervinkler og tykkelser kan fremkomme.

Denne afhandling indeholder motivationen til den udførte forskning, og giver også en introduktion til state-of-the-art indenfor strukturel optimering af vindmøllevinger, inden artiklerne A, B og C præsenteres i appendiks.

Thesis Details

This dissertation provides an introduction to the research topics of the PhD project. The work of this PhD project has been documented through three journal articles (two published, and one submitted). This dissertation serves as a short introduction to the main research area of structural optimization of wind turbine blades.

Thesis Title:	Structural Optimization of Wind Turbine Blades
PhD Student:	Jonas Heidemann Sjølund
PhD Supervisor:	Erik Lund Professor, PhD, MSc Department of Materials and Production Aalborg University, Denmark

Publications in refereed journals

A) J. H. Sjølund, E. Lund. Structural gradient based sizing optimization of wind turbine blades with fixed outer geometry. *Composite Structures*, 203:725-739, 2018.

B) J. H. Sjølund, D. Peeters, E. Lund. A new thickness parameterization for Discrete Material and Thickness Optimization. *Structural and Multidisciplinary Optimization*, 58(5):1885–1897.

C) J. H. Sjølund, D. Peeters, E. Lund. Discrete Material and Thickness Optimization of Sandwich Structures. *Composite Structures*, Submitted November 2018

Publications in proceedings with review

E) J. H. Sjølund, E. Lund. Continuous plygroup thickness optimization of offshore wind turbine blades. *Abstract in proceedings of 16th Internal symposium DCAMM*, Middelfart, Denmark, 13-15th March 2017.

F) E. Lund, J.H. Sjølund. On Gradient Based Structural Optimization of a Wind Turbine Blade. *Proceedings of 21st International Conference on Composite Materials*, Xi'an, China, 20-25th August 2017, 11 pages.

G) J. H. Sjølund, E. Lund. Continuous thickness optimization of offshore wind turbine blades with parameterizations tailored for manufacturability. *Abstract in pro-*

ceedings of 6th ECCOMAS Thematic conference on the mechanical response of composites, Eindhoven, The Netherlands, 20-22nd September 2017.

H) J. H. Sjølund, E. Lund. Composite Thickness Optimization of Offshore Wind Turbine Blade with Fixed Outer Geometry. *Proceedings of 30th Nordic Seminar on Computational Mechanics NSCM30*, Copenhagen, 25. - 27. October, pp. 184-187, 2017.

This thesis has been submitted for assessment in fulfillment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured.

Contents

Chapter 1

Introduction

In this chapter an introduction to the overall research topic is provided.

1.1 PhD Project

This PhD project is part of the research project *OPTI_MADE_BLADE* which has been funded by the Innovation Fund Denmark. The overall objective and success criterion of the project is to reduce the cost of offshore wind turbine blade by 30%. The reduced cost should be achieved through a faster molding cycle time, a reduction in man-hours per produced blade, and a reduced use of materials. This particular PhD project aims to reduce the use of materials by improving the structural design methods used for wind turbine blades. The target is that material savings should contribute to 5% of the savings. The hypothesis is that by developing improved optimization methods it is possible to reduce the mass of wind turbine blades, and thereby reduce the cost of materials. In practice, the material savings target can not be evaluated in this thesis due to confidentiality of mass and material properties of the studied wind turbine blade. However, based in the results in Paper 1, the author believes that the showcased methods can yield significant mass reductions. Besides Aalborg University, the partners involved in the project are LM Wind Power, DTU Wind Energy, Fiberline Composites, and Eltronic.

1.2 Wind energy

As a result of global warming, renewable energy is more relevant than ever. Wind energy is one of the most promising sources of renewable energy due to its cost. The cost of energy is often given as levelized cost of energy (LCoE), which is lifetime cost divided by energy production, taking into account initial capital expenditures, operational costs, interest rate, and of course the expected amount of generated energy. The cost of onshore wind energy in 2016 was approximately 70 \$/MWh, while 2020 projects are estimated to cost 50 \$/MWh according to recent reports by the International Renewable Energy Agency (IRENA, 2018) and the U.S. Energy Information Administration (EIA, 2018). These estimated costs of onshore wind energy in 2020 are comparable with the cheapest fossil fuel energy sources, as seen in Figure 1.1 from IRENA (2018). Despite this, one of the main challenges of onshore wind energy is spacing constraints. There is only a limited number of high wind speed sites (typically along the coast), and among these sites there may be opposition to the placement of wind turbines due to their appearance, impact on wildlife, and noise pollution.

Offshore wind turbines offer a solution to the onshore space constraints, and whereas offshore wind energy has traditionally been twice as expensive as onshore wind energy (150 $/MWh in 2016), recent advances in the supply chain and in wind turbine technology have greatly reduced the price of offshore wind energy (see Figure 1.1). Nonetheless, these predictions correspond to the best wind sites in relatively shallow waters, and continued development is required to ensure that offshore wind energy is competitive against fossil fuels. The National Renewable Energy Laboratory (NREL, 2017) uses reference wind turbine projects and recent data sources to estimate and break down the cost of onshore and offshore wind energy, respectively. The capital expenditure distribution of a reference 4.71 MW fixed-bottom offshore wind turbine is shown in Figure 1.2 (NREL, 2017). Here, the cost of an offshore wind turbine (above-foundation) is approximated to one third of the total capital cost. By way of comparison, in onshore wind energy, the turbine comprises approximately 67% of the total capital costs. The main reason for this large

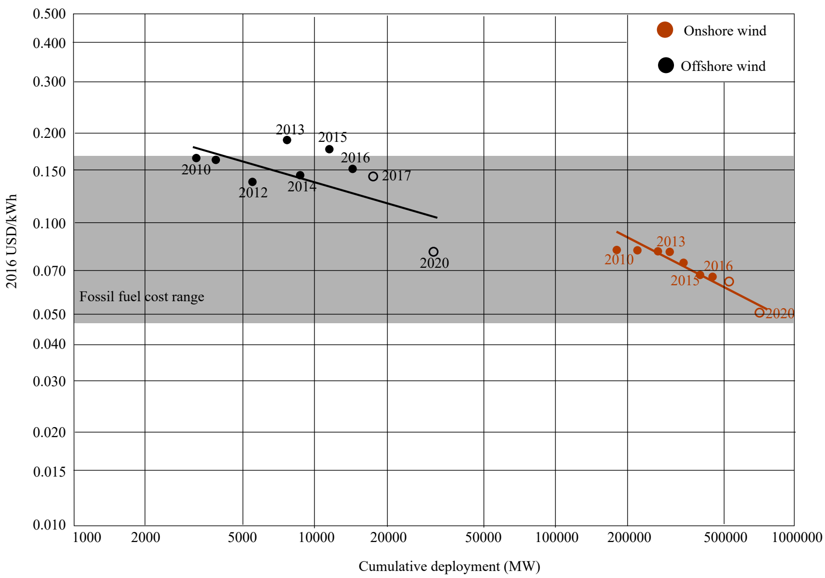


Fig. 1.1: Globally weighted average of cost of energy of onshore and offshore wind energy. Each circle represents a project or an auction result. Figure reproduced from IRENA (2018).

difference is the significant costs associated with offshore sites such as foundation, installation, and transportation.

In this project, the main focus is on wind turbine blades. Wind turbine blades correspond to approximately 20% of the turbine (above-foundation) capital costs (NREL, 2017). Hence the blades alone constitute approximately 6% of the total capital costs of an offshore wind turbine, and reducing the cost of offshore wind turbine blades is significant to reducing the overall LCoE of offshore wind energy. However, these numbers also highlight that cost reductions in wind turbine blades can not stand alone, but should be accompanied by progress in all other areas related to wind turbines.

The cost of wind turbine blades comes from the cost of mold, floor space, material, development, and man-hours. Improving manufacturing methods can reduce the man-hours and decrease the cycle time per blade, which is important due to a limited number of molds. Another approach to decrease costs is improved design methods. Better design methods can be used to improve the aerodynamics of wind turbine blades and thereby increase the energy production or reduce loads. Improved design methods may also be used to improve the internal geometry, decreasing the blade mass while not compromising structural integrity. In this thesis the outer geometry is assumed fixed so that the mold can be re-used and therefore focus is on improving

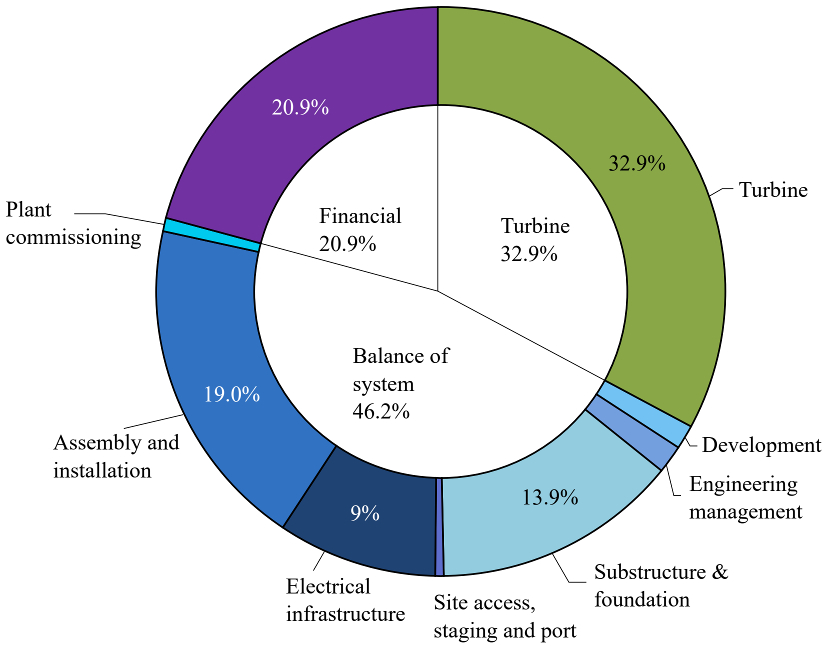


Fig. 1.2: Breakdown of capital cost of an offshore wind turbine blade. Figure reproduced from NREL (2017)

the internal geometry by minimizing blade mass while considering structural criteria. Reducing the mass of a wind turbine blade can also be beneficial to the wind turbine drive-train and tower as gravitationally induced loads are reduced.

1.3 Wind turbine blades

The main principle of wind turbines is to convert wind energy to a torque which can be converted to electricity. This conversion from wind to torque is achieved by the wind turbine blades as shown in Figure 1.3. Here the relative wind speed results from the combination of the incoming wind and the rotation of the rotor. Higher pressure on one side of the wind turbine blade cross section (airfoil) yields a lift force component resulting in the driving torque.

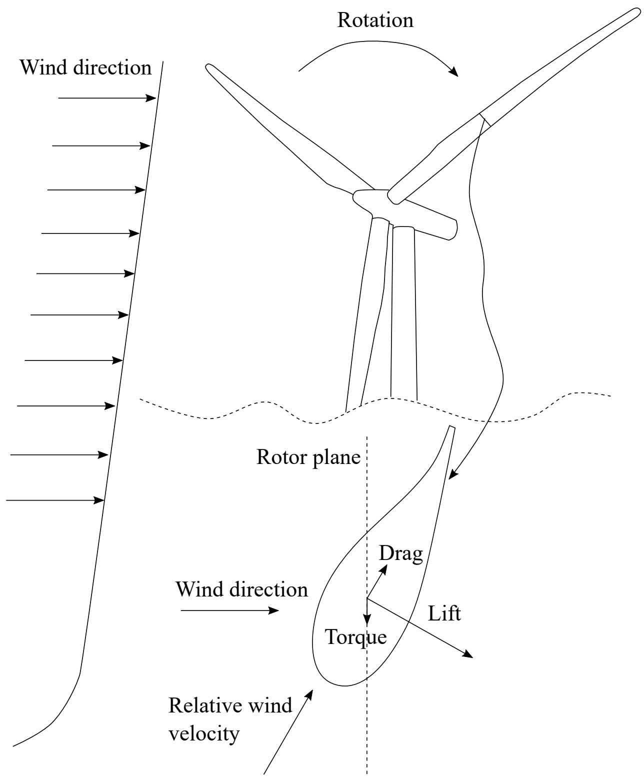


Fig. 1.3: Wind turbine principle.

1.3.1 Materials

All modern wind turbine blades are laminated composite structures. A laminated composite structure is a structure made from bonded layers (laminated) consisting of at least two materials (composite). One of the main advantages of laminated composite structures is that the stiffness and strength can be tailored. Wind turbine blades mainly use fiber reinforced polymers (FRP) where long and stiff fibers, e.g., glass or carbon fibers (GFRP/CFRP), are embedded in a softer polymer material (resin) such as polyester or epoxy. An exploded view illustration of a four-layered laminate is shown in Figure 1.4. In such a structure the main stiffness is in the direction of the fibers. If all fibers are oriented in the same direction, a very stiff structure is obtained in that direction, while in the other directions the stiffness is relatively low. This can be used to produce weight efficient wind turbine blades, as they are basically hollow beam like structures subject to bending with most of the stiffness and strength requirements being in the length direction of the blade.

A laminate consisting of only one type of fiber reinforced polymer is called a monolithic laminate. However, in general wind turbine blades use a combination of materials. In modern wind turbine blades a combination of glass and carbon fibers may be utilized to achieve sufficient stiffness and strength. Furthermore, parts of wind turbine blades are created as sandwich panels using core materials such as PVC foams or balsa wood, see for example Thomsen (2009).

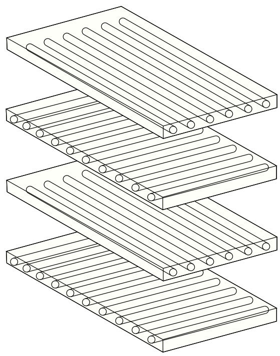


Fig. 1.4: Exploded view of a four-layered laminated composite structure with two different fiber angle directions.

1.3.2 Manufacturing

Wind turbine blades can be manufactured in many different ways. This thesis takes offset in the method where the upwind and downwind parts of the blade are produced separately, and where the load carrying parts of the blade are integrated in the aerodynamic shell. The upwind and downwind parts are each manufactured using a single-sided mold corresponding to the outer geometry of the wind turbine blade. In these molds the blade is built up from dry non-crimp fiber mats. Robots can in some cases assist the placement of fiber mats as shown in Figure 1.5a. In this stage of the process also dry core material is placed in the mold as shown in Figure 1.5b. Once all dry materials have been placed in the two molds, resin is infused using a vacuum process. The shear webs are manufactured in a similar way. When the upwind and downwind sides, including shear webs, have been infused, they are glued together as shown in Figure 1.5c. The final blade is shown in Figure 1.5d.

(a) Dry non-crimp fiber mats are placed in the mold.

(b) Dry flexible balsa mats are placed in the mold.

(c) The upwind and downwind parts have been infused with resin and are now about to be glued together.

(d) Finished wind turbine blade (except for surface treatment).

Fig. 1.5: Wind turbine blade production.

1.3.3 Structure

A wind turbine blade cross section resulting from the described manufacturing process can be seen in Figure 1.6. The glue lines tying the upwind side, downwind side, and shear webs together can also be seen. The cross section of the blade is shown in three different positions. In the root a cylindrical shape is used, which is gradually transitioned into an aerodynamic airfoil. The load carrying parts of the wind turbine blade are here integrated in the aerodynamic shell. The main laminate consists mainly of unidirectional (UD) fiber mats, and carries most of the flapwise loads. In-between the main laminate in the upwind and downwind parts are the shear webs. The shear webs carry most of the shear from flapwise loads. The shear webs are made as sandwich panels to prevent local buckling, and $\pm 45^\circ$ face sheet layers are used to provide shear stiffness. In a similar manner UD laminate at both the trailing edge (TE) and leading edge (LE) helps carry the edgewise loads, while sandwich panels in-between carry shear load and prevent buckling. In general the blade is covered by $\pm 45^\circ$ plies to tie the different regions of the blade together and to provide damage tolerance.

Wind turbine blades are usually structurally verified according to norms such as IEC (2005) or DNV-GL (2015). These norms describe both the combination of the model fidelity, the load cases, and the required structural criteria. In some cases the norms allow for different approaches, and each approach is associated with different partial safety factors. For example in DNV-GL (2015), buckling can be verified either using non-linear finite element analysis (FEA) of full blade, linear FEA of full blade, linear FEA of cross-sections, or analytical methods. Each option is associated with different partial safety factors. The purpose of structural verification is to ensure that a blade is capable of withstanding the loads it is subjected to during its lifetime. Since many different approaches can be used, the norm calculations should not be confused with accurate wind turbine blade ultimate failure simulations. Ultimate failure and collapse of wind turbine blades have been studied in a number of cases and involve complicated failure modes requiring high-fidelity non-linear simulation models, see for example Jensen et al. (2006); Overgaard and Lund (2010); Overgaard et al. (2010).

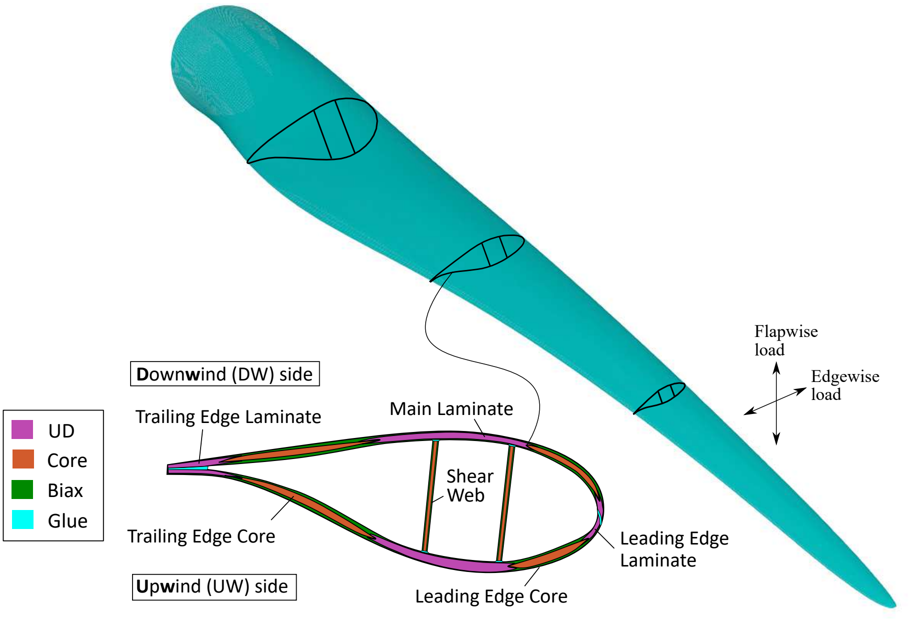


Fig. 1.6: A wind turbine blade and three typical cross sections.

1.3.4 Design

Design of wind turbine blades is a multi-disciplinary problem, and in the early conceptual design stage it is often called rotor design. Ideally, a rotor design finds the aerodynamic shape and internal geometry of a wind turbine blade which minimizes the cost of energy while considering manufacturing, failure modes in all load cases, and the couplings between structure, aerodynamics, and control systems. However, due to the complexity of this problem, rotor design procedures are usually simplified significantly. An overview of recent advances in wind turbine blade design can be found in Brøndsted and Nijssen (2013), and an introduction to wind turbine aerodynamics can be found in Hansen (2008).

Examples of rotor design using mathematical optimization can be found in Fuglsang and Madsen (1999); Døssing (2011); Bottasso et al. (2012); Zahle et al. (2016). In Fuglsang and Madsen (1999) the cost of energy is minimized while considering rotor chord, twist, airfoil relative thickness, structural shell thickness, and pitch angle as design variables. The cost of various parts is divided into a fixed part representing, e.g., manufacturing and transport, and a variable part depending on the design loads. The structural model is based on a linear elastic I-beam and structural constraints include extreme and fatigue strains. Fatigue loads are found using time domain aero-elastic calculations based on a non-linear 20 degree of freedom model. Gradient-based optimization is used with semi-empirical sensitivities. Interestingly, the optimization leads to a lower annual energy production than the baseline, but with even larger mass reductions, yielding a reduction in cost of energy of 3.5%. Døssing (2011) instead use optimization to minimize fatigue loads. Design variables include chord, twist, and airfoil relative thickness, while constraints include tip deflection, annual energy production, and blade mass. Aero-elastic simulations are performed using state-of-the-art code 'HAWC2', and cross-sectional properties are calculated taking into account the airfoil shape.

Bottasso et al. (2012) describes a framework for minimizing cost of energy. The multi-disciplinary design problem is divided into the two separate problems of maximizing annual energy production and minimizing blade mass. The argument is that the annual energy production mainly depends on the aerodynamic design (such as chord, twist, and relative thickness), and not so much on shell thickness and internal geometry. Hence first the annual energy production is maximized with frozen structural parameters, and next the mass is minimized with frozen aerodynamic parameters. This process is repeated until convergence. Gradient-based optimization is used, and structural constraints include eigenfrequencies, fatigue and extreme strains, and tip displacement. Furthermore, detailed 2D finite element models of cross sections in combination with advanced beam theory is used to find fully populated cross sectional stiffness matrices taking into account all couplings, and also to retrieve stresses and strains. Zahle et al. (2016) use a similar framework for maximizing the annual energy production. Design variables completely describe the aerodynamic shape and length of the blade, and also include spar cap width and various uni-directional and tri-axial ply-group thicknesses. Also here advanced beam theory is used to calculate cross sectional stiffness matrices and to retrieve stresses and strains. Gradient-based optimization is used, and constraints include extreme strains, loads/torque, mass, mass moment, and tip displacement. However, as opposed to Bottasso et al. (2012), the multi-disciplinary problem is solved directly (without splitting it to two separate problems). This is made possible by utilizing efficient parallelization of computations in combination with 600 available cores.

In all these cases the structural models used for rotor design are based on beam models ranging from simple I-beam models to advanced beam theory models utilizing 2D finite element models of cross sections, and to the authors knowledge this corresponds to state-of-the-art within rotor design. However, beam models can not be used to accurately predict local shell buckling which is often an important criteria in wind turbine blades. Moreover, beam models do not account for spanwise tapering or curvature. Furthermore, even the advanced beam models may not accurately predict stresses and strains near the constrained root (Bottasso et al., 2014; Blasques et al., 2015). The research hypotheses presented in the following section takes offset in these deficiencies of beam models, questioning if and how shell or solid finite element models can be used as basis for structural optimization of modern wind turbine blades.

1.4 Objectives of the PhD project

The objective of this PhD project is related to the overall target of the project to reduce the cost of wind turbine blades. Part of the reduced cost should come from mass savings. In this PhD project the goal of reducing wind turbine blade costs is targeted by improving structural design methods. If structural design methods can be significantly improved it can potentially lead to wind turbine blade mass reductions. This leads to the following research hypotheses which are investigated in this PhD project:

- Can state-of-the-art full scale 3D solid-shell finite element models of modern offshore wind turbine blades be used as a basis for structural optimization taking all relevant structural and manufacturing criteria into account while subject to a realistic set of load cases?
- How can a modern offshore wind turbine blade be efficiently parameterized for structural optimization such that manufacturability is ensured and a reasonable number of design variables is obtained?
- How can structural optimization be used on a ply basis to discover non-intuitive fiber angle choices and thickness distributions which can help reduce mass while ensuring the structural integrity of wind turbine blades?

The first two research hypotheses are primarily investigated in Paper A, while the third research hypothesis is investigated in Papers B and C. Papers A, B, and C can be found as appendices to this thesis. The purpose of the following chapter is to provide an introduction to state-of-the-art of structural optimization of wind turbine blades, divided into two main sections on thickness and topology / multi-material optimization, respectively. Finally, the last chapter provides a summary of the three papers including a conclusion and suggested future work.

1.4.1 Limitations

The two main limitations in this thesis is that the structural-aerodynamic coupling is not considered, and that fatigue is not included. The structural-aerodynamic limitation is justified by keeping the aerodynamic (outer) geometry constant which is relevant if the manufacturing mold should be re-used. However, even with the aerodynamic geometry constant, changes in the internal geometry affects the blade stiffness and mass distribution, which in turn change the blade loads. This limitation is also discussed in Paper A, where a simple solution is proposed. However, including the coupling between structure stiffness and loads is left for future work. Fatigue is an important design driver in wind turbine blade design. However, efficiently including fatigue constraints with mean stress effects in gradient-based optimization is an active area of research, and is also left to future work.

Chapter 2

State-of-the-art

This chapter will describe state-of-the-art methods and examples of structural optimization of wind turbine blades. Optimal structural design of wind turbine blades is non-trivial, even with the outer geometry fixed, due to many load cases, conflicting structural criteria, and manufacturing constraints. Therefore structural optimization is often used in the design process of wind turbine blades. The best optimization method and parameterization depends much on the purpose of the optimization. Structural optimization for fixed outer geometry of the composite structure can roughly be divided into the two categories of thickness (sizing) and topology optimization. Thickness optimization of wind turbine blades is a matter of finding the optimal shell thickness throughout a blade, whereas topology optimization is typically used to determine the internal geometry layout. The state-of-the-art application of these methods in the context of wind turbine blades will be discussed in the following sections.

2.1 Thickness optimization

In thickness optimization of laminated composite structures the thickness of one or more layers are used as design variables. Wind turbine blades are often modelled using equivalent single layer (ESL) shell finite elements, and in this case a change in layer thickness does not change the nodal geometry of the finite element model. Moreover, offset shell elements are very convenient here since the outer geometry is well known. Hence offset ESL shell elements can favorably be used to generate a 3D finite element model based on the outer geometry, which in turn allows for relatively straight-forward sizing optimization. If solid or solid-shell elements are used, sizing optimization becomes slightly more complicated as changing a thickness also involves moving nodes. In the following literature review, sizing optimization of wind turbine blades is divided into heuristic and gradient-based approaches.

2.1.1 Heuristic methods

Heuristic methods are trial-and-error based methods in the sense that objective and constraints must be re-evaluated to assess the impact of a change in design variables. The genetic algorithm (GA) is based on Darwin's 'survival of the fittest' principle. This method is very popular for composite optimization, see for example the recent review by Nikbakt et al. (2018) where references are sorted by optimization methodology. Heuristic approaches are convenient since they do not require gradients, thereby allowing for discrete design variables without modification. Composite structures are usually defined in terms of discrete variables (number of plies, and finite choices of fiber angle), and heuristic methods are therefore relatively straight forward to use. Moreover, since gradients are not required, heuristic methods are convenient to use in combination with commercial structural analysis software.

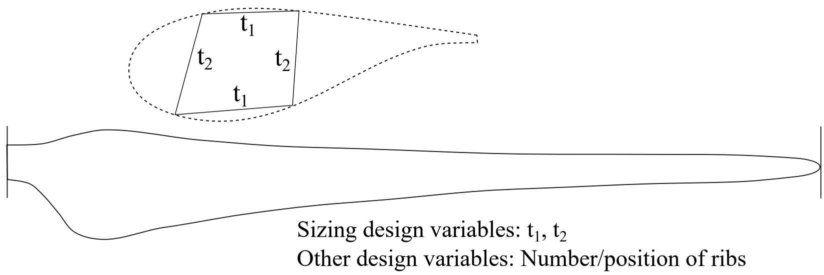
Heuristic methods are especially favorable when it comes to considering manufacturing and stacking sequence rules since such rules can be difficult to formulate in gradient-based methods. A good overview of common laminate design guidelines can be found in Irisarri et al. (2014). Examples of heuristic methods applied to optimization of variable thickness composite panels subject to manufacturing constraints can be found in Kristinsdottir et al. (2001); Soremekun et al. (2002); Adams et al. (2004); Irisarri et al. (2014). One manufacturing constraint is the so-called blending constraint, which is that adjacent panels must be interconnected by continuous plies. Kristinsdottir et al. (2001) handle blending by identifying a key region (the most severely loaded), from which all plies must emanate, and once a ply is dropped it can not be added back. Adams et al. (2004) use a guide laminate approach where all laminates in a structure can be obtained by deleting one or more plies from the guide laminate.

Application to wind turbine blades

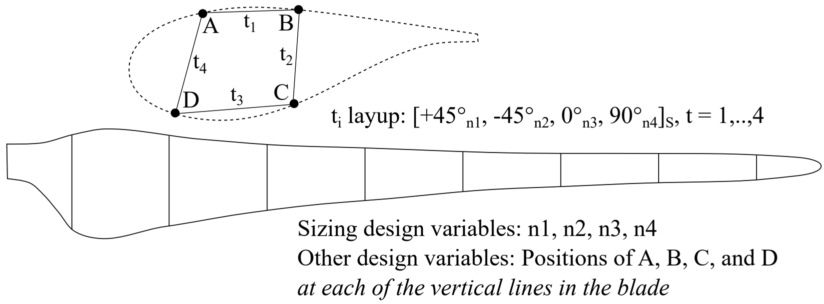
Heuristic methods used to size wind turbine blades can be found in Jureczko et al. (2005); Pirrera et al. (2012); Chen et al. (2013); Barnes and Morozov (2016); Albanesi et al. (2018). Jureczko et al. (2005) use a genetic algorithm and a shell finite element model with four design variables, one for the shell thickness of the entire blade, one for the web thickness, and two related to the geometry. This parameterization is visualized in Figure 2.1a.
Pirrera et al. (2012) use a genetic algorithm, but with a beam finite element model. The main spar of the blade is sized at 8 locations along the length of the blade. At every spanwise location, each of the four walls of the main spar are optimized. Each of the walls have four design variables representing the number of plies with fiber angles of $+45°$, $-45°$, $90°$, and $0°$. Furthermore, four additional design variables are used to represent the positions of the main spar corners. The design variable types are visualized in Figure 2.1b.
Chen et al. (2013) use design variables to represent the layer thickness of UD, biax, triax, coating, panel core, and web thickness. In doing so, the optimized result is a

scaling of the initial blade, with different scaling factors for each material/layer type. Barnes and Morozov (2016) use continuous design variables to represent the thickness of spar caps, shear web skins, and trailing edge reinforcement at six stations along the length of the blade. Moreover, design variables also represent the position of shear webs. The problem is solved using a genetic algorithm.
Albanesi et al. (2018) use a straight forward parameterization, where design variables correspond to the starting and stopping position of each ply (in the length direction of the blade). Furthermore, additional design variables represent the material choice of each ply, allowing for either UD, biaxial cross-ply ($0°/90°$), biaxial angle-ply ($\pm 45°$), or no material. This parameterization is quite similar to the actual manufacturing process shown in Figure 1.5. The layup is allowed to vary in thickness at ten equally spaced positions longitudinally, while the layup is constant circumferentially. This results in 48 design variables and a genetic algoritmn in combination with a shell finite element model is used to solve the problem. This parameterization is visualized in Figure 2.1c.

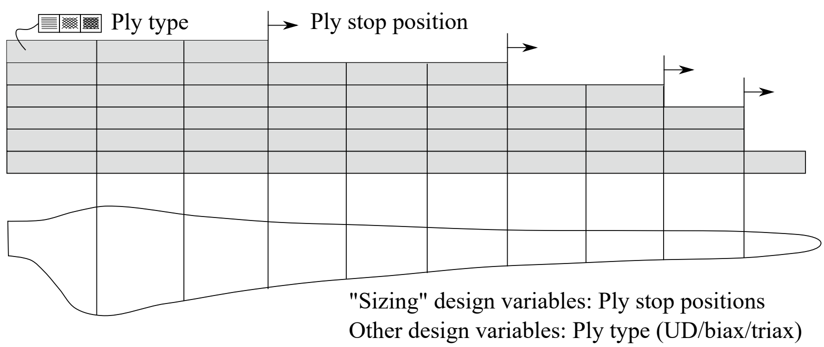
These examples show the flexibility of heuristic methods, which can be used for any choice of parameterization, any structural criteria, and any commercial analysis software. The main problem, as is also evident from the examples, is the limitation on the number of design variables due to the curse of dimensionality. Due to this, heuristic methods often require coarse or simplified parameterizations.



(a) Parameterization used in Jureczko et al. (2005).



(b) Parameterization used in Pirrera et al. (2012).



(c) Parameterization used in Albanesi et al. (2018).

Fig. 2.1: Visualization of different parameterizations of wind turbine blades used in combination with heuristic optimization algorithms.

2.1.2 Gradient-based methods

Gradient-based methods use design sensitivities to determine how the design variables should be changed. Most gradient-based methods rely on solving approximate sub-problems iteratively. One of the perhaps most general approaches is sequential linear programming (SLP). In this approach the problem is linearized around the current design variables. The resulting linear sub-problem can then be solved with linear programming algorithms such as the simplex method. Since the linearized sub-problem is only a good approximation for small changes in design variables, move-limits control how much design variables can change. This procedure is done sequentially until the specified convergence criteria is fulfilled. Compared to heuristic methods, gradient-based methods can handle problems with a much larger number of design variables given that gradients are calculated in an efficient manner. Furthermore, gradient-based methods require design variables to be continuous. Often discrete design variables, such as a number of plies, are relaxed to a continuous thickness. This in turn means that the optimized design must be post-processed to achieve a manufacturable design. For composite structures the post-processing can be complicated due stacking sequence requirements (often referred to as laminate design guidelines).

Gradient-based thickness optimization have been used to design general composite structures many times in literature. Schmit and Farshi (1973) used continuous variables to represent the thickness of specified orientation angles. The parameterization is shown in Figure 2.2 left). This approach was used to minimize the mass of plates subject to multiple load cases and constraints on the strength and stiffness. To obtain a physically realizable laminate, an integer number of plies are approximated by rounding. A similar approach is used in Mateus et al. (1991); Costin and Wang (1993); Mateus et al. (1997). Furthermore, Costin and Wang (1993) does this while including manufacturing constraints on the rate of thickness change between adjacent zones as shown in Figure 2.2 right).

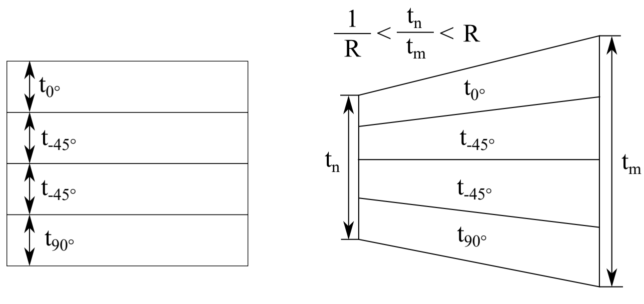


Fig. 2.2: Left) Visualization of the parameterizations used in Schmit and Farshi (1973); Costin and Wang (1993). Right) Visualization of the constraints on the rate of thickness change in Costin and Wang (1993), where the ratio of the total thickness in zones n and m must be within a certain interval.

Application to wind turbine blades

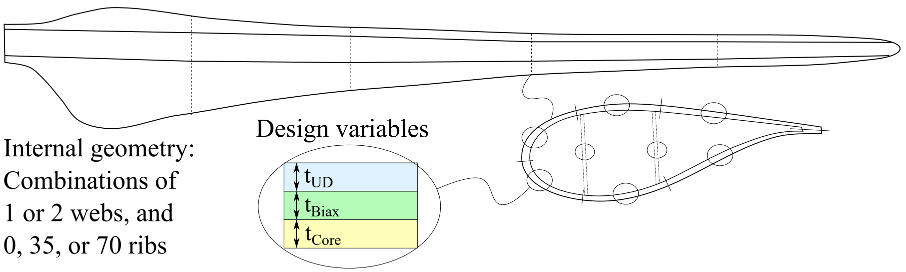
Gradient-based methods are used to size wind turbine blades in Forcier and Joncas (2012); Buckney et al. (2013a); Bottasso et al. (2014); Sjølund and Lund (2018). In both Forcier and Joncas (2012) and Buckney et al. (2013a) classic topology optimization is used in a preliminary design stage to determine where to position webs and ribs, followed by a subsequent gradient-based sizing optimization.

Forcier and Joncas (2012) divide the blade into five longitudinal regions and the cross section into trailing edge skin, leading edge skin, spar cap, and webs/ribs for both downwind and upwind sides as is shown in Figure 2.3a. In the resulting patches (groups of finite elements having the same laminate layup) both the thickness of biax, UD, and core material is sized using gradient-based optimization with up to 385 design variables. The optimization is performed for various web/rib configurations based on the initial topology optimization. Smeared laminate properties are used such that the stacking sequence does not influence the results. Buckney et al. (2013a) use a similar parameterization but only consider a 5 m section of the blade. Here the thickness of upper and lower caps, aerodynamic shell, webs, trailing edge reinforcement and foam cores are used as design variables, along with the distribution of UD and biax plies. This is also done for different internal geometry configurations.

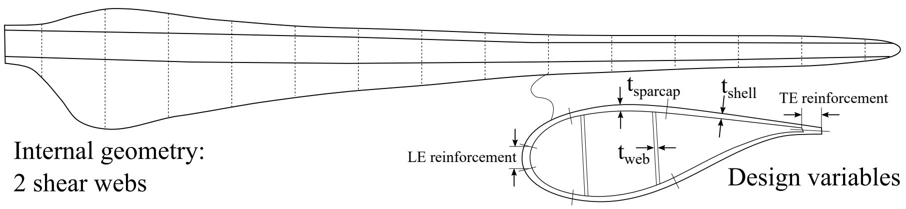
Bottasso et al. (2014) use 14 longitudinal stations, and the 53 used design variables represent thickness of skin, shear webs, spar caps, and area of leading and trailing edge reinforcements, as illustrated in Figure 2.3b. A combination of advanced beam models and 3D solid and shell finite element models are used in a multi-level gradient-based optimization loop. Advanced beam models are utilized in the coarse level optimization and 2D finite element models are used to establish the full cross sectional stiffness matrix which is input to the beam model, that can also be used to retrieve stresses and strains. In the next level 3D solid and shell models are used to calibrate the criteria used in the coarse level, and to adjust core thicknesses with respect to buckling as this can not be evaluated in the beam model.

In Paper A, Sjølund and Lund (2018) use 36 longitudinal stations, and divide the cross section into 10 regions as shown in Figure 2.3c, resulting in 406 design variables. A 3D solid-shell finite element model is used in the optimization process while sensitivities are found in a semi-analytical manner. The use of a 3D finite element model allows including buckling criteria directly in the optimization. The optimization is performed based on a fixed outer geometry and a frozen load envelope consisting of 12 load cases. The optimized result has six active buckling load cases, two active failure index load cases, and one active displacement load case. Post-processing is performed subsequently in order to ensure a manufacturable result. The post-processing increases the mass of the blade, but also the margin of safety of all criteria.

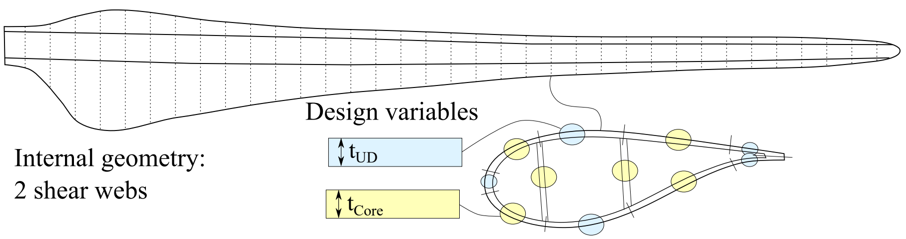
These examples demonstrate how gradient-based sizing optimization can be used to optimize the shell thickness of wind turbine blades subject to multiple criteria and using various types of finite element models. Compared to heuristic methods, gradient-based methods allow for relatively many design variables, allowing more realistic parameterizations. However, typically a subsequent post-processing step is required to achieve a manufacturable design, for example by obtaining a discrete number of plies everywhere and taking into account other requirements not possible to include in the optimization.



(a) Parameterization used in Forcier and Joncas (2012) where the blade is divided into five longitudinal sections, and the cross section into six regions including a number of regions depending on the web/rib configuration.



(b) Parameterization used in Bottasso et al. (2014) where the blade is divided into 14 longitudinal sections, and the cross section into five regions.



(c) Parameterization used in Sjølund and Lund (2018) where the blade is divided into 36 longitudinal sections, and the cross section into 10 regions (separate regions for downwind and upwind is used).

Fig. 2.3: Visualization of three different parameterizations used in gradient-based structural optimization of wind turbine blades.

2.2 Topology and multi-material optimization

2.2.1 Classic topology optimization

The literature on classic topology optimization is extensive. However, much information can be found in the book Bendsøe and Sigmund (2004). In the following only a very short description of classic topology optimization will be given. In classic topology optimization, a so-called density design variable ρ_e determines if there should be material or not in a given element e. This can be written as:

$$\rho_e = \begin{cases} 1 \text{ if there is material in element } e \\ 0 \text{ otherwise} \end{cases} \tag{2.1}$$

In this manner a domain is parameterized such that in each element it can be determined if there should be material or not. In practice ρ_e is allowed to vary continuously between 0 and 1 such that gradient-based optimization can be used, and material is 'removed' by scaling the constitutive matrix $\mathbf{E}$ by its associated density design variable, such that the effective constitutive matrix in the element becomes:

$$\mathbf{E}_e = \rho_e \mathbf{E} \tag{2.2}$$

However, since an intermediate valued design variable ρ_e is non-physical, the problem is modified such that 0-1 values are favored. A solution to this is penalizing intermediate values using the Solid Isotropic Material with Penalization (SIMP) scheme, introduced in Bendsøe (1989), where the density design variable is raised to a power p:

$$\mathbf{E}_e = \rho_e^p \mathbf{E} \tag{2.3}$$

Then for $p > 1$, intermediate values of ρ_e yield a reduced stiffness while the mass is left unpenalized. The optimal material distribution is of course problem specific. A much used criterion is minimization of compliance (maximize stiffness) while subject to a mass/volume constraint. In recent work by Aage et al. (2017) topology optimization is used to maximize the stiffness of a full-scale aeroplane wing using more than 1 billion finite elements. Interestingly, the internal geometry of the optimized aeroplane wing has similarities to a hornbill bird beak.

Application to wind turbine blades

Classic topology optimization has been applied for wind turbine blades in a number of examples (Forcier and Joncas, 2012; Buckney et al., 2013a,b). Forcier and Joncas (2012) use topology optimization for preliminary design of a wind turbine blade section for maximum stiffness. Using approximately 500,000 elements this results in a blade having the well known spar caps, while the internal layout is a mixture between shear webs and ribs (ribs are stiffener plates perpendicular to the longitudinal direction). A similar approach, but for the full blade and using approximately 2,500,000 elements can be found in Buckney et al. (2013a) and Buckney et al. (2013b). This also results in a traditional spar cap design with a mixture of webs and ribs. In all cases topology optimization is used to gain valuable insight into the stiffness-optimal internal geometry. However, due to the complicated geometries obtained from topology optimization it is best suited for conceptual design. Another drawback is the large number of finite elements and design variables which means that taking into account static stress, fatigue, and buckling is often computationally infeasible. Due to this, many topology optimization studies include only variants of compliance, displacement, mass and volume objectives/constraints.

2.2.2 Multi-material topology optimization

Multi-material topology optimization is an extension of classical topology optimization, and the question is no longer if there should be material or not, but rather which material. Based on Sigmund and Torquato (1997) this can be written as:

$$\mathbf{E}_e = \left(1 - x_e^p\right)\mathbf{E}_1 + x_e^p \mathbf{E}_2 \tag{2.4}$$

where x_e is the design variable representing the 'mixing' of the two material candidates $\mathbf{E}_1$ and $\mathbf{E}_2$ in element e. Here $x_e = 0$ corresponds to choosing candidate 1, while $x_e = 1$ corresponds to choosing candidate 2.

The Discrete Material Optimization (DMO) method in Stegmann and Lund (2005) is a generalization of multi-material topology optimization for any number of candidate materials and for use in laminated composite structures. Again the general idea is to let the effective constitutive properties of each layer be a weighed sum of candidate material constitutive properties. This is combined with equivalent single layer shell finite elements which are very convenient for modelling composite structures. Since there can be multiple candidates in each layer in each patch (group of elements), three indices are now used for the parameterization. For an element e associated with patch p this can for every layer l be written as:

$$x_{plc} = \begin{cases} 1 \text{ if candidate } c \text{ is selected in layer } l \text{ of patch } p \\ 0 \text{ otherwise} \end{cases} \tag{2.5}$$

One of the proposed schemes in Stegmann and Lund (2005) is given as:

$$\mathbf{E}_{el} = \sum_{c=1}^{n_c} w_c \mathbf{E}_c = \sum_{c=1}^{n_c} \left(x_{elc}^p \prod_{j=1}^{n_c} \left(1 - (x_{el(j \neq c)})^p\right)\right) \mathbf{E}_c \tag{2.6}$$

Similar to equation (2.4), the increase of one candidate lower weight functions related to other candidates (also called self-balancing). However, as can be seen in Niu et al. (2010), this weight function tends to form a plateau near design variable values of one, therefore requiring high penalization powers to obtain discrete designs.

Hvejsel and Lund (2011) instead let design variables directly scale each of the candidate constitutive properties. This results in a one-to-one ratio between the number of design variables and number of candidates. Furthermore, multiphase penalization schemes are introduced. The multiphase SIMP scheme is introduced as:

$$\mathbf{E}_{el} = \sum_{c=1}^{n_c} w_c \mathbf{E}_c = \sum_{c=1}^{n_c} x_{plc}^{p} \mathbf{E}_c \tag{2.7}$$

This is combined with linear equality constraints to ensure that the candidate material design variables sum to one, i.e. ensuring the presence of at least one candidate:

$$\sum_{c=1}^{n_c} x_{plc} = 1 \tag{2.8}$$

An alternative to the DMO parameterization is the Shape Function with Penalization (SFP) approach which can be found in Bruyneel (2011). Here the number of design variables are reduced by using shape functions. For example, two coordinates (R,S) can be used to interpolate between four candidate materials, one in each coordinate corner. This approach is generalized to any number of candidate materials in Gao et al. (2012).

Application to wind turbine blades

The DMO approach has been used to structurally optimize wind turbine blades in multiple cases, see Lund and Stegmann (2005); Lund and Johansen (2008); Lund et al. (2008); Blasques and Stolpe (2012). In all cases material candidates include GFRP with fiber angles 0°, 45°, −45°, 90°, and foam.

In Lund and Stegmann (2005) the compliance of a wind turbine main spar is minimized. The optimization yields expected results with the spar caps using UD/0° in all layers while webs are dominated by foam in the middle, and a mixture of UD/0° and biax ±45° in the outer layers. The optimization is based on a shell finite element model with 9600 elements, and is performed in both patch and element-wise configurations resulting in 6006 and 364,800 design variables, respectively.

In Lund and Johansen (2008) buckling load factors are maximized in the trailing edge panel of a wind turbine blade section. Except for the trailing edge panel, all other parts of the blade section are kept constant. As expected foam is used in the internal layers resulting in a sandwich type panel. In the outermost layers, and adjacent to the spar cap, UD/90° layers are chosen, providing a stiff connection to the spar cap. On the other hand biax ±45° layers are preferred in the outermost layers near the trailing edge. The multi-criteria optimization by Lund et al. (2008) includes simultaneous stiffness and buckling criteria, and also a case with only failure criteria. Stiffness and buckling are conflicting criteria, and the optimization yields a combination of UD/0° and biax ±45° in the spar cap that is subject to compression. The spar cap in tension uses only UD/0° and webs are dominated by foam material. The case with only failure criteria results in a mainly UD/0° design (foam is not considered a candidate here).

Blasques and Stolpe (2012) also use a multi-material approach to maximize the stiffness of a wind turbine blade cross-section subject to 15 load cases. This yields a UD/0° spar cap design with two shear webs made of pure biax ±45°. This optimization is based on advanced beam theory utilizing a 2D finite element mesh of the cross section, and include constraints on mass, shear center, and mass center.

As seen from these examples, the DMO method can successfully be used to optimize the layup of large composite structures, having multiple candidate materials for each layer. However, large composite structures such as wind turbine blades are usually variable thickness structures, using ply-drops to change the local number of plies. In the next section, extensions to the DMO method, allowing for variable thickness structures, are explored.

2.2.3 Discrete Material and Thickness Optimization (DMTO)

Multi-material optimization can be combined with classic topology optimization to add the capability of designing discrete variable thickness structures. Two similar ways of combining the DMO method with density design variables can be found in Sørensen and Lund (2013) and Gao et al. (2013). Moreover, in Sørensen et al. (2014) this combination of DMO and topology optimization is termed Discrete Material and Thickness Optimization (DMTO). If a patch and a domain respectively represent a group of elements associated with a density or material candidate design variable, the parameterization can be written as:

$$\rho_{dl} = \begin{cases} 1 \text{ if there is material in layer } l \text{ of domain } d \\ 0 \text{ otherwise} \end{cases} \tag{2.9}$$

$$x_{plc} = \begin{cases} 1 \text{ if candidate } c \text{ is selected in layer } l \text{ of patch } p \\ 0 \text{ otherwise} \end{cases} \tag{2.10}$$

If the design variables are allowed to vary continuously in the range of 0-1, and they act by scaling the constitutive matrix, then the DMTO formulation for a given layer l in element e associated with material patch p and geometry domain d becomes:

$$\mathbf{E}_{el} = v\left(\boldsymbol{\rho}\right) \sum_{c=1}^{n^c} w\left(\mathbf{x}\right) \mathbf{E}_c \tag{2.11}$$

$$\sum_{c=1}^{n^c} x_{plc} = 1 \quad \forall\left(\rho, l\right) \tag{2.12}$$

$$\rho_{dl} \in [0;1] \quad \forall\left(d, l\right) \tag{2.13}$$

$$x_{plc} \in [0;1] \quad \forall\left(p, l, c\right) \tag{2.14}$$

where v and w are weight functions which can be used to penalize intermediate design variables. The multiphase SIMP scheme is written as (Hvejsel and Lund, 2011):

$$v\left(\boldsymbol{\rho}\right) = \rho_{dl}^{q} \tag{2.15}$$

$$w\left(\mathbf{x}\right) = x_{plc}^{p} \tag{2.16}$$

while the multiphase RAMP (rational approximation of material properties) scheme is given as (Stolpe and Svanberg, 2001; Hvejsel and Lund, 2011):

$$v(\boldsymbol{\rho}) = \frac{\rho_{dl}}{1 + q(1 - \rho_{dl})} \tag{2.17}$$

$$w(\mathbf{x}) = \frac{x_{plc}}{1 + p\left(1 - x_{plc}\right)} \tag{2.18}$$

This formulation allows simultaneous thickness and multi-material optimization of composite structures, while SIMP or RAMP penalization schemes help ensure that (almost) discrete designs are obtained. Similar to what is often done in classic topology optimization, penalization powers can be gradually raised.

It is important to note that with this formulation, material must be removed from the top (the outer plies), as otherwise non-physical intermediate voids appear. In Sørensen and Lund (2013) and Sørensen et al. (2014) this is solved by only removing material from the top, resulting in external ply-drops. Simply constraining $\rho_{d1} \leq \rho_{d2} \leq \ldots \leq \rho_{d(n_l)}$ is not sufficient since density bands arise where densities settle on the same intermediate value. Instead so-called thickness constraints are introduced. These piecewise linear constraints limit the maximum allowable density in layer $l + 1$ based on the current density in layer l:

$$\rho_{d(l+1)} \leq f(\rho_{dl}, T) \tag{2.19}$$

where

$$f(\rho_{dl}, T) = \begin{cases} f_1(\rho_{dl}, T) = a_1\rho_{dl}, & \text{if } \rho_{dl} \leq 1 - T \\ f_2(\rho_{dl}, T) = a_2\rho_{dl} + b_2, & \text{otherwise} \end{cases} \tag{2.20}$$

$$a_1 = \frac{T}{1 - T}, \quad a_2 = \frac{1}{a_1}, \quad b_2 = \frac{2T - 1}{T} \tag{2.21}$$

where T is a parameter that controls the slope of functions f_1 and f_2. The piecewise linear functions in (2.20) are plotted in Figure 2.4a. Often $T = 0.1$ is used, which in practice limit the density to change in one layer at a time, while higher values of T allow density changes in more layers at once. This difference is visualized in Figure 2.4b.

An alternative parameterization can be found in Sørensen and Lund (2015). Here only one through-the-thickness design variable, $\tilde{\rho}_e$, is used to represent the density of all layers in a domain, and hence if there are four layers, a density of $\tilde{\rho}_e = 0.25$ corresponds to one full layer. Layerwise densities, ρ_{dl}, still exist, but are calculated based on the through-the-thickness density. The layerwise density is basically determined using a step function. Again, in the four-layer example, a $\tilde{\rho}_e$ lower than 0.25/2 yields a layerwise density $\rho_{d1} = 0$, while $\tilde{\rho}_e$ larger than 0.25/2 yields a layerwise density $\rho_{d1} = 1$. However, instead of using a step function, a continuous approximation is used to accommodate gradient-based optimization. In this manner thickness constraints are no longer needed, and the number of design variables are significantly reduced. However, material is still removed from the top, resulting in

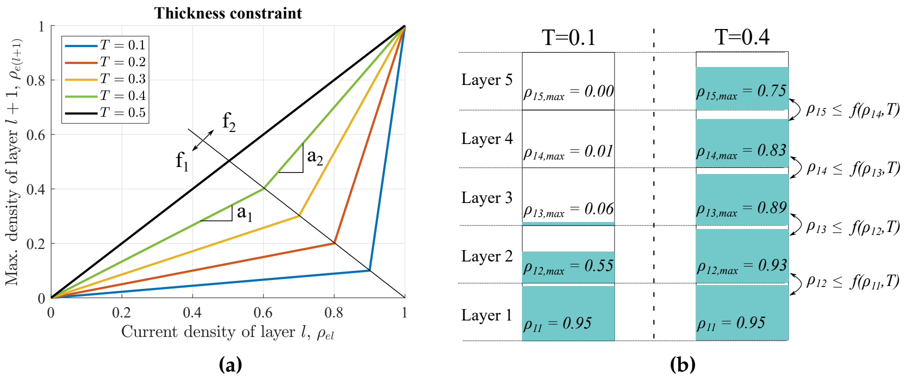


Fig. 2.4: a) Plot of the piecewise linear thickness constraint, (2.20), for different values of the T parameter. b) Visualization of the maximum allowable density in subsequent layers for $T = 0.1$ and $T = 0.4$, based on a density in the first layer of 0.95.

external ply-drops.

In practice, ply-drops are always covered in order to avoid delamination. In order to allow internal ply-drops, a new thickness formulation to the DMTO method is proposed in Paper B (Sjølund et al., 2018). The DMTO parameterization as given in equations (2.9)-(2.10) is unchanged, but density design variables are changed to scale ply thicknesses rather than constitutive properties. In this manner the formulation can be written as:

$$\mathbf{E}_{el} = \sum_{c=1}^{n_c} w\left(\mathbf{x}\right) \mathbf{E}_c \tag{2.22}$$

$$\tilde{t}_{el} = v\left(\boldsymbol{\rho}\right) t_{pl} \tag{2.23}$$

where $\tilde{t}_{el}$ is a calculated pseudo ply thickness. This pseudo ply thickness is equal to the physical ply thickness t_{pl} for a density of one, and equal to zero for a density of zero. Here it is assumed that all candidates in layer l element e have the same physical ply thickness t_{pl}. This change removes the issue of intermediate voids and thereby allow for internal ply-drops. Furthermore, this parameterization is in some cases less sensitive to the choice of the T parameter used in the thickness constraints (2.20). This can result in faster convergence, as larger values of the T parameter makes it possible to have larger changes in density in more layers.

The new thickness formulation also adds new possibilities with regard to applying DMTO for sandwich structures which is explored in Paper C (Sjølund et al., 2019). Since intermediate voids can no longer appear, it is possible to change densities of both internal core plies and external face sheet plies simultaneously. If core plies and face sheet plies are divided in this way, it is also possible to use different physical ply thicknesses. This is very relevant when using balsa plates as core material, and GFRP face sheet plies. Furthermore, local symmetry of the layup can easily be enforced with the new thickness formulation, as opposed to when material must be removed from the top.

Application to wind turbine blades

The DMTO method is used to optimize a wind turbine main spar in Sørensen et al. (2014); Lund (2018); Sjølund et al. (2019). In Sørensen et al. (2014) the mass of a main spar is minimized while subject to displacement, buckling, eigenfrequency, and manufacturing constraints. The main spar is modelled with ESL shell elements, and the optimization is performed using different parameterizations, and also with and without a foam candidate. As expected, the spar caps are dominated by 0° candidates, while the webs mainly utilize foam and some ±45° layers. When foam candidates are not allowed (i.e. enforcing a monolithic layup) the designs turn out significantly heavier. Furthermore, manufacturing constraints include limits on the maximum number of identical subsequent plies, and the thickness variation rate.
A similar example both with regard to geometry and included criteria is studied in Lund (2018). However, a maximum strain failure criteria constraint is added ensuring that strains do not exceed allowable values. Since strains are calculated at the top and bottom of every layer in every element, this results in a large number of criteria. In order to reduce this number, aggregate functions are used. In this manner the number of criteria functions is reduced from 286.720 to 448 (the number of patches), and is thereby efficiently taken into account.

Also in Paper C (Sjølund et al., 2019) a similar main spar is studied. In this case the new thickness formulation is utilized to achieve a locally symmetric sandwich structure with relatively thick balsa layers as core material. The two external face sheet plies are always present, and are chosen to be ±45° for damage tolerance. Additional face sheet plies can choose between 0°, 90°, and ±45°, but are symmetric around the core. Due to the constant external face sheet plies, variable density in the face sheet plies result in internal ply-drops. In the optimization the mass is minimized while subject to displacement, buckling and manufacturing constraints. Due to high requirements on buckling load factors, some core layers are utilized in the spar caps. However, the core layers push the inner face sheet layers inward, and decrease the area moment of inertia of the cross section. Hence the amount of core layers is a compromise between cross sectional bending stiffness and local bending stiffness. In order to ensure a manufacturable design, two different strategies are utilized to provide smooth thickness distributions in the longitudinal direction.

These examples demonstrate how Discrete Material and Thickness Optimization can be used to optimize large composite structures both with regard to thickness and fiber angle on a ply-basis. DMTO has been demonstrated with multiple structural and manufacturing constraints, allowing for realistic and manufacturable designs. The large flexibility that the DMTO method provides comes at the cost of many design variables. Due to the number of design variables, either super computers or code improvements are required to design full modern wind turbine blades using DMTO. Furthermore, some post-processing is still expected due to patch/domain grouping of elements, and rounding of non-discrete design variables (despite penalization).

Chapter 3

Summary of Results and Conclusion

This chapter serves as a brief summary of the included papers. Each paper will be introduced separately and objectives, methods, and results will be highlighted. Then, a statement of the contributions and of the impact of the work will be presented. Lastly, suggestions and recommendations for future work within this field of research are given.

3.1 Description of Papers

3.1.1 Paper A

In Sjølund and Lund (2018) the authors show how structural gradient-based sizing optimization can be used to minimize the mass of modern offshore wind turbine blades subject to realistic and representative loads and structural criteria. The optimization takes offset in a 73.5 m offshore wind turbine blade where the mold should be re-used and hence the outer geometry is fixed. The blade parameterization is tailored for manufacturability, and for reducing the amount of design variables. Hence rather than having design variables for each ply, ply-group thicknesses (groups of plies with the same material and fiber angle) are used as design variables. The basis for the optimization is a solid-shell finite element model with no inherent restrictions.

The parameterization takes offset in a typical blade design where the cross section is divided into main laminate, trailing edge, leading edge, intermediate sandwich regions, and shear webs. Moreover, the blade is divided into 36 (2 m) longitudinal sections. The combination of the cross sectional and longitudinal divisions result in 403 patches, where thicknesses of ply-groups can change individually within prescribed ply-drop constraints. The ply-group design variables represent the thickness of uni-directional (UD) material in the main laminate, trailing edge, and leading edge, while the balsa core thickness is considered in intermediate sandwich regions and in shear webs. Based on DNV-GL (2015) realistic criteria for displacement, buckling, and failure strains are established. Buckling load factors and the maximum strain failure criterion are evaluated in 12 different load cases (maximum bending moment in 12 different directions) while displacement is checked in a flapwise load case.

The mass of the wind turbine blade is minimized using an in-house code. Sensitivities are calculated in a semi-analytic manner combining direct differentiation of the governing discretized equations with central finite differences of element terms. Because solid-shell elements are used, the sensitivity analysis also involves moving nodes. The node move direction and distance depend on whether the node is associated with the outer shell or the internal shear webs, and the number of adjacent patches. Sequential linear programming (SLP) is used to solve the optimization problem combined with a merit function approach to ensure feasibility, adaptive move-limits to avoid oscillations of design variables, and a global convergence filter to choose if a solution can be accepted or not. The optimized blade design has a mass of 24185 kg, with six active buckling load cases, two active failure index load cases, and one active displacement constraint.

The optimized blade is subsequently post-processed to obtain a more manufacturable design. The post-processing consists of three parts where the first is rounding the continuous ply-group thicknesses such that they correspond to a whole number of plies. Second, the layup is refined to an element level from the 2 m long patches. Third, starting and stopping the same ply multiple times is avoided (filling of local valleys). The post-processing results in a slightly heavier blade of 24556 kg, but also increases the margin of safety of all structural criteria.

3.1.2 Paper B

In Sjølund et al. (2018) the authors propose a new thickness formulation for Discrete Material and Thickness Optimization (DMTO). In the original DMTO method density design variables are used to determine if there should be material or not in a given layer. Inspired by classic topology optimization this has traditionally been achieved by scaling constitutive properties. An issue with scaling constitutive properties is that removing intermediate layers results in intermediate voids. So far this has been solved by only removing material from the top, resulting in external and exposed ply-drops, while in practice ply-drops are always covered to avoid delaminations. Furthermore, another issue with only removing material from the top is that often the largest structural sensitivities are located in the outermost layers when local bending is present. Hence the constraints ensuring material removal from the top are conflicting with the sensitivities on where to place material. These conflicting requirements have traditionally been solved by (more or less) only allowing one layer to change at a time. However, for many layers this can yield slow convergence.

In this paper the density design variables are instead used to scale the ply thicknesses. By scaling the ply thicknesses intermediate voids can not occur, thereby allowing for internal ply-drops. Moreover, all layers in a given element have the same compliance sensitivity as long as material candidate weights are equal and no penalization is applied. This allows for density changes in more layers simultaneously. Moreover, it is demonstrated how solid-shell elements can be utilized in the DMTO method as changing a thickness also involves moving nodes, and how the continuous geometry of solid-shell elements is handled across elements with different thicknesses.

The new thickness formulation is demonstrated in three numerical examples where either compliance is minimized with a mass constraint or the mass is minimized with either compliance or displacement constrained. The first example is a simple five-element cantilever beam in bending. In this example it is demonstrated how the new thickness formulation is more robust with respect to the parameter controlling the density difference in adjacent layers, yielding more discrete results in less iterations. A similar tendency for more discrete results is seen in the second example where a corner-hinged plate is studied. In the final and third example a 20-layered cantilever beam is studied. In this example it is demonstrated how a full density top layer can be added to cover the ply-drops. Furthermore, in this example it can clearly be seen how allowing density changes in multiple layers at once speed up convergence significantly.

3.1.3 Paper C

In Sjølund et al. (2019) the authors use Discrete Material and Thickness Optimization (DMTO) in combination with the new thickness formulation to design sandwich structures. The DMTO method has been used for sandwich structures previously, but with a core candidate material available in all layers. When a core material is available in all layers it means that atypical sandwich structures can result from the optimization. For example it may result in designs with exposed core material, core material not centered, non-symmetric face sheets, etc., and while this can be useful for exploration, then ideally constraints ensuring a traditional sandwich structure should be available. Here, a traditional sandwich structure is assumed to have its core layers in the middle of the laminate, covered by face sheet plies which are symmetric around the core.

Using the new thickness formulation it is possible to simultaneously size face sheets and core layers without introducing intermediate voids. Moreover, different ply thickness can be used for face sheets and core layers which is relevant when using, e.g., balsa as core material. Furthermore, it is straight forward to ensure symmetric face sheets around the core. All this makes it possible to optimize variable thickness sandwich structures with multiple available fiber angles for each face sheet ply while also ensuring a manufacturable and practical result.

The approach is demonstrated in three numerical examples. In all examples the mass of a structure is minimized while subject to either displacement (compliance), buckling, or both constraints simultaneously. In the first example a simple constant stiffness plate in compression is optimized. With only a compliance constraint this provides the expected monolithic UD/0° plate since the GFRP candidate has a higher specific stiffness than the balsa core candidate. When a buckling criteria is used instead the maximum number of core layers is utilized in combination with ±45° plies for face sheets. In the combined case with the two conflicting criteria a compromise is achieved. In the second example a cylinder with a fixed outer geometry is optimized. With the outer geometry fixed, any core ply will push the internal face sheet inward, and therefore lower the area moment of inertia. Hence with only a displacement constraint, zero core plies are used. When both displacement and buckling constraints are present the optimization is a compromise between sufficient local bending stiffness to prevent buckling, and a high area moment of inertia to reduce displacement.

In the third example a wind turbine main spar is studied. The optimization of the main spar yields spar caps with many face sheet layers, and also some balsa layers to avoid buckling. The webs are dominated by balsa layers, and in general use as few layers as allowed within the included ply-drop constraint. However, the results are not very manufacturing friendly. Local buckling near the load application point at the tip yields a sudden increase in thickness, and in general the thickness distributions along the length of the main spar are not very smooth. To ensure a more manufacturable result, peak thickness positions (along the length) are defined for both balsa and face sheets, based on results from the first optimization. A subsequent optimization is then performed. This provides more manufacturable results at the costs of a small increase in mass, and the time needed for a subsequent optimization.

3.2 Conclusions and contributions

The overall objective of this work has been to develop and apply methods for structural optimization of offshore wind turbine blades while taking manufacturing constraints into account. The proposed methods for structural optimization of wind turbine blades have been published in three papers. The main contributions from each paper are:

- In Paper A, it is shown how a 3D solid-shell model of a full scale 73.5 m offshore wind turbine blade can be used as basis for structural gradient-based sizing optimization. Gradient-based sizing optimization of shell-like structures is a mature technology, and this paper shows that modern computers combined with an efficient parameterization with relatively few design variables allows optimizing such a large structure while taking into account multiple load cases and criteria according to design guidelines. The five simultaneously active buckling criteria at convergence show that including buckling in multiple load cases is important. Furthermore, it is shown how solid-shell elements can be utilized for sizing optimization as it involves moving nodes. The author is not aware of similar high-fidelity structural optimization studies of wind turbine blades.

- In Paper B, a novel thickness parameterization for Discrete Material and Thickness Optimization (DMTO) is proposed. Here a relatively simple change is proposed such that density design variables scale ply thicknesses rather than constitutive properties. This change ensures that intermediate voids can not occur, and therefore material must not be removed from the top. This enables internal ply-drops, allowing more realistic structures. Furthermore, the change has an effect on the design sensitivities. It is shown how this change can in some cases help convergence and yield more discrete results.
- In Paper C, it is shown how the new thickness formulation for DMTO can be utilized to optimize sandwich structures. The new thickness formulation allows separating core and face sheet layers, thereby ensuring a traditional sandwich stacking sequence with core players placed in the middle, covered by symmetric face sheets. Furthermore, since core and face sheet layers are separated, it is possible to use different ply-thicknesses which is essential when using balsa as core material.

3.3 Future work

The presented approaches for optimization of wind turbine blades can be extended in many ways. In the following some suggestions for future work is given. One suggestion for future work is related to a manufacturability issue encountered in Paper A and Paper C. Here laminate thickness jumps lead to so-called local valleys resulting in plies that are started and terminated multiple times, which is not desireable to manufacture. In both papers post-optimization steps are taken to obtain a more manufacturable layup. However, if the manufacturing constraints are included from the beginning, a different result may be obtained. Therefore, a suggestion for future work is to formulate constraints to avoid unnecessary starting/stopping of plies.

Another issue where more work is needed, is on the transition regions from a thick monolithic layup to a sandwich layup. Future work could highlight how these transition regions can be modelled, parameterized, and optimized efficiently. In practice the transition regions have many ply-drops over a short distance, and GFRP layers are overlapping tapered core plies which may have been machined. In Paper A, a coarse transition is assumed between the main laminate and adjacent core regions. However, the transition may be important to, e.g., buckling as it essentially corresponds to the boundary conditions of the panel. A similar coarse transition is achieved between the wind turbine main spar patches in Paper C. Refining the transition zone will make the problem more computationally expensive, and a suitable parameterization that ensures a good connection between the regions is still not straight forward.

Finally, in Paper A and C there are two important simplifications which call for further work. The first simplification is the frozen load envelope. There is an aero-elastic coupling between the blade stiffness/mass distribution, and the load envelope. This coupling is ignored, and further work is needed to clarify its importance. If the load envelope changes significantly in each structural iteration, it may be needed to include the load sensitivities in the problem. However, to do this it may be needed to simplify the load calculation. Otherwise, if the coupling is very small it may be sufficient to update the load envelope and re-run the optimization. The other important simplification is the frozen internal geometry, for example the width of the main laminate, the position of shear webs, etc. Including these parameters to the optimization problem may also contribute to significant mass savings.

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Paper A

Structural gradient based sizing optimization of wind turbine blades with fixed outer geometry

J. H. Sjølund, E. Lund

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The layout has been revised.

Abstract

In this work the mass of a 73.5 m offshore wind turbine blade is minimized while considering manufacturing constraints, tip displacement, buckling, and static strength criteria when subject to an extreme load envelope consisting of 12 load directions. The gradient based sizing optimization takes offset in the outer geometry and loading from a commercial 73.5 m wind turbine blade where the manufacturing mold should be re-used and hence the outer geometry is kept constant. A solid-shell finite element model of the full blade is used as basis for the optimization. The blade is divided into patches and thicknesses of ply-groups (groups of contiguous plies with the same material and fiber orientation) are used as design variables. The design variables are assumed continuous in the optimization phase. Sequential linear programming (SLP) is used to solve the problem with semi-analytical gradients. In the post-processing phase the lay-up is refined and ply-group thicknesses are rounded to a whole number of plies. The gradient based sizing optimization results in a reduced mass and many active constraints across multiple load directions while the post-processing ensures manufacturability.

Keywords wind turbine blade structural design; gradient based sizing optimization; manufacturing constraints; laminated composites

Paper B

A new thickness parameterization for Discrete Material and Thickness Optimization

J. H. Sjølund, D. Peeters, E. Lund

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Abstract

In this work a new thickness parameterization which allows for internal ply-drops without intermediate voids is introduced in the Discrete Material and Thickness Optimization (DMTO) method. With the original DMTO formulation material had to be removed from the top in order to prevent non-physical intermediate voids in the structure. The new thickness formulation relies on a relation between density variables and ply-thicknesses rather than constitutive properties. This new formulation allows internal ply-drops which is essential for composite structures as it is common practice to cover dropped plies as to avoid delaminations. Furthermore, it is demonstrated how the new thickness formulation in some cases improve the convergence characteristics. Finally, it is also shown how solid-shell elements can be utilized within the DMTO method for structural optimization of tapered laminated composite structures.

Keywords Discrete material and thickness optimization; laminated composites; manufacturing constraints

Paper C

Discrete Material and Thickness Optimization of sandwich structures

J. H. Sjølund, D. Peeters, E. Lund

The paper has been submitted to Composite Structures

The layout has been revised.

Abstract

In this paper Discrete Material and Thickness Optimization (DMTO) is used to optimize sandwich composite structures subject to both displacement and linear buckling constraints. Using a new thickness formulation where density design variables scale ply thicknesses rather than constitutive properties, it is possible to size both core and face sheet plies simultaneously. This makes it possible to have different ply thicknesses for core and face sheet layers while also covering ply-drops. Furthermore, separating core and face sheets allows enforcing a symmetric lay-up which can be important to avoid warping during curing. The approach is demonstrated in three numerical examples of increasing complexity.

Keywords Discrete material and thickness optimization; laminated composites; sandwich structures

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