ON GRADIENT BASED STRUCTURAL OPTIMIZATION OF A WIND TURBINE BLADE

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ABSTRACT

The paper presents investigations of structural optimization of a wind turbine blade where the objective is to minimize mass while taking a number of structural constraints together with manufacturing considerations into account. In this study the parameterization is restricted to thickness variables of a number of plygroups in order to obtain a good thickness distribution. The two most important ultimate load cases are considered, and it is demonstrated how gradient based optimization techniques can be used to improve the design.

1 INTRODUCTION

Gradient based structural optimization of laminated composite structures is a mature technique where a number of different parameterization methods are available. The authors have performed much research on developing the Discrete Material Optimization (DMO) and Discrete Thickness and Thickness Optimization (DMTO) methods that can be applied for solving multi-material laminate design problems. With these methods the distribution of fiber reinforced polymer (FRP) material oriented at different chosen fiber angles together with possible core materials in case of designing sandwich structures can be determined [1-6]. Manufacturing constraints or ply book rules like upper limits on the number of identical plies, allowable ply drop rates, etc., can be included in this parameterization.

However, in case of performing structural optimization of large scale laminated composite structures like offshore wind turbine blades, the DMTO approach will yield very many design variables. Typically, the objective is to reduce mass while constraints related to stiffness, buckling load factors, eigenfrequencies, local failure criteria, manufacturing constraints, etc., must be taken into account for the multi-load case design problem. Thus, the resulting mathematical programming problem may become large scale and very challenging to solve.

This work will present some parameterization approaches applied for mass minimization of a 73 m wind turbine blade for offshore wind turbines, taking some of the structural and manufacturing constraints into account. In parts of the blade the number of design variables may be reduced significantly to finding the thickness distributions of unidirectional (UD) fiber mats as these are the governing factors for satisfying the strain and displacement constraints. Similarly, the very large amount of local strain constraints can be aggregated into much fewer global constraints using P-norm functions. In this way the number of design variables and constraints can be reduced significantly while still taking a number of important manufacturing constraints into account in the optimization problem.

2 THE WIND TURBINE BLADE

The study takes offset in a 73 m wind turbine blade for offshore wind turbines. The finite element model of the blade is shown in Figure 1. The model consists of 82286 nodes and 20949 9-node layered shell elements.

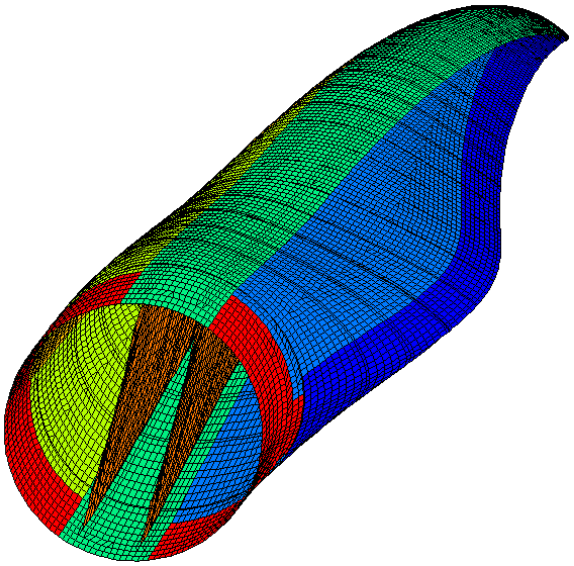

Figure 1: Finite element model of the wind turbine blade studied.

The model is fixed at the root end and extreme load envelopes of the bending moments have been provided at 30 different cross sections of the wind turbine blade. The envelopes at each cross section contain the maximum bending moments at 12 different load directions based on multiple design load cases. See Figure 2 (left) for the extreme load envelope at the root section.

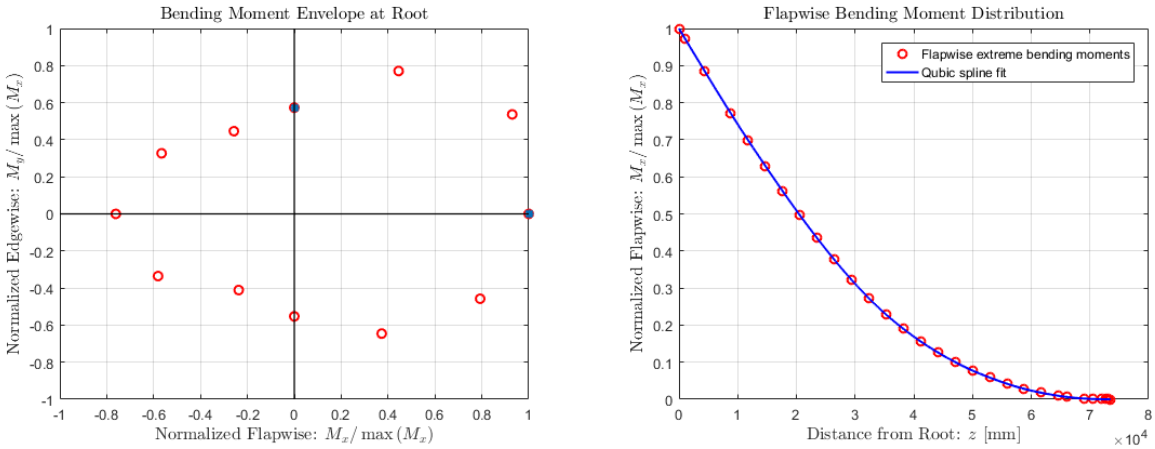

Figure 2: Left) Extreme load envelope at root section. Maximum bending moments for 12 different load directions extracted from multiple design load cases. Right) Cubic spline fit of flapwise extreme moments along the length of the blade.

In this study only two load points from the envelope are considered: flapwise (flap-to-downwind bending) and edgewise (edge-to-leading) which are marked with black dots in the left figure. The approach can easily be extended to include more envelope points on the expense of computational time. In the finite element model the loads are applied as pressures on the shell elements defining the main laminate of the wind turbine blade. These elements are illustrated with dark green color in Figure

1. Continuous distributions of the flapwise and edgewise bending moments are approximated using cubic spline fits through the 30 points for each case, see Figure 2 (right). For this calculation of the finite element loading the blade is divided into 123 longitudinal sections and for each section an equal pressure is applied to the elements located in the section interval. The pressure is calculated as the change in shear force over that given interval.

3 LAYUP AND PARAMETERIZATION

A simplified wind turbine blade layup has been constructed for the purpose of this example. The notation used for the different parts of the wind turbine blade is defined in Figure 3 where a typical cross section of the blade is shown. Basically, the main laminate must carry flapwise bending, the leading edge/trailing edge laminates must carry edgewise bending, sandwich panels are introduced between these to prevent local buckling, and the sandwich shear webs are needed due to the shear load.

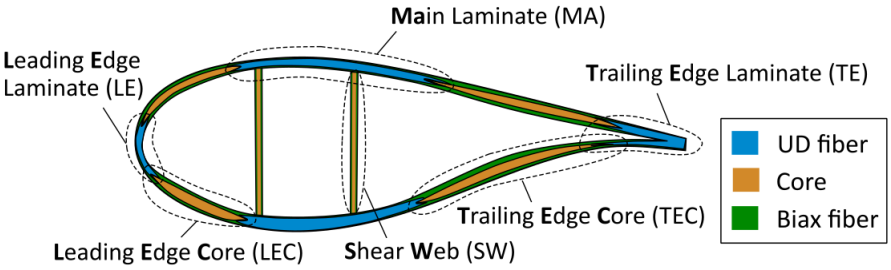

Figure 3: Typical cross section of the wind turbine blade.

The layup is basically defined through plygroups and a sequence of plygroups. A plygroup is defined as a group of plies of the same material. A plygroup can have varying thickness along the length of the blade. Hence the main laminate consisting of only UD plies and with changing thickness is considered as a plygroup. A sandwich structure will on the other hand require two plygroups: face material and core, with a sequence of face-core-face. The outer shell of the simplified wind turbine blade layup consists of 9 plygroups: cover gel, root UD, main laminate UD, leading edge UD, leading edge core, trailing edge UD, trailing edge core, root biax and "all over" biax. The notation "all over" refers to that the plygroup is used around the entire cross section of the blade. The shear webs are defined using only two plygroups: web biax and web core. This is illustrated in Figure 4 for a given cross section where abbreviations defined in Figure 3 are used for defining thicknesses of plygroups.

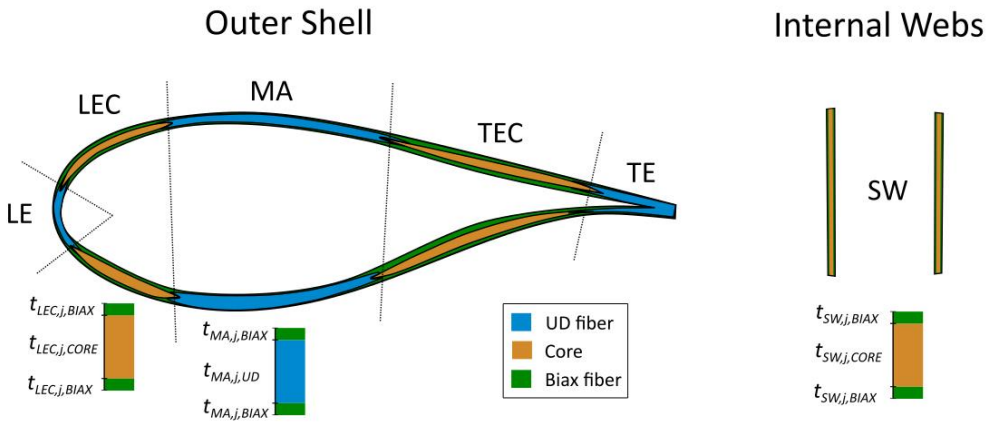

Figure 4: Parameterization of cross section number *j* of wind turbine blade. Left) Outer shell. Right) Internal webs.

The blade layup is defined through a sequence of these plygroups. The sequence defining the outer shell is listed in Table 1, and the sequence defining the internal shear webs is listed in Table 2. Sequence no. 1 is the first layer in the mold and hence the outer layer of the final blade. Initial plygroup thickness distributions will be illustrated later on in Section 5 describing the results. The initial thickness distributions are inspired by distributions seen in commercial wind turbine blades.

Outer Shell				
Sequence no.	*Plygroup name*	*Restricted to*	*Design Variable*	*Comment*
1	Cover gel	All over	No	Outer gel layer for protection of blade
2	All over biax	All over	No	Layers of biax all over the blade
3	Root biax	All over	No	Additional layers of biax near root
4	Main laminate UD	Main laminate	Yes	-
5	Root UD	All over	Yes	UD layers near root to distribute bolt loading and provide thickness for bolt inserts.
6	Leading edge UD	Leading edge	Yes	-
7	Trailing edge UD	Trailing edge	Yes	-
8	Leading edge core	Core towards leading edge	Yes	Balsa material to prevent buckling
9	Trailing edge core	Core towards trailing edge	Yes	Balsa material to prevent buckling
10	All over biax	All over	No	Layers of biax all over the blade

Table 1: Sequence of plygroups defining the layup of the outer shell of the blade. Sequence no. 1 is the first layer in the mold, and will hence represent the outer surface of the finished blade.

Internal Webs			
Sequence no.	Plygroup name	Restricted to	Comment
1	Web biax	Webs	Biax used as sandwich flange
2	Web core	Webs	Balsa used as sandwich core
3	Web biax	Webs	-

Table 2: Sequence of plygroups defining the layup of the internal shear webs.

In this study it is chosen to restrict the design variables to continuous thicknesses of the different plygroups, i.e., the choice of material, fiber angles and layup sequence is fixed. Thus, the optimized design may require some postprocessing where the thickness of each plygroup is converted to a discrete number of layers.

In Figure 4 some of the thickness design variables associated to plygroups for the different parts of cross section number j are illustrated. In general, the design variables are denoted $t_{i,j,k}$ where index i denotes circumferential region, j denotes longitudinal region, and k denotes the plygroup sequence number. Thus, the blade is divided into a number of longitudinal regions as illustrated in Figure 5. For the results shown in this paper, the length of each interval is 2 m, such that 37 longitudinal regions are defined.

The thickness changes between regions must not be too abrupt, so ply drop constraints are defined between all adjacent regions. As an example, a plydrop limit between the two patches shown in Figure 5 results in two linear constraints, where P is allowable change in thickness per meter:

$$t_{MA,3,UD} - t_{MA,4,UD} \leq d \cdot P$$
$$t_{MA,4,UD} - t_{MA,3,UD} \leq d \cdot P \quad (1)$$

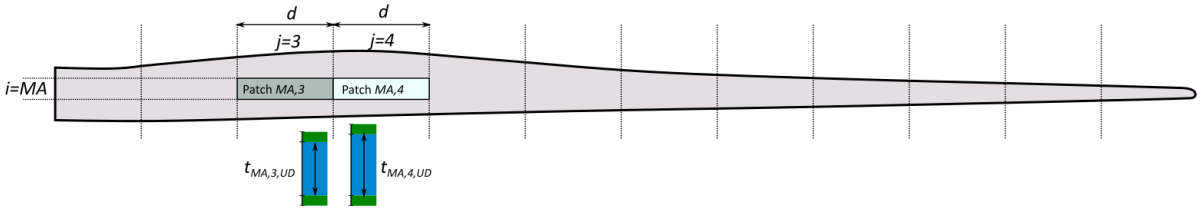

Figure 5: Longitudinal parameterization of the wind turbine blade. The distance *d* is the longitudinal length of a given region. Thickness variables for main laminate UD are shown for longitudinal regions 3 and 4.

In Figure 6 the circumferential and longitudinal regions are illustrated.

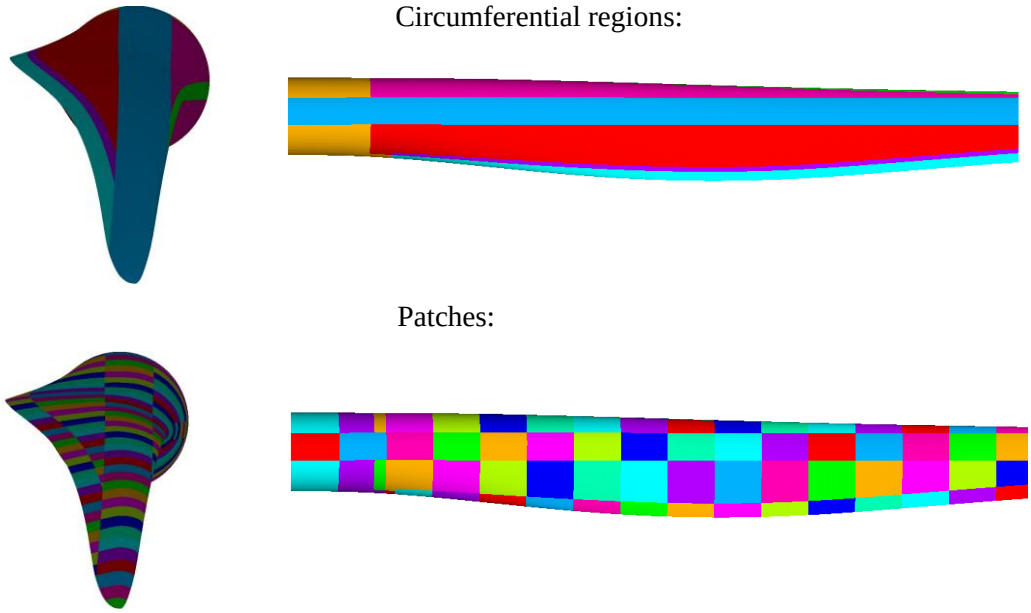

Figure 6: Parameterization of wind turbine blade illustrated on finite element model.

In the root end, the circular cross section must be remained in order to distribute the bolt loading well, and thus the thickness variables of this section are linked circumferentially. Thus, the total number of thickness variables for this parameterization is 278, and 444 ply drop constraints are defined. The parameter P is set to 5 mm/m.

4 OPTIMIZATION APPROACH

The design optimization approach applied in this work is based on the ideas introduced by Schmit in 1960 [7] of minimizing cost by means of Mathematical Programming techniques. The application of gradient based structural optimization for laminated composite structures has been applied for decades with the earliest works in the seventies by [8]. In our group a general purpose finite element based analysis and design optimization tool MUST (the MUltidisciplinary Synthesis Tool, [9]) has been developed, and the developments in this paper are implemented into this tool.

The optimization problem solved in this work is given as:

$$
\begin{aligned}
&\text{Objective :} && \min_{\mathbf{t}} \; m && && \text{(mass)} \\
&\text{Subject to :} && \lambda_n^{flap} \geq 1.0, && n = 1,\ldots,4 && \text{(flapwise buckling load factors)} \\
& && \lambda_n^{edge} \geq 1.0, && n = 1,\ldots,4 && \text{(edgewise buckling load factors)} \\
& && |u_{tip}^{flap}| \leq 25.0m && && \text{(flapwise tip displacement)} \\
& && \max(FI^{flap}) \leq 1.0 && && \text{(max failure index, flapwise load case)} \\
& && \max(FI^{edge}) \leq 1.0 && && \text{(max failure index, edgewise load case)} \\
& && \text{ply drop constraints} && && \text{(manufacturing constraints)} \\
& && \underline{t_{i,j,k}} \leq t_{i,j,k} \leq \overline{t_{i,j,k}}, && && \text{(thickness design variables)}
\end{aligned}
\tag{2}
$$

Here m is the mass of the blade, λ_n^{flap} and λ_n^{edge} the flapwise and edgewise buckling load factors, u_{tip}^{flap} the flapwise tip displacement, and FI^{flap}, FI^{edge} are failure indices computed for flapwise and edgewise loading. The design variables $t_{i,j,k}$ refer to the 278 thickness design variables, and $\underline{t_{i,j,k}}$, $\overline{t_{i,j,k}}$ are lower and upper limits on the thickness variables.

For the flapwise loading case the buckling load factors are close, and it is necessary to include several load factors in the optimization problem in order to take mode switching into account. Here 4 buckling load factors for each of the load cases have been sufficient.

Failure indices are computed using the max strain criterion at the top and bottom of each layer of each element. Thus, for the finite element model applied this generates 183,306 failure indices for each load case. This is a very large number of constraints to include, and one option is to apply active set strategies for only considering the largest values. This can be combined with aggregation functions, such that global strength measures are computed using, e.g., Kreisselmeier-Steinhauser (KS) functions or P-norm functions [10-13]. In this work P-norm functions are applied for the largest failure indices computed within each of the patches shown in Figure 6, thereby reducing the number of failure index constraints to 206 for each load case. The P-norm function $FI_{PN}^{i,j}$ approximating the largest failure index value $\max(FI_m^{i,j})$ for patch i,j is computed as:

$$
FI_{PN}^{i,j} = \left(\sum_{m=1}^{n_{FI}^{i,j}} (FI_m^{i,j})^P \right)^{1/P} \tag{3}
$$

where the number of failure indices to include for each patch, $n_{FI}^{i,j}$, is set to 50. The parameter P controls the level of smoothness, and the P-norm approaches the original max function as $P \rightarrow \infty$. However, a high value of P causes numerical problems, and in this work a value of 8 is used for P. The P-norm function is an upper bound estimate to the largest value, and therefore the adaptive constraint scaling method described in [12] is applied. In this way the global strength approximations are scaled towards the true maximum values, taking iteration history into account.

The gradients of all functions are computed using semi-analytical design sensitivity analysis based on either the direct differentiation method or the adjoint method. Details can be found in, e.g. [1-6] or [14].

The mathematical programming problem is solved using Sequential Linear Programming (SLP) combined with a merit function approach, an adaptive move limit strategy and a global convergence filter, see details in [6]. This is a very robust optimization algorithm that can handle a large number of constraints without problems. The LP subproblems are solved using CPLEX version 12.6, se [15].

5 RESULTS

The optimization iteration history is shown in Figure 7. The mass of the wind turbine blade has been reduced from 24780 kg to 22019 kg after 16 design iterations. After 16 iterations the relative change in design variables is less than 0.1% which is the convergence criterion applied. The relative change of the mass objective function in the last iteration is 0.2%.

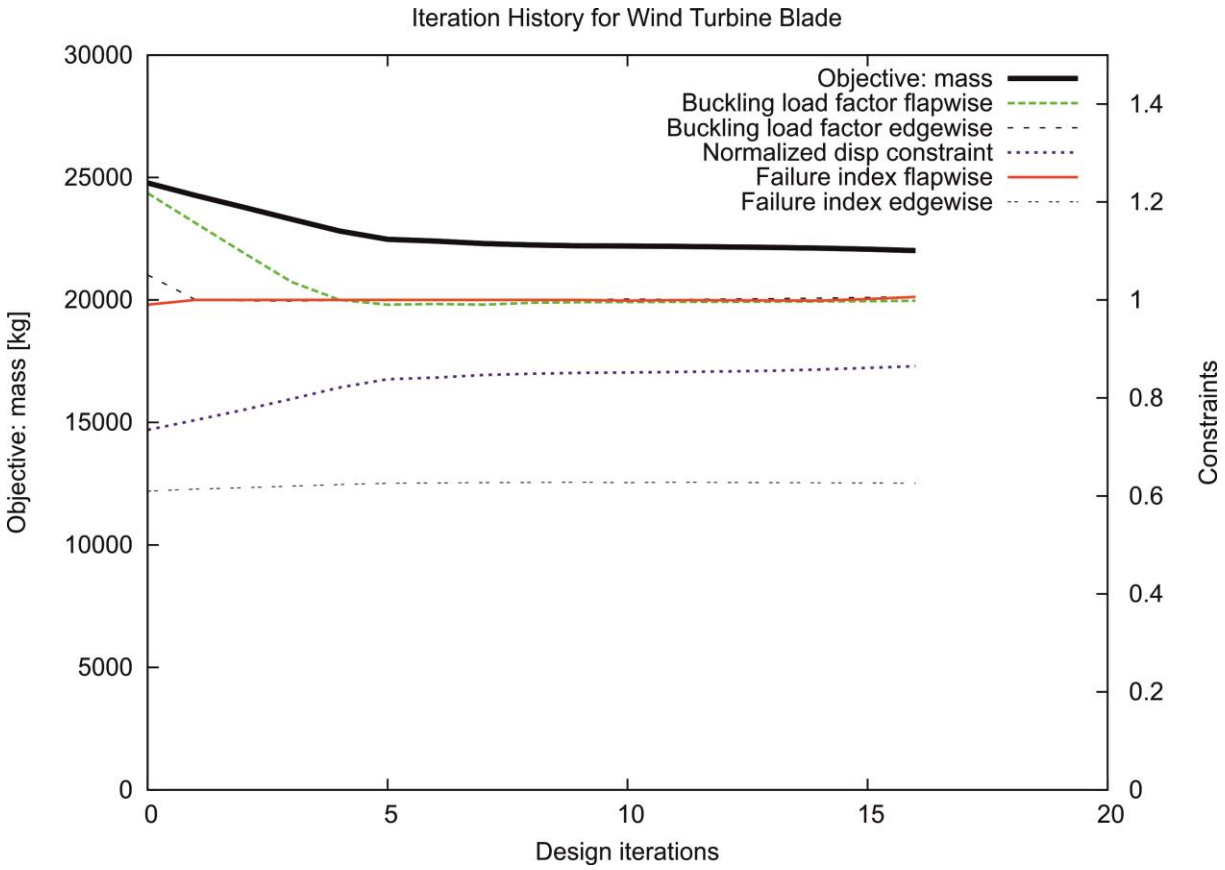

Figure 7: Optimization iteration history.

From Figure 7 it can be seen that it is mainly the two buckling constraints and the failure index in the flapwise loadcase that are governing the optimization. These three constraints are fulfilled within the 0.5% accept tolerance that was specified for the global convergence filter of the SLP algorithm. A more strict constraint violation criterion could have been applied, if wanted. For the flapwise buckling load factors, the four lowest load factors vary within 4.5% for the optimized design. The iteration history illustrates the robustness of the optimization approach as only very small fluctuations are seen.

The initial and optimized plygroup thicknesses along the length of the blade for TE/TEC/MA/LEC/LE/SW regions are shown in Figures 8-13.

The trailing edge sees an almost uniform reduction in thickness of all plygroups across the full length of the blade, see Figure 8. The same can be said for trailing edge core, leading edge, leading edge core and shear webs, see Figures 9, 11, 12 and 13.

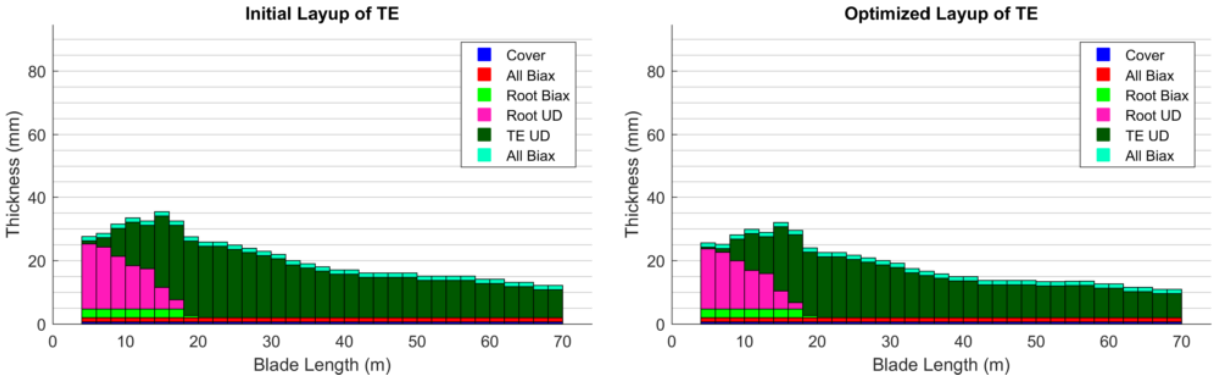

Figure 8: Trailing edge plygroup thickness distribution. Left) Initial. Right) Optimized.

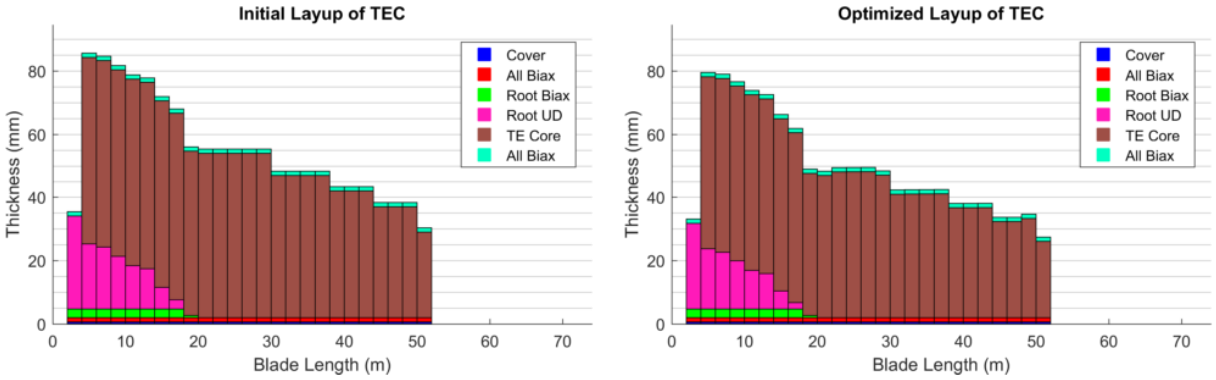

Figure 9: Trailing edge core plygroup thickness distribution. Left) Initial. Right) Optimized.

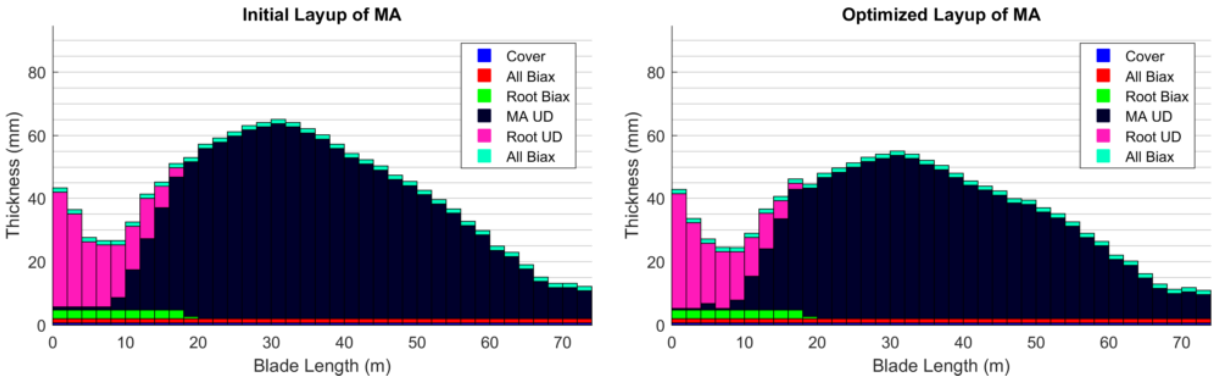

Figure 10: Main laminate plygroup thickness distribution. Left) Initial. Right) Optimized.

In the main laminate the reduction in thickness is primarily occurring in the MA UD plygroup, see Figure 10. Although a thickness reduction is also seen in the Root UD plygroup, this reduction is limited by the thickness requirement at the root, and subsequent plydrop constraints. A couple of additional observations can be made. It is seen that the thickness of the MA UD plygroup is increased slightly in the interval of 4-6 m, while no increase is seen in the next interval from 6-8 m. This results in a local thickness decrease and increase which is unfavorable from a manufacturing point of view. A similar situation is found in the shear webs where a local increase in thickness can be seen between 2-4 m. Such changes in thickness could be avoided by adding more constraints on allowable thickness

changes.

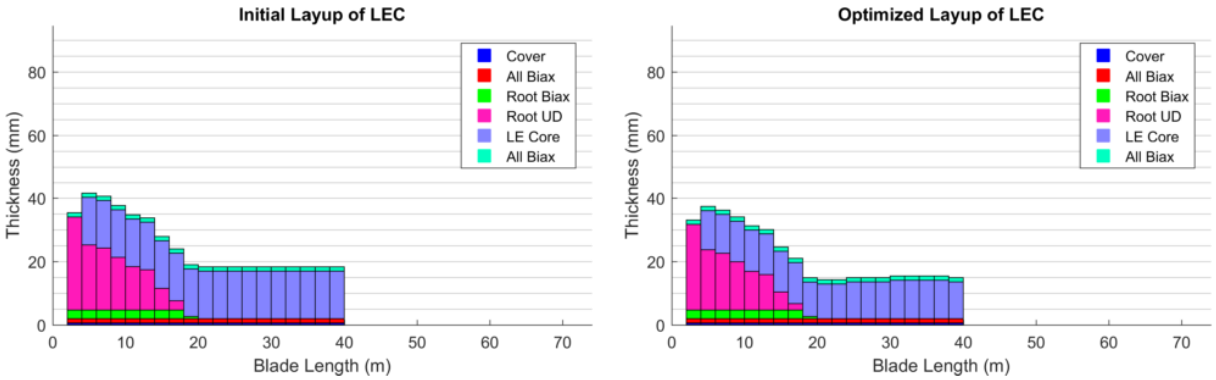

Figure 11: Leading edge core plygroup thickness distribution. Left) Initial. Right) Optimized.

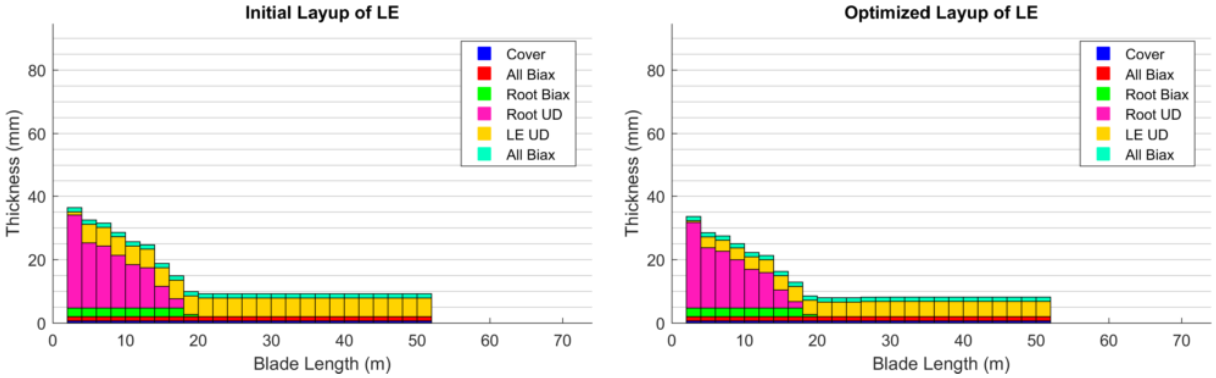

Figure 12: Leading edge plygroup thickness distribution. Left) Initial. Right) Optimized.

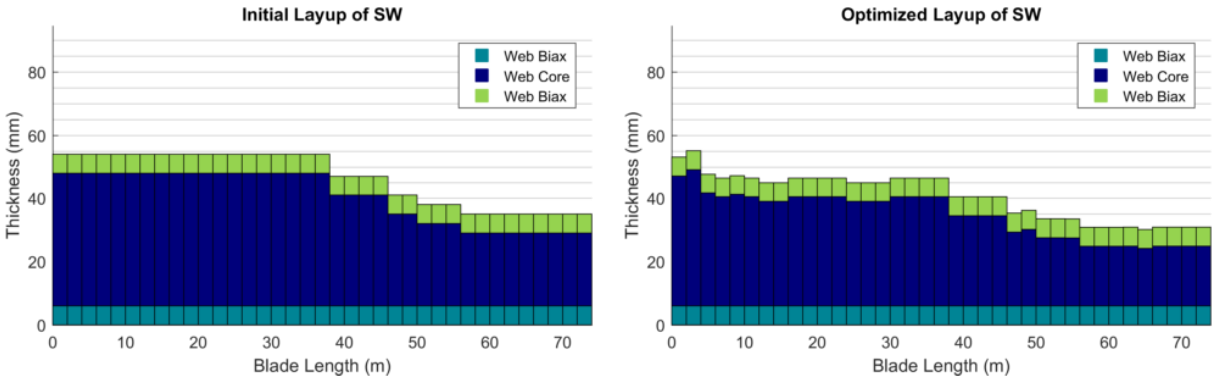

Figure 13: Shear webs plygroup thickness distribution. Left) Initial. Right) Optimized.

The optimized design has a very uniform distribution of failure indices. In Figure 14 the maximum failure index for each element through-the-thickness is shown for the critical flapwise load case, demonstrating that the blade is designed very well from a strength point of view.

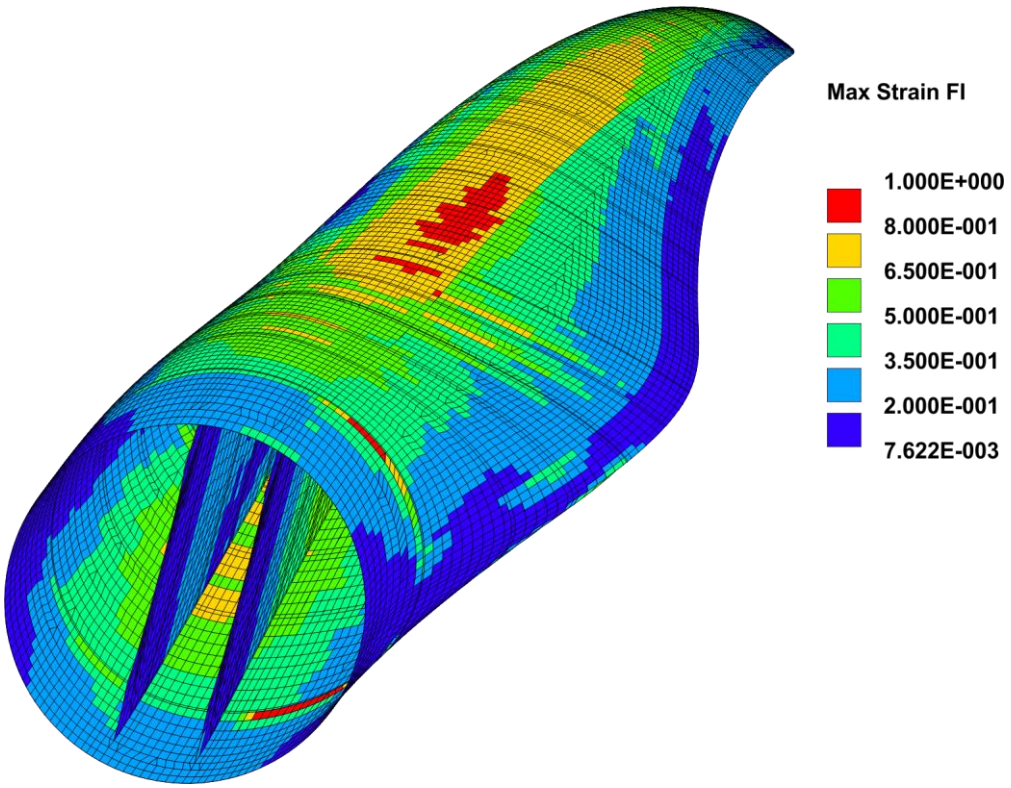

Figure 14: Plot of maximum through-the-thickness failure index for flapwise load case.

6 CONCLUDING REMARKS

Results have been presented for the mass minimization of an offshore wind turbine blade and the potential of applying structural optimization techniques for such challenging real-life design problems have been demonstrated. This is ongoing work, and a number of things will be added to the study. First of all, all the load cases shown in Figure 2 will be incorporated including fatigue load cases, such that the optimization will take into account both ultimate load cases as in the results shown in this paper together with fatigue constraints. Eigenfrequencies can also be included, and the mass reduction will probably be lower when all relevant criteria and load cases are included in the problem formulation. The linear buckling load factors together with tip displacements will be verified by geometrically nonlinear analyses and comparisons with relevant experimental values. The failure criterion to apply will be investigated, and finally, the design obtained when converting the continuous thicknesses to a discrete number of plies will be investigated. This conversion might result in quite different ply thicknesses and thereby different response values. One way to avoid this could be to apply the DMTO method for the parameterization [4-5] whereby a discrete number of plies is obtained, at the cost of introducing more design values.

ACKNOWLEDGEMENTS

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