Structural optimization of wind turbine blades

minimization of mass

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Challenge, objective and method

Challenge: Rotor diamater continues to increase in size ->

increased mass and loads

Objective: Reduced mass of blade:

- Reduced cost of materials
- Lighter rotor (benefits to many parts in drive train & tower)

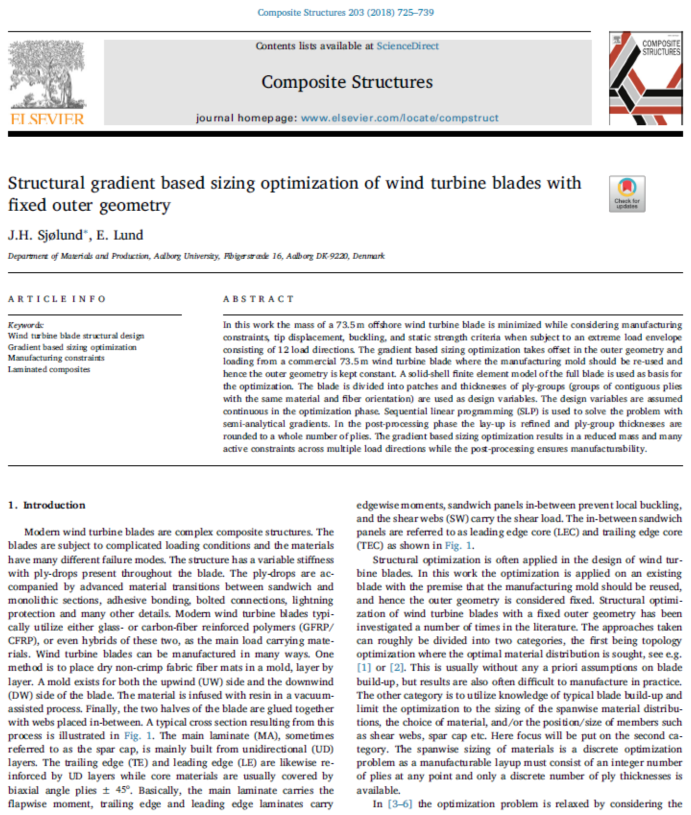
Method: Structural optimization techniques – gradient based optimization

Basic idea

Basic idea
- Take offset in existing production method
- Keep it simple (number of design variables)
- Use full-scale 3D solid-shell FE model
  - No inherent restrictions (unlike beam models)!

Minimize mass of 73.5 m offshore wind turbine blade
- State-of-the-art in-house research code
- Re-use mold (outer geometry fixed)
- Constant loads – 12 load cases considered
- Find weight-optimal layup
  - Tip displacement constraint
  - Strain constraints
  - Buckling constraints
  - Manufacturing constraints

Paper: *Structural gradient based sizing optimization of wind turbine blades with fixed outer geometry, Composite Structures, 2018*



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

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A R T I C L E I N F O

Keywords:
Wind turbine blade structural design
Gradient based sizing optimization
Manufacturing constraints
Laminated composites

A B S T R A C T

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.

1. Introduction

Modern wind turbine blades are complex composite structures. The blades are subject to complicated loading conditions and the materials have many different failure modes. The structure has a variable stiffness with ply-drops present throughout the blade. The ply-drops are accompanied by advanced material transitions between sandwich and monolithic sections, adhesive bonding, bolted connections, lightning protection and many other details. Modern wind turbine blades typically utilize either glass- or carbon-fiber reinforced polymers (GFRP/CFRP), or even hybrids of these two, as the main load carrying materials. Wind turbine blades can be manufactured in many ways. One method is to place dry non-crimp fabric fiber mats in a mold, layer by layer. A mold exists for both the upwind (UW) side and the downwind (DW) side of the blade. The material is infused with resin in a vacuum-assisted process. Finally, the two halves of the blade are glued together with webs placed in-between. A typical cross section resulting from this process is illustrated in Fig. 1. The main laminate (MA), sometimes referred to as the spar cap, is mainly built from unidirectional (UD) layers. The trailing edge (TE) and leading edge (LE) are likewise reinforced by UD layers while core materials are usually covered by biaxial angle plies ± 45°. Basically, the main laminate carries the flapwise moment, trailing edge and leading edge laminates carry edgewise moments, sandwich panels in-between prevent local buckling, and the shear webs (SW) carry the shear load. The in-between sandwich panels are referred to as leading edge core (LEC) and trailing edge core (TEC) as shown in Fig. 1.

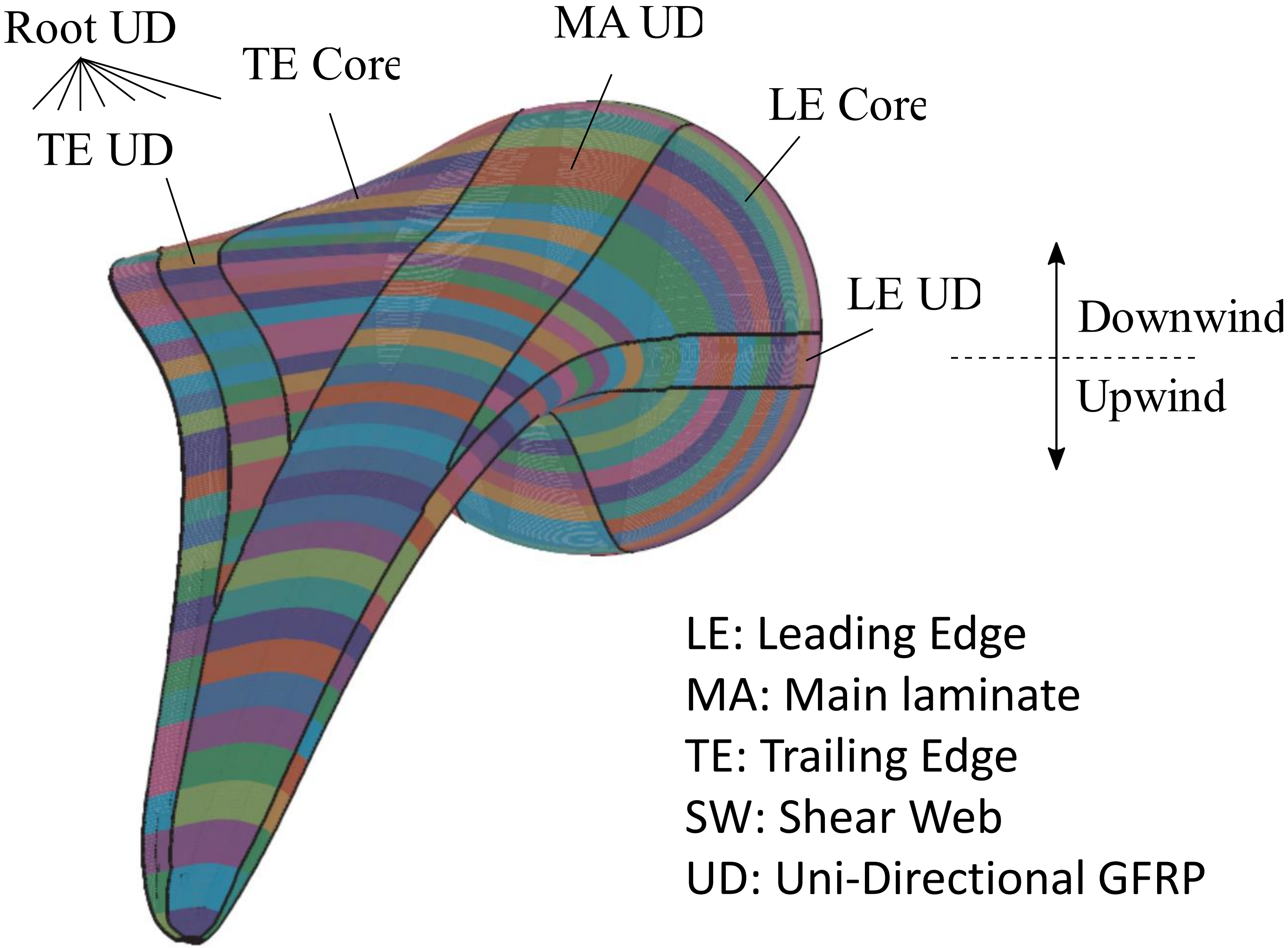
Structural optimization is often applied in the design of wind turbine blades. In this work the optimization is applied on an existing blade with the premise that the manufacturing mold should be reused, and hence the outer geometry is considered fixed. Structural optimization of wind turbine blades with a fixed outer geometry has been investigated a number of times in the literature. The approaches taken can roughly be divided into two categories, the first being topology optimization where the optimal material distribution is sought, see e.g. [1] or [2]. This is usually without any a priori assumptions on blade build-up, but results are also often difficult to manufacture in practice. The other category is to utilize knowledge of typical blade build-up and limit the optimization to the sizing of the spanwise material distributions, the choice of material, and/or the position/size of members such as shear webs, spar cap etc. Here focus will be put on the second category. The spanwise sizing of materials is a discrete optimization problem as a manufacturable layup must consist of an integer number of plies at any point and only a discrete number of ply thicknesses is available.

In [3–6] the optimization problem is relaxed by considering the

Basic idea

Basic idea:
- Divide blade into patches
- Change the thickness of ...
  .. in each patch

(Takes offset in production method)

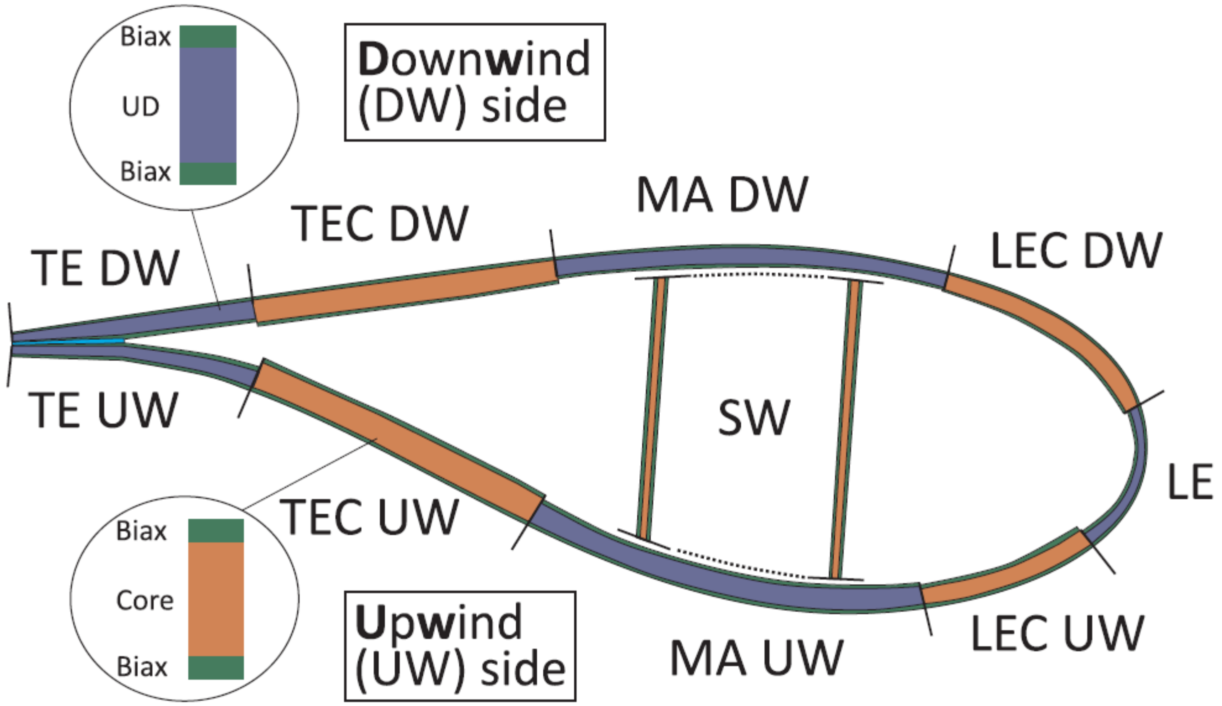


LE: Leading Edge
MA: Main laminate
TE: Trailing Edge
SW: Shear Web
UD: Uni-Directional GFRP

Design variables

Design variables

- Thickness of UD ply-group *or* core-material in each patch
- Total number: 406



LE: Leading Edge
MA: Main laminate
TE: Trailing Edge
SW: Shear Web
UD: Uni-Directional GFRP

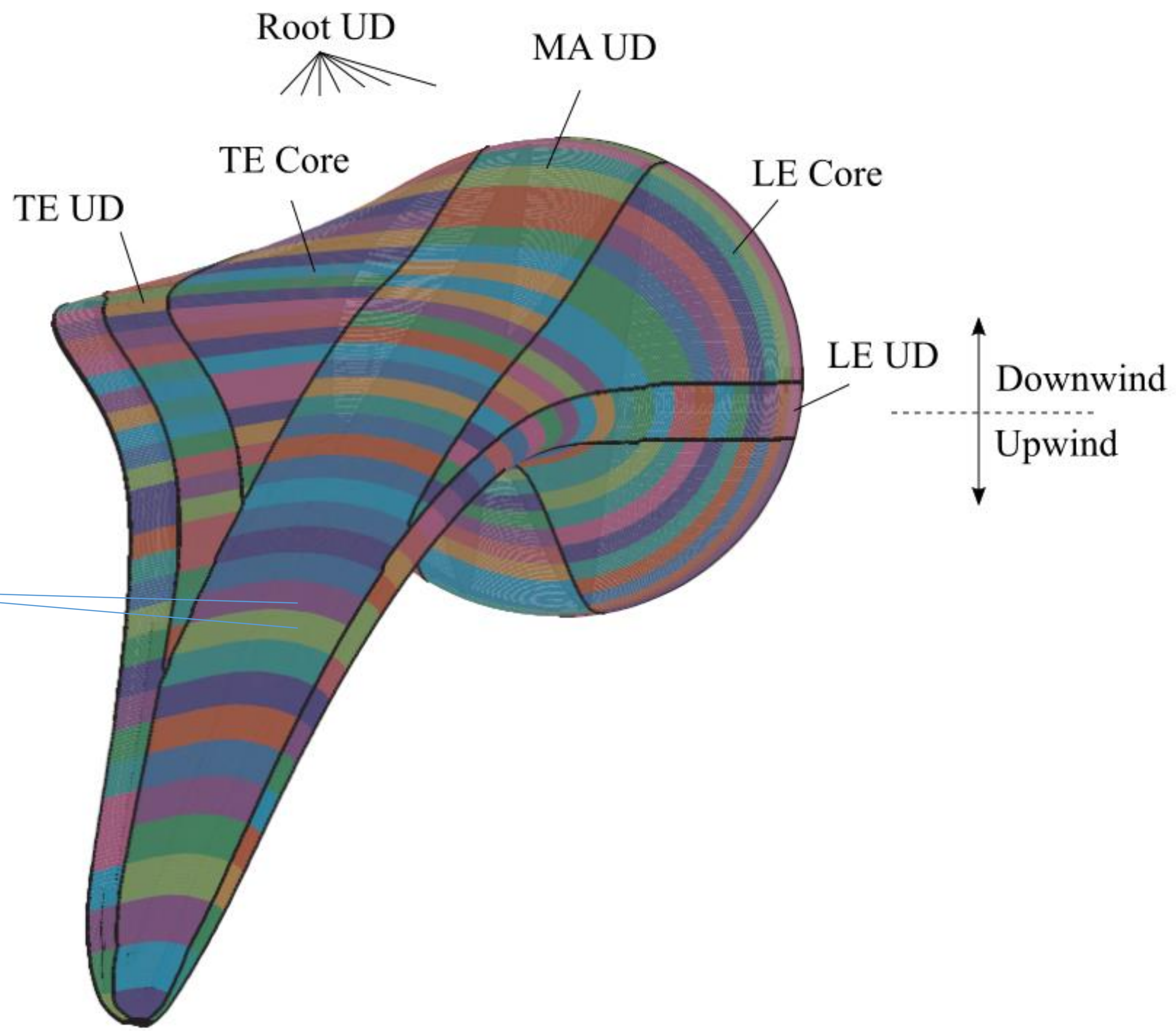
Manufacturing constraints

Manufacturing constraint:

- Limit on thickness change from patch to patch

Example:

- Min. ply-drop distance: 200 mm
- Patch length: 2 m (coarse model)
- Max. thickness change between patches: 10 plies



Optimization problem

Objective:

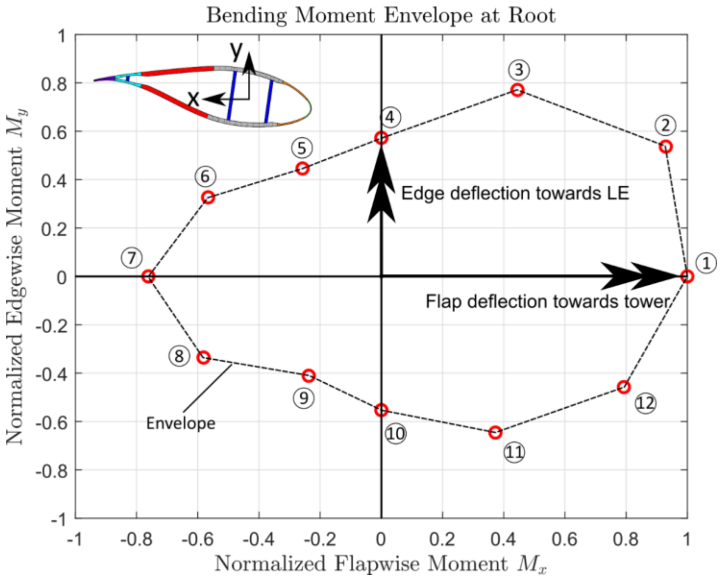
- Minimize mass

Subject to:

- Buckling load factors (12 load cases)
- Max. strain failure indices (12 load cases, reduced using p-norm functions)
- Tip displacement (flapwise load case only)

... = 25 structural constraints

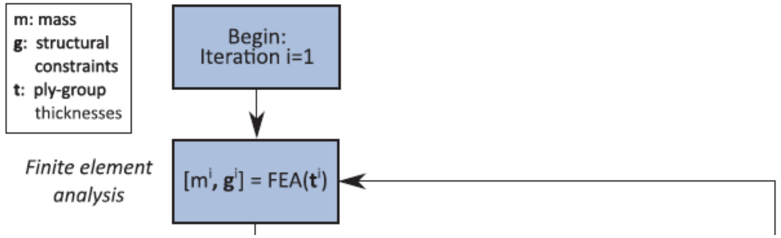
... + 678 ply-drop constraints



Solution approach

Solution approach (SLP – Sequential Linear Programming):

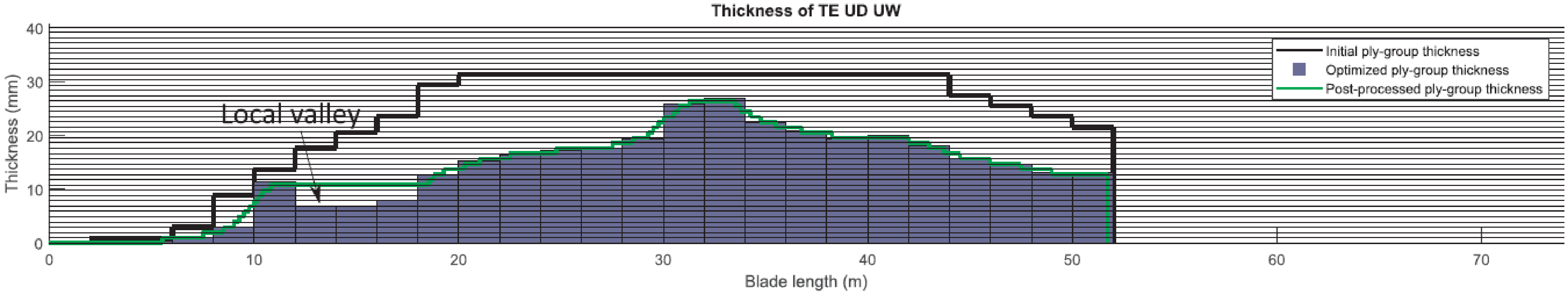
- Finite element analysis
- Gradients: Design Sensitivity Analysis
  - Efficient method (not by 406*25 analyses...)
  - ABAQUS also supports this from 2018 version
- Linear programming
- Accept solution?
- Repeat...



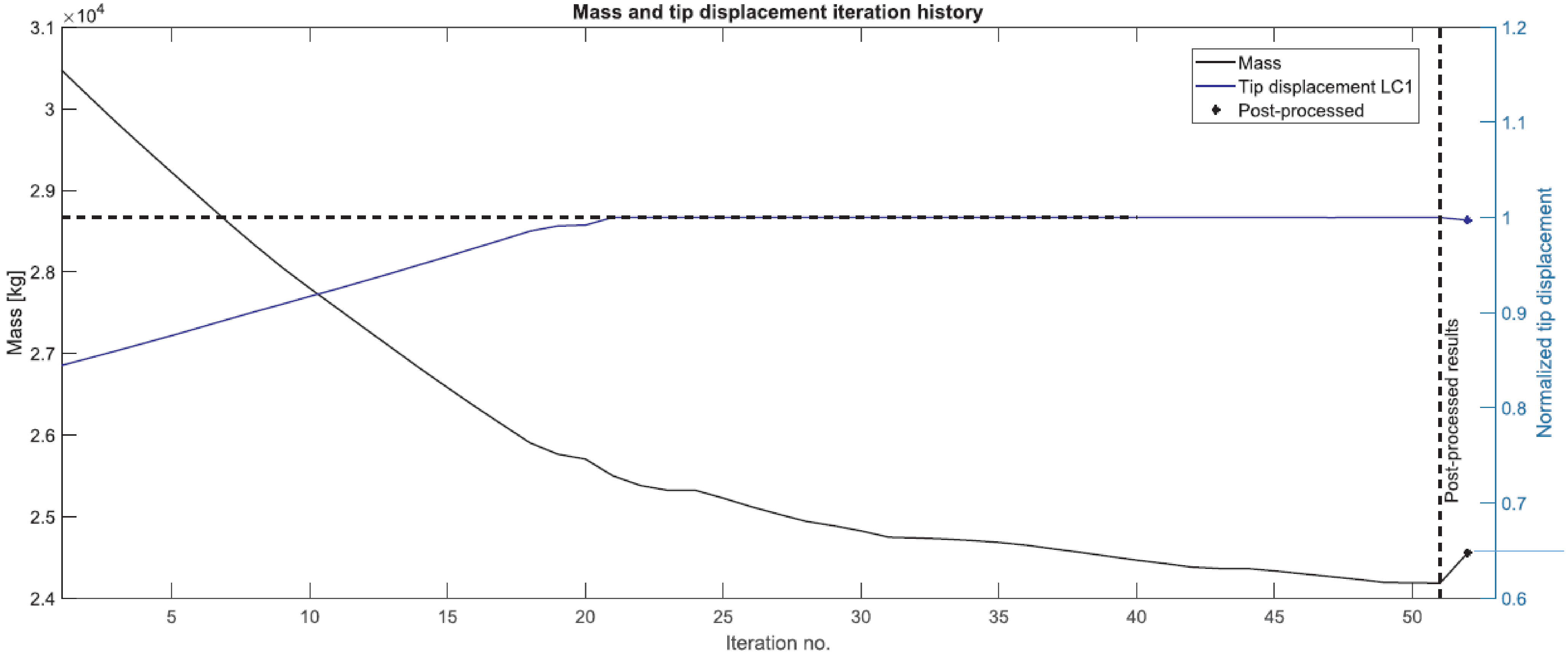
Post-processing

Manufacturable layup:

- Whole number of plies
- Avoid local valleys
- Interpolate between 2 m sections



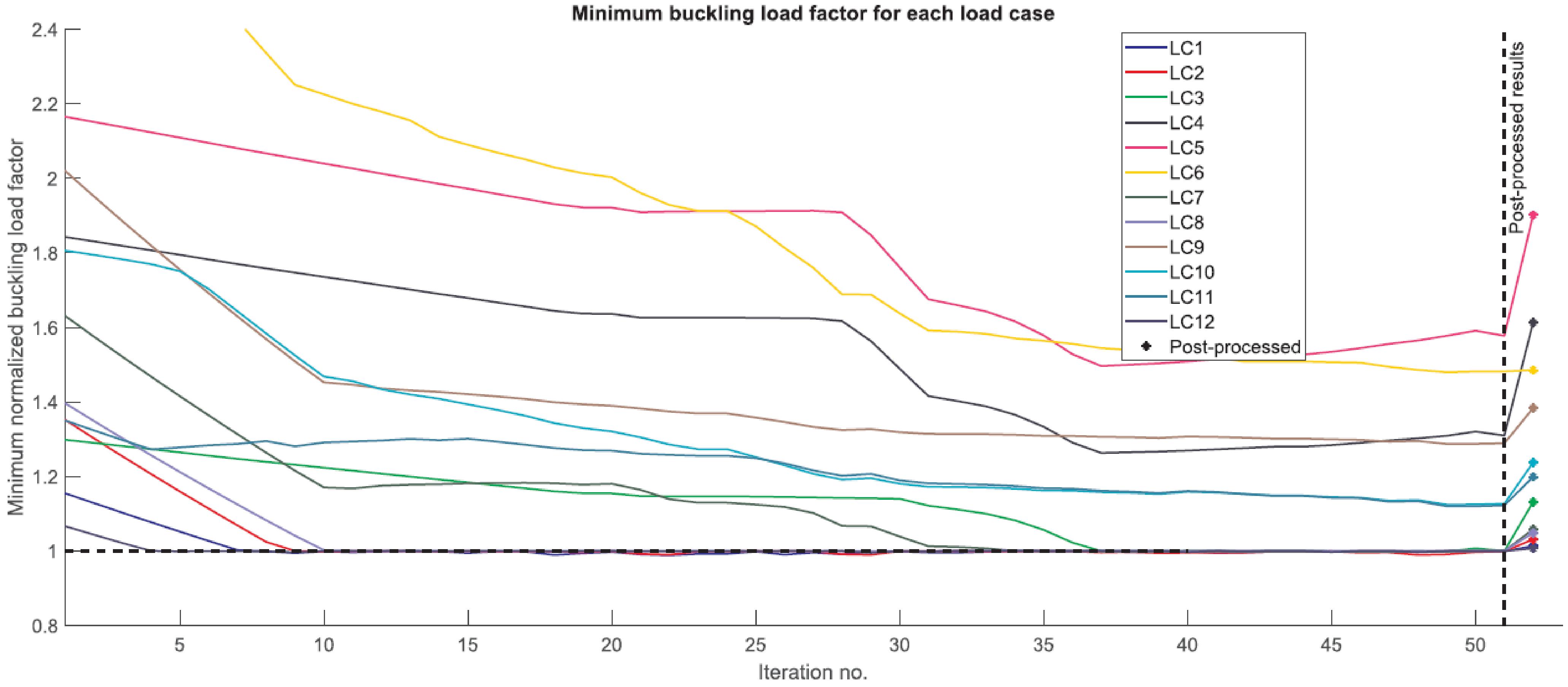
Convergence – mass and tip displacement



18.5 m

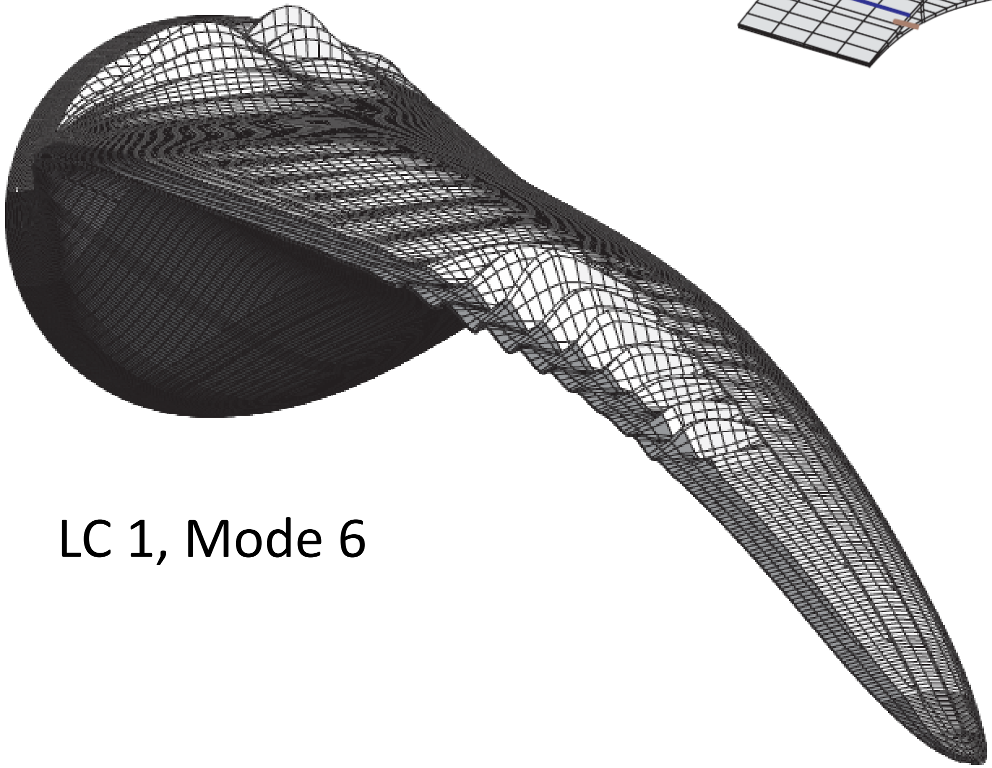
24556 kg

Convergence - buckling

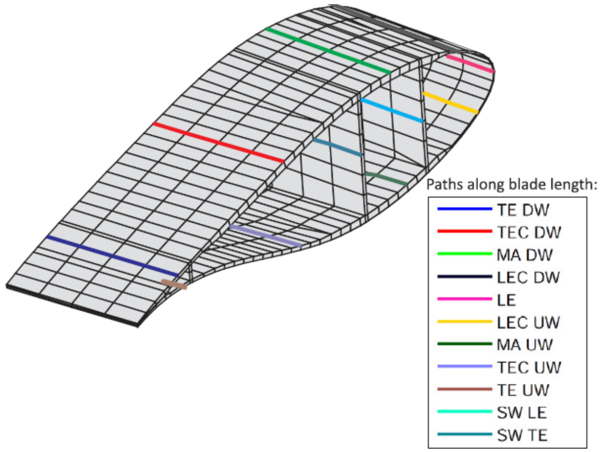


Buckling modes

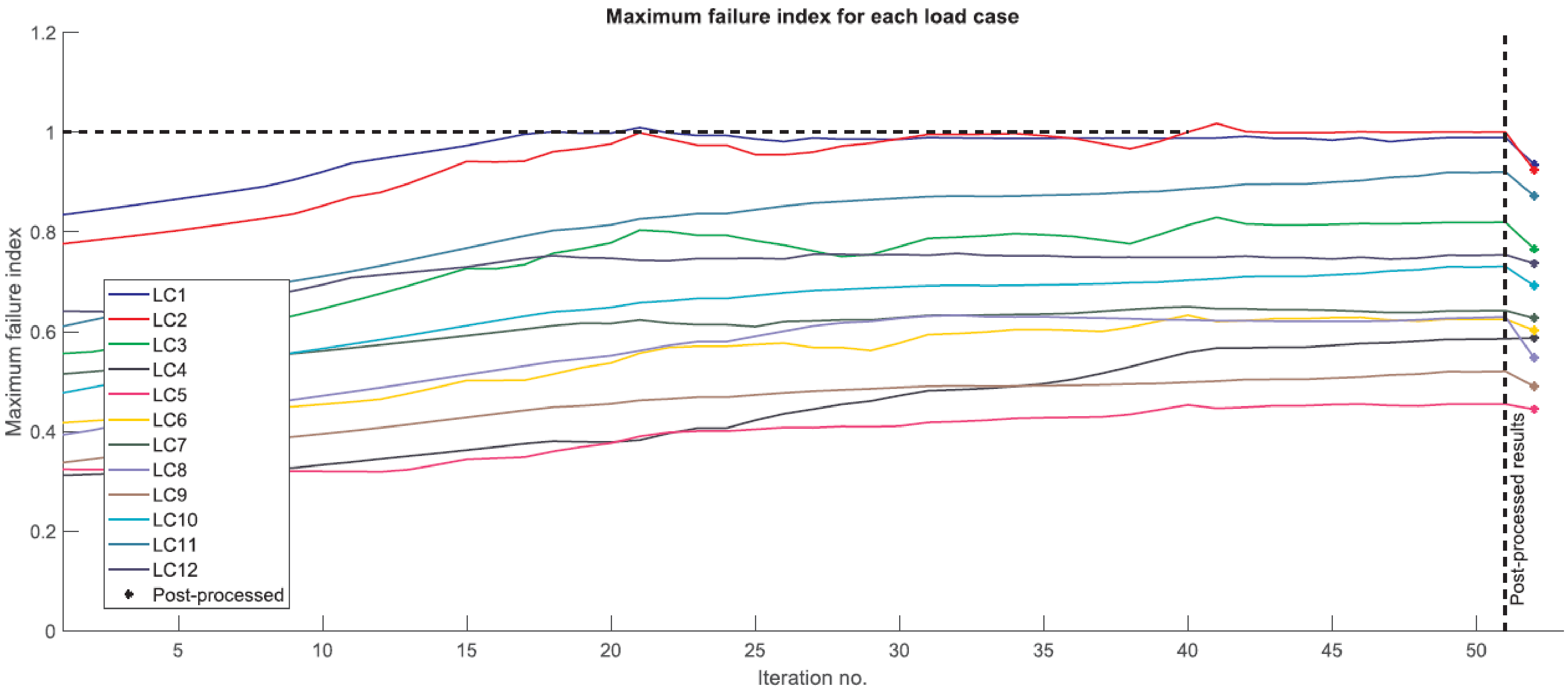
Buckling load factors very close (limit is 1.96).
Mode 6 spans most of blade. Well distributed stiffness!



LC 1, Mode 6



Convergence – failure indices



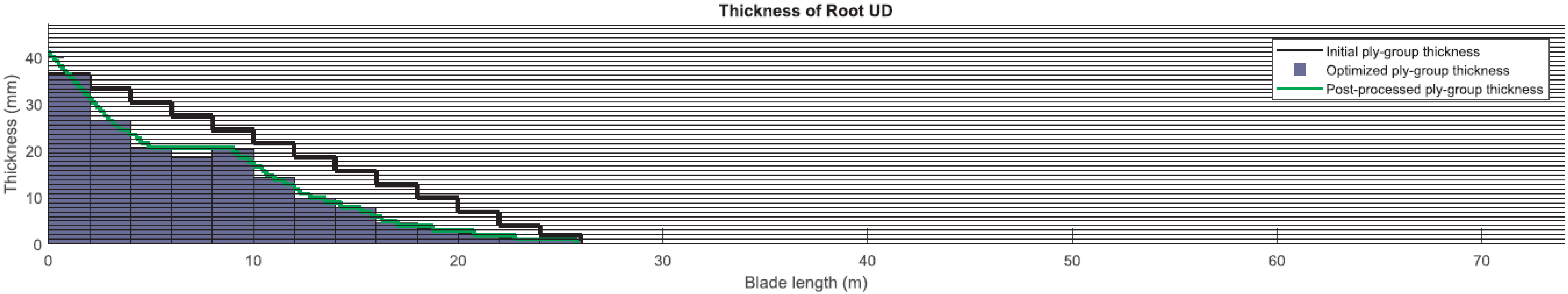
Results

Results:

- 10 plots like below
- See paper in Composite Structures for all plots and in-depth discussion.

Root UD:

- Heavy ply-group (”all-over”)
- Better to increase individual regions
- Small increase from 8-10 m needed to prevent buckling



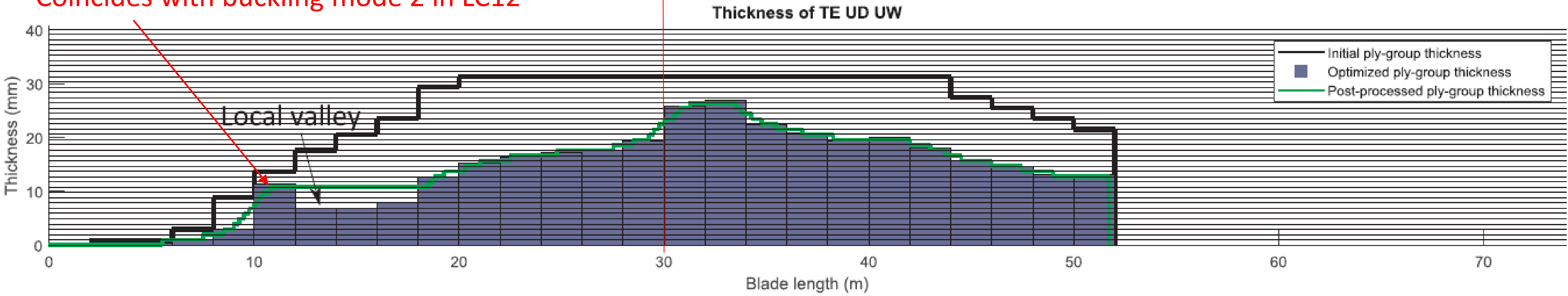
Results

TE UD UW (UD material in trailing edge upwind side):

- Local valleys filled
- UW side much lighter than DW side
- Buckling critical

Termination of 3rd shear web. Important for buckling

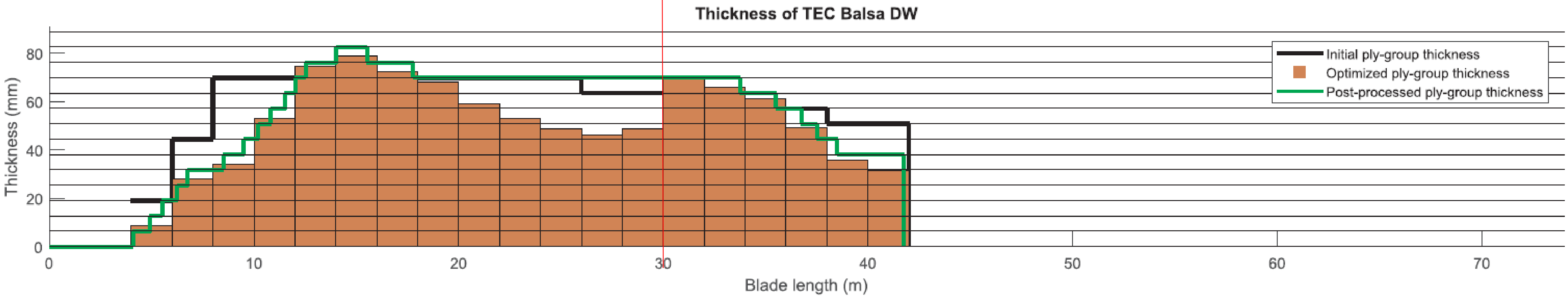
Coincides with buckling mode 2 in LC12



Results

TE Core Balsa (DW) similar

Termination of 3rd shear web. Important for buckling



Potential – concluding remarks

- Gradient based optimization of composite structures is a mature technology
- Commercial FE tools (e.g. Abaqus) provide sensitivities of laminate thicknesses and angles -> can be integrated in existing design process
- Demonstrated with success for mass minimization of 73.5 m offshore wind turbine blade
- Parameterization involving multi-material topology and thickness optimization also developed (in in-house code)

Questions?