Optimizing the Lamination Plan of a Canting Keel

N. Zehnder * and P. Ermanni

Center of Structure Technologies, Swiss Federal Institute of Technology Zürich, Leonhardstrasse 27, CH-8092 Zürich, Switzerland

A laminate optimization methodology capable to find the optimal shape, size, and position of patches of reinforcement fibers is applied on a real-world structure. The entire lamination plan of a sailboat keel under bending and twisting loads is optimized in order to minimize the angle of attack at the tip of the structure. The optimization is performed on three different lay-up schemes with increasing complexity and their numerical results are compared to a reference lay-up. In order to show the methods robustness, the optimizations are allways started from randomly chosen starting points in the design space of the corresponding parameterization.

Key words: Global optimization, structural optimization, evolutionary algorithms, composites, laminates, keel, sailing boat

1 Introduction

In earlier works [1] an optimization methodology built to find the best lamination plan of complex structures was introduced. In addition to the more often used optimization parameters which describe the material itself (material properties, material thickness, and material orientation) the method has the ability to find the optimal shape, size, and position of the area where the material is applied. With reference to the abovementioned work such an area is called *patch geometry*. This name is derived from the basic building entity

* Corresponding author. Tel.: +41-1-632-7174. fax +41-1-633-1125
Email address: zehnder@imes.mavt.ethz.ch (N. Zehnder).

of a laminated structure, i.e. the patch of reinforcement fibers. The method's functionality has been validated on academic examples, but it has not yet been tested with multiple patch geometries. Therefore the present article describes the application of the optimization methodology on the entire lamination plan of a sailing boat keel. The problem and its environment are introduced briefly in the following:

In classical sailboat designs the keel has to fullfill two totally different tasks. First of all it supports the ballast bulb which contributes to the righting moment of the boat and second it acts as a hydrofoil to improve the luffing efficiency of the boat [2–6]. In more modern designs the two tasks are separated and distributed to independent structures, a so-called canting keel and specialized daggerboards or fins. The canting keel still supports the ballast bulb, but in contrary to its fixed counterpart it can be articulated to both sides of the hull to improve the bulbs righting moment, whereas the lift to weather is produced by the daggerboards or fins [1]. In such a configuration the keel loses its fluid-dynamic functionality, but nevertheless it is still dragged through the water and it is of vital importance to reduce its drag. The drag of the keel fin certainly is influenced by various parameters, but in this work only the position of the ballast bulb relative to the keel fin is of interrest (see Figure 1). The centered bulb configuration (*T-shape*) introduces no twisting moment, but the possibility that kelp or trash gets stuck is high. With an *L-shaped* keel in contrary, the chance that something gets stuck is smaller and it is more robust to grounding. The major drawback of this shape is the twisting moment which is introduced into the keel. Since twisting of the keel fin increases the angle of attack and therefore also increases the drag, it should be eliminated. In this work we assume that a trailing ballast bulb is preferable, but the twisting of the keel fin should be minimized for the abovementioned reasons. The present article investigates to what extent the twisting can be influenced solely with the laminate lay-up of the keel.

2 The Model

The keel to be investigated is roughly $3\,m$ in length and its sections are $0.6\,m$ deep. The keel is canted by 40^o relative to the boat, while the entire boat itself is healed by 14^o, resulting in an overall angle of 54^o to the vertical. The tip of the keel fin is loaded with forces equivalent to a bulb of $3\,tons$ hanging of the leading edge. With a closed mold process with an interior pressure bag in mind, the keel is modeled as a single shell without interior structure, whereas the detailed construction of the hinged root is left aside. Instead, the structure

[1] http://www.cbtfco.com

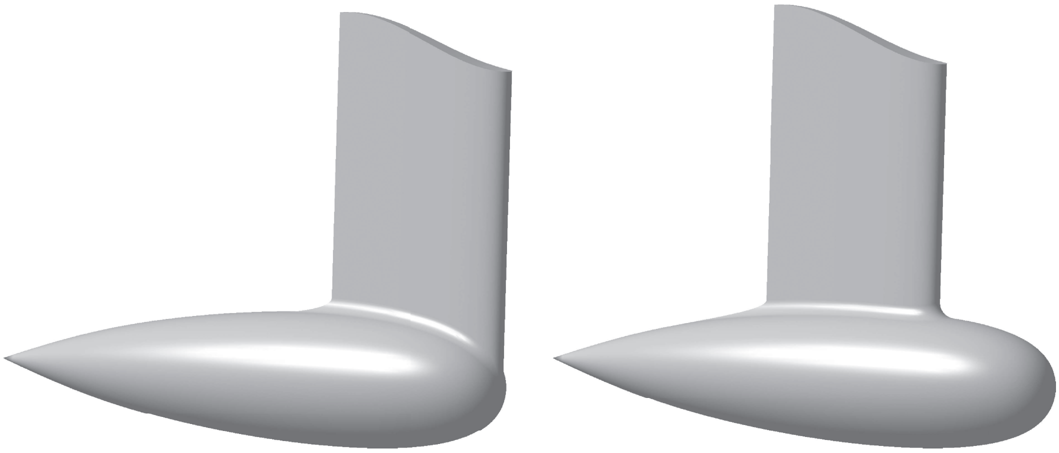

Fig. 1. Two different ways to position the ballast bulb relative to the keel. The *L-shape* to the left and *T-shape* to the right

is clamped at some distance from the hinge where local effects have decayed (see Figure 2). The tip section is modeled as a rigid plate, where the forces can be applied without causing unrealistic local deformations.

The objective of this optimization is to minimize the twisting of the keel's tip with a constrained mass and a constrained middle displacement of the tip section. The measure for the keel twist is the angle Θ of the tip section, which is calculated from the appropriate nodal deformation vectors in global coordinates.

$$\Theta = arctan(\frac{u_{l_x} - u_{t_x}}{u_{l_y} - u_{t_y}}) \tag{1}$$

Whereas $\vec{u_l}$ denotes the deformation vector of a node laying on the leading edge and $\vec{u_t}$ the corresponding vector of a node laying on the trailing edge. The middle displacement d of the tip section is given by the same two vectors as:

$$d = |\vec{u_m}| = \frac{|\vec{u_l} + \vec{u_t}|}{2} \tag{2}$$

The displacement d is constrained in such a way that it will not exceed $0.1\,m$ and the mass of the keel fin is constrained in the same manner to $250\,kg$.

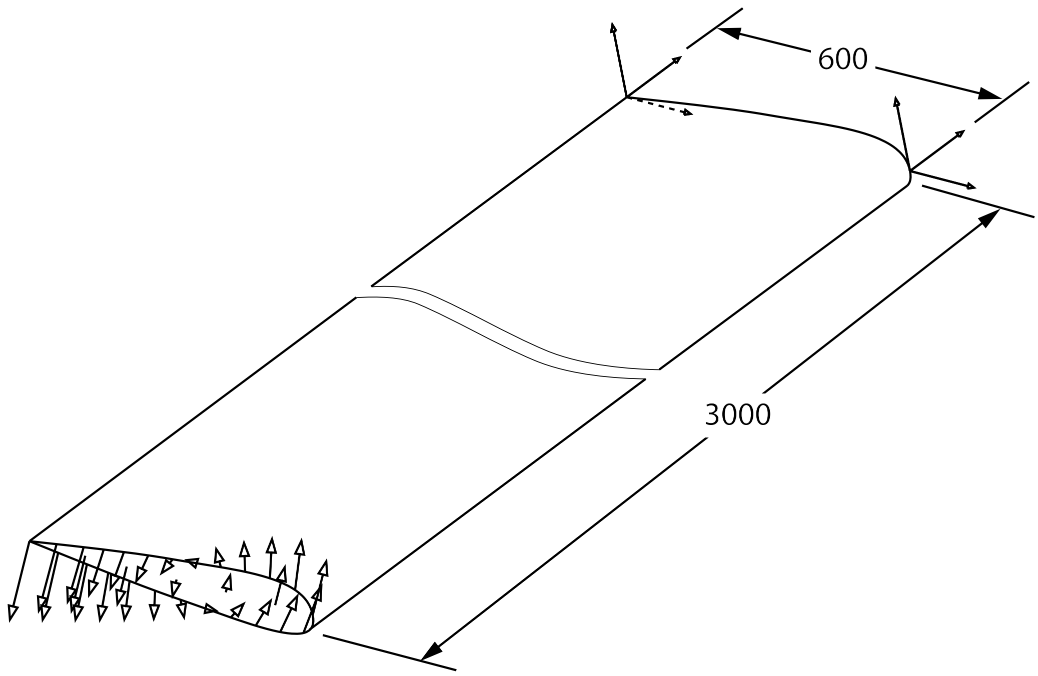

Fig. 2. The model of the keel with the restrained translations at the root and the nodal forces acting on the tip of the structure. All measures are in mm.

3 Patch Parameterization

According to the parameterization scheme presented in [1] the patch is the smallest indivisible entity of laminated structures, i.e. the basic building element. It consists of the three orthogonal sets of parameters, patch material, material orientation, and patch geometry.

Patch material: It is assumed that the fin is built in prepreg technology using unidirectional or woven carbon material. The woven material is applied not as a single layer but always in pairs of two layers whose orientations differ by 45^o, resulting in a $[0^o, 90^o, +45^o, -45^o]$ laminate. It is evident from the polar diagrams of Figure 3 that the laminate can be modeled as a transversely-isotropic material with a Young's modulus of $29.7\,GPa$ and a Poisson's ratio of 0.48. The compacted thicknesses of the two materials are given as $0.2\,mm$ for the unidirectional and as $0.4\,mm$ for the weave laminate. In this example the thickness of the patch material is the only optimization parameter the patch material provides. It simulates the placement of multiple layers of material within allways the same patch geometry. Hence, the thickness can only have values equal to multiples of the single layer thickness.

Patch geometry: Figure 4 shows the two different patch geometries used to build the lay-up of the keel. The *longitudinal patch*, shown on the left hand side, is parameterized by the position (P_x, P_y) of its base point and through its width W and length L. Whereas the second patch geometry, the *angular*

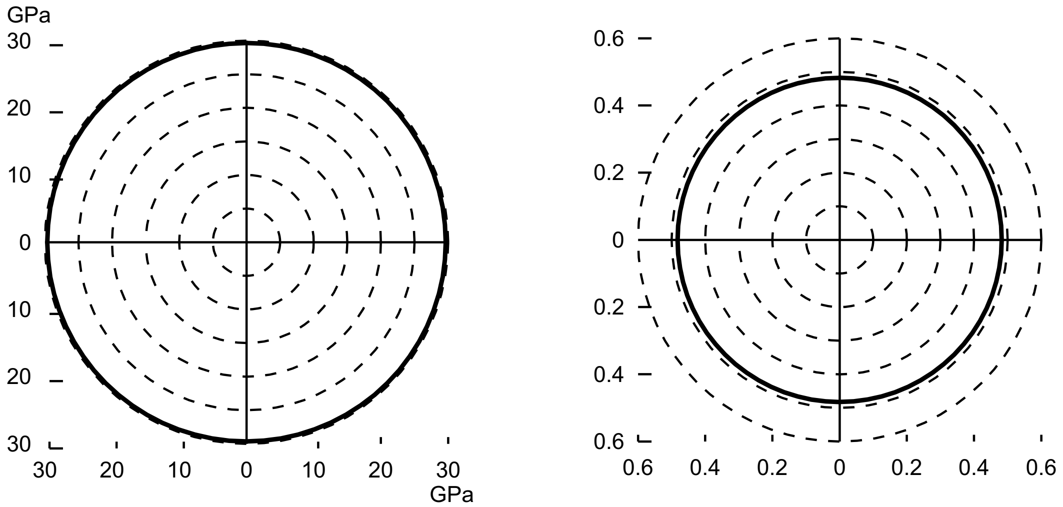

Fig. 3. Homogenized Young's modulus and Poisson's ratio of the used laminate.

patch, shown on the right hand side of Figure 4 is parameterized with its angle α and the position of its pivot point $(P_x,\ P_y)$. The width is not used as an optimization parameter and is set to $\frac{1}{3}\,m$ such that a roll of $1\,m$ in width can be split into three smaller rolls. In length, the angular patch allways starts at the boundaries of the side it is applied upon.

Material orientation: Both patches possess a fixed material orientation given by the edge of the banded structures (see Figure 4). This is assumed as to minimize the cuttings of rolled weave and UD materials.

4 Model Parameterization

Using the two abovementioned types of patches, three different lay-up parameterizations are set up and optimized. They vary by the number of applied patch geometries and by the amount of optimization parameters in use.

Fixed patch geometries: This parameterization only allows changes in material thickness as optimization parameters. It is intended to serve as a benchmark for the subsequent parameterization schemes with moving patches. Since the keel has to perform the same on starboard and on port, the lamination plan is mirrored at its middle plane and all patch geometries are defined on the keels starboard side.

All patch base points are fixed to the trailing edge of the keels root, whereas the patch widths and lengths are evenly distributed over the entire surface. Since the patches overlap, this setup facilitates to reinforce the trailing edge and the root of the structure which is necessary to move the shear center of the

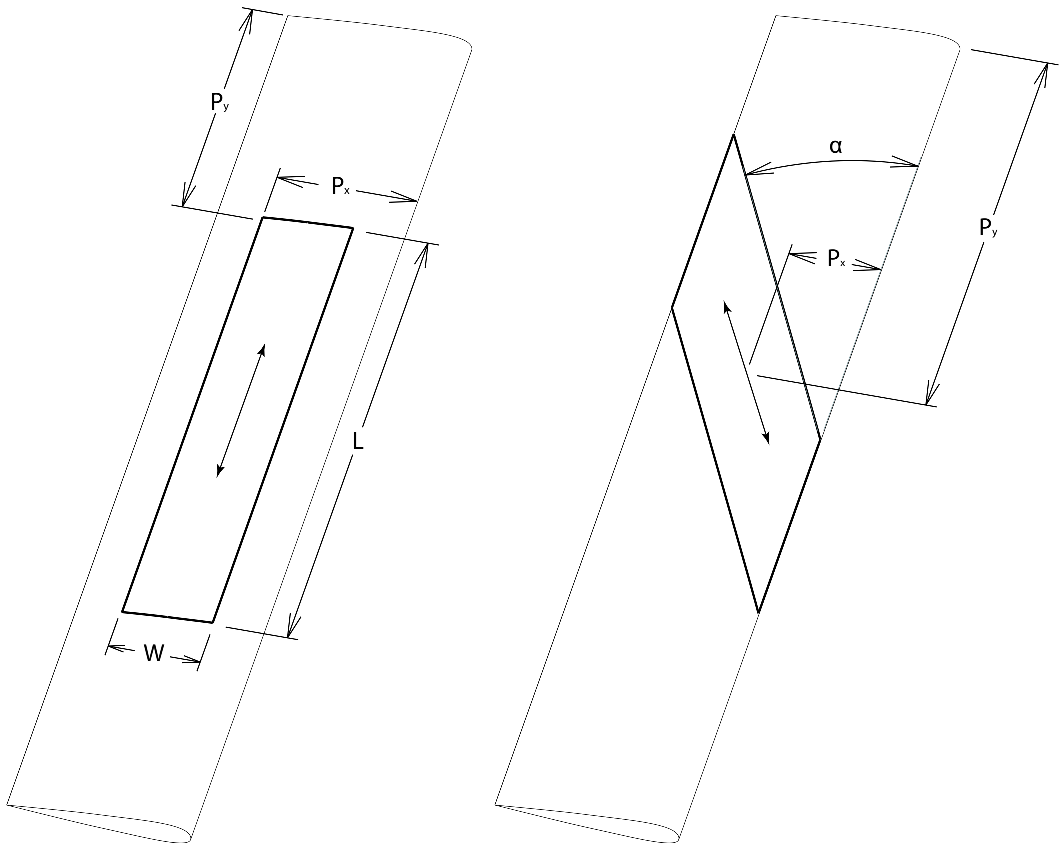

Fig. 4. The two different patch geometries used to build the lamination plans of the structure. The double ended arrows denote the material orientation.

cross sections towards the trailing edge. In Figure 5 three representative patch geometries are shown to the left and all patch outlines together are shown in the rightmost picture.
This results in a lay-up with 24 different patches to one side of the keel structure, whereas ever two possess the same patch geometry but different materials (UD or weave). The optimization parameters are 24 different material thicknesses which can be changed by multiples of their appropriate material thicknesses.

Sizing of longitudinal patch geometries: Here the sizing of multiple patches is used for the first time on a real-world structure. This parameterization resembles the above, except that the widths and lengths of all patches can be changed, whereas all base points are still fixed to the trailing edge of the root section for the abovementioned reason. Additional to the 24 thicknesses, 11 lengths and 11 widths are free to change, resulting in a total of 46 optimization parameters. To ensure structural integrity, one fixed patch covers the entire surface of the structure

Angular patches: In this parameterization ten angular patches are added to each side of the structure. These patches are allowed to change their angle,

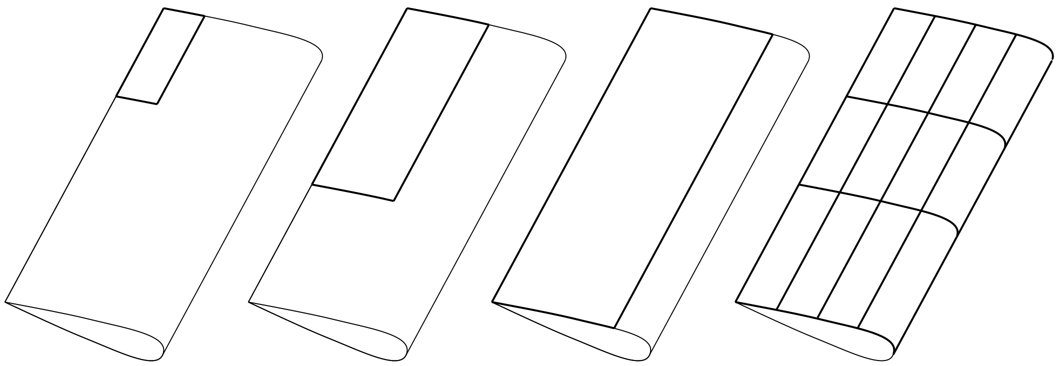

Fig. 5. To the left a choice of three different patch geometries and to the right the entire lamination plan showing all patch boundaries.

	reference		fixed		longitudinal		angular	
Mass [kg]	243	100%	250	103%	249	102%	239	98%
d [mm]	118	100%	95	81%	87	74%	96	81%
Θ [deg]	1.61	100%	1.46	91%	1.39	86%	0.69	43%

Table 1
All results compared to a reference structure built entirely in laminate material of identical thickness on the entire surface.

position and their unidirectional material thicknesses. The coordinate P_x of the patches pivot point is constrained to $300\,mm$, the middle of the profiles depth. Therefore the position is given by one parameter solely and the amount of three optimization parameters describe a patch geometry sufficiently. Together with the 46 optimization parameters of the longitudinal patches a total number of 76 parameters are to be optimized.

5 Results

The numerical results of the three different parameterization schemes are given in Table 1 where they are compared to a solution entirely built of laminate material with a constant thickness on the entire surface. The optimized lamination plans are discussed in detail in the following for all three parameterizations.

Fixed patch geometries: Figure 6 shows the best thickness distribution found for the fixed patch parameterization on the left hand side. The figure gives a qualitative view of the thickness distributions of the resulting 12 laminates. In order to cover the entire span of 100%, the thinnest laminate is assigned 0% and the thickest laminate 100%, whereas the rest of the laminates

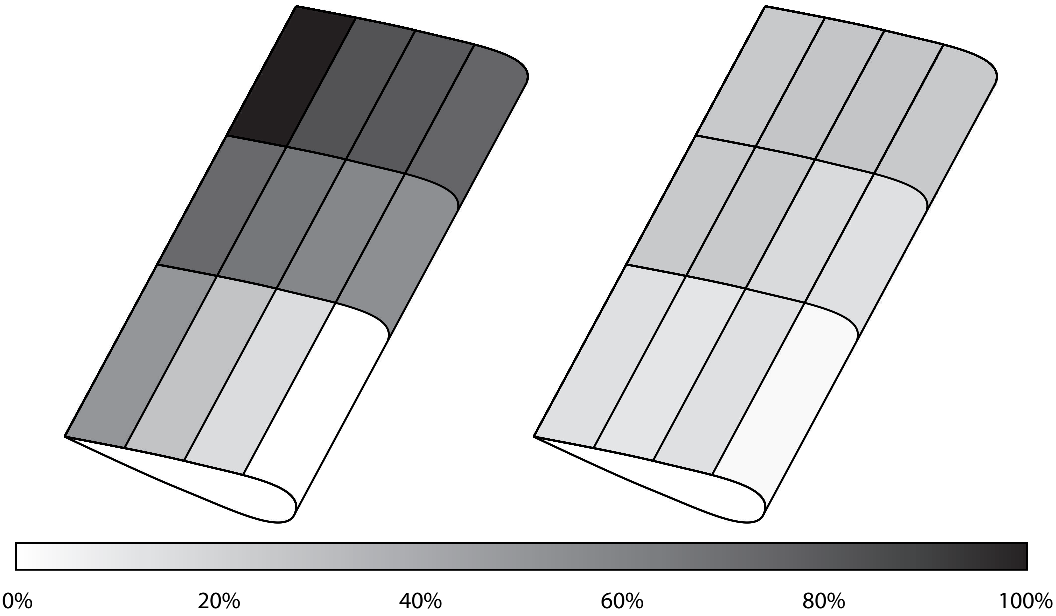

Fig. 6. The best solution found for the fixed patch parameterization. To the left the distribution of overall material thicknesses and to the right the amount of UD material.

relative thicknesses t_r are given through:

$$t_r = \frac{t_l - t_{min}}{t_{max} - t_{min}} \tag{3}$$

The value t_l denotes the thickness of the corresponding laminate, whereas t_{max} and t_{min} are given through the absolute thickest and thinnest laminate. On the right hand side of Figure 6 the amount of unidirectional fibers related to the according laminate thickness is displayed. It can be seen that the trailing edge and the root of the structure are reinforced, as was expected. That the amount of UD fibers never exceeds 25% in all laminates is because the shear modulus of the UD material is only half of the laminates shear modulus. Since the optimization seeks for the least torsional deformation and the longitudinal patches can not orient their material, the shear modulus is the determining factor for the choice of material.
From Table 1 it can be seen that a simple redistribution of material decreases the angle of attack at the tip by 9% and the overall deflection d by 19% compared to the reference structure.

Sizing of longitudinal patch geometries: The results of this optimization are displayed in Figure 7 in the same manner as described above. Since it is based on the same global idea to move the shear center of the cross sections to the trailing edge, the solution resembles the solution of the fixed patch geometries, but it shows a finer discretization of the thickness distribution and especially less material at the leading edge. The maximum amount of UD ma-

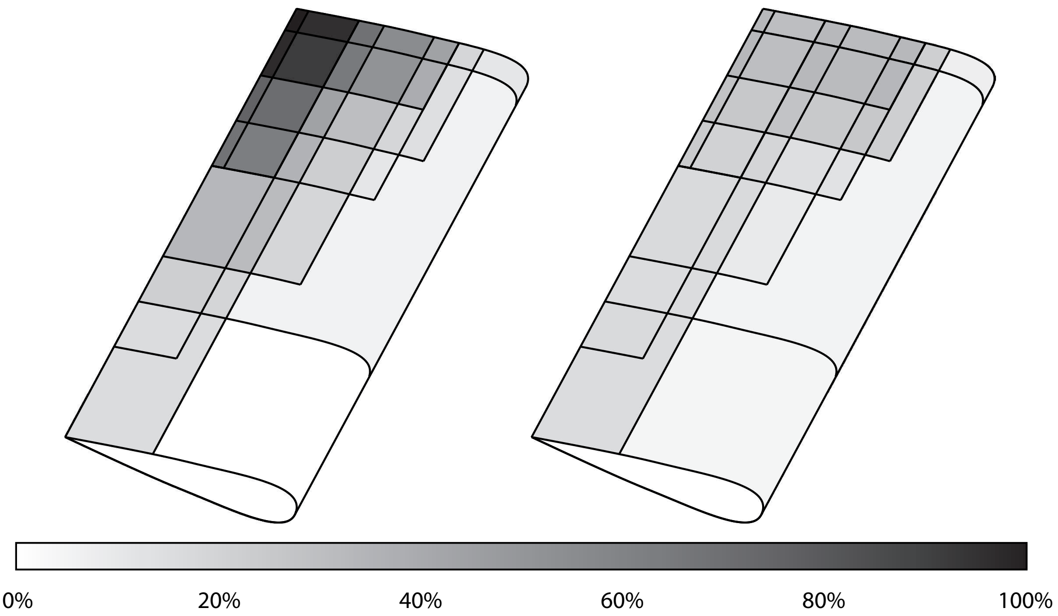

Fig. 7. The best solution found for the sized patch parameterization. To the left the distribution of overall material thicknesses and to the right the amount of UD material.

terial per laminate is with 33% higher compared to the fixed parameterization. The structure is still characterized by 12 different patch geometries per side, but due to the irregular patch distribution, the amount of different laminates in the structure is increased from 12 to 31.
Thanks to the enhanced flexibility of the lamination plan, the angle Θ is decreased by 5% compared to the fixed parameterization.

Angular patch geometries: The outlines of all 22 patch geometries of the best solution ever found are shown in Figure 8 on the left hand side. With these 22 different patch geometries, the present solution consists of 181 different laminates. From these numbers the advantage of the parameterization based on physical layers rather than on laminate regions becomes evident. However, the amount of different laminates complicates the qualitative display of the laminates thicknesses and is therefore left aside, but some geometrical result of the lay-up is discussed in the following. The longitudinal patches orient themselves again at the trailing edge, but their geometries and hence their thicknesses are more homogeneously distributed over the entire length of the structure. As to the positioning of the angular patches two interesting observations can be made: All angular patches start or end in the same location as another angular patch. As can be seen from the middle picture of Figure 8, there is one point on the trailing edge where four patches come together. Whereas the leading edge has four evenly distributed points where two patches coincide (see Figure 8 on the right hand side).
The additional possibility to use unidirectional material in an appropriate angle leads for Θ to a decrease of 50% from the longitudinal patch parame-

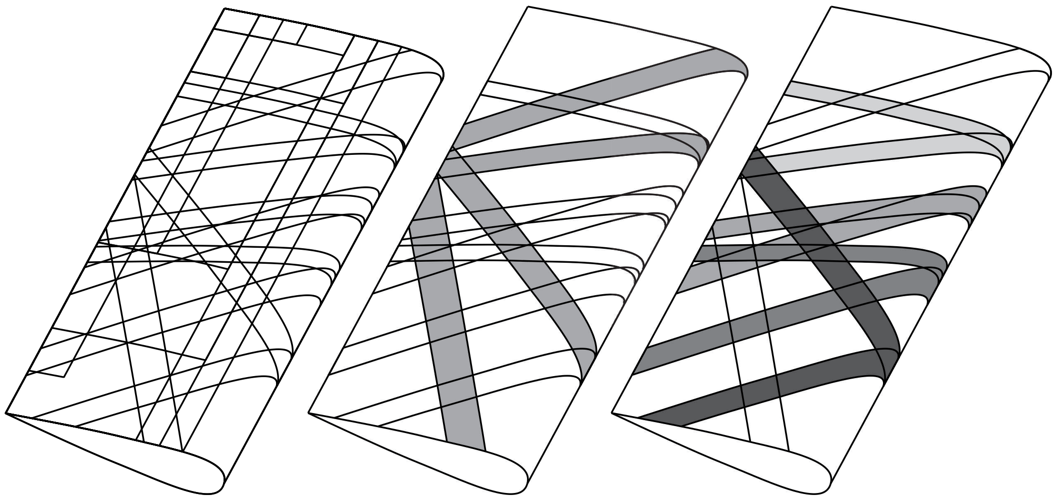

Fig. 8. The best solution ever found for the angular patch parameterization. From left to right: All patches outlines, the patches coinciding at the trailing edge, and the patches coinciding at the leading edge

terization. Compared to the reference structure it is even decreased by 57%.

6 Conclusion and Outlook

The methodology which until now has been applied on academical examples only, has proven to work well on a real structure. The fundamental idea to use the basic building element of such a structure (i.e. the patch) to build up the parameterization allows to describe structures built of multiple laminates in a simple way. Moreover, if the parameterization is built with a certain lay-up process in mind, the optimized results remain manufacturable.
The optimization together with the parameterization build a robust methodology, which finds good solutions from randomly chosen starting points.

The goal to find a generally applicable methodology for the global laminate optimization has been achieved. As a next step it would be interresting to apply the methodology on various different problems, e.g. use the allready implemented stacking sequence parameters to optimize the strength of laminates. Since the method is implemented using CATIA, it is well possible to investigate the interaction of the shape and the lamination plan simultaneously.

7 Appendix: Optimization details

The organization of the entire optimization is done by the in-house developed program DynOPS (Dynamic Optimization Parameter Substitution). DynOPS uses an Evolutionary Algorithm based on the Evolving Objects library [2] together with a universal gene implementation presented by König [7] and Wintermantel [8] as optimization engine. Such algorithms search for better solutions by mimicking natural evolution, working with populations of individuals. New solutions are found through *Selection*, *Reproduction*, *Mutation*, and *Replacement* operators acting on the parent generation, producing a child generation, which serves as new parent generation, and so forth [9].

The evaluation of one single individual requires a sequence of two different custom-built simulation tools: First, a distinct set of parameters provided by DynOPS is mapped to the geometry and the entire finite element model is built and written to a text file by a program based on the the CATIA V5R13 libraries [3]. Second, this file is read, the model solved, and the results written to another file to be read by DynOPS with a finite element tool using the FELyX library [4].

DynOPS has the ability to distribute the time consuming evaluations to several computers using the PVM [5] library.

All evaluations are performed on 14 dual processor computers with 2.8 GHz Intel Xeon processors with 2 GB RAM running under Windows XP Pro and Cygwin [6].
On this hardware, one evaluation run of the keel structure including the draping of all layers, the mapping of the laminate properties to the finite elements, and the solution of the finite element model of about $6 * 10^4$ degrees of freedom takes approximately seven minutes.

All optimizations are started with randomly initialized individuals, i.e. the initial population is found through a random distribution of all optimization parameters. This ensures that no additional bias is given to the chosen parameterization which in return has to be stable to ensure that all (or most) randomly initialized parameter sets represent feasible individuals.

The optimizations are performed with populations equal in size to the amount of optimization parameters.

[2] http://eodev.sourceforge.net
[3] http://www.3ads.com/products-solutions/brands/CATIA/
[4] http://sourceforge.net/projects/FELyX
[5] http://www.csm.ornl.gov/pvm/
[6] http://cygwin.com

Acknowledgements

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