A CASE STUDY ON ESTABLISHED AND NEW APPROACHES FOR OPTIMIZED LAMINATE DESIGN

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Abstract

Optimized laminate design, although crucial for high-quality lightweight parts, still remains a challenge for engineers. The high number of mutually dependent parameters requires expert skills – and really good designs can only be obtained when load paths are considered appropriately, which is frequently missed out on when simply replacing isotropic material by quasi-isotropic laminate. Therefore, both commercial software solutions and approaches from research have been put forward to support engineers at finding adequate layups. In this paper, using a bike rocker arm demonstrator, a lightweight benchmark under displacement constraint is conducted with the goal of reducing mass using three approaches: OptiStruct (Altair), *mfk*CODE (from research) and a combination of a specific topology optimization algorithm for transversely isotropic materials and *mfk*CODE. The resulting conceptual designs are discussed both quantitatively and qualitatively.

1. Challenges of composite structures design

Interest in the application of composite materials and their engineering is on the rise – due to many reasons: regulatory requirements [1] i.e. lightweight design being a means to fulfill emission targets and surface finish requirements in the automotive industry; economical requirements, e.g. fuel-saving in the aerospace industry [2], and many more. Yet, composite design yields many challenges: a huge number of dependent parameters like fiber orientation, layer thickness, layer sequence; many different manufacturing processes including automated fiber placement, unidirectional tapes, 3D printing, hand lay-up and many more imposing constraints on the design; economical requirements (material and manufacturing costs [3]), to name a few. To cope with these challenges, a variety of methods exist, ranging from rather simple ones like carpet plots over more sophisticated methods like Classical Laminate Theory (CLT) to integrated CAE approaches like *Altair OptiStruct for Composite Analysis;* and *mfk*CODE, which was developed at Friedrich-Alexander-University Erlangen-Nuremberg, Technical Faculty, Engineering Design [4]. The latter two approaches offer the possibility of obtaining a composite design proposition for a given shell geometry, loads and boundary conditions in a structured and reproducible way. In contrast to the formerly mentioned methods (carpet plots, net theory, CLT…) their usage is not limited to experts and not depending on local samples in highly stressed areas. Furthermore, fiber orientations can be optimized in discrete steps (OptiStruct) or even continuously (*mfk*CODE), thus a pre-selection of a small number of directions (0/90/+45/-45) is unnecessary.

Presuming a given shell geometry, most approaches lack the capability of modifying the geometry beforehand by either shape optimization, topology optimization, or even both. To the author's knowledge, Altair OptiStruct offers topology and topography optimization capability, yet not specifically for anisotropic materials. This specific optimization, however, can lead to much more composite-suitable geometries [5–7].

Most currently applied topology optimization algorithms usually do not consider anisotropic material properties, possibly leading to less-than-optimal geometries [8]. Thus, a bionic topology optimization method for transversely isotropic materials, *mfk*TOPO, was proposed [9].
Building on the aforementioned methods, this contribution introduces, applies and compares three different approaches (or combinations thereof) to composite structure design: (1) Altair OptiStruct for Composite Analysis; (2) *mfk*CODE; (3) a combination of *mfk*TOPO and *mfk*CODE, modifying the geometry first, and then applying the composite design approach. In the following, the three approaches will be introduced briefly.

2. Selected design approaches for lightweight composite structures – a short introduction

2.1. Altair OptiStruct

To obtain concept designs for composites optimized for minimum weight and maximum strength [10], Altair OptiStruct is a software solution already used in practice, e.g. at Airbus [11], and in science e.g. by [12].

When using OptiStruct for composite design, a three-step process is followed as proposed in [13]: free-size, size and ply bundle stacking optimization (Figure 1).

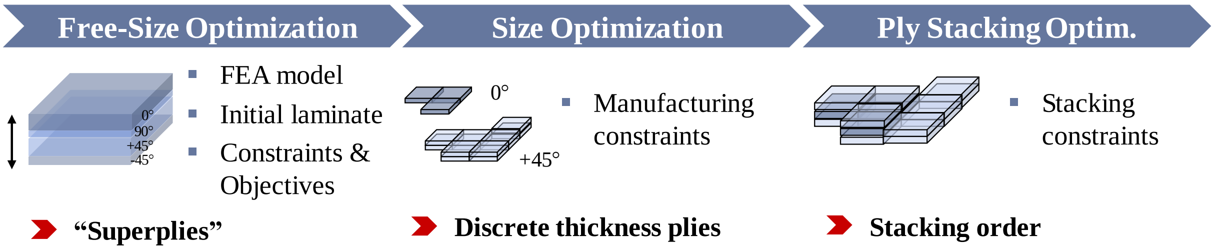

Figure 1. Laminate design process with Altair OptiStruct.

After creating a CAD geometry and conducting usual FE preprocessing steps, a laminate (or multiple laminates) are created containing a selection of fiber angles. These angles form the basis for the successive optimization steps: In the optimized laminate, exactly these fiber directions will be found.

- In the first *free*-size optimization step, so-called "superplies" are created, which means plies of various directions with *locally* varying thickness. Constraints like minimum and maximum laminate thickness can be considered and an objective (e.g. minimum weight) as well as constraints (e.g. maximum deformation) specified.
- In the second *size optimization* step, the "superplies" are separated into plies of discrete thicknesses. The thickness steps are usually pre-defined by manufacturing constraints, e.g. prepreg thickness.
- In the third *stacking optimization* step, the stacking sequence of the discrete-thickness plies is optimized, again considering constraints like maximum number of subsequent same-orientation plies.

For each of these steps results can be obtained, e.g. mass required to fulfill constraints. The final result is a concept design. An example will be demonstrated later in this paper.

2.2. *mfk*CODE

The **co**mposite **de**sign approach *mfk*CODE by Klein et al. [4,14] follows a four-step process as illustrated in Figure 2.

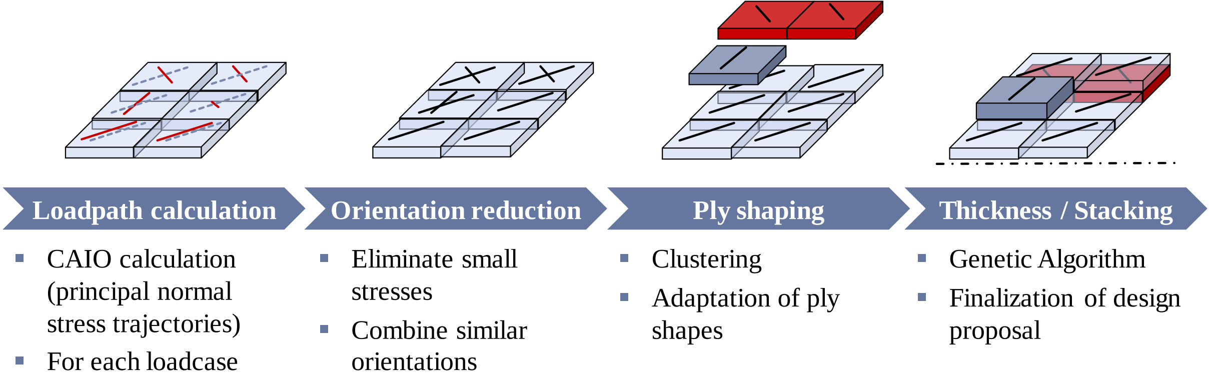

Figure 2. Laminate design process using *mfk*CODE, adapted from [4]

After, again, setting up a FE model, in the *first step* the loadpath trajectories are computed (principal normal stress trajectories) using a modified version of the Computer Aided Internal Optimization (CAIO) method as proposed by [6,15]. Eliminating shear and increasing in-fiber normal stresses, this method uses bionic principles as observed with tree growth and achieves stiffness (fibers bear more load) and strength optimization (less matrix failure). No fiber orientation has to be pre-defined [4]. Further modifications by Klein allow multiple loadcase computation, multi-layer consideration and adequate handling of areas with isotropic stress states [14]. As due to many loadcases and layers also many fiber orientations may emerge locally, these are reduced by eliminating those orientations related to small principal stresses and combining similar orientations in the *second step*. In the *third step*, a clustering algorithm considering both fiber orientation and geometry forms plies from these orientations, which are subsequently manually adapted by the user with multiple assistance functions. The thickness and stacking optimization is done in *step 4* using a genetic algorithm in order to cope with the discrete optimization problem including many local minima.

The former approach by Altair OptiStruct and *mfk*CODE have in common that the final result is a design proposal, optimized for stiffness and strength (usually) and meeting the manufacturing and other constraints as defined by the user. In contrast, the optimization routines are different (mathematical optimization in OptiStruct vs. empirical optimization in *mfk*CODE). Predominantly, *mfk*CODE does not require pre-selection of fiber orientations, thus leaving more design freedom for potentially closer-to-optimum results. Additionally, *mfk*CODE's ply shapes are pre-clustered and can be manually adapted in *step 3*, which tendencially leads to more manufacturability. This approach thus supports a wider range of the product development process than OptiStruct.

2.3. *mfk*TOPO – topology optimization for transversely isotropic materials

The topology optimization approach for transversely isotropic materials *mfk*TOPO was first introduced in [9]. The simultaneous optimization of both material distribution and fiber orientations bears some challenges, at the same time offers advantages. The mutual dependency of fiber direction and material distribution demands special adaptations for mathematical optimizers, many local minima occur; pre-definition of allowable fiber orientations is possible and may help solving the problem more quickly, yet stands against real "optimal" results (which could depend on "in-between fiber orientations"). Many iterations become necessary, although some conventional optimization methods exist (e.g. [8]).

On the plus side, simultaneously optimized results seem sensible. When considering transversal isotropy during optimization, resulting structures seem to have less orthogonal joints, opposed to the “classical” results resembling Michell structures [16]. A simple, academic one-layer example is shown in Figure 3, which was reproduced after a *mfk*TOPO result. Less orthogonal joints also seem intuitive, as more load is transferred into the fiber than having to cross the matrix.

Figure 3. *mfk*TOPO, process in principle.

The *mfk*TOPO approach used here is an empiric optimization algorithm based on adapted versions of the Soft Kill Option (SKO) [6,17] and the previously mentioned CAIO method, which are combined with functionality like definition of volume fraction, minimum structural member size and multi-loadcase functionality. Comparable to the laminate optimization approaches, it starts from a FE model (shell geometry, boundaries, loads); after the optimization is conducted, a geometry proposition for later steps (e.g. laminate optimization) is obtained. Laminate optimization should then result in less differently oriented layers, as regions of multiaxial stress should be reduced.

3. Comparison of selected approaches

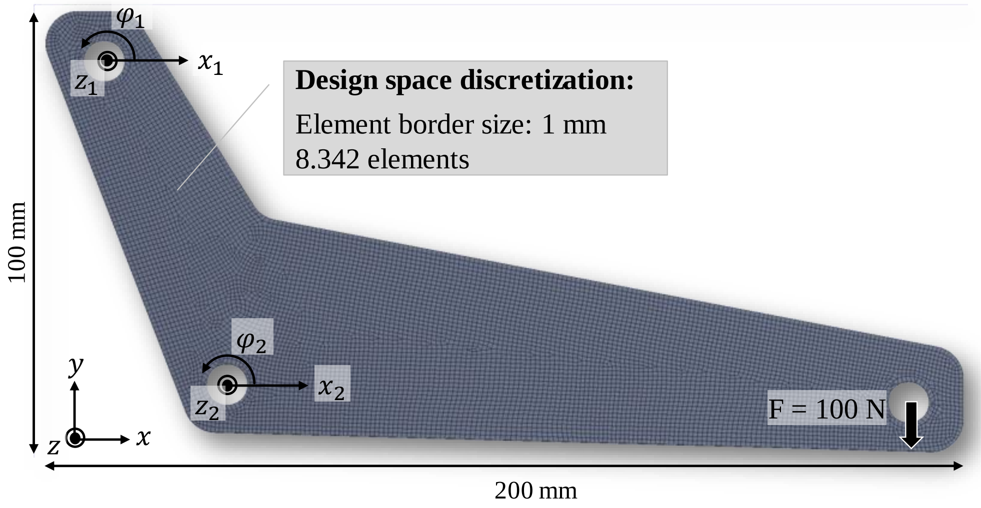

Figure 4. Demonstrator for the case study.

To compare the laminate optimization approaches and demonstrate the combined approach of topology and consecutive laminate optimization, a bike rocker arm (usually bearing the spring of a mountain bike) is chosen as an example to be both practical and also intuitively comprehensible at the same time. This demonstrator is inspired by [18] and was previously used by the author for more theoretical scrutiny at DESIGN 2018 (not published at this time). All degrees of freedom are fixed at the drill holes on the left side; onto the border of the drill hole on the right, a force of 100 N in negative Y direction is applied.

3.1. Altair OptiStruct results

In the following, the results of the three optimization steps (introduced in chapter 2.1) are presented. The objective is to minimize weight while keeping the maximal displacement in force direction (negative Y, Figure 4) below 0.1 mm. A minimum structural member size of 5 mm was set up to ensure not-too-fine structures.

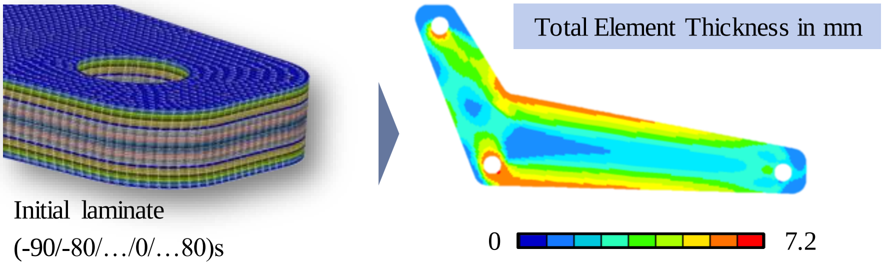

Figure 5. Result after free-size optimization.

For the free-size optimization step, an initial CFRP laminate (-90/-80/…/0/…80)s was created (Figure 5). Its symmetry should avoid coupling [3]. To ensure comparability with *mfk*CODE, which is capable of continuous angle optimization, very narrow orientation angle steps (10°) were selected. The result reflects the bending loadcase, as maximum thickness can be found at farthest distance from the neutral fiber. The edge, where stress peaks occur, is particularly reinforced, as are the fixed boundary drilling holes.

The individual plies, at this stage, have varying thicknesses and must be optimized to have discrete thicknesses in order to ensure manufacturability, Figure 6.

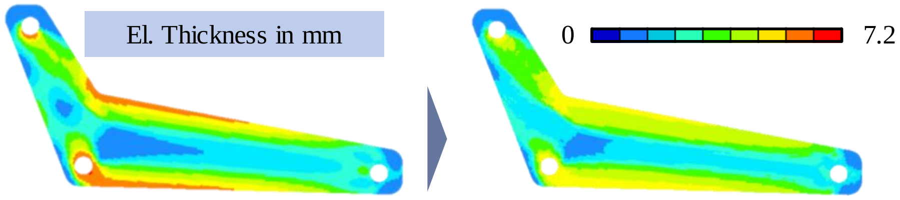

Figure 6. Result after size optimization. Left: continuously varying ply thicknesses; right: discrete ply thicknesses.

For the rocker arm, the manufacturable ply thickness was set to 0.1 mm. Observing the thickness sum of all -10° plies, discrete steps emerge (Figure 7 on the right). Total thickness is an integer multiple of the manufacturable ply thickness of 0.1 mm. Obviously, the plies are made for a concept design, as these are quite freely shaped.

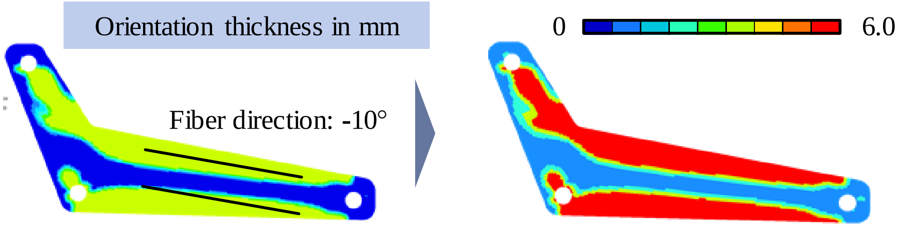

Figure 7. Result before (left) and after (right) size optimization: sum of all -10° plies‘ thicknesses.

The third step, ply stacking optimization, was conducted. Of course, as the geometry and all stress states are plane and the laminate is symmetric, changing the stacking order is without effect. Table 1 presents a summary of the numerical results of the two optimization steps. A density of 2 g/cm³ was assumed, using material parameters of an epoxy carbon unidirectional prepreg (E_1=121000 N/mm², E_2=8600 N/mm², G_{12}=4700 N/mm², ν_{12}=0.27 out of the ANSYS material database).

Table 1. Numerical results of the OptiStruct optimization.

Result	Free-Size	Size
Mass	54.25 g	55.31 g
Max. Displacement	-0.0999 mm	-0.0957 mm

For this demonstrator, fast convergence can be observed (11 and 7 iterations for free-size and size optimization, respectively). The initial "free-size" mass of 54.25 g increases by 2.0 % when merely discrete thicknesses are allowed in size optimization. Also, the objective is a little less closely met (absolute displacement is smaller than in free-size optimization). Both optimizations meet the displacement constraint.

3.2. *mfk*CODE results

For *mfk*CODE results the same settings as for OptiStruct were chosen as far as possible. Differences exist concerning minimum member size, as final ply shapes are manually adapted in *mfk*CODE.

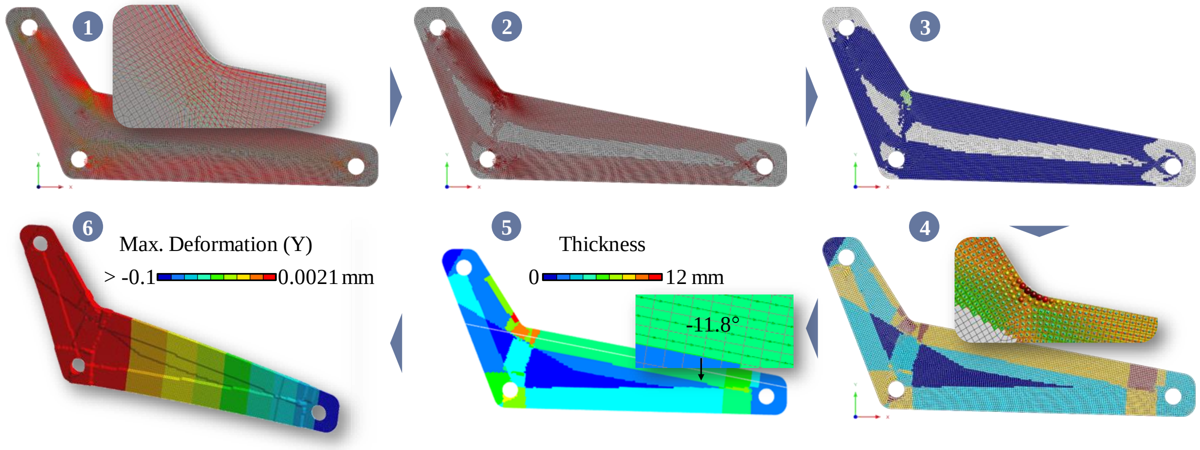

Figure 8. *mfk*CODE: Optimization process and results.

The six steps shown in Figure 8 represent: load path computation (1), reduction of "small" principal normal stress directions (2); unification of similar directions (3) – as there's just one load case and optimization layer here, this step doesn't change the result; adaptation of pre-clustered layer geometries using assisting functions (4), thickness optimization using ANSYS ACP (5) and the final simulation result (6). It becomes obvious that the result generated by *mfk*CODE is closer to a final design, showing many regions with similar width and fiber orientation, as required for manufacturing using UD-tapes. Inner-ply fiber orientations are constant – but not fixed to specific angles, as shown in the detail in Figure 8, step (5). Numerical results are presented in Table 2 with the same manufacturable ply thickness and (assumed) material density as above. For drilling holes reinforcement, a woven epoxy prepreg material model from ANSYS library was used, for the unidirectional plies an unidirectional prepreg material model with the same stiffness properties as used in OptiStruct before.

Table 2. Numerical results of the *mfk*CODE optimization.

Result	Continous thickness	Discrete th.
Mass	56.56 g	58.44 g
Max. Displacement	-0.0999 mm	-0.0964 mm

The total mass of the design is a bit higher than the OptiStruct results (+4.3 % / +5.6 % for continuous and discrete thickness optimization, respectively). In both cases, the displacement constraint is satisfied.

3.3. *mfk*TOPO + *mfk*CODE results

Starting with *mfk*TOPO, a topology optimization with orthotropic material properties is conducted using a minimum structural member radius of 2.5 mm for a certain degree of manufacturability. Extremely thin members are avoided. Its result is converted into a shell geometry, left in Figure 9.

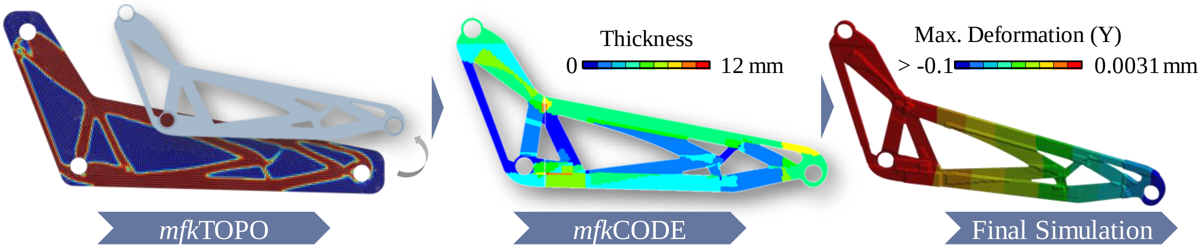

Figure 9. *mfk*TOPO + *mfk*CODE: Optimization process and results.

After that, the *mfk*CODE routine as presented in Figure 8 is conducted, followed by the thickness optimization process. This leads to a layup as shown in the middle of Figure 9. The final simulation on the right shows that also for this case the displacement constraint is satisfied. As noted in Table 3, mass is significantly reduced when compared to the other approaches (around -30 %). Areas with multiple fiber orientations are scarce as fiber angles follow the struts.

Table 3. Numerical results of the combined optimization.

Result	Continous thickness	Discrete th.
Mass	38.58 g	39.11 g
Max. Displacement	-0.0999 mm	-0.0986 mm

4. Conclusions

This compact comparison of the three optimization procedures allows to draw some conclusions while at the same time leaving room for further scrutiny.

- For the given demonstrator, both OptiStruct and *mfk*CODE lead to similar layup propositions in most areas and require similar mass to fulfill the displacement constraint. However, OptiStruct ends at an early concept stage (no further modification of plies to allow consideration of manufacturing constraints). The new approach *mfk*CODE results in much more realistic ply shapes. That, in turn, requires a bit more mass – but not as much as could be expected, presumably because fiber angles are optimized continuously.
- Conducting topology optimization with transversally isotropic material properties, *mfk*TOPO, in combination with *mfk*CODE leads to a significant reduction of mass while fulfilling the displacement constraint.
- For the reason of shortness, strength criteria and others (like buckling) were not considered in this paper, rather focusing on the approaches' general methodology and usability.
- The optimization results are rather conceptual, which can exemplarily be seen from a certain shortage of considering manufacturing issues (e.g. where to drape upon?). To bridge the gap between the conceptual designs and manufacturable products, further discussion and work is necessary.

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