Weight Reduction through Composites and Optimization

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Abstract

The progressive climate change also requires a rethink in the automotive industry. It is well-known that the heavier the vehicle is, the more energy it needs to get moving. For example, fuel consumption and pollutant emissions can be significantly reduced by optimizing the weight of automobiles.

The use of innovative materials such as advanced composites, which have long been used in the aerospace industry, can also be used in future vehicle constructions to meet the energy consumption requirements. Regardless of the branch of industry, lightweight structures must be the goal of our efforts to use raw materials more sparingly.

In that context, the CAE software must not only support laminates but also optimization methods with regard to their design. In the optimization of laminates, which can often be characterized by orthotropic material behavior, the layer thicknesses and ply angles are available as design parameters in addition to the material parameters. Constructive restrictions such as discrete ply angles, a symmetrical and balanced stack reduce the dimension of the optimization problem.

Furthermore, the value ranges of the material characteristic values are subject to restrictions due to the positive definiteness of the strain energy, which differ depending on the underlying material law (e.g. transversal isotropic, orthotropic).

This contribution analyses the application of optimization methods in the environment of laminate structures with respect to the identification of material parameters and the optimization of laminates with respect to certain target functions and corresponding constraints.

Only a successful application of optimization methods in practice can increase the acceptance in design departments and thus justify the area-wide application of optimizations from the beginning of the product development process. All computations are carried out in PERMAS, whereas post-processing is done in VisPER and permasgraph. PERMAS specific keywords are denoted by capital letters and a preceding dollar sign in the subsequent text.

1. Introduction

The optimization of laminates is a broad field with many application possibilities. Due to the anisotropy alone, the number of material parameters increases from 3 for isotropic material (E, ν, ρ) to 7 for anisotropic shell material (E_1, E_2, ν_{12}, G_{12}, G_{23}, G_{31}, ρ) or 10 (E_1, E_2, E_3, ν_{12}, ν_{23}, ν_{13}, G_{12}, G_{23}, G_{31}, ρ) for general orthotropic behavior. In addition, there is the layer structure of the laminate, which allows the variation of angle α and thickness t per layer. All anisotropic materials require the definition of a material reference system $MATREF in the system variant. The orientation of the material reference system can be exported as a result by using DEFAULT SET VERIFICATION = RESULTS in the user control interface (*.uci) in order to check it afterwards with VisPER [17]. Within the laminate, the layers can in turn consist of different materials. Another possibility is to optimize the stacking sequence and the overall number of layers in a stack. This shows the complexity when considering the optimization of laminates [14]. However, stacking sequence optimization is not considered here and can be found elsewhere, e.g. [4, 7, 9, 10, 12]. With the help of manufacturing constraints [4, 13, 15] one tries to reduce the number of design variables again. The usual manufacturing restrictions in the literature include discrete angles and thicknesses, a balanced symmetrical structure and a limitation of successive layers with identical angles. With regard to optimization, many different constraints are used. These include displacement constraints, buckling factors, eigenfrequencies, compliance, mass, and failure criteria to name a few.

The fully integrated optimization in PERMAS [16] supports laminates since version 17. Topology optimization based on a Solid Isotropic Material with Penalization (i.e. SIMP) approach is used to apply free sizing to laminate structures ($DVTPAR KIND = PLY) in order to get ply shapes from the optimized thickness distributions. This reflects the fact that for a ply stack under given fiber angles not all plies are needed over the entire structure to bear the loads. The result will specify the element sets which need to have a certain ply of the ply stack. Moreover, sizing of laminates is now supported, where ply thicknesses and angles can be optimized. The optimization itself is performed using one of the following algorithms:

- CONLIN (Linear Convex Programming): A simple and robust method using analytical derivatives, only useful with linear analyses.
- ACP (Adapted Convex Programming): This out of-core and parallelized solver is recommended for large optimization tasks, nonlinear behavior, and complex manufacturing conditions.
- OC (Optimality Criteria Method): Used for freeform optimization tasks.

More algorithms are available with module AOS (Advanced Optimization Solvers). This module provides additional optimization solvers which essentially extend the range of applications for the integrated optimization in PERMAS. The extensions are as follows:

- By Trust Region method based local methods adaptive step-size control is facilitated. This extends the previous static modification limit chosen by the user.
- Trust region methods keep track of the best point. They reject points, where no improvement is achieved. This extends the previous methods, where any new point is accepted.
- Methods for derivative-free optimization and global optimization are available.

The local methods include the following derivative based methods:

- **SQP** (Sequential Quadratic Programming). This is a damped Newton method combined with an active set strategy for the optimality equations. It is the best general-purpose method (but not necessarily in structural mechanics). Second order information is available by BFGS update.
- **SLP** (Sequential Linear Programming): This method uses only linear approximation. Usually, it is slower than SQP due to missing 2nd order information. It is sometimes more robust than other gradient based methods (e.g. in the case of steep gradients).
- **SCP** (Sequential Convex Programming): Usually, best-of-class method for classical optimization problems arising in structural mechanics. Module OPT uses a method which belongs to SCP class of optimization methods.

When derivatives are not available, e.g. in contact problems or nonlinear material behavior, or when the accuracy of computed derivatives is not sufficiently high (like sometimes in frequency response analysis), then derivative-free methods can be applied. The new derivative-free (local) methods comprise the following approaches:

- Derivative-based methods using finite differences (with SQP, SLP, SCP). Functions should be smooth enough and the choice of the finite difference parameter for the interval should not be a problem.
- Derivative-free method **WLIN** (**W**edge constraint, **Lin**ear approximation). There is no need to choose a finite difference parameter. This method can be used for noisy problems.

When global minima have to be found, local methods are not appropriate any more. For such global optimization tasks, the following approaches are available:

- By applying the Multi-Start method (**MS**) and using random points derivative-based methods can be used to localize minima. This is combined with keeping track of the best point. This approach can be seen as an automatic trial method. A maximum number of loops is used to terminate the analysis.
- Another method is **LDR** (Locally improved variant of the Dividing Rectangles (DiRect) algorithm). This method has been generalized to work with constrained problems. It could be improved by solving local subproblems. It generates a sequence of points that is dense in the design space and hence guarantees to approximate the global solution. Because this method is slow and only useful for small models, a suitable model reduction is highly recommended.

Optimization is equipped with a general break/restart facility. To this end, a running optimization can be stopped and restart files are prepared. So, the restart can be made at any already performed optimization loop. Before restart, optimization parameters can be modified to influence the convergence behavior of the optimization. The restart uses the restart file to continue the optimization from the already reached status.
$DVMPAR is used to relate a design variable to a certain property (thickness and or angle) of a ply. Ply failure criteria ($DCONSTRAINT PLYFAILURE) may be used as constraints for the laminate sizing optimization. Standard failure criteria such as *Tsai-Wu* and *Hoffmann* are directly available, whereas additional criteria can be defined by own user functions.
Laminates are defined within the MATERIAL block using $LAMINATE with two different options DESTYPE = {<u>PLY</u>, MATRIX}. The former (default) option requires an additional $PLY statement, that is used to define the stacking sequence. The second option is related to the classical laminate theory (CLT) using the **A, B, D** stiffness matrices. The extended laminate theory (ELT) considers a transverse shear stiffness matrix **G.** This relationship is defined via the material definition in combination with DESTYPE = MATRIX. The stacking sequence can be redefined by $PLYDAT within the system variant.

2. Examples

The first example is taken from [5] and is used to illustrate the free sizing capabilities of PERMAS. The shape of the shell is defined by a bivariate polynomial $z(x,y) = h-(2h/L^2)[(x-L/2)^2+(y-L/2)^2]$, $0 \leq x, y \leq 500$, where h denotes the apex and L the length and width, respectively. The shell is loaded by a nodal point force $F_z=-100$ N and the displacements at the four corner nodes are suppressed ($u=v=w=0$). The shell consists of 8 layers $[0°,45°,-45°,90°]_S$ and 80x80 SHELL4 elements. The initial thickness of each layer is t=2 mm and may be varied in the interval [0.1,2] mm. The objective is to minimize the weight subjected to a displacement constraint at the apex in z-direction. The material properties of GFRP are E_1= 38 [GPa], E_2=E_3= 9 [GPa], G_{12}=G_{13}= 3.6 [GPa], ν_{12}=ν_{13}=ν_{23}= 0.3 and ρ=1.87E-09 [t/mm^3]. The 45° and -45° layers are assigned to the same design element during the optimization, in order to obtain a balanced stack.

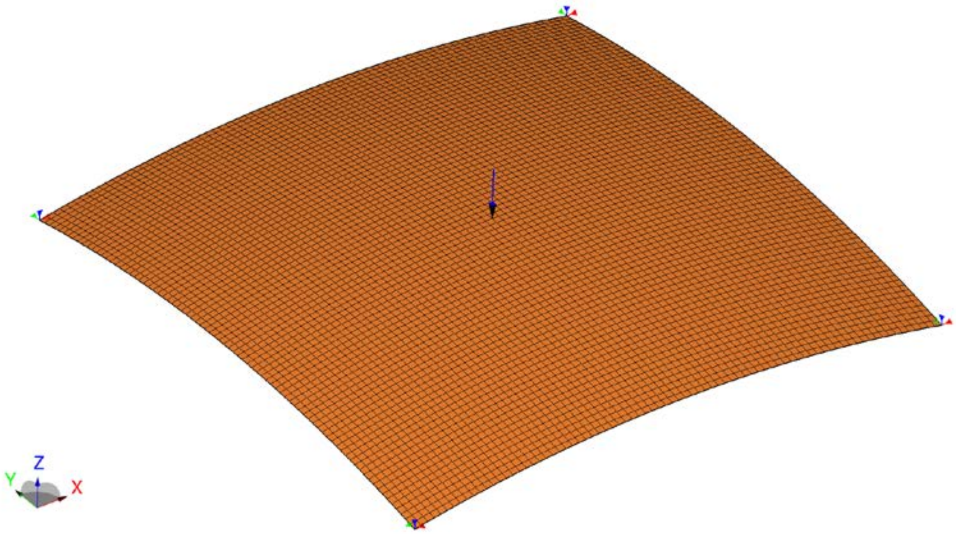

Figure 1: Boundary conditions and loads of a corner hinged shell

Fig. 2 shows the thickness distribution in the different layers. Red color denotes the maximum thickness, whereas blue color denotes the minimum thickness of the corresponding layer.

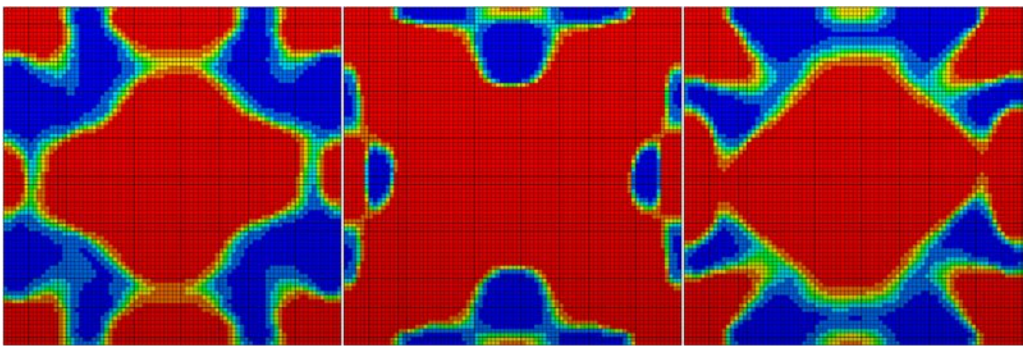

Figure 2: Thickness distribution for α=0°, α=±45°, α=90° (from left to right)

The second and third example is taken from [11]. Fig. 3 illustrates a laminated cylinder. The objective is to minimize the weight subjected to an eigenfrequency constraint for the first eigenfrequency f_1> 1155 [Hz]. The thickness of the plies 1,2,4 tend towards the lower bound, whereas the thickness of the fifth ply tend towards the upper limit (Fig.4).

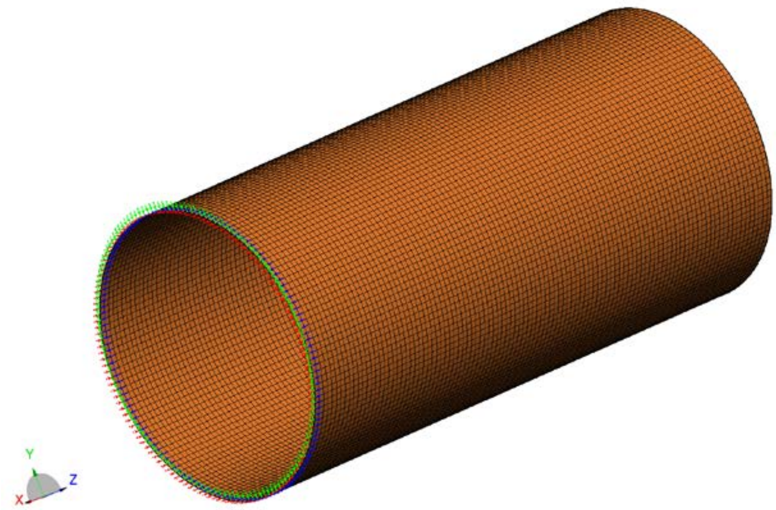

Figure 3: Laminated cylindrical shell: L=200 [mm], R=50 [mm], [90°,0°,45°,0°,90°], t_i=0.4, E_1=137.9 [GPa], E_2=10.34 [GPa], ν_{12}=0.29, G_{12}=G_{13}=6.89 [GPa], G_{23}=3.9 [GPa], ρ=1.0E-09 [t/mm^3]

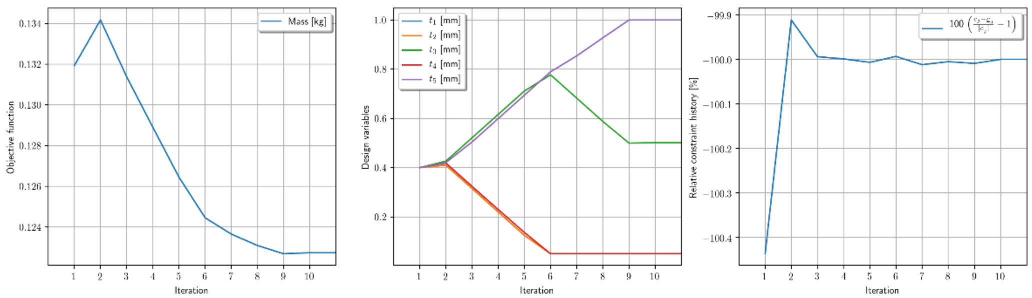

Figure 4: Optimization results of the laminated cylindrical shell

The third example is a U-shaped profile (Fig. 4) with a length L=200 [mm], width *w*=150 [mm] and height *h*=40 [mm]. The whole model is divided into 5 parts, which are highlighted by different colours. The material parameters are given by E_1=137.9 [GPa], E_2=10.34 [GPa], ν_{12}=0.29, G_{12}=G_{13}=6.89 [GPa], G_{23}=3.9 [GPa] and ρ=1.0E-09 [t/mm^3]. One end of the profile is clamped. The finite element model consists of 4958 SHELL4 elements and 5100 nodes. All five parts have the asymmetric stacking sequences [0°,45°,-45°,0°,-45°,45°,0°]. The objective is to maximize the fundamental eigenfrequency by varying the ply angles of the three parts in the xz-plane. Fig. 5 depicts the evolution of the design variables and the objective function. The first eigenfrequency is raised from 826 Hz to 939 Hz.

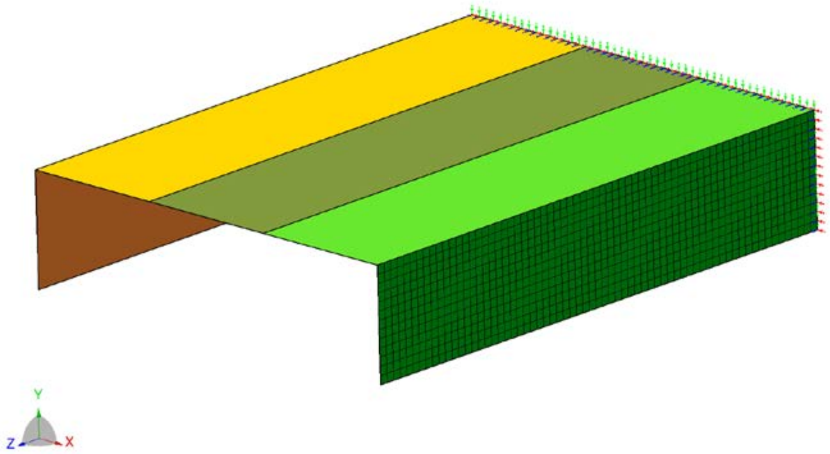

Figure 5: U-shaped profile

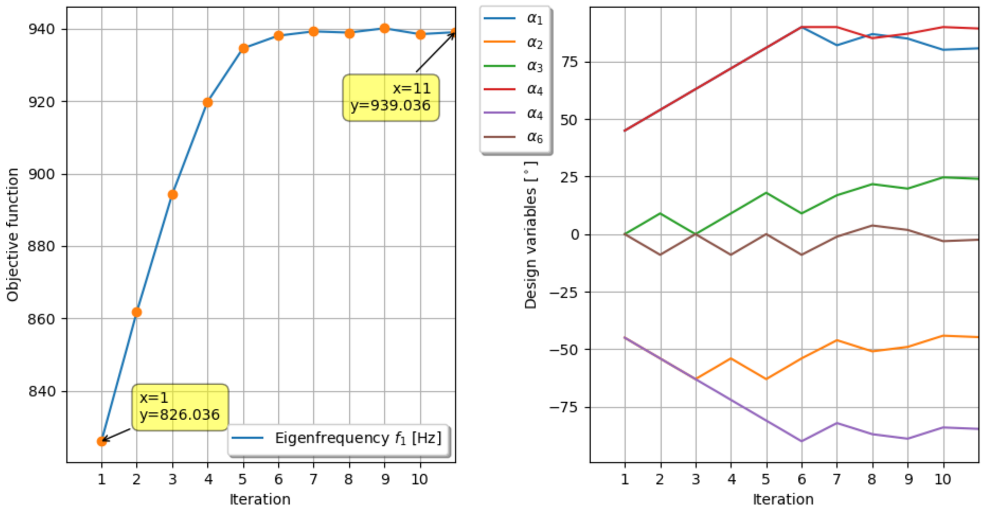

Figure 6: Objective function and design variables

The last example is taken from [1] and focuses on a shape optimization of a cantilever composite plate with a central circular hole. The width *w* and the diameter *d* of the hole are introduced as design variables. Due to the mesh morphing capabilities no remeshing is needed during the shape optimization. The goal of the optimization is to minimize the weight subjected to an eigenfrequency constraint $f_1 > 155$ [Hz]. The material properties used for the composite layers are E_1=156.5 [GPa], E_2=E_3=15.65 [GPa], G_{12}=G_{13}=5.19 [GPa], G_{23}=1.98 [GPa], ν_{12}=0.32, ν_{23} =0.35 and ρ=1.77E-09 [t/mm^3]. The symmetric stacking sequence is given by $[0°, -45°, 45°, 90°]_S$. The total thickness of the plate is given by $\sum_{i=1}^{8} t_i = 2.26$ [mm]. The red and blue arrow in Fig. 6 denotes the design variables that control the variation of the width and the diameter. Additional planar and axial symmetries for the two design elements and $DERESTRAINT BOUND definitions guarantee that the circular form of the hole is retained when the width is modified. Conversely, a variation of the diameter does not lead to a mesh modification of the contour of the beam. The length of the beam is L=140 [mm]. The initial width and radius are given by *w*=25 [mm] and *r*=3.25 [mm], respectively. Fig. 7 illustrates the results of the shape optimization. The design is feasible, since active constraints reach ± 100% and violated constraints exceed ± 100%.

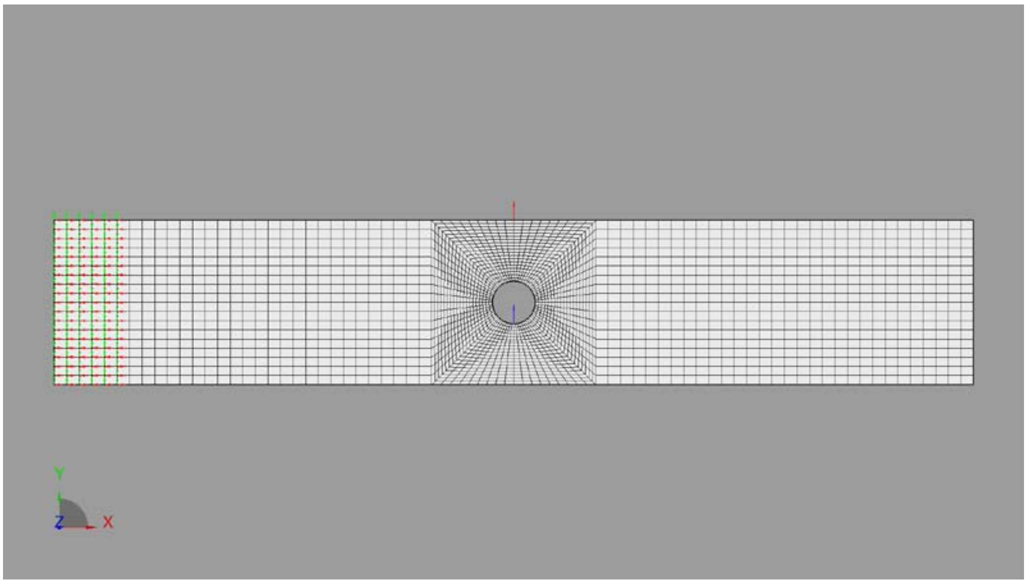

Figure 7: Finite element model of the cantilever beam

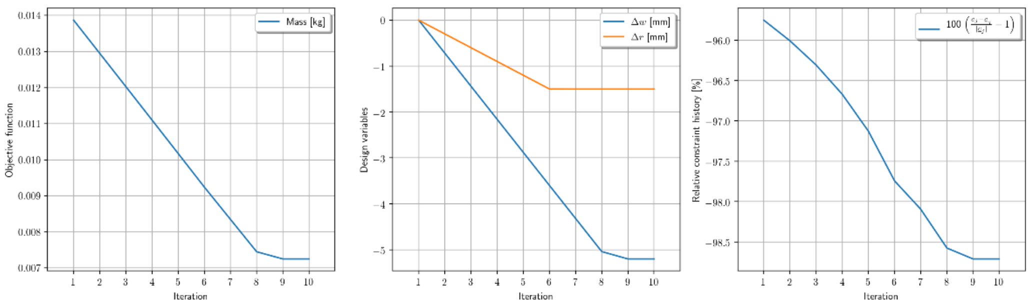

Figure 8: Results of the optimization: Objective function, Design variables and relative constraint history

3. Summary and Outlook

Various optimization possibilities have been demonstrated in connection with laminates using several examples from the literature. The results are promising and motivate to increase the use of laminates in practice. Many other aspects such as the inclusion of failure criteria and optimization with regard to buckling factors [6, 8, 9] and sound radiation are in preparation.

4. References

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