Design Optimization of a CFRP Wing Cover for the AFP Process

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Abstract:

The economic use of carbon fibre reinforced plastics in large aerospace structures requires cost-effective production technologies. In recent years, many advances have been made in automation technology, such as Automated Fibre Placement (AFP) and Automated Tape Laying (ATL) technologies.

In the design process, new methods were established to include the boundary conditions of the production process. The optimization process now focuses not only on weight reduction, but also on an improved cost/weight ratio. Most of the research on this topic has been done in the field of conceptual design, as the highest percentage of the manufacturing costs incurred later is defined by decisions made in the early design phase.

But there is also a potential for reducing production costs in the detailed design phase. In the Composite Design department of the DLR Institute of Composite Structures and Adaptive Systems the detailed design of a wing cover skin section was optimized for the AFP process. Ply shapes and ramp geometries were modified to reduce the number of courses needed for ply lay-up and thus the production time. Incomplete courses with less than all available tows as well as repeated stops and accelerations of the fiber placement head due to unnecessary tow-cutting operations were avoided.

With these approaches, the total lay-up time could be reduced by 3.4 %, whereas the on-surface time of the fibre placement heads even decreased by 5 % compared to the reference design, while the structural weight remained constant. The optimization strategies originally developed for the AFP process are also applicable to the ATL process.

The optimized design was analyzed in 3 sections and compared to the reference design for 408 combinations of longitudinal, transversal and shear loads, showing only minor differences in strength and stability.

Introduction

Automated fibre lay-up technologies such as Automated Fiber Placement (AFP) or Automated Tape Laying (ATL) have undergone enormous improvements in the recent years. When composites were first introduced to the aircraft industry in the 1980s, most work had to be done manually, making manufacturing of composite parts expensive and time-consuming. In today's production processes automated fiber lay-up enables much higher production rates. Nevertheless high-rate production scenarios for short- and medium-range aircraft are still very challenging to realize, even when using the highest-performance (most powerful) commercially available machines.

Further improvements can be expected in research into new manufacturing solutions. The German Aerospace Center (DLR) at the Center for Lightweight Production Technology (ZLP) in Stade has invented and co-developed a plant concept with a novel robot-based multi-head fibre placement facility (GroFi) along with sensor systems and simulation tools [1,2]. In 2017, the first wing cover in multi-head mode with two lay-up platforms working simultaneously was built as part of the EWiMa (Efficient Wing Cover Manufacturing) project funded by the German Federal Ministry of Economics and Energy [3].

In addition to the further development of manufacturing technologies, component design can also be optimized to reduce manufacturing costs and production time. In the past, much has been done to optimize both, weight and costs. Previous research focused on the concept phase, in which (design) decisions later have the greatest influence on weight and costs [4, 5].

As the results of the conceptual design are not directly usable for the manufacturing of parts, further detailed design steps are necessary. These design steps also provide the opportunity to further optimize the production process, while path planning and NC-file generation are based on exact ply shapes. In general, these ply shapes are not designed to meet the specific requirements of the lay-up machine.

Aims and Scope

This paper focuses on the final design loop of wing covers, before the manufacturing engineering takes over. It describes a strategy for modifying ply contours to reduce lay-up time and improve the efficiency of the fibre placement process and thus to reduce production costs.

Detailed composite design, cost analysis and structural analysis are involved in this design loop. In a conventional design process, those steps are performed one after the other. Detailed design is based on structural design using design rules for laminate stacking and ramp geometries. The manufacturing costs are a result of the subsequent design process. Material is added in each step of the sequential process: Ramps between different laminate stackings are extended from thicker areas to thinner laminates. The path planning for the fibre placement heads is designed to fully cover the ply shapes. As single courses of an AFP-machine cannot be arbitrarily short, additional material must be applied to achieve the minimum course length.

If constraints of the production process are taken into account during detailed design, including structural analysis, unnecessary material can be avoided, in which leads to a reduction in weight and production costs. This means that the conventional sequential design process must be transformed into a closed loop, in which design modifications can be evaluated to maintain structural performance such as strength, stiffness and low weight.

The proposed procedure is applied to a section of a wing cover, manufactured in AFP technology and described later in the case study. In general, the design strategies described in this paper are not limited to wing covers or to the AFP process and can also be applied to any other planar composite part manufactured with automated fibre lay-up such as Automated Tape Laying (ATL).

The main target of structural optimization is to find the weight-optimized design that is able to carry all loads and meet the stiffness requirements. Multidisciplinary design optimizations such as cost/weight optimization look for the best compromise between different objectives. This paper does not describe a closed optimization method, but strategies to reduce production time and costs without losing structural performance such as weight-gain or loss of strength and stiffness. The starting point for design optimization is the result of structural optimization. It has to be ensured, that the design modifications do not have a significant impact on weight and strength.

Most likely, any design change will affect both, weight and cost. Any advantageous design solution improves at least one target value better than the other or even saves weight and costs. The decision as to whether a solution is advantageous can be made by comparing the gradient $\Delta C/\Delta m$, where ΔC is the cost change and Δm is the weight change. Simply put, this gradient says, how much a kilogram of weight saved can cost or how much extra weight is acceptable to save costs.

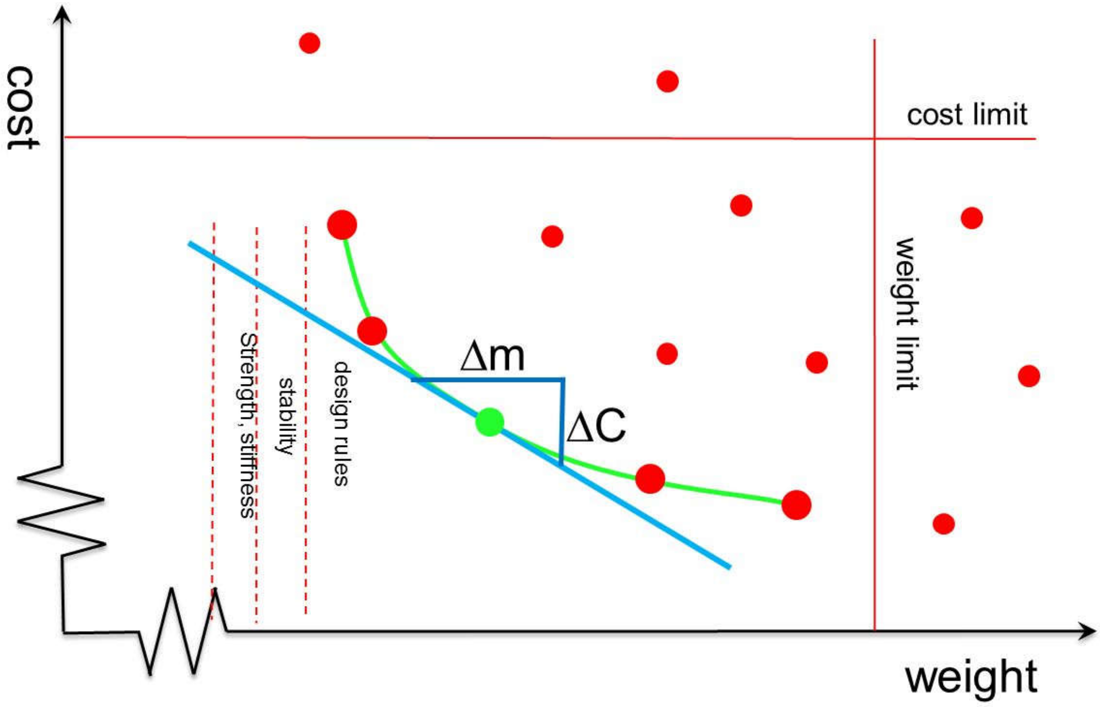


Figure 1 Pareto optimization for weight and cost

Figure 1 shows a cloud of possible design solutions by weight and cost. Assuming that the initial design is neither the lightest nor the cheapest solution, any design solution on the left side of the gradient represents a better design. The best solutions within given weight and cost limits are those on the pareto front, while the most favorable solution is the one corresponding to the given $\Delta C/\Delta m$ gradient.

Method

A detailed cost model is required to assess detailed design modifications. A cost analysis tool is available for the GroFi research facility, which provides the production costs for each individual lay-up path, divided into non-recurring costs (investment) and recurring costs (material, cutting, labour, energy, maintenance, building use, ancillary costs). In addition to the costs, information about the minimum and maximum tow length, the number of tows and surface area is also provided. The cost analysis is based on the detailed coverage simulation of the lay-up process [3].

An analysis of previous lay-ups showed that some courses have an unfavorable relation of mass output and lay-up time. Particularly very short courses have a higher proportion of unproductive workflows such as positioning movements of the fibre placement head, acceleration and deceleration and cutting. Also noticeable are courses, in which fewer tows are deposited, since the required course-width is smaller than possible.

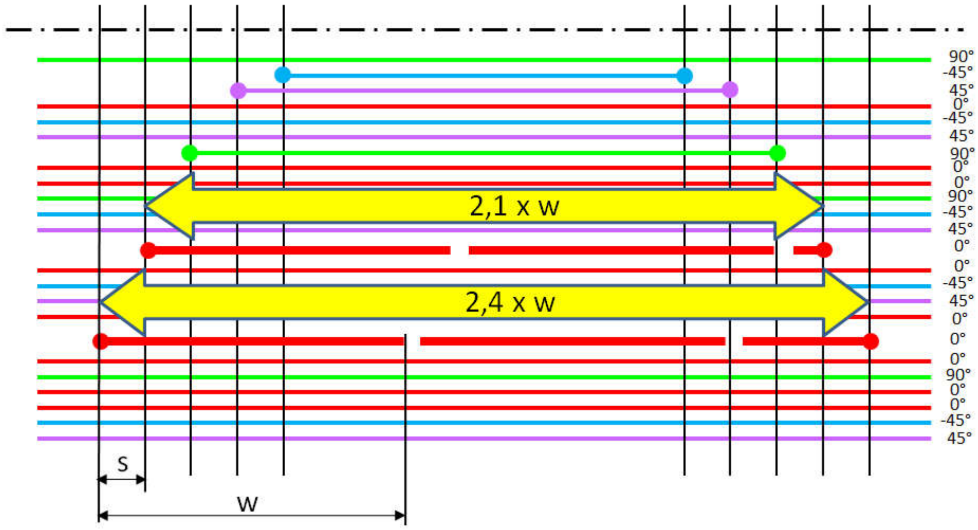
A reduction of the lay-up time can be achieved by reducing the total number of courses, avoiding incomplete courses and reducing deceleration phases for cutting one tow after the other. Therefore, the ply shapes must be designed according to the geometry that can be deposited by the fibre placement heads in full width and without successive cutting single tows, and without adding material and weight.

In this thesis two approaches were developed to achieve the above-mentioned goals. The first approach considers ply contours parallel to the fibre direction. The width of the fibre placement heads of the GroFi research facility is 102 mm (4”). Each ply whose width is not an exact multiple of this value requires incomplete courses with less than all available tows at least on one side. Local reinforcements and transition zones from one laminate thickness to another require ramps, as not all of the additional plies can end at the same location. The stagger value between two plies in those ramps is typically much smaller than the width of the fibre placement head or half the width for symmetrical ramps.

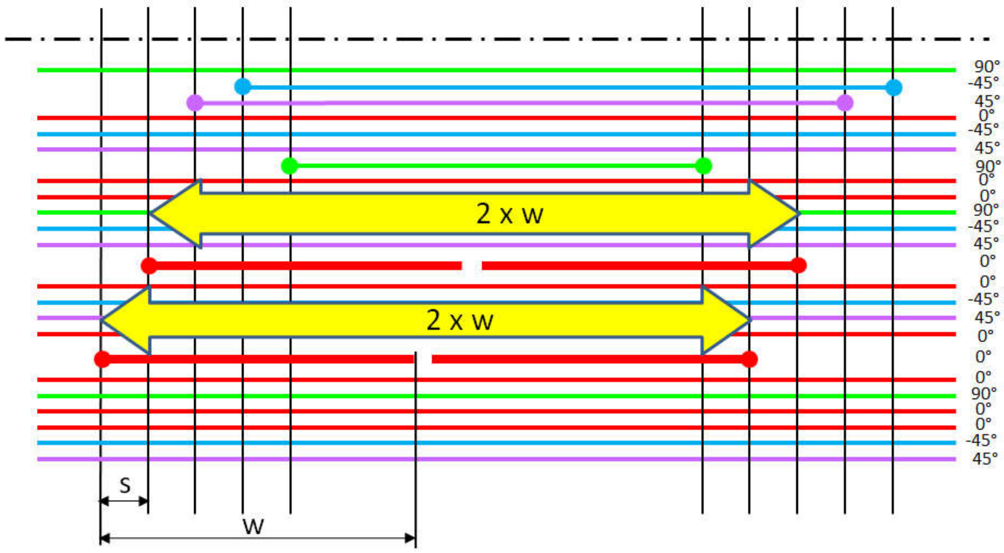
With asymmetric staggering, ramps can be designed for constant ply widths, as shown in Figure 2. The upper figure shows a conventional, symmetrical ramp design where each additional ply is offset by a constant value s on both sides. Under the assumption that the ply boundaries run parallel to the 0° fibre orientation, the adaption of the exact ply edges leads to incomplete courses at least on one side.

The asymmetrical ramp design is shown in the figure below. The 0° plies correspond to the staggered positions with an exact width of two complete courses (2w). The remaining staggered positions are filled with other plies that have to be cut anyway.

Non-parallel ply contours that intersect with lay-up paths require a different treatment, the second approach. In order to avoid successive cutting steps of single tows, it is proposed to create ramps by interlacing production-optimized plies, as shown in Figure 3.



Symmetric ramp design



Asymmetric ramp design

Figure 2 Asymmetric ramp for matching multiple width of the fiberplacement head

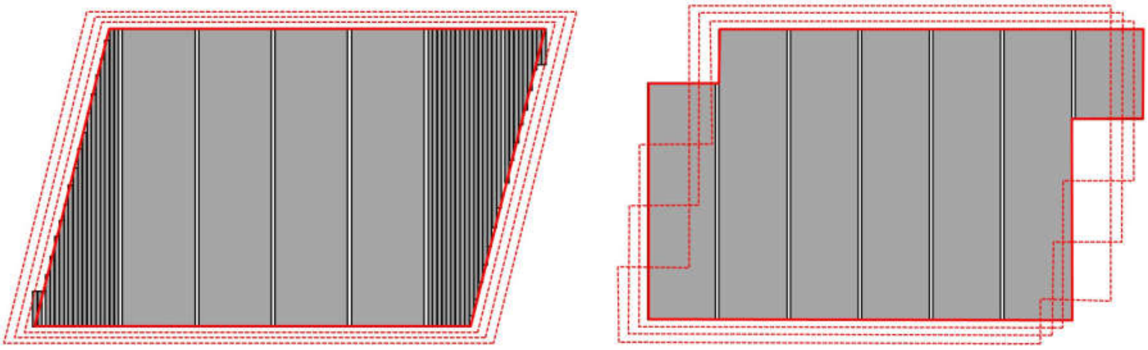


Figure 3 Conventional design vs. optimized design

Conventional uniform ramps (left) are generated by constant staggering from one ply to the next. When matching the given ply contour, single tows have to be cut. Allthough less material is placed, the lay-uptime even increases for incomplete courses, as repeated deceleration and acceleration phases are always necessary for tow-cutting.

Production optimized ramps (right) result from interlacing ply contours, each of which is designed to avoid incomplete courses, and to use the complete width of the fibre placement head and cutting all tows at once.

Structural Analysis

A finite-element model of different sections is used for the structural analysis. In addition to the lay-up sequence, the load components of longitudinal, transversal and shear loads are parametrically defined. The components of the load vector N are varied by the variables φ and θ, as shown in Figure 4.

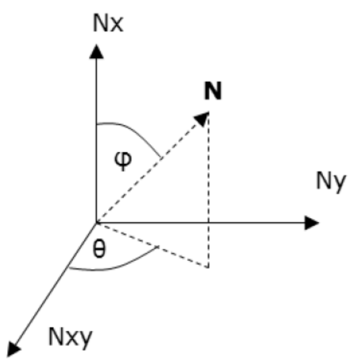


Figure 4 Load vector

While the variable φ determines the portion of the longitudinal load Nx, q defines the ratio of the transversal load Ny to the shear load Nxy. With φ = 0, the resulting load vector is a pure compression load, whereas for $\varphi = \pi$ it is a pure tensile load. For $\varphi = \pi/2$ only combinations of transversal and shear loads occur.

No.	longitudinal / transversal / shear
1	Compression / - / -
2	Compression / - / Shear
3	Compression / Tension / Shear
4	Compression / Tension / -
5	Compression /Compression/ Shear
6	Compression /Compression/ -
7	- / - / Shear
8	- / Tension / Shear
9	- / Tension / -
10	- /Compression/ Shear
11	- / Compression / -
12	Tension / - / Shear
13	Tension / Tension / Shear
14	Tension / Tension / -
15	Tension /Compression/ Shear
16	Tension /Compression/ -
17	Tension / - / -

Table 1 General load combinations

The value range is $\varphi \in [0,\pi]$ and $\theta \in [0,2\pi]$. With increments of $\Delta\varphi = \pi/16$ and $\Delta\theta=\pi/12$ there are a total of 408 load cases with 17 fundamentally different load combinations according to Table 1.

For each load case, the strength is analysed in one section of the conventional ramp and three sections of the production optimized design for fibre failure using the Yamada-Sun criterion and for inter-fibre-failure using the Puck criterion. With the resulting reserve factors for both criteria, for each load combination the maximum amount of the load vector can be calculated that leads to either fibre failure or inter-fibre (matrix) failure.

For the case study, a reference section of 1,750 mm x 1,350 mm is chosen around the thickest part of the wing cover (green square in Figure 5) and the design modifications described above are applied to the production optimized design.

The reference design consists of 3 different basic ply shapes. 58 Full plies extend over the complete area. In the upper part, 53 further plies are added to form the frontspar area of the wing cover. An additional 50 trapezoidal plies are inserted in the pylon area. Modifications of full plies are restricted to the upper

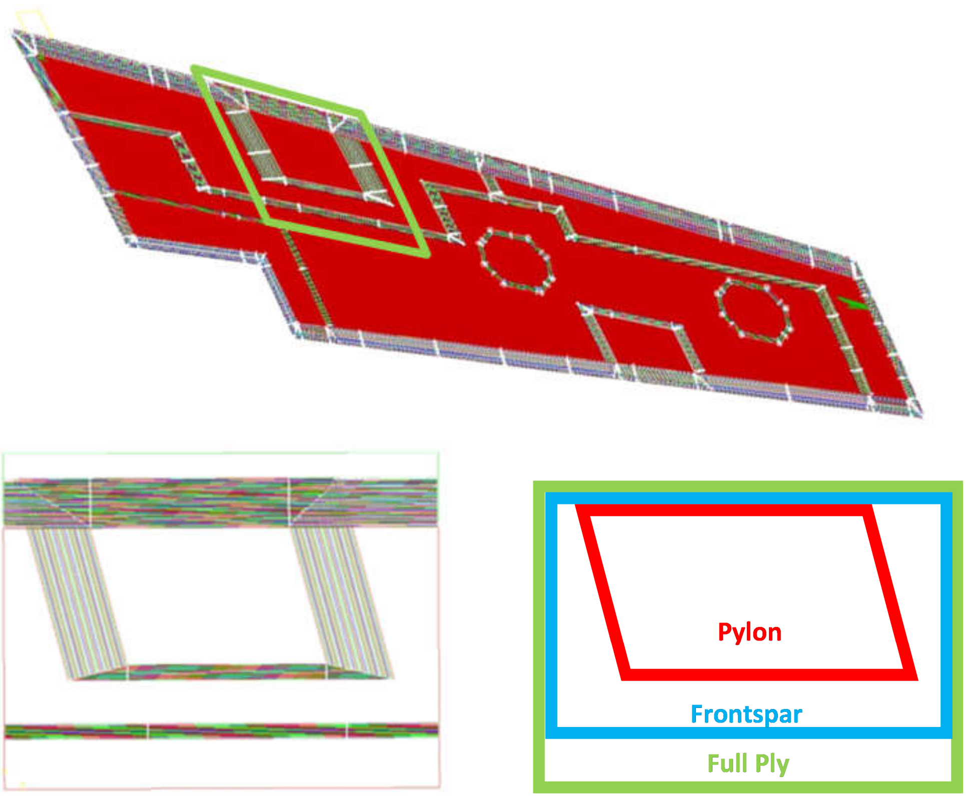


Figure 5 Reference design as part of a full scale wingcover

Case Study

In the EWiMa (Efficient Wing Cover Manufacturing) project, a wing cover was developed to demonstrate the multi-head capability of the GroFi facility. The wing cover is 8 m long and 2.80 m wide and includes typical features of the actual wing cover designs defined by Airbus. However, the design is neither optimized for real flight loads, nor is it based on a real wing geometry. Laminate thickness is between 7 mm [60/30/10] in the base area and up to 20 mm [44/44/12] in a patch area at a typical position for attaching the engine pylon.

edges, while the other edges remain unchanged. The frontspar-plies are only modified at the upper and lower edges. Only the plies of the pylon-shape are modified at all edges.

The cost analysis of the reference design shows that only 13 % of the total costs are non-recurring costs caused by investments. The main part of the total costs are the material costs (62%), followed by the labour costs (9%), building occupancy (8%) and additional costs, e. g. for vacuum bagging, release agents (5%). The costs for maintenance, energy and tow-cutting are each less than 2% of the total costs.

The cost model is based on a fixed production scenario with a given batch size, and it is assumed that the capacity of the facility is sufficient for all parts to be produced. So the saving of production time does not lead to decreasing investment costs.

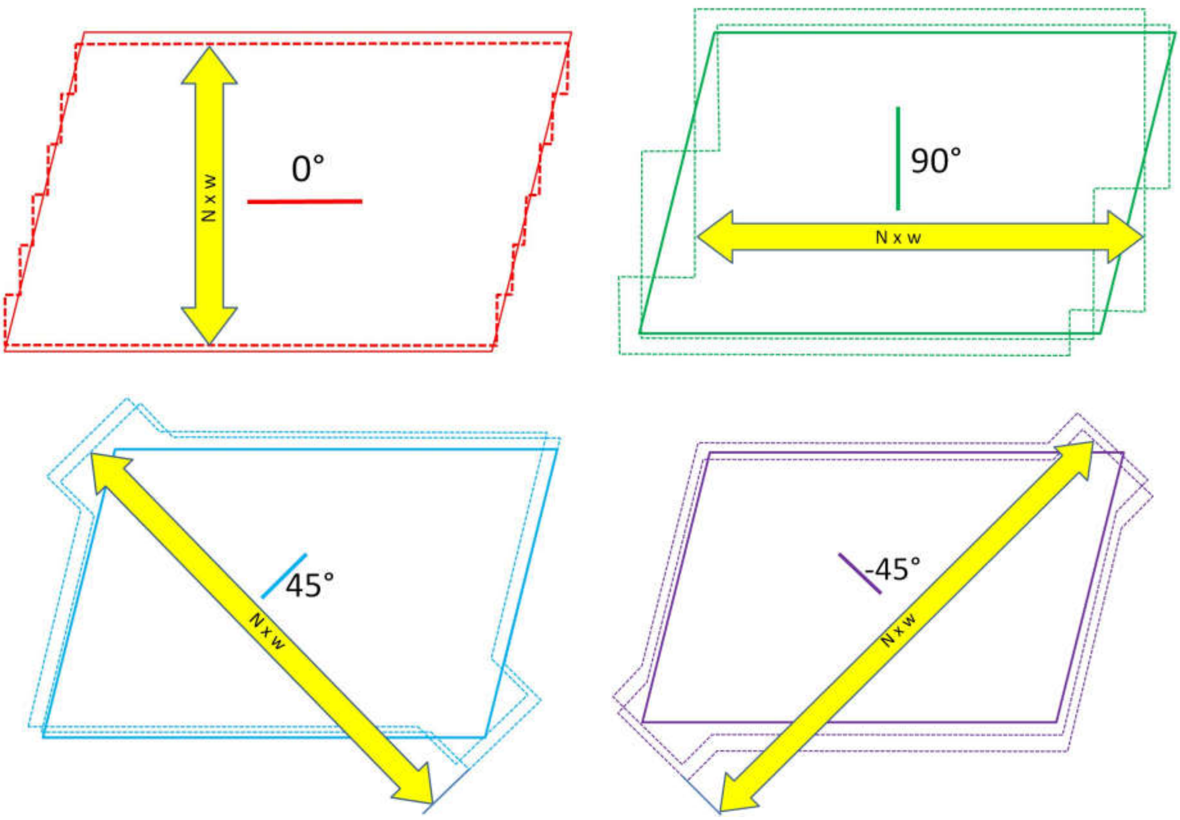


Figure 6 Ply shape optimization for 0°, 90° and +/-45° plies

Material cost will decrease with weight savings. The additional costs cannot be influenced by design changes of the ply shapes, by production time or weight. Only the labour costs and the building occupancy costs are dependent on the production time, so that less than 20 % of the total costs can be influenced by a reduction of production time. On the other hand, cost savings due to speeding up the production process can easily be offset by increasing weight and material costs.

Figure 6 shows the general modification of the pylon shape plies for each fibre orientation. The optimized design of the reference part reduced the layup time by 18 minutes (-3.4 %), whereupon the off-surface time of the fibre placement head, e. g. for positioning movements decreased by 5 minutes (-2.0 %) and the on-surface time for material deposition dropped by 13 minutes (-5 %).

The total number of courses decreased by 34 (-1.5 %), because incomplete courses occurred only in full plies and plies of the frontspar shape, while not all edges of those plies were modified. None of the optimized plies of the pylon shape required a course with less than all 16 tows.

The part weight remained the same within the boundaries of the engineering edge of part (EEOP). By a slightly steeper ramp outside the EEOP, which is removed after trimming, the total weight of the untrimmed part is even lower and thus also the material costs.

The structural analysis is performed in one section of the reference design and in three sections of the optimized design. The results are shown in Figure 7. Each square of the matrix represents a load case, depending on the variables φ and θ. Only minor differences in the acceptable load vector are visible. All strength deviations are within +/- 5 % of the reference design, while there are more load cases with higher acceptable load vectors in the optimized design than vice-versa. Especially in the range of $\varphi < 1/8\pi$ and $\varphi > 7/8\pi$, where longitudinal loads dominate, the acceptable load vectors do not differ by more than 0.4 % from the reference design.

Discussion & Outlook

The optimization of the ply contour showed a potential for reducing the lay-up-time. Though cost-savings from shortening the production time are small, accelerating the production process by more than 3 % means that 31 optimized parts can be manufactured in the same time as 30 conventional parts. As long as there are no weight penalties or loss of strength and stiffness, there is no reason not to take advantage of the benefits.

The time-savings were achieved primarily by avoiding incomplete courses and adapting the ply contours to a multiple of the width of the fibre placement heads. Each ply can have only two incomplete courses, one on each side. For this reason, the proposed approach has less impact on large plies, e. g. full plies of large structures, but more impact on smaller patches. It must be shown

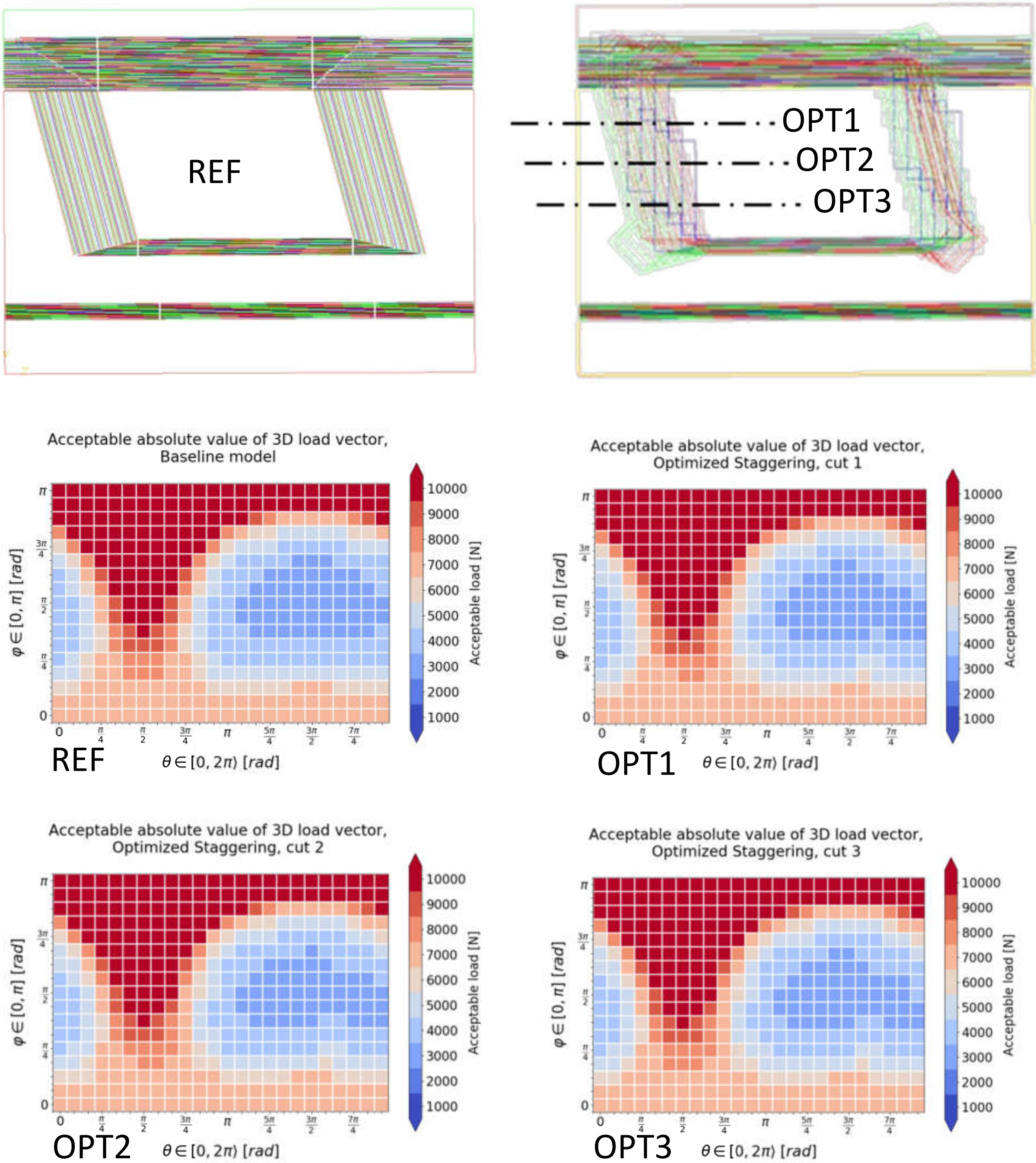


Figure 7 Acceptable load vector, comparison of reference and optimized design

which time and cost savings are possible for a complete wing cover.

The modifications to the reference design were made manually. It has not been proven that the result is the best possible solution, neither in terms of production time, nor in terms of strength and stiffness. Based on the preliminary results, it is necessary to establish specific design rules, depending on the critical load cases the design engineer can chose from. With these available design rules, it can also be possible to automatically modify and optimize ply shapes.

Current work focuses on the Automated Fiber Placement (AFP) process, but in general the proposed strategies are also suitable for Automated Tape Laying (ATL). New production technologies such as robot-based fibre placement even offer possibilities for the combined operation of ATL and AFP units and can benefit from both technologies. Large full plies can be produced more efficiently with ATL technology, while smaller patches can benefit from AFP technology.

The simultaneous operation of multiple fibre placement units, as demonstrated at the GroFi research facility, places further demands on component design, as the efficient workshare between different units can be facilitated by a suitable design, e. g. by realizing a stacking sequence that allows as many platforms as possible to work simultaneously of. Large full plies with 0° fiber orientation require free movement of the fibre placement units over the entire length. By cleverly integrating additional necessary plies into the stacking sequence, unnecessary idle times can be avoided, if additional plies can simultaneously be deposited within patches and local reinforcements.

The structural limitations of ply shape optimization also require further investigation through numerical simulations confirmed by tests, both static and fatigue.

Different production scenarios influence the cost model and thus the results of ply shape optimization. If the material costs contribute to a high share of the total costs, weight savings have a greater influence on production costs, which can even allow an increase of the production time to a certain amount.

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