Research Article

Optimizing Variable-Axial Fiber-Reinforced Composite Laminates: The Direct Fiber Path Optimization Concept

Lars Bittrich,1 Axel Spickenheuer,1 José Humberto S. Almeida Jr.1,1,1 Sascha Müller,2 Lothar Kroll,2 and Gert Heinrich1

1Mechanics and Composite Materials Department, Leibniz-Institut für Polymerforschung Dresden e. V., Hohe Str. 6, 01069 Dresden, Germany
2Institut für Strukturleichtbau, Technische Universität Chemnitz, 09107 Chemnitz, Germany

Correspondence should be addressed to José Humberto S. Almeida Jr.; humberto@ipfdd.de

Received 18 September 2018; Revised 17 December 2018; Accepted 16 January 2019; Published 19 February 2019

The concept of aligning reinforcing fibers in arbitrary directions offers a new perception of exploiting the anisotropic characteristic of the carbon fiber-reinforced polymer (CFRP) composites. Complementary to the design concept of multiaxial composites, a laminate reinforced with curvilinear fibers is called variable-axial (also known as variable stiffness and variable angle tow). The Tailored Fiber Placement (TFP) technology is well capable of manufacturing textile preforming with a variable-axial fiber design by using adapted embroidery machines. This work introduces a novel concept for simulation and optimization of curvilinear fiber-reinforced composites, where the novelty relies on the local optimization of both fiber angle and intrinsic thickness build-up concomitantly. This framework is called Direct Fiber Path Optimization (DFPO). Besides the description of DFPO, its capabilities are exemplified by optimizing a CFRP open-hole tensile specimen. Key results show a clear improvement compared to the current often used approach of applying principal stress trajectories for a variable-axial reinforcement pattern.

1. Introduction

Recently, the demand for energy efficient systems leveraged the use of CFRP lightweight composites in structural components. These materials are increasingly being employed in aeronautical, aerospace, and automotive applications. Due to the high cost of carbon fibers, their efficient usage becomes essential [1]. By employing a variable-axial (VA) fiber design, stiffness and strength properties may be improved when comparing to classical CFRP designs [2]. Thereby, the term VA means varying the fiber orientation at the ply level. The desired performance of CFRP composites is achieved by guiding the loads almost exclusively along the fiber orientation and thus minimizing the shear load of the matrix. For a technical realization, TFP technology, which was developed at Leibniz-Institut für Polymerforschung Dresden (Germany), is well suited. Basics and some applications of TFP technology are described in [3, 4]. The placement of carbon fibers is usually carried out by stitching dry rovings, as shown in Figure 1. The roving is guided through a rotatable roving pipe onto a base material, where a sewing thread applied in the zig-zag-pattern holds it in place.

Several approaches have been developed to optimize VA composites. An extensive overview of curvilinear fiber-reinforced composites was recently performed by Ribeiro et al. [5]. Under the name variable angle tow steering, Weaver et al. [6] improved the postbuckling performance of composite panels with a VA layout, whereas Panesar and Weaver [7] optimized blended bistable laminates suitable for morphing flap applications. Duvaut et al. [8] implemented a varying fiber density in order to consider local stress intensity. For a similar purpose, the local layer thickness was varied by Parnas et al. [9] as an additional design parameter. Groh and Weaver [10] proposed a minimum-mass design of a typical aircraft wing panel under end-compression. Khani et al. [11] developed a mathematical optimization algorithm for variable stiffness panels using lamination parameters. Van Campen et al. [12] proposed a methodology to convert
known lamination parameters distribution for a VA composite laminate into realistic fiber angles, with minimum loss of structural performance. Cho and Rowlands [13] reduced stress concentrations in an open-hole laminate with a genetic algorithm.

In contrast to optimization procedures, principal stress criterion has been often used for deriving curvilinear fiber paths, e.g., [14–17]. Kelly et al. [18], Waldmann et al. [19], and Malakhov and Polilov [20] designed the curvilinear fiber path based on the concept of aligning fibers following the load path by placing fibers along principal stresses. Both approaches were assumed to be optimization criteria, although no mathematical optimization process was explicitly carried out and were assumed to be optimization criteria, although no mathematical description of the optimization algorithm to be placed with a slight overlap to avoid gaps between neighboring rovings, while parallel laminates can be produced for a small range of distances between neighboring rovings. The thickness $t$ is calculated according to the following (see Figure 2):

$$t = \frac{A_{\text{rov}}}{d} = \frac{T_i}{\rho \phi}$$

where $A_{\text{rov}}$ is the roving cross-section area, $d$ is the distance between neighboring rovings, $T_i$ is the roving fineness, $\phi$ is the fiber volume fraction, and $\rho$ is the fiber density.

For arbitrary nonparallel roving placement, the thickness evaluation becomes more complex. As a starting point for the mathematical description of the optimization algorithm to be placed with a slight overlap to avoid gaps between neighboring rovings, while parallel laminates can be produced for a small range of distances between neighboring rovings. The thickness $t$ is calculated according to the following (see Figure 2):

$$t = \frac{A_{\text{rov}}}{d} = \frac{T_i}{\rho \phi}$$

where $A_{\text{rov}}$ is the roving cross-section area, $d$ is the distance between neighboring rovings, $T_i$ is the roving fineness, $\phi$ is the fiber volume fraction, and $\rho$ is the fiber density.

For arbitrary nonparallel roving placement, the thickness evaluation becomes more complex. As a starting point for the mathematical description of the optimization algorithm to be placed with a slight overlap to avoid gaps between neighboring rovings, while parallel laminates can be produced for a small range of distances between neighboring rovings. The thickness $t$ is calculated according to the following (see Figure 2):

$$t = \frac{A_{\text{rov}}}{d} = \frac{T_i}{\rho \phi}$$

where $A_{\text{rov}}$ is the roving cross-section area, $d$ is the distance between neighboring rovings, $T_i$ is the roving fineness, $\phi$ is the fiber volume fraction, and $\rho$ is the fiber density.

For arbitrary nonparallel roving placement, the thickness evaluation becomes more complex. As a starting point for the mathematical description of the optimization algorithm to be placed with a slight overlap to avoid gaps between neighboring rovings, while parallel laminates can be produced for a small range of distances between neighboring rovings. The thickness $t$ is calculated according to the following (see Figure 2):

$$t = \frac{A_{\text{rov}}}{d} = \frac{T_i}{\rho \phi}$$

where $A_{\text{rov}}$ is the roving cross-section area, $d$ is the distance between neighboring rovings, $T_i$ is the roving fineness, $\phi$ is the fiber volume fraction, and $\rho$ is the fiber density.

For arbitrary nonparallel roving placement, the thickness evaluation becomes more complex. As a starting point for the mathematical description of the optimization algorithm to be placed with a slight overlap to avoid gaps between neighboring rovings, while parallel laminates can be produced for a small range of distances between neighboring rovings. The thickness $t$ is calculated according to the following (see Figure 2):

$$t = \frac{A_{\text{rov}}}{d} = \frac{T_i}{\rho \phi}$$

where $A_{\text{rov}}$ is the roving cross-section area, $d$ is the distance between neighboring rovings, $T_i$ is the roving fineness, $\phi$ is the fiber volume fraction, and $\rho$ is the fiber density.

For arbitrary nonparallel roving placement, the thickness evaluation becomes more complex. As a starting point for the mathematical description of the optimization algorithm to be placed with a slight overlap to avoid gaps between neighboring rovings, while parallel laminates can be produced for a small range of distances between neighboring rovings. The thickness $t$ is calculated according to the following (see Figure 2):

$$t = \frac{A_{\text{rov}}}{d} = \frac{T_i}{\rho \phi}$$

where $A_{\text{rov}}$ is the roving cross-section area, $d$ is the distance between neighboring rovings, $T_i$ is the roving fineness, $\phi$ is the fiber volume fraction, and $\rho$ is the fiber density.

For arbitrary nonparallel roving placement, the thickness evaluation becomes more complex. As a starting point for the mathematical description of the optimization algorithm to be placed with a slight overlap to avoid gaps between neighboring rovings, while parallel laminates can be produced for a small range of distances between neighboring rovings. The thickness $t$ is calculated according to the following (see Figure 2):

$$t = \frac{A_{\text{rov}}}{d} = \frac{T_i}{\rho \phi}$$

where $A_{\text{rov}}$ is the roving cross-section area, $d$ is the distance between neighboring rovings, $T_i$ is the roving fineness, $\phi$ is the fiber volume fraction, and $\rho$ is the fiber density.

For arbitrary nonparallel roving placement, the thickness evaluation becomes more complex. As a starting point for the mathematical description of the optimization algorithm to be placed with a slight overlap to avoid gaps between neighboring rovings, while parallel laminates can be produced for a small range of distances between neighboring rovings. The thickness $t$ is calculated according to the following (see Figure 2):

$$t = \frac{A_{\text{rov}}}{d} = \frac{T_i}{\rho \phi}$$

where $A_{\text{rov}}$ is the roving cross-section area, $d$ is the distance between neighboring rovings, $T_i$ is the roving fineness, $\phi$ is the fiber volume fraction, and $\rho$ is the fiber density.
the analytical description of such a preform the placement path is used, which is the basis for the fiber placement with a TFP machine. This path or more generally a sequence of paths will be referenced as the design pattern. The simplest mathematical description is a sequence of straight lines in two dimensions. Curved placement paths, e.g., containing primitives such as arcs or splines, will be approximated with a sequence of short straight lines within the accuracy of primitives such as arcs or splines, will be approximated with two dimensions. Curved placement paths, e.g., containing mathematical description is a sequence of straight lines in paths will be referenced as the design pattern. The simplest a TFP machine. This path or more generally a sequence of path is used, which is the basis for the fiber placement with.

Figure 2: Schematic depiction of (1).

The coarse-graining is done by integrating the function in the whole plane of \( x', y' \). By using the definition of the line thickness distribution \( t_{\text{line}} \), a solution for this convolution can be expressed in terms of error functions. This makes a numerical implementation very fast. This Gaussian thickness distribution represents a Gaussian weighted average of the roving volume density in the area around the point at which the thickness needs to be computed. For single straight rovings, this thickness distribution leads to a Gaussian cross-section area, which roughly approximates the real cross-section areas for the TFP process, as shown in microsections by Uhlig et al. [32]. Other smoothing functions such as a cylindrical average approximate the cross-section of a single roving to a closer degree. However, the resulting laminates exhibit many discontinuities, which negatively influence the convergence of the modeling. With the Gaussian thickness distribution the laminate boundary needs to be defined by a cut-off thickness, as the Gaussian is nowhere exactly zero.

The main challenge for numerical modeling is to obtain the geometry and the fiber orientation based on the placement pattern of a single layer. Successive layers are stacked on top of each other without regard to draping behavior, which is fine as long as thickness gradients of the lower layers are small enough. The description is restricted to layers of noncrossing rovings or at least to roving placements where overlapping rovings cross at small angles, such that an element wise average of fiber orientation is meaningful. Note that, for many examples which contain a self-crossing

\[
\begin{align*}
\delta(x-x_0) &= \frac{1}{2\sigma^2} \int t_{\text{line}}(x', y') \
&\cdot \exp \left( -\frac{(x-x')^2+(y-y')^2}{2\sigma^2} \right) dx' dy' 
\end{align*}
\]

The main challenge for numerical modeling is to obtain the geometry and the fiber orientation based on the placement pattern of a single layer. Successive layers are stacked on top of each other without regard to draping behavior, which is fine as long as thickness gradients of the lower layers are small enough. The description is restricted to layers of noncrossing rovings or at least to roving placements where overlapping rovings cross at small angles, such that an element wise average of fiber orientation is meaningful. Note that, for many examples which contain a self-crossing function is only an intermediate step as the total fiber volume is concentrated along the infinitely thin lines and an infinitely high thickness is obtained on the lines and zero elsewhere. However, the function \( t_{\text{line}} \) already fulfills the normalization condition. By integrating over the total design space or any area containing all line segments the total fiber volume \( V_{\text{tot}} \) is obtained:

\[
V_{\text{total}} = \int t_{\text{line}}(x, y) \, dx \, dy = \sum_i A_{\text{rov}} d_i
\]
roving path, the layer can be split into smaller layers with noncrossing rovings. In Figure 4, a schematic description of the modeling procedure is shown. Based on a two-dimensional (2D) mesh of the planar design space a three-dimensional finite element model is derived using localized information of the Gaussian thickness distribution and the averaged fiber orientation. The thickness is evaluated at each corner node and the fiber orientation at the center of each element. The fiber orientation is well defined for linear line segments. The elemental fiber orientation is averaged by a thickness weighted average of all linear line segments, which contribute to the total thickness at the center point of each element.

Successive layers can be stacked on top of each other. The resulting three-dimensional (3D) FE model represents a piece-wise linearization per element of the locally averaged characteristics, namely, thickness and fiber angle. Alternatively, the thickness and fiber angle can be combined at the center of the FE into a 2D layered shell element description to obtain a model for the same fiber layout with less computational cost. The main difference arises from neglecting the out-of-plane component of the fiber orientation and thickness gradients within an element.

Next, two numerical examples are considered by using DFPO. For both cases, the following parameters are used: fiber volume fraction ($\varphi$) of 58%; roving fineness ($T_r$) of 400 tex; density ($\rho$) of 1.76 g.cm$^{-3}$; and width smoothing parameter ($\sigma$) of 1 mm.

2.2. Case 1: Open-Hole Tensile Specimen. An open-hole specimen under tensile loading is chosen to demonstrate the modeling capabilities and the optimization of VA laminates by employing the DFPO approach. Their specimen geometry and dimensions are presented in Figure 5(a). In order to directly evaluate the capabilities of the proposed optimization framework, the specimen comprises two layers, achieved by stacking a carbon fiber TFP layer (layer to be optimized) on top of the base material ($\mp 45^\circ$ carbon fiber woven fabric with areal weight of 256 g/m$^2$). Figure 6 shows in detail the two-layer open-hole specimen in study.

Based on a 2D meshing of the supporting plane, the local thickness is evaluated at each node for each laminate layer along the FE mesh, as it is shown in blue color scale (Figure 7(b)). In addition, the elemental fiber orientation (Figure 7(a)) is set as the averaged fiber orientation at the center of each element. In areas where the current considered fiber pattern places no rovings, the thickness computation yields effectively zero. However, to provide a continuous mesh in this case, a very small thickness of 0.001 mm is set at the corresponding nodes and the corresponding element material properties are set to resin properties (blue elements in Figure 6). The corresponding FE model additionally incorporates at the bottom of the laminate a layer of constant thickness (0.24 mm) of base material, as Figure 6 depicts.

Symmetrical boundary conditions are applied along all axes of the specimen. The load is applied at the top-edge of the specimen. These details can be seen in Figure 6. Finite element simulations are carried out in ANSYS APDL using quadratic SOLID186 and linear SOLID185 elements (ANSYS library reference).

2.3. Case 2: Narrow-Middle Tensile Specimen. In order to provide another example for the applicability of the proposed DFPO framework, a sample under the same loading conditions has been considered. For that, a narrow-middle specimen under tensile loading is analyzed and optimized. Details on the geometry and dimensions of the narrow-middle tensile specimen are shown in Figure 5(b). In order to evaluate the capabilities of DFPO, similarly to the open-hole specimen, the sample consists of two layers, attained by stacking a carbon fiber TFP layer (layer to be optimized) on top of the base material ($\mp 45^\circ$ carbon fiber woven fabric with areal weight of 256 g/m$^2$). The material properties of both UD carbon fiber/epoxy TFP layer and the carbon fiber/epoxy woven fabric laminated composites used in the FE models and optimizations are presented in Table 1.

3. Optimization Process

The optimization problem for the fiber path is described by the minimization of an objective function, in which compliance minimization is the objective function, which analogously stands for stiffness maximization ($\bar{S}$) under variation of each roving placement path $C_i$. Within the context of the actual optimization, two compliances are aimed to be minimized as follows:

\[
\text{Stiffness optimization : } \min_{C_i} \left( \max_{\Omega_i} u_y \right) \quad (6)
\]

\[
\text{Strength optimization : } \min_{C_i} \left( \max_{\Omega_i} \text{MIA} \right) \quad (7)
\]

where minimizing the maximum of the displacement in $y$-direction is the objective function for stiffness optimization, whereas minimization of the maximum of MIA (mode interaction parameter) is the objective function for strength optimization. This MIA parameter is related to the physically based failure mode concept developed by Cuntze [33]. With this criterion, it is possible to distinguish several failure modes, namely, tension and compression induced failure modes for fiber failure and compression, tension, and shear induced inter-fiber-failure modes. Cuntze’s Failure Mode...
Figure 5: Geometry and dimensions for the open-hole (a) and narrow-middle (b) tensile specimens reinforced with UD fibers (reference layouts for the optimizations).

Table 1: Material properties for both TFP and base material layers.

|                      | TFP layer: unidirectional CFRP | Base material: CFRP woven fabric (±45°) |
|----------------------|-------------------------------|---------------------------------------|
| $E_1 (GPa)$          | $9.56$                        | $62$                                  |
| $E_2 = E_3 (GPa)$    |                               | $7.67$                                |
| $G_{12} = G_{13} = G_{23} (GPa)$ | $5.76$ | $4.17$                                |
| $\nu_{12} = \nu_{13} = \nu_{23}$ |                  | $0.258$                               |
| $\nu_{12} = \nu_{13} = \nu_{23}$ |                  | $0.033$                               |

Concept (FMC) is based on the stress and strengths quantities, which means that MIA (failure parameter) is calculated based on the stress state of the laminate at each interaction along the analysis. In other words, if $MIA \geq 1$, then the laminate fails; analogously if $MIA < 1$, the laminate is safe. Additionally, all failure modes can be combined into a single numerical value suitable for optimization with the mode interaction (MIA) quantity. Since the whole formulation of Cuntze’s FMC is very extensive, its full description can be seen in [33].

Mathematically, the dimensionality of the optimization problem of even a single roving path is infinite. However, due to limited production accuracy, the placement path can be modeled using a finite set of parameters within some placement path representation.

The optimization flowchart is implemented and presented in Figure 8. The parameterized fiber layout is represented by a finite set of coefficients, e.g., spline control points. The 2D fiber path is computed which in turn is analyzed by the 3D modeling tool to generate the finite element model. The local thickness and fiber orientation are taken into account. Loads and boundary conditions are applied and then the model is solved. Based on this solution, the target optimization value (compliance minimization or stiffness
Figure 7: Geometry (black contour), fiber rovings (red lines) (a), and thickness distribution for the open-hole tensile test specimen (b).

Figure 8: Optimization procedure for Direct Fiber Path Optimization.
maximizations) is derived. The optimization value is the sole input value for gradient free optimization algorithms, such as BOBYQA (Bound Optimization BY Quadratic Approximation) by Powell [34], which can modify the fiber path parameters within predefined boundaries to achieve a minimal displacement value. As long as no gradients are derived only gradient free optimization algorithms can be used. BOBYQA provides a fast converging algorithm for smooth optimization functions due to its quadratic approximation also implementing box constraints that can be used to restrict the fiber pattern to within reasonable locations. Details on the optimization parameters are given in Section 3.2. In general, other optimization values, such as failure stress, can be applied. However, the convergence to overall good solutions is much better for stiffness optimization in comparison to strength optimization. Thus, for a strength optimization, a stiffness optimized layout is used as an initial layout.

3.1. Convergence Study. For the use in optimization procedures, the numerical model must be sufficiently stable and free of mesh dependence, once otherwise numerical fluctuations lead to nonconverging behavior in the optimization algorithm.

For layers that fully cover the design space such that neighboring rovings overlap, i.e., maximum displacement in y-direction $\max(u_y)$ (Figure 9(a)) and maximum MIA (Figure 9(b)), the simulation converges or stabilizes with increasing the number of elements ($N$), as Figure depicts. Regarding stiffness optimization (Figure 9(a)), the FE model composed of quadratic elements (SOLID 186) easily converges for any element size, whereas for the FE model with linear elements (SOLID 185), the model converges well with a minimum number of 20,000 elements. On the other hand, for strength optimization (Figure 9(b)), both element types take a while to converge, but for a mesh density of 200,000 elements, the FE model converges for both linear and quadratic elements. In this way, for the stiffness objective function, the mesh with 20,000 elements has been employed in all further optimization and FE analyses.

The convergence is only achieved if the boundaries of the rovings overlap the previous and next rovings, thus forming continuous layers without gaps. If the rovings do not fill the whole mesh, this base mesh elements need to be aligned along the bounding contour of the fiber layers to allow a realistic material description per element.

3.2. Open-Hole and Narrow-Middle Specimens Optimization. In this section, the parameterization of the fiber layout is described in more detail. For both examples, only the 0° layer is optimized. However, in general, multiple layers can be parameterized in a similar way and the collective parameter sets are combined to form a single optimization parameter vector. A basis or an initial fiber layout is chosen and the parameterization describes only modifications of this layout. For the 0° layer of both examples, a layout of equidistant straight and parallel fibers is chosen as an initial layout. Deviations from this layout are restricted to shifts in x-direction (see coordinate system in Figure 6), which limits possible layouts to angles of less than 90° between fiber orientation and the load which is parallel to the y-direction. In addition, closed loops cannot be described with such an approach. The angle limitation is useful especially if multiple layers are considered where fiber layers are assigned to specific “tasks”, which should not be exchanged between layers during the optimization. (Closed loops and abruptly ending fibers within the part are also impractical for production with TFP.) Similar to Nagendra et al. [35] the fiber path is modeled based on 2D cubic B-splines. However, only deviations from the initial path are described, the straight and parallel fiber layout in this case, with the spline functions. The x-coordinate of the placement path is given by

$$x \rightarrow f(u_k, v) = \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} p_{ij} B_i(u_k) B_j(v) + au_k$$  (8)

where $B_i$ are spline basis functions and the control points $p_{ij}$ define the optimization parameters. The linear scaling factors $a$ and $b$ determine the total length scale. An equidistant set of $u_k$ defines the different rovings next to each other in x-direction and the total set of curves for each roving path along the y-direction is given by variation of $v$:

$$C^v_k(u_k, v) \rightarrow \left( \frac{f(u_k, v)}{b v} \right)$$  (9)
For $p_{ij} = 0$, the initial layout with straight fibers $C_k(u_k, v)$ is obtained. By fixing $p_{ij} = 0$ for $j = 1$ and $j = 2$, the boundary conditions of equidistant rovings in the clamping area with a smooth transition can be fulfilled. The demand for smooth rovings also at the symmetry line $y = 0$ leads to additional restrictions of $p_{ij} = p_{ij+1}$ for $j = N_y - 1$. The optimization parameters for both examples are 16 independent control points ($N_x = 4, N_y = 7$) at the beginning and increase up to 112 obtained by node insertion after BOBYQA algorithm converges for a lower resolution. In principle, BOBYQA algorithm converges even for larger number of optimization parameters of several hundreds of parameters. However, the manufacturing precision limits meaningful increase of the resolution. The optimization is considered to be converged if the control points do not change by more than 0.005 mm between successive iterations. The initial resolution of 16 parameters converges in about 60 iterations and takes about 10 min in a typical workstation.

**4. Results and Discussion**

Figure 10 shows the various layouts of the open-hole specimen. The reference layout with equidistant and parallel fibers is given in Figure 10(a), the stiffness optimization result is in Figure 10(b), and for comparison the result of a principal stress orientation of fibers is given in Figure 10(c)). The optimization results provide a different solution when compared to previously optimized fiber pattern for open-hole tensile specimen, as can be seen in [9, 14, 28], where they employed the principal stress criterion. Not surprisingly, DFPO achieves better improvement than those ones. The disturbance of fibers reaches much farther away from the hole, such that globally straighter fibers with overall similar length are obtained.

In addition to the open-hole specimen, another example is provided to demonstrate the potential of the DFPO framework for another case. Then, a tensile specimen with a narrow section in the middle is considered, where the ratio of the narrow section to the full width is 50%. Due to the smooth transition region of the narrowed section, the principal stress layout (Figure 11(c)) works very well in this case and more fiber rovings divert from the straight path (Figure 11(a)). The DFPO solution is qualitatively similar to the open-hole solution but with stronger fiber concentration due to the stronger narrowing of the defect (Figure 11(b)). In addition, in this case, the effect of the optimization using DFPO is much more “global” compared to the principal stress layout.

Figure 12 presents the stiffness and strength increase of the optimized fiber layouts relative to the reference design (Figure 10(a)). The principal stress oriented layout (Figure 10(c)) yields to a 5% increase in stiffness (Figure 11(a)) (20% for the second example) and about 139% increase in strength in terms of Cuntze fiber failure mode interaction max(MIA) (Figure 12(b)) (237% for the second example), whereas the DFPO-optimized layout (Figure 10(b)) results in about 9% increase of stiffness (25% for the second example) and 197% increase in strength (275% for the second example). Please note that the boundary conditions of the optimizations were such that the total number of rovings next to each other was fixed and thus the volume and mass change for different fiber layouts. However, the increase in volume of 0.6% for principal stress and 1.6% for DFPO (5.9% and 6.3%, respectively, for the second example) is smaller than the gain in both stiffness and strength.
In contrast to the principal stress design, DFPO represents a real optimization procedure and consequently takes global and not just local features of the specimen into account. The thickness distribution is nonuniform in both cases and a thickness concentration near the defect of the structure is observed. In the DFPO case this thickness concentration extends further from the defect area than in the principal stress layout. The fiber length of single rovings is much more uniform along each family of specimen for the DFPO-optimized, such that the load balance of all rovings under tensile load is better. Compared to other optimization techniques where elemental fiber orientations and thickness values are optimized without correlations induced by endless fibers, in DFPO, each fiber layout considered in every optimization iteration is already manufacturable and no subsequent adaptation is necessary. Thus, these gains obtained by the optimization can be fully transferred to the application.

5. Conclusions

The key objective of this investigation was to present a novel methodology for optimizing the fiber path with a
variable-axial fiber reinforcement design by employing a novel optimization methodology, called Direct Fiber Path Optimization (DFPO). The main achievement is the local optimization of both fiber angle and thickness at each finite element along the base mesh in order to reach global optimum. DFPO demonstrated its capabilities on the optimization of both open-hole and narrow-middle examples under uniaxial tension. For both cases, the results show a clear increase in both stiffness and strength compared to a reference design with equidistant straight fiber-reinforced parallel fibers, as well as compared to the principal stress oriented layouts.

**Data Availability**

The data used to support the findings of this study are available from the corresponding and first authors (bittrich-lars@ipfdd.de) upon request.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

**Acknowledgments**

The authors would like to thank K. Uhlig for fruitful discussions and E. Richter (both from IPF-Dresden) for his support with the figures. The financial support of DFG grants HE 4466/29-1 and KR 1713/19-1 is also gratefully acknowledged; José Humberto S. Almeida Jr. acknowledges CAPES and Alexander von Humboldt Foundations for the financial support.

**References**

[1] J. H. S. Almeida, M. L. Ribeiro, V. Tita, and S. C. Amico, “Stacking sequence optimization in composite tubes under internal pressure based on genetic algorithm accounting for progressive damage,” *Composite Structures*, vol. 178, pp. 20–26, 2017.

[2] A. Spickenheuer, *Zur Fertigungsgerechten Auslegung Von Faser-Kunststoff-Verbundbauteilen Für Den Extremen Leichtbau Auf-\* basis Des Variabelaxialen Fadenablageverfahrens Tailored Fiber Placement [Ph.D. Thesis], Technische Universität Dresden, Fakultät Maschinenwesen, 2014.

[3] P. Mattheij, K. Gliesche, and D. Feltin, “Tailored fiber placement - mechanical properties and applications,” *Journal of Reinforced Plastics and Composites*, vol. 17, no. 9, pp. 774–786, 1998.

[4] C. Cherif, Ed., *Textile Werkstoffe für den Leichtbau*, Springer Berlin Heidelberg New York, 2011.

[5] P. Ribeiro, H. Akhavan, A. Teter, and J. Warmiński, “A review on the mechanical behaviour of curvilinear fibre composite laminated panels,” *Journal of Composite Materials*, vol. 48, no. 22, pp. 2761–2777, 2014.

[6] P. M. Weaver, K. D. Potter, K. Hazra, M. A. R. Savemythapulle, and M. T. Hawthorne, “Buckling of variable angle tow plates: From concept to experiment,” in *Proceedings of the 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, USA, May 2009.

[7] A. S. Panesar and P. M. Weaver, “Optimisation of blended bistable laminates for a morphing flap,” *Composite Structures*, vol. 94, no. 10, pp. 3092–3105, 2012.

[8] G. Duvaut, G. Terrel, F. Léné, and V. E. Verijenko, “Optimization of fiber reinforced composites,” *Composite Structures*, vol. 48, pp. 83–89, 2000.

[9] L. Parnas, S. Oral, and Ü. Ceyhan, “Optimum design of composite structures with curved fiber courses,” *Composites Science and Technology*, vol. 63, no. 7, pp. 1071–1082, 2003.

[10] R. M. J. Groh and P. M. Weaver, “Mass optimization of variable angle tow, variable thickness panels with static failure and buckling constraints,” in *56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Kissimmee, Fla, USA, 2015.

[11] A. Khani, S. T. Isselmuiden, M. M. Abdalla, and Z. Gürald, “Design of variable stiffness panels for maximum strength using laminating parameters,” *Composites Part B: Engineering*, vol. 42, no. 3, pp. 546–552, 2011.

[12] J. M. J. F. Van Campen, C. Kassapoglou, and Z. Gürald, “Generating realistic laminate fiber angle distributions for optimal variable stiffness laminates,” *Composites Part B: Engineering*, vol. 43, no. 2, pp. 354–360, 2012.

[13] H. K. Cho and R. E. Rowlands, “Reducing tensile stress concentration in perforated hybrid laminate by genetic algorithm,” *Composites Science and Technology*, vol. 67, no. 13, pp. 2877–2883, 2007.

[14] M. W. Tosh and D. W. Kelly, “On the design, manufacture and testing of trajectories of steering fibre for carbon fibre composite laminates,” *Composites Part A: Applied Science and Manufacturing*, vol. 31, no. 10, pp. 1047–1060, 2000.

[15] R. Rolles, J. Tessmer, R. Degenhardt, H. Temmen, P. Bürmann, and J. Juhasz, “New design tools for lightweight structures,” B.H.V. Topping and C.A. Mota Soares, in *Progress in Computational Structures Technology*, Saxe-Coburg Publications, Stirling, Scotland, 2004.

[16] S. Setoodieh, M. M. Abdalla, and Z. Gürald, “Design of variable-stiffness laminates using laminating parameters,” *Composites Part B: Engineering*, vol. 37, no. 4-5, pp. 301–309, 2006.

[17] H. Moldenhauer, “Berechnung variabler faserverläufe zur opti- mierung von kompositstrukturen,” *Lightweight Design*, vol. 4, no. 1, pp. 51–56, 2011.

[18] D. W. Kelly, P. Hsu, and M. Asudullah, “Load paths and load flow in finite element analysis,” *Engineering Computations (Swansea, Wales)*, vol. 18, no. 1-2, pp. 304–313, 2001.

[19] W. Waldmann, R. Heller, R. Kaye, and L. Rose, “Advances in structural load flow visualisation and applications to optimal shapes (dsto-rr-0166),” *Technical Report*, Aeronautical and Maritime Research Laboratory, Airframes and Engines Division, Melbourne, Australia, 1999.

[20] A. V. Malakhov and A. N. Polilov, “Design of composite structures reinforced curvilinear fibres using FEM,” *Composites Part A: Applied Science and Manufacturing*, vol. 87, pp. 23–28, 2016.

[21] Y. Katz, R. T. Haftka, and E. Altus, “Optimization of fiber directions for increasing the failure load of a plate with a hole,” in *Proceedings of the American Society for Composites: 4th Technical Conference: Composite Materials Systems*, pp. 62–71, Blacksburg, Virginia, 1989.

[22] G. Duvaut, G. Terrel, F. Léné, and V. Verijenko, “Optimization of fiber reinforced composites,” *Composite Structures*, vol. 48, no. 1-3, pp. 83–89, 2000.
[23] H. K. Cho and R. E. Rowlands, "Optimizing fiber direction in perforated orthotropic media to reduce stress concentration," *Journal of Composite Materials*, vol. 43, no. 10, pp. 1177–1198, 2009.

[24] J. Wiśniewski, "Optimal design of reinforcing fibres in multi-layer composites using genetic algorithms," *Fibres & Textiles in Eastern Europe*, vol. 12, no. 3, pp. 58–63, 2004.

[25] X. Legrand, D. Kelly, A. Crosky, and D. Crépin, "Optimisation of fibre steering in composite laminates using a genetic algorithm," *Composite Structures*, vol. 75, no. 1-4, pp. 524–531, 2006.

[26] K. Dems and J. Wisniewski, "Optimal fibres arrangement in composite material," in *Proceedings 8th World Congress on Structural and Multidisciplinary Optimization*, pp. 1–10, Lisboa, Portugal, 2009.

[27] J. Turant and K. Dems, "Design of fiber reinforced composite disks using evolutionary algorithm," in *Proceedings 8th World Congress on Structural and Multidisciplinary Optimization*, Lisboa, Portugal, 2009.

[28] J. Bardy, X. Legrand, and A. Crosky, "Configuration of a genetic algorithm used to optimise fibre steering in composite laminates," *Composite Structures*, vol. 94, no. 6, pp. 2048–2056, 2012.

[29] A. Spickenheuer, M. Schulz, K. Gliesche, and G. Heinrich, "Using tailored fibre placement technology for stress adapted design of composite structures," *Plastics, Rubber and Composites*, vol. 37, no. 5-6, pp. 227–232, 2008.

[30] A. Albers, N. Majic, and D. Troll, "Modeling approaches for the simulation of curvilinear fiber-reinforced polymer composites," in *Proceedings NAFEMS Seminar: Progress in Simulating Composites*, Wiesbaden, Germany, 2011.

[31] K. Uhlig, A. Spickenheuer, L. Bittrich, and G. Heinrich, "Development of a highly stressed bladed rotor made of a CFRP using the tailored fiber placement technology," *Mechanics of Composite Materials*, vol. 49, no. 2, pp. 201–210, 2013.

[32] K. Uhlig, M. Tosch, L. Bittrich et al., "Meso-scaled finite element analysis of fiber reinforced plastics made by Tailored Fiber Placement," *Composite Structures*, vol. 143, pp. 53–62, 2016.

[33] R. G. Cuntze, "Efficient 3D and 2D failure conditions for UD laminae and their application within the verification of the laminate design," *Composites Science and Technology*, vol. 66, no. 7-8, pp. 1081–1096, 2006.

[34] M. J. D. Powell, *The BOBYQA algorithm for bound constrained optimization without derivatives*, Department of Applied Mathematics and Theoretical Physics NA06, 2009.

[35] S. Nagendra, S. Kodiyalam, J. Davis, and V. Parthasarathy, "Optimization of tow fiber paths for composite design," *The American Institute of Aeronautics and Astronautics - AIAA Journal*, vol. 95-1275, pp. 1031–1041, 1995.
