Iso-contour method for optimization of steered-fiber composites

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The research presented in this paper is focused on a method for optimization of fiber-steered composite shell structures. The main idea of this method is related to the level-set method: in order to steer the fibers, iso-contour lines of an artificial hyper-surface, defined over a 2D geometry domain, are used. Thus, the smoothness of this artificial surface can guarantee continuity/smoothness of the obtained fiber paths. This can be used to create manufacturable steered fiber composites. Finally, by modifying this artificial surface, we can control the fiber paths and optimize the design of a composite part for the specific needs.

Nomenclature

GP	=	Gaussian process interpolation
RBF	=	Radial basis function

I. Introduction

ADVANCED composite materials are used more and more in industrial applications for the aircraft and aerospace structures. Due to their superior and flexible mechanical properties and low weight the composite materials can be an attractive alternative to metals. Especially for the applications when assembly simplification, high strength, high stiffness and good fatigue resistance are of interest.

One of commonly used types of composites is fiber-reinforced laminates. All fibers are usually aligned in parallel in each layer, which limits the composite design flexibility. More complex fiber alignments can provide more freedom, when fiber directions can be tuned to improve specific load-carrying capabilities of the composite part. For example, to reduce stress concentration of a composite plate with holes, curved-fiber composites can be used. Several different methods were proposed to find optimal fiber orientation distributions. Gürdal and Olmedo [1] used angle variations for continuous linear fiber. They introduced a fiber path definition and formulated numerical solutions for simple rectangular plates. Hyer and Charette [2] proposed to choose the fiber orientations so that the fibers in a particular layer were aligned with the principal stress directions in that layer. Hansel and Becker [3] proposed a heuristic optimization algorithm for minimization of the weight of composite laminates. In that method the elements with low stress measures are removed in each layer. IJsselmuiden et al. [4] used the fiber angles at the nodes of an FE model as design variables. Their approach is adapted to use lamination parameters.

Each of these approaches has its drawbacks and benefits. For example, approaches, working with predefined types of fiber path cannot allow arbitrary fiber paths. Methods, based on node/element variation of fiber orientation usually end up with a large number of design variables, which makes it challenging to find the optimal design. Also, obtained optimal solutions are often non-manufacturable due to non-smooth fiber paths.

The research presented in this paper is focused on solving the described difficulties by allowing more flexibility to the fiber path definitions and by creating smooth optimal fiber paths; at the same time the number of design variables is kept relatively low. All these requirements should ideally result in a powerful method for the fiber-steered composite optimization for shell structures.

II. Iso-contour method

In this paragraph, the main steps of the 2D fiber steering optimization method are described. The key idea of the proposed method is to use an artificial surface, which is defined over the 2D domain, in order to control fiber paths. Now, the proposed method will be describerd more in detail for 2D geometry. The scheme of the method is presented in Fig. 1. First of all, a box domain, containing the geometry domain should be defined, and Cartesian coordinates are defined over this rectangular box. Overlaid control points are then defined in this 2D

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box, e.g. based on the mesh, where the number and locations of the points can be varied. To control the artificial surface, a "height" is assigned to each of these control points and a surface is fitted over all control points, interpolating the heights. In the current work, non-parametric surfaces are used, such as Radial Basis Functions (RBF), Gaussian Process Interpolation (GP) and 2D splines. Spline interpolation requires grid-based positioning of the control points, while RBF and GP allow flexible point locations [5]. In this case, locations of control points can be adjusted to fit specific geometry elements (e.g. holes, etc.) and thus allow more flexibility for fiber paths in some regions. Similar to a geodesic map, the iso-contour lines can be obtained from this artificial interpolating surface. This iso-contours guide the fiber paths at each point of the 2D geometry domain, with the fiber direction aligned to the iso-contour line.

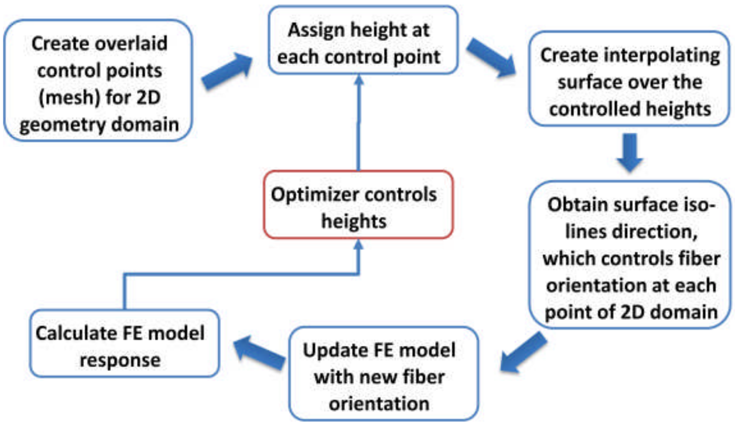

Figure 1. The workflow of the iso-contour based method.

Finally, the "heights" defined in the control points are the design variables, which means, that the number of control points represents the dimension of the optimization problem. In the current work, a simple evolutionary algorithm is used to find optimal "heights" at the control locations, corresponding to optimal fiber paths.

In this work, it is assumed that homogenized properties of the fiber reinforced composite (e.g. laminates) are already known, and fit into the orthotropic material model. In this case, the main principal axis of this orthotropic material is aligned with the fiber direction. Changing of the fiber direction of the composite is then equal to rotating the material's principal axes.

In order to perform the fiber paths optimization, finite-element (FE) method simulations are used. For example, fibers can be steered for the structure compliance minimization under specified load case. The method can be easily used with commercial FE tools, as it doesn't require any modifications of the FE code. Only the ability to control the local coordinate system (LCS) of finite elements is needed. For each element, fiber orientation is aligned with the iso-contour line, passing through the element centroid, and is adjusted by the finite-element LCS rotation. Combination of the proposed iso-contour based fiber paths definition, evolutionary optimizer and FE simulations is used here for fiber-steered composites optimization.

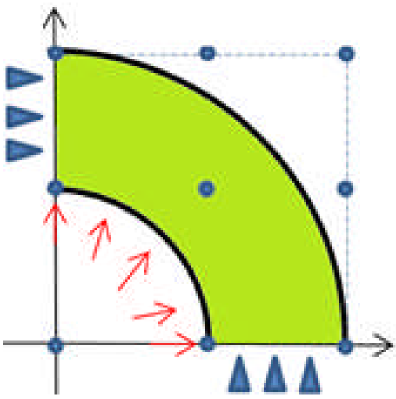

Figure 2. Ring plate with inner loading.

III. Testing of algorithm

The proposed method was implemented as a python class. For performing FE simulations, the ANSYS software is used and DAKOTA software is used for the optimization. To demonstrate the performance of the proposed method, several simple 2D examples were used and their results are described below.

The following homogenized orthotropic material properties were used for the test optimization problems:
Young's moduli are equal $E_x = 1.3 \cdot 10^{11}$ Pa, $E_y = 1 \cdot 10^{10}$ Pa, $E_z = 1 \cdot 10^{10}$ Pa, shear moduli are: $G_{xy} = 5 \cdot 10^{9}$ Pa, $G_{yz} = 27 \cdot 10^{9}$ Pa, $G_{xz} = 5 \cdot 10^{9}$ Pa, and Poisson's ratios are: $\nu_{xy} = 0.35$, $\nu_{yz} = 0.2$, $\nu_{xz} = 0.35$.

For the FE analysis 2nd order shell elements (SHELL281) are taken. These elements can also be used for the modeling of layered composite shells or sandwich constructions.

As was mentioned before, three different interpolating surface types are considered in this work:

- Gaussian process interpolation (GP);
- Radial basis function (RBF);
- Spline interpolation.

Ring plate test problem

The ring plate with inner loading test problem (as shown in Fig. 2) is used to illustrate the method, compare different available surface types and also to show the benefits of flexible control points positioning. Dimensions of the ring are: inner radius is 1m and outer radius equal 2m. The objective of optimization is to minimize the averaged internal extension of the ring. The number of design variables is only nine, which corresponds to 3×3 control points of the grid-based "mesh" (see Fig. 2).

Due to the symmetry of geometry, applied boundary conditions (BC) and loads w.r.t. X and Y axis, $1/4^{th}$ part of the ring are used for simulations.
Fig. 3 shows the optimal artificial 3D surface configuration with corresponding iso-lines, from which optimal fiber directions are obtained. The iso-contour layout is in agreement (over the physical ring geometry domain) for all tested surfaces, while surfaces are relatively different (e.g. GP and RBF have maximum values at the origin, while spline has a minimum). This illustrates one potential difficulty of the optimization method, which is that a unique iso-contour layout can be generated by variety of 3D surfaces.

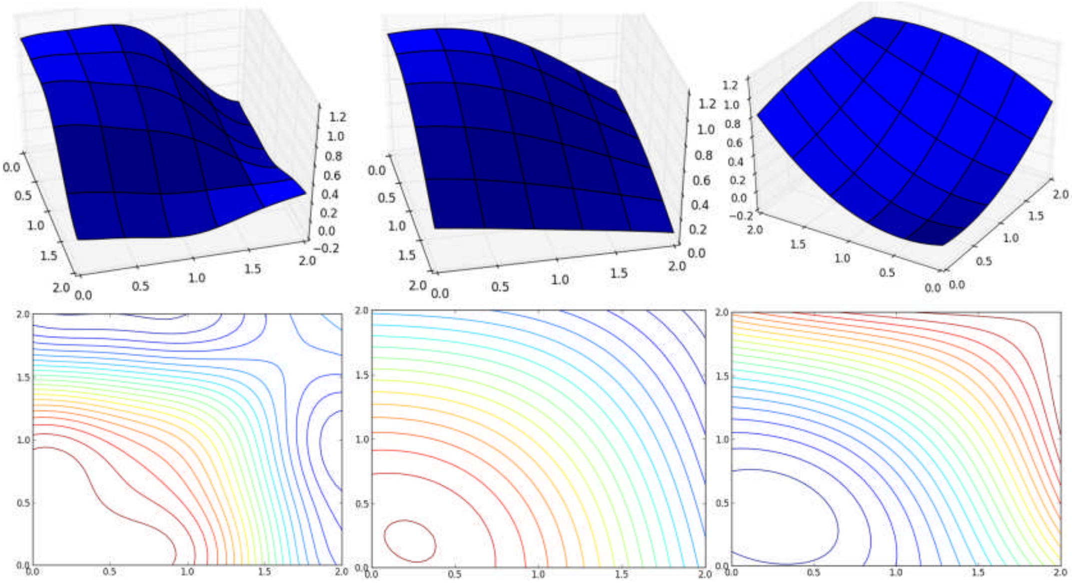

Figure 3. Interpolating 2D surface and corresponding iso-lines; GP (left), RBF (middle), splines (right).

In Fig. 4 the optimal fiber paths are shown as the fiber angle at each element. The obtained solution is very close to the predictable optimal circumferential fiber alignment. The optimal results were obtained: for GP after 1391 iterations, RBF – 1584 iterations and for splines after 1594 iterations. Extensions for each surface type are: for GP is $3.459 \cdot 10^{-4}$ m, RBF is $3.177 \cdot 10^{-4}$ m and splines is $3.22 \cdot 10^{-4}$ m, with RBF being the best.

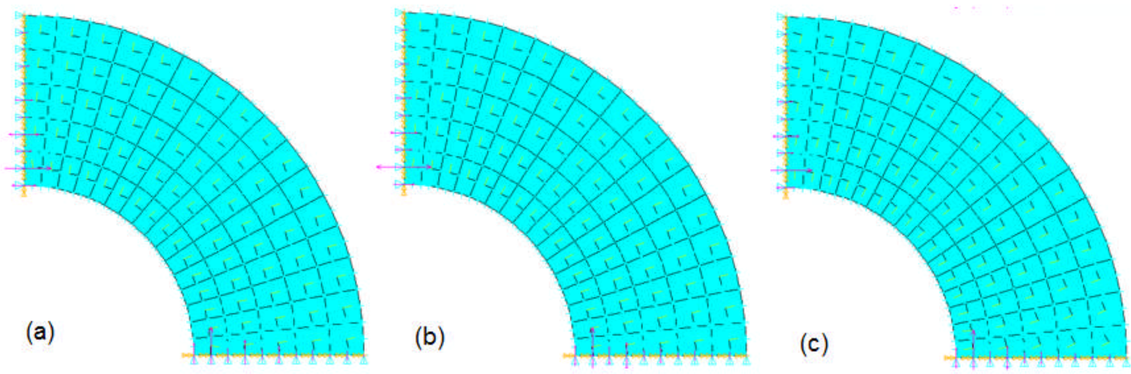

Figure 4. Comparison of the fiber angle at each element for GP (a), RBF (b) and splines (c).

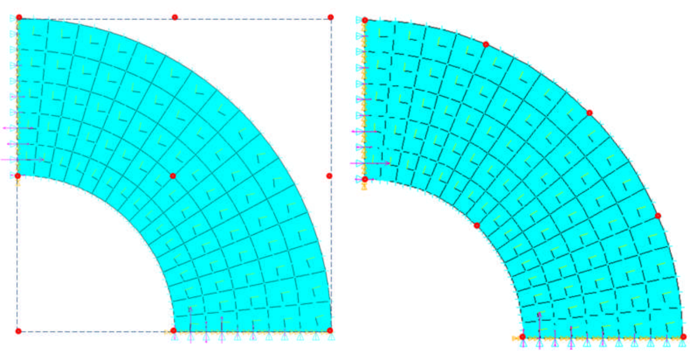

Figure 5. Comparison of results for different position of control points for GP.

Now the control points are redistributed to mach better the curved geometry of the ring, as shown in Fig. 5. The optimal fiber paths, obtained with new points positioning, are even closer to the ideal circumferential alignment. This simple example shows how flexible control points positioning can improve optimization results.

Finally, for this example, all interpolating surfaces give similar close to optimal alignment for the fiber paths, with RBF being a bit better.

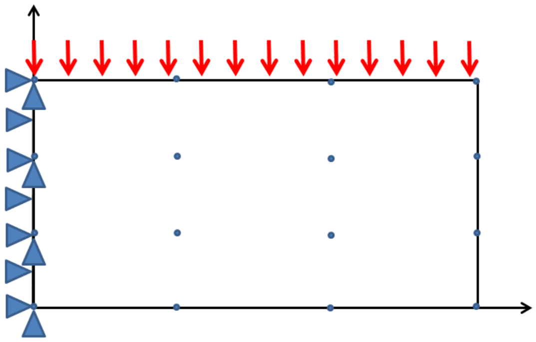

Figure 6. The plate in bending test problem with overlaid control points shown.

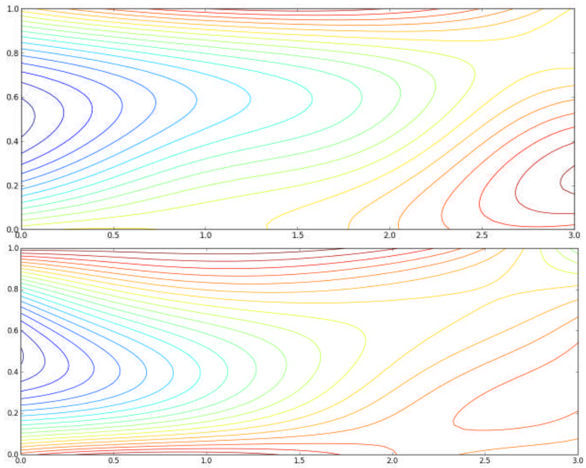

Figure 7. Comparison of results for RBF (top) and spline (bottom) surface interpolations.

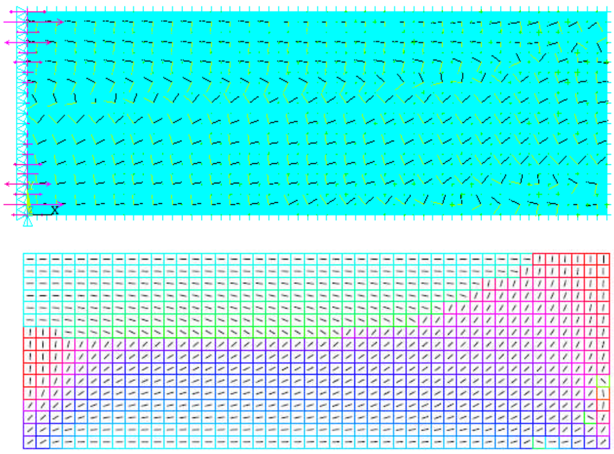

Figure 8. Comparison of results for RBF (top) and results obtained by Setoodeh (bottom).

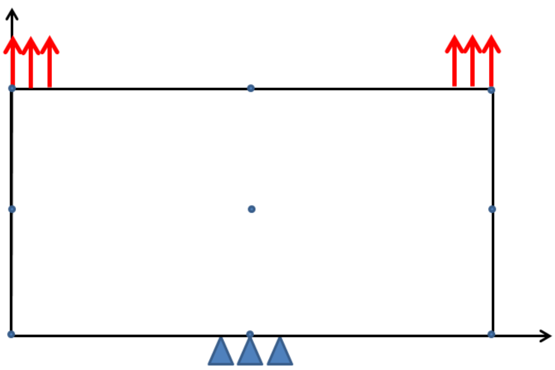

Figure 9. Two loads carrying plate test problem with overlaid control points shown.

Plate in bending test problem

For the second example, a simple plate in a bending problem with uniformly distributed top in-plane loading is considered as shown in Fig. 6. Dimensions of the plate are defined similar to Setoodech [6], with the sides' aspect ratio 3:1. The left side of the plate is fixed.

The number of design variables is equal to 16 (4×4) control points of the "mesh" (see Fig. 6). The objective is to minimize the average displacement on the top line, which corresponds to compliance minimization.

The aim of this test problem is comparison of fiber paths design obtained by the proposed method and results obtained by using Cellular Automata method [6]. RBF and spline surfaces are considered for this example.

The comparison of results for RBF and spline surface interpolation is shown in Fig.7.
As can be seen, both interpolations show similar optimal solution for the 4x4 "mesh". Very similar results were obtained by Setoodeh. Comparison of the fiber angle at each element for both methods is shown in Fig.8. The differences of the results are mainly in the right part of the plate, in the left part fiber paths are almost the same. That can be explained because the overall structure stiffness is mainly affected by the plate design near the clamped side, while the right part of the plate doesn't contribute to the stiffness a lot, which means that the optimizer considers the right design area near the clamp much better. Another important point is that paths, obtained with the proposed method, are much smoother than in the optimal solution from Setoodeh.

Apart from good agreement with the literature, this example also shows the ability of the method to capture rather complicated optimal fiber paths.

Two loads carrying plate example

The last example shows how the optimal fiber paths are related to the results obtained with topology optimization for isotropic materials. Optimal topology and optimal fiber paths will be compared for the supported plate with a top loading, shown in Fig. 9, which is defined similar to [7]. The dimensions of the plate are taken as 16x10 m. The number of design variables is equal to 9 (3×3 control points). The objective of the optimization is to minimize the average displacement on the top line.

First of all, the topology optimization problem for isotropic material was solved using ANSYS software. Result of this topology optimization is shown in Fig. 10 (left) and in an agreement with the result, reported in [7]. After that, the proposed method was applied to find the optimal fiber paths for the same problem in case of anisotropic fiber-reinforced composite material. RBF is used for the surface fit here, as it showed better results for previous test problems. The optimal iso-contours and corresponding fiber orientations in the FE model are presented in Fig. 10 (b) and (c) respectively. Visual comparison of these results shows, that obtained optimal fiber paths are following the topology optimization results, resulting in the stiffer structure.

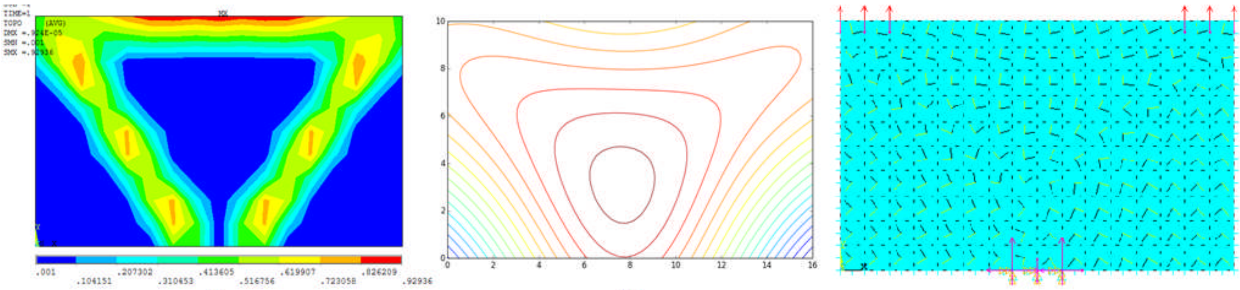

Figure 10. Results for supported plate with a top loading: topology optimization (a), iso-lines for RBF surface (b) and corresponding fiber angle at each element (c).

IV. Conclusion

In this work, the iso-contour based method for the fiber-steered composite materials optimization for 2D problems was formulated. The key idea of the proposed method is to use an artificial surface, which is defined over the 2D geometry domain, in order to control fiber paths. The method is implemented in Python and can be connected with commercial FE codes, used for simulations.

The method was tested with several 2D problems and produced reasonable results, which are in an agreement with the solutions obtained using different techniques and reported earlier in the literature. Also, optimal fiber paths show some similarity with the optimal topology designs. A nice feature of the method is that relatively complicated fiber paths layouts can be obtained using a small number of design parameters. Several interpolating surfaces were tested, all giving in general similar solutions. The method is capable of producing smooth fiber paths, and can be adapted for different geometrical features (e.g. refined near the holes, etc.).

Some further research is needed to solve the problem of multiple interpolating surfaces, producing same iso-contours, which now causes the optimizer to end in the near-optimal solutions sometimes (in this case, fiber paths are still close to optimal layout). Next steps would be to adapt the method for multilayer problems, with each steered fiber layer optimized independently. Also, the effect of different fiber density on the resulting material properties/thickness could be included in the method.

Acknowledgments

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