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IT'S ON A ROLL: DRAPING COURSES OF GLASS FIBER FABRIC IN A WIND TURBINE BLADE MOLD BY MEANS OF OPTIMIZATION

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Summary: *The draping of glass fiber fabric in a wind turbine blade mold is analyzed and optimized. Unlike for smaller composite parts, the size of the blade mold section necessitates multiple courses, i.e. roll-widths of fabric. The overarching goal is thus to determine the optimal placement of these courses under considerations of producibility and structural performance. The preliminary results presented here show a reduction of shear angles of 61% compared to a baseline design.*

1. INTRODUCTION

Wind turbine blades are manufactured from light and strong composite materials. The fiber material, predominantly glass fiber non-crimp fabric (NCF), is rolled out in the blade mold in courses and subsequently infused with the resin. The blade designers will typically specify e.g. the fiber orientations and thicknesses in various regions of the blade. These instructions must be translated into what courses to be placed where in the mold while at the same time paying attention to draping effects, i.e. fabric shearing arising from double mold curvatures. Fabric shear entails a rotation of the rovings which thus facilitates the conformation of the fabric to the double curved mold surface. There is, however, a limit to how much shear can be achieved with a fabric. In other words, the draping of courses does not come with complete freedom.

Draping on a double-curved mold can be analyzed with a kinematic draping algorithm [1], e.g. commercially available with programs such as Composites Modeler for Abaqus/CAE [2], Ansys ACP [3] and Fibersim [4]. The algorithm assume that the roving extensional stiffness is infinite and the fabric shear stiffness is zero. These assumptions enable the modeling of the fabric as a grid of pin-jointed cells. The kinematic draping model can predict the draped pattern with reasonable accuracy and a low computational effort on molds as long as the shear angles are moderate in magnitude. To this end, the applicability of optimization techniques is attractive as employed by a number of researchers.

Skordos et al. [5] (see also [6]) successfully combined a Genetic Algorithm (GA) with a commercial draping program to minimize the shear angles of a composite component. Kaufmann et al. [7] considered cost/weight optimization of a composite part and included a kinematic draping algorithm in their framework. The objectives considered were fiber angle deviations (difference between actual and nominal fiber orientation of a ply), the magnitude of the computed shear angles, and material waste, i.e. trim-off.

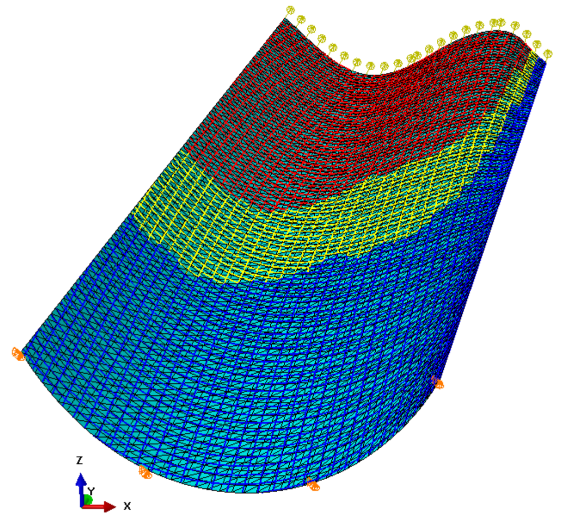

Figure 1. The FE model with draping mesh colored based on shear angle: Blue: 0°- 2.5°, yellow: 2.5°- 5.0°, red: > 5°. The max. shear angle is 12.3°.

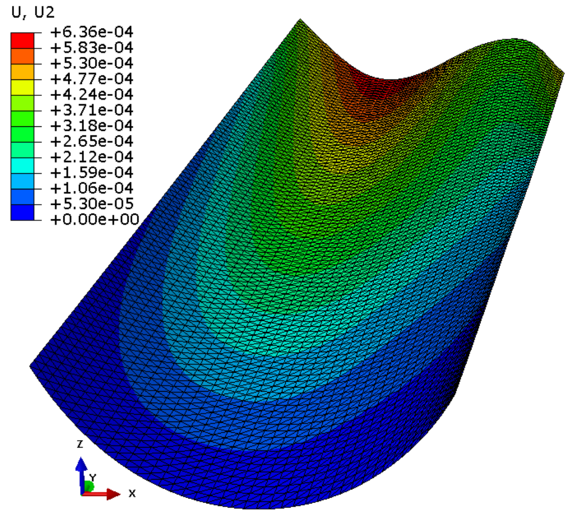

Figure 2. Displacements in y (elongation) in finite element model with draped fiber angles. The max. value is $6.363\ 10^{-4}$ m.

In this study the applicability of a kinematic draping algorithm in combination with optimization for a wind turbine blade mold is investigated. The paper first explores the influence of using the changed fiber orientations due to draping effects in a structural analysis (Section 2.). This is followed by a description of the in-house kinematic draping code (Section 3.) and the optimization setup (Section 4.). Afterwards, preliminary results are presented (Section 5.) followed by a conclusion of the paper (Section 6.).

2. THE INFLUENCE OF DRAPING EFFECTS IN A STRUCTURAL ANALYSIS

The example in this section serves to underline the importance of taking the draping effects into account. As will be demonstrated, draping effects are not only related to manufacturing but also affect the structural performance of the final composite part. The mold surface used in this study is created to resemble a section of a wind turbine blade mold. Specifically, the changes in geometry from the circular root to an aerodynamic profile result in double curvatures, hence necessitating fabric shear. In this example 10 UD plies with the properties listed in Table 1 are used. Two different finite element (FE) models are created for comparison: one with ideal or projected fiber orientations and one in which the fiber orientations are transferred from a draping analysis, hence taking the reorientation into account. Both models are subjected to a fixation in x, y, z-displacements at the root end (min. y coordinate) and a static load of 215 kN divided on all 43 nodes at the far end (max. y coordinate). The draping analysis for this example (Figure 1) was created with Composites Modeler for Abaqus/CAE and is based on a single overall layer where a fiber is forced to follow the right mold edge (located at max. x coordinate). The result of the FE analysis in Abaqus for the model with the draped fiber

Table 1. Structural properties of plies in FE analysis.

$\mathbf{E_1}$	$\mathbf{E_2}$	$\boldsymbol{\nu_{12}}$	$\mathbf{G_{12}}$	$\mathbf{G_{13}}$	$\mathbf{G_{23}}$
130 GPa	9 GPa	0.3	4.2 GPa	3 GPa	3 GPa

orientations is shown in Figure 2 as the y-displacement. Comparing to the results of the model with ideal/projected fiber orientations, the maximum y-displacement has increased by 11.8% (from $5.691\ 10^{-4}$ m to $6.363\ 10^{-4}$ m), the compliance has increased by 8.9% (from 97.2 Nm to 105.8 Nm) and the maximum in-plane principal strain has increased by 75.3% (from $2.359\ 10^{-4}$ to $4.135\ 10^{-4}$). Thus, the model with the fiber orientations from a draping analysis, is in general more compliant due to all the fibers not being in the 0° (y) direction.

3. KINEMATIC DRAPING OF COURSES IN A BLADE MOLD

While the commercial implementations of the kinematic draping algorithm are easy to use and integrate well with CAD-programs, there are in general also some issues, especially when it comes to draping of courses and optimization:

- Limited options of controlling the draping pattern and course dimensions.
- Limitations in scriptable interfaces.
- Computational overhead due to using an external program for analysis.

For these reasons it was decided to develop an in-house kinematic draping code in MATLAB which also offers a comprehensive optimization toolbox / library. The basic algorithm is available in a repository [8] and is described in detail in [9]. The algorithm works by first creating a pair of *generators*, here a row and column of grid nodes that span the entire fabric area. Afterwards, the nodes constrained by the generators are placed. This operation is sketched in Figure. 3. For this study two extensions have been introduced. The first extension is the ability to use a *steering curve* as a generator, i.e. a smooth curve on the mold surface defined by a set of points. The second extension is a more efficient algorithm for calculating geodesic lines which

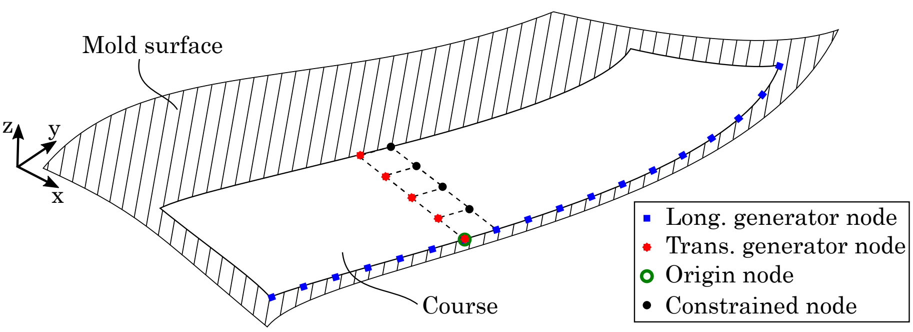

Figure 3. The kinematic draping algorithm with longitudinal and transverse generators.

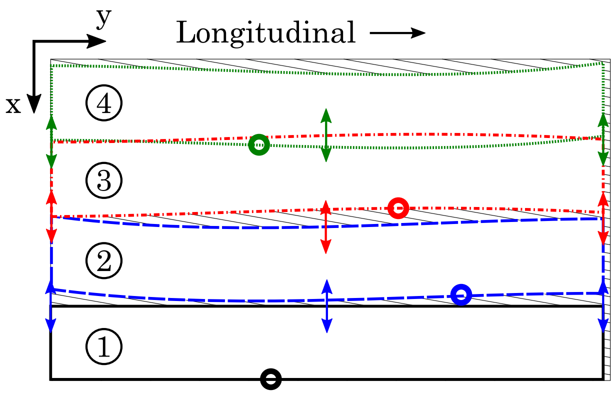

Figure 4. Top view of the parameterization used with the course placement optimization. The colored circles indicate the origin node location. The colored vertical arrows indicate the offset relative to the previous course edge defined at 0%, 50% and 100% of the course length which is the basis for the steering curve definition.

can also be used as a generator curve. This algorithm is a solution to the initial value geodesic problem, i.e. the determination of a geodesic line of a given length from a starting point and a direction. It relies on iterative *unfolding* of the triangles of the mold surface mesh to a common plane such that the geodesic line can be computed as a straight line [10].

The material studied is a glass fiber unidirectional (UD) non-crimp fabric (NCF) with a backing layer. Experimental investigations have shown that the fabric deforms in pure shear for the shear angles relevant for wind turbine blade production, which is thus the kinematic basis for the draping algorithm.

4. OPTIMIZATION SETUP

In this study, four courses (0.35 m $\times$ 4 m) are considered to cover the mold surface. For each course, its placement is determined by a steering curve in the longitudinal direction and a geodesic curve in the transverse direction. At their intersection, the transverse geodesic curve is perpendicular to the longitudinal steering curve. Thereby, the intersection corresponds to a grid node of zero shear. This node is denoted the *origin node* (see Figure 3). The 1st course is draped along the longitudinal edge at maximum x. The subsequent three courses are draped along a longitudinal steering curve defined relative to the previous course edge. The design variables of the optimization problem are thus the origin node for each course (four in total) and the three transverse offsets of the longitudinal steering curve for each course (nine in total) as sketched in Figure 4. Notice that this setup can result in gaps as well as overlaps between adjacent courses, the impact of which is discussed in the next section. A baseline design with the origin node located at the 0% course length and with a constant gap of 5 mm for all courses is shown in Figure 5.

The criteria considered in this optimization setup are the magnitude of the shear angles (γ) and deviations of the UD fiber angles from the nominal angle of 0°, i.e. the y-direction (ψ).

The shear angles are readily computed as the angles between adjacent cell edges and the UD fiber angles can be computed based on the longitudinal cell edges. A *p-norm* function is used to aggregate the field quantities into a single representative number. A value of $p = 12$ is chosen which gives high importance to the highest values. The problem of placing the fiber courses using optimization is formulated as follows with the design variables assembled in the vector **a**:

$$\begin{aligned} \underset{\mathbf{a}}{\text{minimize}} \quad & \left(\sum_{i=1}^{N_\gamma} |\gamma_i|^p \right)^{1/p} + \left(\sum_{j=1}^{N_\psi} |\psi_j|^p \right)^{1/p} \\ \text{s.t.} \quad & 0\,\% \leq a_k \leq 100\,\% \qquad , k = 1, ..., 4 \\ & -40\ \text{mm} \leq a_k \leq 40\ \text{mm} \quad , k = 5, ..., 13 \end{aligned} \tag{1}$$

Here, N_γ and N_ψ are the number of shear angles and fiber angle deviations to aggregate, respectively. Thus, the sum of the shear angle *p-norm* and the UD fiber angle deviation *p-norm* must be minimized. The addition of the two quantities is possible because they have same unit and the same order of magnitude. The bounds on the design variables **a** are such that the first four (origin node location) must be within 0% and 100% of the course length and the remaining nine controlling the steering curve offsets must be within ± 40 mm of the previous course edge.

The optimization problem is solved using MATLAB's Genetic Algorithm (GA). This zero order or stochastic method was chosen because the design space involves multiple local minima.

5. RESULTS AND DISCUSSION

The optimized result is presented in Figure 6. The shear angles vary between -4.62° and 4.72° and thereby cover a range of 9.34°, however, only a magnitude of 4.72° is required from the fabric (because the fabric behaves equally in positive and negative shear). The UD fiber angle deviations have a maximum value of 4.68° and an average of only 0.94° (the baseline design has max.: 6.19° and average: 2.5°.). It can be seen how the 1st course shears the most because it is forced to follow the right edge. The shear distribution has, however, been altered compared to the baseline design by moving the origin node to 59% of the course length. For the remaining three courses, a combination of gaps and overlaps has enabled the courses to be "straightened" and has thereby reduced the shear angles as well as the UD fiber angle deviations. With the origin node locations for courses 2-4 (61%, 72% and 64%), the shear angle distributions have also been adjusted such that the ranges are approximately centered around 0°. The optimization required 2300 objective function evaluations and took 21 minutes on a standard laptop.

The gaps/overlaps between courses is seen to be a convenient way to both reduce the fabric shear as well as aligning the UD fibers with the 0° direction. The structural effect of this course placement must, however, also be assessed. Specifically, what is the trade-off between having the fiber orientations closer to the specified orientation and having areas in the laminate with higher/lower fiber density. Because the laminate stack consists of many layers, the fiber density issue could maybe be alleviated by compensating with other gaps/overlaps throughout

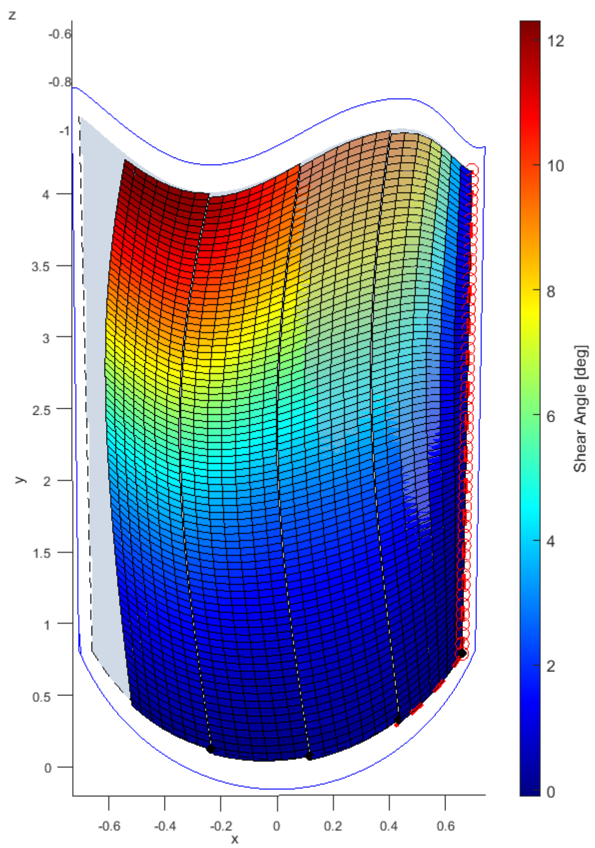

Figure 5. A baseline design. It is similar to the draping result in Figure 1.

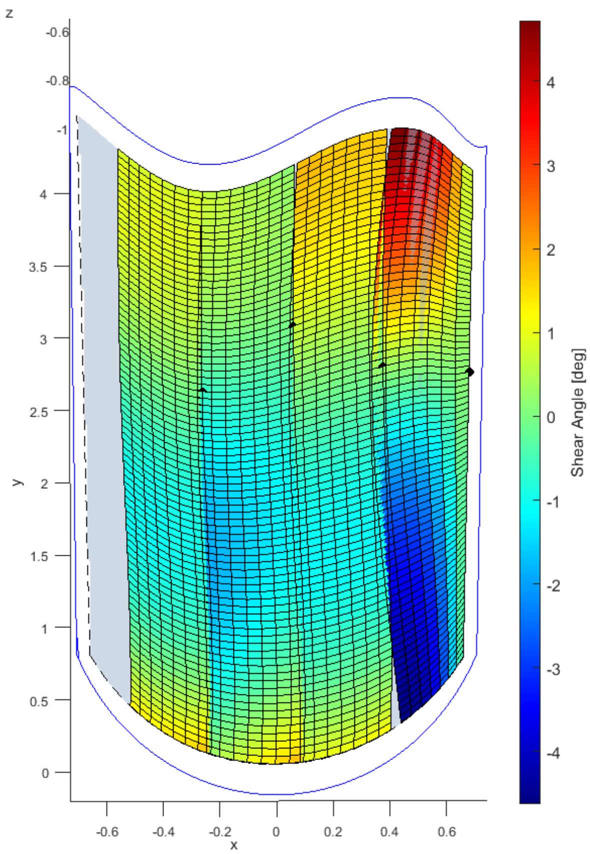

Figure 6. The optimized design. Black dots indicate the origin node locations.

the thickness of the stack. An FE analysis like in Section 2. could also clarify the structural impact.

6. CONCLUSIONS

This paper has presented the challenge of determining the placement of courses of glass fiber fabric in a wind turbine blade mold. Using an optimization algorithm and an in-house implementation of a kinematic draping algorithm, the preliminary results show how the magnitude of the shear angles can be reduced from approximately 12° to 4.7° by altering the conditions of the draping. The next step is to include more effects in the optimization, e.g. the width of the courses and material waste or trim-off. Ultimately, the optimization tool can help to strengthen the step from design to manufacturing.

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