Composite Structures 131 (2015) 895–904

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Optimization of composite structures with curved fiber trajectories

Etienne Lemaire [a], Samih Zein [a], Michael Bruyneel [a,b,*]

[a] SAMTECH s.a. (A Siemens Company), Liège Science Park, Rue des Chasseurs-ardennais 8, Angleur B-4031, Belgium
[b] Aerospace & Mechanical Engineering Department, University of Liège, Belgium

ARTICLE INFO

Article history:
Available online 4 July 2015

Keywords:
Optimization
Fiber placement
Level-set

ABSTRACT

This paper presents a new approach to generate and optimize parallel fiber trajectories on general non planar surfaces based on level-sets and the Fast Marching Method. Starting with a (possibly curved) reference fiber direction defined on a (possibly curved) meshed surface, the new method allows defining a level-set representation of the fiber network for each ply, and so defining the fiber trajectories. This new approach is then used to solve optimization problems, in which the stiffness of the structure is maximized (minimum compliance problem). The design variables are the parameters defining the position and the shape of the reference curve. The shape of the design space is discussed, regarding local and global optimal solutions. The possibility to include in the optimization problem a limitation on the curvature of the trajectories is also addressed.

1. Introduction

The use of composite materials in aerospace, automotive and ship industry allows manufacturing lighter and more efficient mechanical structures. Indeed, proper use of the orthotropic properties of these materials enables further tailoring of the structure to the loadings than when using isotropic materials. However, this comes at the cost of a more complicated design and sizing process firstly because of the orthotropic behavior of composite materials but also because of the manufacturing process which induces specific constraints in the use of these materials.

From the mechanical point of view, one of the most important restrictions resulting from the practical manufacturing of mechanical parts is the orientation of the reinforcement fibers resulting from the layup process. These orientations directly determine the orthotropy axes and cannot be chosen arbitrarily in any point of a given part but rather result from the draping of the reinforcement material over the part. Several models have been developed in order to predict the orientations of the reinforcement fibers after the draping process depending on the properties of the reinforcement materials (see [1] for a review).

One of the first of these models is due to Mack and Taylor [2]. Often called the 'pin-jointed' model [3], it is based on a geometric model and it is well suited to predict the fiber orientation resulting from hand layup of dry woven fabrics. Later, more complex models relying on a finite element mechanical modeling of the reinforcement have been developed for the forming of preimpregnated fabrics as for instance by Cherouat and Bourouchaki [4].

Besides the manufacturing of composites part by hand layup of large pieces of reinforcement material, another group of methods is gaining interest since its first introduction in the 1970s. These methods rely on the robotized layup of bands of unidirectional reinforcement material allowing more accurate and more repeatable manufacturing process [5]. In this group, two main methods can be identified Automated Tape Layup (ATL) and Automated Fiber Placement (AFP). ATL makes use of a robotic arm to layup tapes (up to 300 mm wide) of unidirectional prepeg and benefits from high productivity for large and simple flat parts. But ATL main limitation comes from the relatively high minimum curvature radius (up to 6 m) that can be applied to the prepreg tape without wrinkling. With AFP, this minimum curvature radius is decreased to 50 cm by subdividing the tape into several tows which can be cut and restarted individually. Therefore the manufacturing of more complicated parts can be handled by AFP but with a lower productivity than ATL.

For ATL and AFP processes, one of the manufacturing issues is the determination of successive courses trajectories. Indeed, for these processes, it is crucial that there are no overlaps and no gaps between adjacent courses in order to ensure maximal strength and minimum weight for the final part. In other words, this means that successive layup courses have to be equidistant.

A few researchers have studied the optimal design of ATL/AFP parts. A first group of methods consists in defining an initial course which is then simply shifted over the part to define subsequent

* Corresponding author at: Aerospace & Mechanical Engineering Department, University of Liège, Belgium.

E-mail address: michael.bruyneel@ulg.ac.be (M. Bruyneel).

http://dx.doi.org/10.1016/j.compstruct.2015.06.040
0263-8223/

course as proposed by Tatting and Gürdal [6,7]. Secondly, the courses can be defined as geodesic paths, constant angle paths, linearly varying angle paths or constant curvature path [8]. However, these two approaches do not result in equidistant paths. Alternatively, the subsequent courses can be obtained by computing actual offset curves from an initial curve. This approach is more difficult but leads to equidistant courses and has been investigated by Waldhart [9], Shirinzadeh et al. [10] and Bruyneel and Zein [11] with different numerical schemes. The two first groups of authors propose an approach based on a geometrical description of the part while the third one developed an algorithm able to work with a level-set representation on a mesh of the layup surface. In [12], Bruyneel and Zein used their approach in a parametric study in order to determine the effect on the structural stiffness of curving the fiber trajectory of a single ply laid on a cantilever structure (see also [13]). It is also worth mentioning the work done recently by Brampton and Kim [14] where level-set and optimization approaches are used on planar structures.

The goal of the present paper is to demonstrate further the capabilities of the method proposed by Bruyneel and Zein [11], which is available in an industrial context, by using it for optimal design of composite parts.

This paper starts with a brief introduction describing the method developed in [11,12] to determine equidistant courses for ATL/AFP process. Next, several optimization problems with growing complexity are studied in order to illustrate the interest of the method.

2. Fiber placement modeling

2.1. Fast Marching Method

Bruyneel and Zein [11,12] first proposed the use of level-set and Fast Marching Method (FMM, see [15]) to solve the problem of determining equidistant courses on an arbitrary layup surface. The Fast Marching Method aims at solving the Eikonal equation:

$$\begin{aligned} &|\nabla T(x)| = f, \quad x \in \Omega \setminus \Gamma \\ &T(x) = 0, \quad x \in \Gamma C \Omega \end{aligned} \tag{1}$$

The problem given in Eq. (1) consists in finding a scalar field $T(x)$ such that the norm of its gradient is constant over the domain Ω and that the value of T is equal to zero on a curve Γ of Ω.

As illustrated in Fig. 1, this differential equation can be interpreted as the one characterizing a front propagation at a constant speed where $T(x)$ denotes the time at which the front passes through point x. At time $T = 0$, the front coincides with the curve Γ, therefore, all points located on the curve Γ will have a value of T equal to 0. Then as time increases, the front propagates at a constant speed equal to $1/f$ over Ω. The position of the front Γ_1 at any time T_1 corresponds to the set of point lying on the isovalue $T(x) = T_1$. Since the front speed norm is uniform over the domain, every point of Γ_1 is equidistant from Γ. The set of equidistant curve can therefore be obtained by selecting appropriate isovalues of $T(x)$ over Ω.

Based on a triangular mesh of the layup surface, the developed procedure allows computing fiber orientation on each element of the mesh. At first one needs to define the initial front position on the layup surface. This curve corresponds to the reference course and the definition procedure is presented in next subsection. Secondly, the Fast Marching Method is used to solve the Eikonal equation and to compute the time T at any point of the mesh. The function $T(x)$ is supposed to be piecewise linear by element. Starting from initial values defined by the reference curve, the value of T is progressively computed on the domain by solving the Eikonal equation locally on each triangle of the mesh. For further details about the Fast Marching Method, the interested reader may refer to [15]. Finally, the fiber orientations on each element are defined by computing the direction of the isovalues of $T(x)$ over the considered element. Since those isovalues are equidistant from the reference course, the computed orientations correspond to a gap-less and overlap-less (i.e. constant thickness) layup obtained by ATL or AFP.

2.2. Reference course tracing

The definition of the reference course plays a major role in the context of the present work since the orientation or the control points of the corresponding curve are used as design parameter of the optimization problem.

Because the definition of a curve on a general 3D surface may be a difficult task, we have chosen to resort to an 'artificial' 2D space to define the reference curve and next to map this curve onto the layup surface to obtain the reference course.

This process is illustrated in Fig. 2. The reference curve is defined in the 2D space such that it passes through the axes origin.

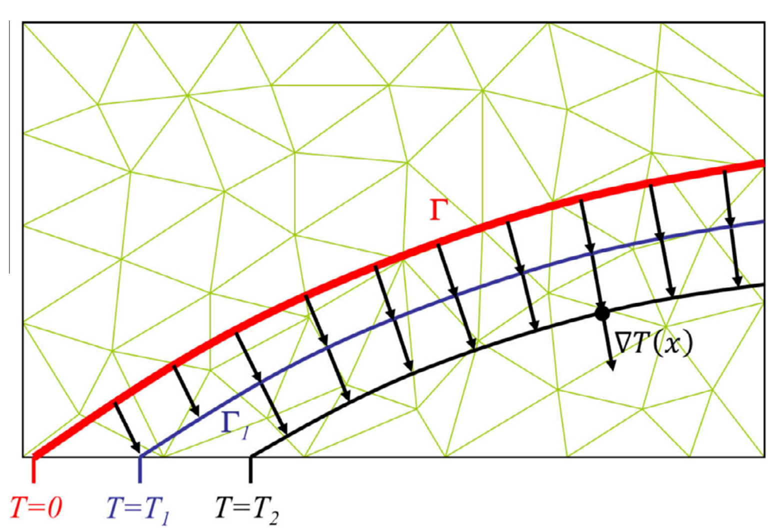

Fig. 1. Front propagation interpretation of Eikonal equation.