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Optimization of variable stiffness composites with embedded defects induced by Automated Fiber Placement

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ABSTRACT

Variable stiffness composite laminates can be manufactured using Automated Fiber Placement (AFP) technology. An improvement in structural performance can be achieved by tailoring their material properties in directions that are more favorable to carry loads. During AFP manufacturing, however, the formation of defects, mainly gaps and overlaps, is inevitable. The extent of a defected zone is generally controlled by two sets of parameters: design parameters; and manufacturing parameters. In this work, we investigate how the parameters governing the formation of defects impact the set of optimal solutions for a multi-objective optimization problem, where in-plane stiffness and buckling load are simultaneously maximized. It is found that increasing the number of tows within a course reduces the amount of defected areas, where the course width is kept constant. Furthermore, the amount of defect areas significantly reduces by using a wide course, which has the effect of both increasing the deviation from the designed fiber path and reducing the number of manufacturable designs. The results show that a complete gap strategy shifts the defect-free Pareto front, obtained without considering the effect of defects, towards lower in-plane stiffness and buckling load; on the other hand, a complete overlap strategy shifts the Pareto front towards higher structural properties.

1. Introduction

Automated Fiber Placement (AFP) is a manufacturing technology that offers great flexibility to build composite laminates with a variety of structural geometries and laminate layups. In particular, complex geometries, such as double curvature surfaces, and non-conventional composites with variable stiffness can be produced by laying down fibers along preferred curvilinear paths within the ply. The structural benefits of variable stiffness laminates are achieved by tailoring the material properties in directions that are more favorable to carry loads within the laminates.

The advantage of using curvilinear fibers to improve the structural performance of a composite laminate has been extensively demonstrated [1–6]. Several studies proposed the optimum fiber path that minimizes the compliance of a cantilever beam [7], maximizes the buckling load of a plate [8], maximizes the buckling load of a hybrid composite shell [9], simultaneously maximizes the buckling load and in-plane stiffness [10]. These works are promising because they demonstrate the structural improvement that tailored curvilinear fiber paths can potentially generate. However, these results are only theoretically optimum, as they do not consider the manufacturing constraints, e.g. the minimum turning radius of the fiber path imposed by an AFP machine. As a result, some of the optimum solutions might not be manufacturable. Alhajahmad et al. [11] accounted for the minimum turning radius in the search for the optimal fiber path that maximizes the buckling load of a plate subjected to pressure and in-plane loads. Furthermore, Blom et al. [12] obtained a fiber path that maximizes load-carrying capability of a cylinder under pure bending load.

The above works assume the laminates to be defect-free (ignoring the presence of defects). In practice, however, the method used by an AFP machine to manufacture a laminate with curvilinear fibers generally leads to the formation of defects in the form of gaps and/or overlaps. During the manufacturing process, the first course (a band of tows) is laid down along the designed fiber path. Subsequently, the first course is repeatedly shifted to cover the whole laminate. If the course width could change continuously, there would not be any defects in the laminate. Since an AFP machine can change the course width only by a discrete value via either adding or dropping tows, small defect areas form within the laminate. Triangular gaps and/or overlaps generally appear between adjacent courses, an AFP process outcome that affects the structural performance of the final laminate. There are several strategies to drop the tows. 0% coverage (complete gap) is a strategy that involves dropping a tow as soon as one edge of the tow reaches a course boundary; it creates small triangular areas without fibers, i.e. gaps. Another method is 100% coverage (complete overlap);

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here, a tow is dropped when both edges of the tow cross the course boundary, thereby creating small areas of triangular overlaps. An intermediate scenario is when the coverage is between 0% and 100% [13]. The strategies explained above can be also followed to add a tow. Another strategy to manufacture a laminate without any gap is to avoid dropping the tows, which results in large overlap areas within the manufactured laminate. This strategy is referred to as the tow-overlapping method.

In the literature, the study of the effect of defects, mainly overlaps, on the mechanical properties of variable stiffness laminates manufactured by AFP has attracted the attention of several researchers. Wu et al. [14] conducted experiments that showed the prebuckling stiffness of a 20-layered variable stiffness panel with tow-overlapping is 27% higher than a $[\pm 45]_{5S}$ cross-ply laminate, while it is only 4% higher for the panel with gaps. Lopes et al. [15] investigated the first-ply failure load of a variable stiffness laminate. They found that the optimum variable stiffness design obtained by Tatting and Gürdal [13,16] increased the first-ply failure load by 24.8% and 33.9% for a complete gap and tow-overlapping strategies, respectively. In another attempt, Lopes et al. [17] further extended the previous results to account for the progressive damage behavior and final structural failure. It was shown that for a flat plate without a central hole, the optimum variable stiffness design can increase the strength by 25.2% and 41.2% for a complete gap and tow-overlapping strategies, respectively. The increase in strength for the plate with a central hole is 13.4% for a complete gap and 55.5% for a tow-overlapping strategy. It should be noted that in the previously mentioned works gaps are not considered in the analysis of the variable stiffness laminates. Blom et al. [18] first investigated the influence of gaps on strength and stiffness of variable stiffness laminates using the Finite Element Method (FEM). They found that increasing the gap areas in the laminate deteriorates both strength and stiffness properties. They also investigated the effect of tow width on the stiffness and strength of a variable stiffness laminate and concluded that in addition to the size of the gap areas, their distribution also has an effect on the structural properties of the laminate.

The area percentage of gaps and overlaps depends on two sets of parameters: manufacturing parameters, such as the tow width, the number of tows in a course, and the tow drop strategy; and design parameters, which define a curvilinear fiber path. In the past, these parameters were not considered in the optimization of a variable stiffness laminate. On the other hand, one expects that optimum fiber paths for an ideal defect-free laminate deviate from those for real manufactured laminates with embedded defects. Hence the aim of this paper is to factor in the effect of gaps and overlaps in the optimization of variable stiffness laminates. In this work, MATLAB subroutines are first developed to calculate the area and extent of gaps and overlaps in a variable stiffness laminate considering both manufacturing and design parameters. Then, the effects of these defects are considered in the calculation of the laminate in-plane stiffness and buckling load. Finally, the optimization problem of maximizing simultaneously in-plane stiffness and buckling load for laminates with embedded defects is formulated and the set of optimal solutions is obtained. A discussion on the effect of design and manufacturing parameters on the optimized variable stiffness designs is presented before the concluding remarks.

2. Fiber path definition

A variable stiffness laminate can be designed by defining a reference fiber path along which the AFP machine places the first course. The entire laminate can be manufactured by shifting the reference fiber path perpendicular to the direction of the fiber angle variation. As a reference fiber path, we consider here a constant curvature path presented by Blom et al. [18]. Along this reference path, the fiber orientation can be obtained as

$$\cos\theta = \cos T_0 + \frac{|x|}{\rho}, \tag{1}$$

where θ is the fiber orientation along the fiber path, T_0 is the fiber orientation at the plate center, and ρ is the turning radius. The fiber orientation varies between T_0 (at the plate center, $x = 0$) and T_1 (at the plate edges, $x = \pm\frac{w}{2}$), where the radius of the path remains constant (Fig. 1a). To manufacture the entire plate, the reference fiber path should be shifted along the y-direction since the fiber orientation varies along the x-direction (Fig. 1b). A single layer with this fiber path definition may be represented by $[+\langle T_0|T_1\rangle]$, where $T_1 = T_0$ represents a case of straight-fiber layer [18]. It should be noted that in this study a minimum turning radius of 0.635 m (25 in.) is considered as a manufacturing constraint imposed by a typical AFP machine.

2.1. Test problem

A 0.254 × 0.406 m (10 × 16 in.) rectangular plate made of 16-ply balanced symmetric laminate $[\pm\theta(x)]_{4S}$ subjected to a uniform end shortening along the y-direction is considered as a case study. Concerning the boundary conditions, the transverse edges are considered free (Fig. 1b) for in-plane displacement and all edges are simply supported against out-of-plane movement. Carbon epoxy Cytec® G40-800/5276-1 material properties used in this study are as follows: E_x = 143 GPa, E_y = 9.1 GPa, G = 4.8 GPa, and ν = 0.3.

3. Design parameters

In Section 2, the reference fiber path for manufacturing a variable stiffness laminate is defined. During manufacturing, the AFP machine head follows the reference fiber path and places the first course, whose centerline exactly matches the reference fiber path. Then, the machine head is shifted to place the subsequent courses. The shift distance is generally chosen to avoid the formation of major gaps or overlaps within the laminate [18]. MATLAB subroutines are developed here to calculate the shift distance, as well as the location, shape, and pattern of gaps and overlaps emerging within the laminate from the AFP manufacturing process [19]. With reference to the shift distance, course boundaries can be obtained based on one-sided or both-sided tow drop approaches. When using a one-sided tow drop approach, one boundary of the course is kept parallel to the reference fiber path and the other one is obtained by shifting the first boundary; as a result, gaps and/or overlaps only appear along one of the course boundaries. In a both-sided tow drop approach, both course boundaries are modified and defined by shifting the reference fiber path; therefore, gaps and/or overlaps appear along both course boundaries. Using the one-sided tow drop approach results in a significantly lower gap and/or overlap area percentage within the laminate compared to the both-sided approach. Fig. 2 shows the gap (shaded area) distribution within the $[+\langle 45|26\rangle]$ lamina and compares the two approaches for 8 tows, each 3.175 mm (1/8 in.) wide inside each course.

It should be noted that the gap area percentage is calculated as the sum of gap area divided by the total laminate area. It can be seen that for this design, the both-sided tow drop approach results in a gap area percentage of 19.9%, which is about twice as much as the gap area percentage that would appear by using the one-sided two drop approach (10.4%). Moreover, the one-sided tow drop approach results in more scattered gap areas compared to the both-sided two drop approach.