



## Defect layer method to capture effect of gaps and overlaps in variable stiffness laminates made by Automated Fiber Placement

Kazem Fayazbakhsh, Mahdi Arian Nik, Damiano Pasini\*, Larry Lessard

Department of Mechanical Engineering, McGill University, Macdonald Engineering Building, 817 Sherbrooke West, Montreal, QC, Canada H3A 2K6

### ARTICLE INFO

#### Article history:

Available online 6 November 2012

#### Keywords:

Variable stiffness composites  
Finite element method  
Defect layer method  
Automated Fiber Placement

### ABSTRACT

A variable stiffness design can increase the structural performance of composite laminates. In this paper, a composite laminate with curvilinear fiber paths is designed to maximize simultaneously its in-plane stiffness and buckling load. After obtaining the Pareto front through a surrogate-based optimization algorithm, two variable stiffness laminates among the solution set are selected that can be manufactured by an Automated Fiber Placement machine. Due to the characteristics of the manufacturing process, defects appearing in the form of gaps and/or overlaps emerge within the composite laminate. MATLAB subroutines are developed here to capture the location and extent of the defects. A novel method, called defect layer, is proposed to characterize the change in properties of each layer in the composite laminates that results from the occurrence of gaps and overlaps. Such a method allows calculating the in-plane stiffness and buckling load of a composite laminate with embedded defects. The results show that by incorporating gaps in the laminates the buckling load improvement resulting from fiber steering reduces by 15% compared to the laminates where gaps are ignored. A maximum improvement of 71% in the buckling load over the quasi-isotropic laminates can be observed for a variable stiffness laminate built with a complete overlap strategy.

© 2012 Elsevier Ltd. All rights reserved.

### 1. Introduction

Automated Fiber Placement (AFP) is a technology capable of combining tape placement and filament winding techniques to overcome their limitations and exploit their benefits. The former technique is generally more efficient in manufacturing large and flat panels but its use is limited to components with simple geometry. The latter, on the other hand, has limitations in terms of the manufacturable shape of a final component, which is basically restricted to convex geometries. An AFP machine typically has a self-contained fiber placement head with multiple degrees of freedom (DOF), which is then mounted on a motion base with several translational DOF. A mandrel with an additional rotational DOF provides a tool surface on which a band of tows, called a “course”, is placed [1]. As a result, more complex geometries, e.g. concave or double curvature surfaces, can be manufactured. Furthermore, tows can be placed in a pre-designed pattern, e.g. a curvilinear path within the plane of laminates. AFP allows the manufacture of variable stiffness laminates with curvilinear fiber paths which offer a more favorable stress distribution and an improved structural performance [2–6].

It has been demonstrated that variable stiffness laminates can simultaneously maximize buckling load and in-plane stiffness,

two conflicting design objectives, as opposed to traditional design strategies of constant stiffness laminates [7,8]. Gürdal et al. [5–7] designed variable stiffness laminates with a curvilinear fiber path, where the fiber angle changes linearly from one end of a plate to the other. They showed that variable stiffness design can decouple the buckling load and the overall in-plane stiffness of the plate. Variable stiffness laminates were designed to provide the same in-plane stiffness as a constant stiffness laminate with higher buckling load and vice versa. Arian Nik et al. [8] used a surrogate-based optimization algorithm and obtained a set of optimum solutions maximizing the in-plane stiffness and buckling load simultaneously. They concluded that both buckling load and in-plane stiffness can be increased with respect to a quasi-isotropic laminate. In the previously mentioned works, the minimum turning radius, which determines the maximum amount of steering that is possible with an AFP machine, was not considered in the design process. As a result, not all the solutions obtained could be manufactured via AFP machine. In addition, these previous works assumed no sudden cut tows within the course and defect-free laminates. Due to the manufacturing features inherent to AFP, however, the laminates are not exempt from imperfections; certain defects, mainly gaps and/or overlaps, often appear in the final part, thereby affecting its structural performance [9].

Several authors conducted experiments to investigate the effect of gaps and/or overlaps on the mechanical properties of a constant

\* Corresponding author. Tel.: +1 514 398 6295; fax: +1 514 398 7365.

E-mail address: [damiano.pasini@mcgill.ca](mailto:damiano.pasini@mcgill.ca) (D. Pasini).

stiffness laminate made by AFP machine. It was found that introducing gaps reduces the laminate strength [10], and the average strain [11], while the overlaps can cause an increase in strength of maximum 13% compared to a non-defective laminate [12], and 93% improvement in buckling load of a panel compared to a straight fiber case [13]. Blom et al. [9] investigated the influence of gaps on the strength and stiffness of variable-stiffness laminates using Finite Element Method (FEM). They found that increasing the total gap area in the laminate deteriorates the strength and stiffness properties. Their work mainly considered gaps and did not model overlaps. In addition, the elements were assumed to be in areas filled with either regular composite material or resin only. This method requires the size of the elements to be small enough to capture precisely the gap areas. Therefore, the number of elements in the FE model drastically increases with the plate size, resulting in a reduced computational efficiency.

In this paper, a novel method, called “defect layer”, is introduced to reduce the computational burden of FE analysis of a variable stiffness composite laminate with embedded gaps and/or overlaps. The method enables to calculate precisely gap and overlap area percentage regardless of the number of elements. The paper is organized as follows: Section 2 describes two variable stiffness laminates selected as case studies. In Section 3, location and extent of gaps or overlaps are first determined using MATLAB subroutines developed by the authors [14]. Then, the defect layer method is introduced to build the finite element model of the variable stiffness laminates under investigation. In Section 4, the results, in particular the effect of gaps or overlaps on the in-plane stiffness and the buckling load, are discussed.

## 2. Problem definition

This section describes the fiber path used to design variable stiffness laminates followed by an explanation of the two test problems including the applied loads and boundary conditions. Two representative designs with an optimum fiber path are selected to investigate the effect of gaps or overlaps on the performance of the laminates.

### 2.1. Fiber path definition

A variable stiffness laminate can be designed by setting a reference fiber path and offsetting the subsequent fibers to cover the whole laminate. To define the reference fiber path, we consider here a constant curvature path presented by Blom et al. [9]. Along the reference path, the fiber orientation can be obtained as:

$$\sin \varphi = \sin T_0 + \kappa|x| \quad (1)$$

where  $\varphi$  is the fiber orientation along the fiber path,  $T_0$  is the fiber angle at the plate center, and  $\kappa$  is the curvature of the fiber path. The fiber orientation varies between  $T_0$  (at the plate center,  $x = 0$ ) and  $T_1$  (at the plate edges,  $x = \pm w$ ) where the curvature 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  $(T_0, \kappa)$ , where  $\kappa = 0$  represents the case of straight fiber.

### 2.2. Test problem

We consider a  $0.254 \times 0.4064$  m ( $10 \times 16$  in) rectangular plate made of 16-ply balanced symmetric laminate subjected to a uniform end shortening along the  $y$ -direction. 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 summarized in Table 1.

As representative laminate design for this problem, we select two variable stiffness laminates and we investigate the effect of gaps or overlaps on their in-plane stiffness and buckling load. Variable stiffness laminates are chosen from the set of optimum solutions (Pareto front) obtained by the simultaneous maximization of the in-plane stiffness and buckling load. The Pareto front is obtained using a Non-dominated Sorting Genetic Algorithm-II (NSGAI) integrated with a surrogate model (Radial Basis Function) algorithm (Fig. 2) [8]. The laminate configurations of design (A) and (B), selected here as case studies, are shown in Table 2. Design (A), which offers the maximum achievable buckling load, is chosen to evaluate the real improvement in the buckling load after considering the effect of gaps or overlaps. Design (B), which offers higher buckling load and the same in-plane stiffness compared to the baseline, is chosen to evaluate the effect of gaps or overlaps on both the design objectives.

We note that no gaps or overlaps in variable stiffness laminates are assumed in the calculation of the objective functions, i.e. in-plane stiffness and buckling load. The objective functions of the variable stiffness laminates are normalized with respect to the corresponding values of a constant stiffness quasi-isotropic laminate with  $[45/0/-45/90]_{2s}$  layup, the baseline.

## 3. Methodology

In this section, we first explain the approach for locating gaps or overlaps in the selected designs. As an example, the distribution of gaps and overlaps for a lamina in design (A) is illustrated. Then, a defect layer method is proposed to build efficient FE models of composite laminates, which includes gaps or overlaps. Finally, the FE models of the design (A) and (B) are created and the effect of gaps or overlaps on the in-plane stiffness and the buckling load is investigated.

### 3.1. Identification of gap or overlap locations

To manufacture the selected design laminates, the AFP machine head places the first course along the reference fiber path. Then, the head is offset along the  $y$ -direction for placing the subsequent courses to cover the whole laminate. The offset value, i.e. the vertical distance between the left and right course boundaries, is determined to prevent the formation of any major gaps and/or overlaps. As a result, the course width is required to change continuously along the fiber path. In practice, however, the AFP machine can change the course width only by a discrete value via either adding or dropping tows. Thus, small areas of triangular gap and/or overlap appear between adjacent courses. There are several strategies to drop the tows. 0% coverage (complete gap) is a strategy that involves the cutting of a tow as soon as one edge of the tow reaches the course boundary; it creates small triangular areas without fibers, i.e. gaps. The other method is a 100% coverage (complete overlap); here a tow is cut 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% [15]. Similar strategies can be followed to add tows, which in turn results in the formation of gaps and/or overlaps.

MATLAB subroutines developed by the authors [14] are used to locate gaps or overlaps for the selected designs. Two strategies, i.e. complete gap and complete overlap are selected to simulate the laminates manufacturing. A complete gap strategy results in a constant thickness laminate, which is essential in certain aerospace applications requiring aerodynamic smoothness. Compared to a

Download English Version:

<https://daneshyari.com/en/article/252109>

Download Persian Version:

<https://daneshyari.com/article/252109>

[Daneshyari.com](https://daneshyari.com)