THE EFFECT OF GAPS AND OVERLAPS ON THE IN-PLANE STIFFNESS AND BUCKLING LOAD OF VARIABLE STIFFNESS LAMINATES MADE BY AUTOMATED FIBER PLACEMENT

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Abstract

The variable stiffness concept can increase the structural performance of composite laminates and provide designers with flexibility for trade-offs between structural properties. In this paper, a composite laminate with curvilinear fiber path is designed to maximize in-plane stiffness and buckling load simultaneously. The Pareto front for the optimization problem is obtained and a variable stiffness laminate within the solution set is selected. These laminates can be manufactured by Automated Fiber Placement (AFP) technology. During the manufacturing process, defects emerge on the composite laminate with the formation of gaps and/or overlaps. MATLAB subroutines are developed to locate gaps or overlaps for variable stiffness laminates. A novel element, called defect element is proposed to build the finite element model of the laminates and calculate their in-plane stiffness and buckling resistance. The results show that a maximum improvement of 54% in the buckling load can be reached for a variable stiffness laminate following a complete overlap strategy. However, when gaps emerge in the laminates, the improvement in the buckling load reduces by 12%.

1 Introduction

An Automated Fiber Placement (AFP) machine is capable of combining tape placement and filament winding techniques to overcome the limitations and exploit the benefits of these two manufacturing methods [1]. An AFP machine can manufacture complex geometries, like concave or double curvature surfaces. Furthermore, tows can be placed in a pre-designed pattern, e.g. curvilinear paths within the plane of laminates. This manufacturing strategy results in "variable stiffness" laminates, an advanced tailoring option that can result in a more favorable stress distribution and an improved structural performance [2].

It is found that variable stiffness laminates can simultaneously maximize buckling load and in-plane stiffness, two conflicting structural design objectives, over traditional constant stiffness designs [3, 4]. Gurdal et al. [3] designed variable stiffness laminates with a curvilinear fiber path, in which 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 in-plane stiffness of the plate. They produced contours showing that there are variable stiffness

laminates that have the same in-plane stiffness as a constant stiffness laminate and at the same time have higher buckling load and vice versa. Arian Nik et al. [4] obtained a set of optimum solutions maximizing in-plane stiffness and the buckling load simultaneously using a surrogate based optimization technique. They concluded that both buckling load and in-plane stiffness can be increased compared to a quasi-isotropic laminate. In the previously mentioned works, it was assumed that the course boundaries are smooth and there are no defects. However, during manufacturing of variable stiffness laminates with an AFP machine certain defects, mainly gaps and/or overlaps, will be introduced to the final part resulting in the structural performance degradation.

Blom et al. [5] 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 deal with overlaps. In addition, in their finite element model, it is assumed that elements are completely either in gap or regular composite material areas. This straightforward approach requires the size of the elements to be small enough to capture the gap areas precisely. Therefore, the number of elements in the FE model will drastically increase by enlarging the plate size, reducing the computational efficiency of the model.

In this research work, the computational burden of FE analysis of a variable stiffness composite laminate with gaps or overlaps is alleviated by developing a novel element, called "defect element". In the following sections, first, variable stiffness laminates are designed for two structural objectives, assuming there are no gaps or overlaps. Then, developed MATLAB subroutines [6] are used to predict the location of gaps or overlaps in the designed variable stiffness laminates. Finally, ANSYS Parametric Design Language (APDL) codes are developed to exploit the defect element for building the FE model of variable stiffness laminates to investigate the effect of gaps or overlaps on the in-plane stiffness and the buckling load.

2 Problem definition

This section describes the fiber path used to design variable stiffness laminates followed by an explanation of the case study, loading, and boundary conditions. Then, one design with optimum fiber path is selected to investigate the effect of gaps or overlaps.

2.1 Fiber path definition

A variable stiffness laminate can be designed by determination of a reference fiber path and offsetting the subsequent fibers to cover the whole laminate. A constant curvature path presented by Blom et al. [5] is considered to define the reference fiber path. The fiber orientation along the reference path can be obtained by Eq. 1.

$$\sin \varphi = \sin T_0 + \kappa |x|, \tag{1}$$

where φ is the fiber orientation along the fiber path, T_0 is the start angle at the plate center, and κ is the curvature. 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 remains constant. To manufacture the entire

plate, the reference fiber path should be shifted along the y-direction since the reference path varies along the x-direction. A single layer with this fiber path definition may be represented by $\langle T_0, \kappa \rangle$, where $\kappa = 0$ represents a straight fiber case.

2.2 Case study

We consider a rectangular plate 0.254×0.4064 m (10×16 in) made of 16-ply balanced symmetric $[\pm\theta_1, \pm\theta_2, \pm\theta_3, \pm\theta_4]_s$ laminate subjected to a uniform end shortening along the y-direction. Concerning the boundary conditions, the transverse edges are free to move. CYCOM 5276-1 carbon epoxy material properties are used.

2.3 Multi-objective optimization problem

Variable stiffness design provides flexibility for trade-offs between different structural properties. In this work, the conflicting objective functions, in-plane stiffness and buckling load are considered. The aim of this section is to find the fibre path parameters (design variables) that simultaneously maximize the in-plane stiffness and buckling resistance of the plate. One way to convert a maximization problem into a minimization problem is to use the inverse of the objective functions. Then, the optimization problem can be written as follows:

$$
\begin{aligned}
&\min_{\mathbf{x}} \left\{ 1 / E_{eq}(\mathbf{x}), \ 1 / N_{cr}(\mathbf{x}) \right\}; \mathbf{x} = \left(T_0, \kappa \right)^T \\
&s.t. \ \left\{ T_0 \in [0^\circ, 90^\circ] \, and \, k \leq 0.635 \, m^{-1} \right\},
\end{aligned}
\tag{2}
$$

where $\mathbf{x}$ is the vector of design variables, i.e., T_0 and k that are the fiber angle at the plate center and the curvature, respectively; E_{eq} and N_{cr} are respectively the equivalent in-plane stiffness and the critical buckling load of the plate. It is worth to mention that T_0 should be integers and $\kappa \leq \dfrac{1}{0.635} m^{-1}$ ($\kappa \leq \dfrac{1}{25} in^{-1}$) to respect the manufacturing constraint.

2.4 Optimization results

Evolutionary algorithms (EA) are widely used to solve multi-objective optimization mainly because they are population-based and can provide a set of solutions in a single run. EAs require a large number of function evaluations to find the Pareto optimal set, thereby increasing the computational cost required to solve this case study [7]. Surrogate-based algorithms are known to be able to significantly reduce the computational cost of multi-objective optimization problems involving variable stiffness composite laminate; for this reason, the surrogate-based optimization algorithm proposed in [4] is utilized here. The optimization results are illustrated in Figure 1 and show a wide extent of the Pareto front. The in-plane stiffness and the buckling load of the variable stiffness plate are normalized using the corresponding values for a constant stiffness quasi-isotropic laminate with [45/0/-45/90]$_{2s}$ layup, i.e. the baseline.
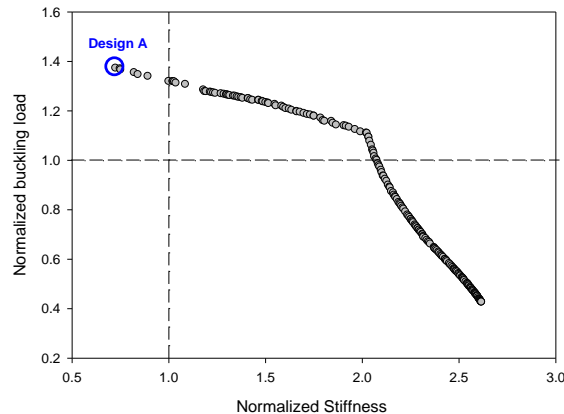
Figure 1. Pareto front obtained by maximizing the buckling load and in-plane stiffness.

A designer can select any solution placed on the Pareto front considering the desirable trade-off between in-plane stiffness and buckling. In this study, we examine one design from the Pareto front, i.e. design (A) (Figure 1). The laminate configuration for design (A) is [±<43|0.0123>/±<44|-0.04>/ ±<35|-0.04>/±<38|-0.04>]$_s$. Design (A), which offers the maximum achievable buckling load, is selected to evaluate the real improvement in the buckling load after considering the effect of gaps or overlaps.

2.5 Locating gaps or overlaps for selected design
To manufacture the selected design laminate, the AFP machine head places the first course along the reference fiber path. Then, it is offset along the y direction for placing the subsequent courses to cover the whole laminate. In-house MATLAB subroutines [6] are used to locate gaps or overlaps for the selected design. Two strategies, i.e. complete gap and complete overlap are selected for simulating the laminate manufacturing. Considering the relative small size of the laminates, 8 tows in each course and tow width of 3.175 mm (1/8 in) are considered as manufacturing parameters. In section 3, the methodology to model the effect of gaps or overlaps on the in-plane stiffness and the buckling load is discussed.

3 Methodology
In this section, a novel element, namely a defect element, is proposed to build a FE model of defected composite laminates. Then, the FE models of the selected design in Section 2 (design (A)) have been created and the effect of gaps or overlaps on the in-plane stiffness and the buckling load has been investigated.

3.1 Defect element
Several researchers have been used FE analysis to investigate the effect of gaps on the stiffness and strength of a composite laminate [5]. In their FE models, the elements either have regular composite material properties or complete gap areas. Therefore, the element size must be set to be sufficiently small to capture the gaps precisely. We propose here a defect element, which can consist of both regular composite material and defect (gaps or overlaps). As a result, the model is capable of capturing the gaps or overlaps more precisely using a lower number of elements compared to the FE approach presented in [5].

The defect element is similar to a regular composite element with modified properties. Defect area percentage (gap or overlap area in each element divided by the element area) is the only parameter used to modify the regular composite element properties. It should be noted that for a defect element containing gap, material and strength properties are reduced while a defect element containing overlap keeps the same material and strength values as a regular composite element but with an increase in the thickness.

In a previous work by the authors, FE analysis was used to study the effect of gaps or overlaps on the longitudinal compression strength of a quasi-isotropic laminate. The FE models were verified using experimental data [8]. The same approach is used here to build the FE model of the defect element for gaps and find the reduction in material and strength properties.

3.1.1 Defect element containing gap

A 0.0254×0.0254 m (1×1 in) single layer $[0]_T$ laminate with a gap at the plate center and along the fiber direction is considered to calculate the defect element properties (Figure 2). Longitudinal compression and tension tests along X (fiber direction) and Y (transverse direction) axes as well as shear test have been simulated using FE analysis to find material ($E_X, E_Y, and\, G$) and strength values ($X_C, X_T, Y_C, Y_T, and\, XY$) for the defect element. Here, for the sake of brevity, the process is explained only for calculating E_X value. A unit displacement is applied at the right and left edges. The laminate is divided into 3 distinct areas as shown in Figure 2(a). Areas 1 and 3 represent non-defective laminate (regular composite) along the X axis while area 2 denotes a gap area. Shell 181 is used to mesh the laminate and the element size in the regular and gap areas are kept the same. The gap width is varied to change the gap area percentage between 0% (regular composite element) and 100% (element completely filled with resin). E_X values for defect element are normalized with respect to the non-defect value and shown in Figure 3. Material and strength properties for defect element versus gap area percentage are plotted in Figure 3a and 3b, respectively. These properties can be described as polynomial functions of gap area percentage and then imported into ANSYS.
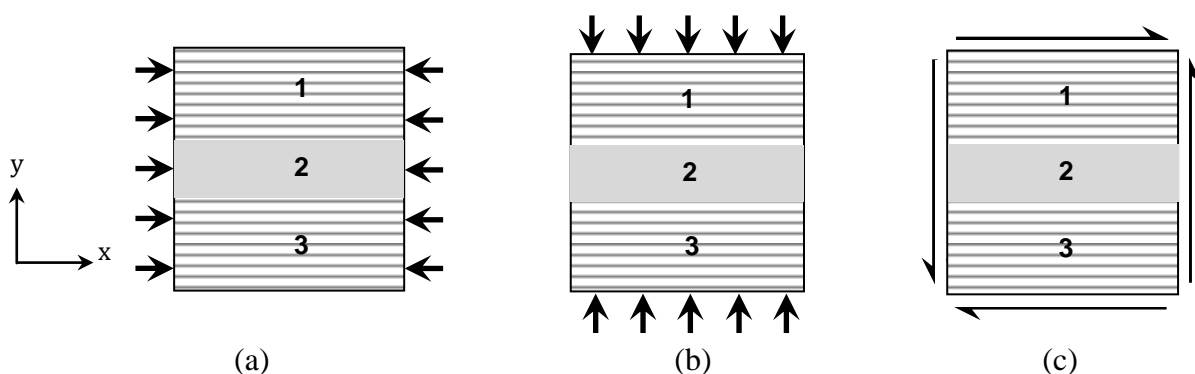

Figure 2. Characterization of defect element properties; (a) Ex; (b) Ey; (c) G.
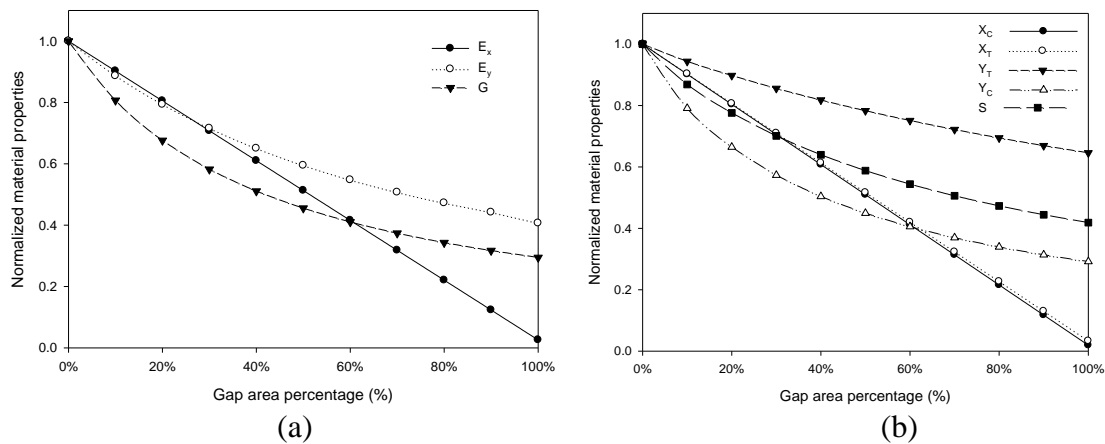
(a) (b)

Figure 3. Modified properties of defect element normalized with respect to the non-defected element; (a) material properties; (b) strength properties.

3.1.2 Defect element containing overlap

A defect element for overlap has the same shape as the one in Figure 2, with a thickness build-up along the fiber direction. The material and strength properties for this defect element have the same values as those of a regular composite material. The defect element is replaced with a regular composite element with higher thickness.

3.2 Building FE model

In-house MATLAB subroutines (Section 2.5) can predict the location of gaps or overlaps for variable stiffness laminates. The next step is to build the FE models for variable stiffness laminates in ANSYS. The number of elements should be large enough to maintain constant fiber orientation within each element. Elements might exist in regular composite areas (0% gap or overlap) or contain any defect area percentage between 0% and 100%. A MATLAB subroutine is developed to create a FE mesh for variable stiffness laminates. The fiber orientation at each element mid-point is calculated using Eq. 1 and is considered as the element fiber orientation. The defect area percentage of each element is obtained using image processing capability in MATLAB.

This approach reveals to be more efficient than previous methods in [5]. Figure 4a shows the gaps for one layer in design (A). To build its finite element model by following the approach proposed in [5], 10240 elements are used since the same element length-to-tow-width ratio as in [5] is considered (Figure 4b). Elements might exist fully in composite material areas (white, 0% gap) or in gap areas (black 100% gap). Figure 4c depicts the finite element model for the same layer using the defect element approach with the same number of elements. Here, elements might have any gap area percentage ranging from white (0% or no gap) to black (100% complete gap). By comparing Figures 4b and 4c, it can be concluded that the finite element model build based on the defect element approach can capture the gaps and their shape more precisely. It is worthy to mention that the approach described in [5] has limited application for large structures because the element length is also governed by the tow width. On the other hand, the defect element approach can handle large structures because the tow width does not constrain the element length.
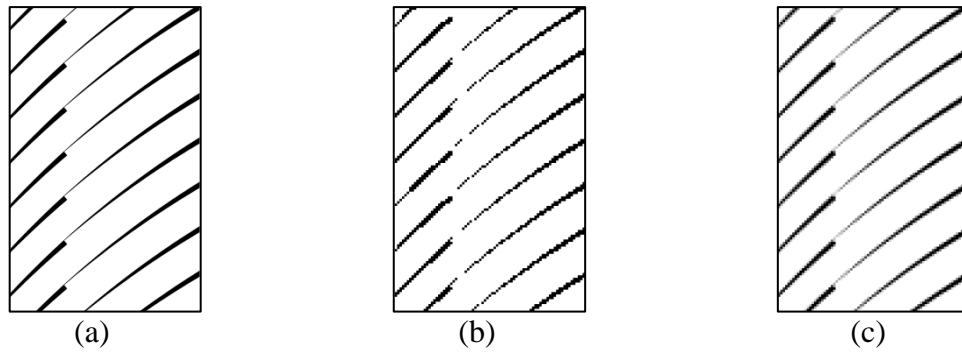
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Figure 4. Comparison between approaches developed to capture the gaps; (a) the true model; (b) Approach proposed in [5]; (c) the defect element approach.

4. Results and discussion

In this section, the effect of gaps or overlaps on the in-plane stiffness and buckling load of the variable stiffness laminate (design (A)) has been investigated. The results of the FE simulations are normalized with respect to the baseline and reported in Table 1.

Laminate		Normalized stiffness	Normalized Buckling load
Design (A)	*Ignoring defects*	*0.73*	*1.37*
	Full gap	0.61	1.26
	Full overlap	0.78	1.54

Table 1. Normalized stiffness and normalized buckling load with respect to the baseline for designs (A).

As it was expected, gaps reduce the in-plane stiffness and the buckling load while overlaps increase both design objectives. It should be recalled that design (A) has the maximum improvement in the buckling load compared to the baseline. Design (A) is expected to provide 37% higher buckling load over the baseline if gaps and overlaps are neglected. However, it can be seen from Table 1 that following the full gap strategy (0% coverage) for design (A) will result in only 26% improvement in the buckling load compare to the baseline. In other words, the emerging gaps (from the fiber steering) in the laminate reduce the improvement by 11%, which is about one third of the expected improvement in the buckling load. On the other hand, following a full overlap (100% coverage), which produces thickness build-ups in the laminate, results in an increased buckling load of 54% over the baseline. This increase is 16% more than the improvement expected without considering the effect of overlaps, which is about half of the improvement that can be obtained in the buckling load from fiber steering.

For design (A), higher buckling load comes at the cost of a reduction in the in-plane stiffness. Ignoring the presence of gaps or overlaps, the improvement in the buckling load is obtained at the cost of 27% reduction in the in-plane stiffness. While including the effect of gaps results in 12% more reduction in the in-plane stiffness. However, a complete overlap strategy can improve the in-plane stiffness of design (A) by 5%. It can be concluded that gaps have a more significant effect on the in-plane stiffness compared to overlaps.

5 Conclusion

In this research work, the concept of variable stiffness design is used to maximize simultaneously in-plane stiffness and buckling load. The Pareto front is obtained and a design

among the optimum solutions is selected which has the maximum improvement in the buckling load over the quasi-isotropic laminate (baseline). The effect of gaps or overlaps on the in-plane stiffness and the buckling load of the selected design is investigated using a novel element, called defect element. As it was expected, gaps reduce both the in-plane stiffness and the buckling load, whereas overlaps have the opposite effect. For the selected design, a maximum improvement of 54% in the buckling load over the baseline is reached following the complete overlap strategy in the laminate manufacturing. This improvement decreases to 22% with a complete gap strategy. Future work is required to investigate the effect of tow width and course width on the defects distribution and structural performance of variable stiffness laminates. Furthermore, other designs on the Pareto front can be considered and the effect of gaps or overlaps on the in-plane stiffness and the buckling load can be investigated. Structural properties, like strength and fundamental frequency can also be explored.

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