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Effects of gaps and overlaps on the buckling behavior of an optimally designed variable-stiffness composite laminates – A numerical and experimental study

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ABSTRACT

This paper reports an experimental and numerical investigation of the effects of gaps and overlaps on the buckling behavior of variable-stiffness composite laminates. In the experimental study, variable-stiffness composite laminates with a constant-curvature fiber path were manufactured and tested under uniaxial compression to failure with simply supported edges. The tested panels were optimized to simultaneously maximize the in-plane stiffness and the buckling load. Two manufacturing strategies – complete overlaps and complete gaps – were adopted to allow the independent effect of each type of defect to be investigated in isolation. In the numerical study, a two-dimensional finite element model was built using the commercial software Abaqus through a Python input script. A MATLAB routine was also implemented to localize the gaps and overlaps within the studied variable-stiffness laminates. A linear buckling analysis was performed to calculate the pre-buckling strength and the critical buckling load for each tested composite laminate. Thereafter, a nonlinear analysis using the Riks method was performed to predict the load–displacement relationship, considering the geometric imperfections of cured composite laminates. A good correlation was observed between the results obtained from the finite element simulations and from the experiments.

1. Introduction

Automated fiber placement (AFP) is a technology that is currently widely used for advanced manufacturing in the aerospace industry to fabricate large composite aerospace structures with complex geometries [1]. Because of its high production rate and its good accuracy and repeatability, the AFP process reduces design and manufacturing costs as well as run-times [2–4]. In addition to the advantages mentioned above, the AFP process allows the designer to control the fiber orientation inside a ply with high precision, thereby enabling the manufacture of variable-stiffness laminates [5]. This particular potential allows the designer to optimize the properties at every point in a laminated composite structure, which can, in turn, lead to improved design quality [6].

Many studies [7–31] have reported that by including the fiber orientation angle at each point in a composite structure as a design variable in their optimization framework, designers can better tailor their designs to satisfy appropriate load constraints.

However, during manufacturing of variable-stiffness laminated structures, AFP machines introduce inescapable defects into the final product. The most common AFP process-induced defects are overlaps (i.e., resin-poor areas) and gaps (i.e., resin-rich areas) [6,32]. Current AFP machines are equipped with software that provides various means of limiting the occurrence of such defects and for controlling their size and location within a structure [6]. Nevertheless, the effects of these manufacturing-induced defects on the mechanical performance of variable-stiffness composites are still not well understood, which hinders the complete fulfillment of the potential of AFP [33]. Thus, a better understanding of the influence of such defects on the mechanical properties of composite structures would be of great benefit for fully exploiting the variable-stiffness concept for the design and application of composites.

Numerical and experimental studies were performed by Wu et al. [34] to study the buckling performance of tow-steered composite panels subjected to uniform end-shortening. The investigated panels consisted of 20 plies with curvilinear fiber paths manufactured according to two fabrication strategies: the tow-drop and overlap method. The results were compared with those

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of a $[\pm 45]_{5s}$ cross-ply baseline, and it was shown that the overlap strategy yielded considerable improvements in the buckling and post-buckling characteristics of tow-steered panels without causing a significant increase in structural weight.

Jegley et al. [35,36] designed, manufactured and tested flat composite laminates with curvilinear fiber paths under in-plane compressive or shear loads. Their results indicated a substantial improvement in the overall elastic properties of variable-stiffness laminates compared with their constant-stiffness counterparts.

Furthermore, in our previous work [37,38], an in-depth experimental investigation was conducted to quantify the effects of representative manufacturing defects on the buckling behavior of steered composites panels. In this study, a new test device was built to conduct compression-buckling tests on rectangular, simply supported fiber-steered laminates. During the experiments, the load–displacement curves, strain gauge responses and buckled shapes were recorded. The obtained experimental results indicated that the composite panels manufactured using the curvilinear fiber concept exhibited better structural performance than those fabricated using straight fibers. However, it should be noted that in our previous work, the studied composite panels were designed with a linear varying fiber orientation angle. Unfortunately, this approach lacks a certain flexibility in directly controlling the curvature of the fiber paths, resulting in local tow wrinkling [39], which reduces the quality of the final product. Furthermore, it limits the mechanical improvements; that can be achieved using the concept of controlled fiber steering. A further limitation associated with this kind of fiber paths is the inaccuracy in the calculation of the defects introduced during the manufacturing phase. Indeed, the localization of defects and the calculation of their areas are performed either manually or using a complex software (which still requires further improvement efforts). Consequently, this approach may lead to inaccuracy in the estimated values. To overcome these limitations, Tatting and Gürdal [5] proposed to define the fiber paths with a constant curvature. Such a formulation enables the direct control of the radius of curvature. Additionally, it can facilitate to automatic calculation of the amount of defects and a better understanding of their effects on the structural performance of the material. Recently, Blom et al. [40] presented a theoretical method to predict the positions of the tow-drop areas into tow-steered laminate plies with constant-curvature fiber paths. This method was later implemented in the finite element model to determine the reduction in the stiffness and strength properties of variable-stiffness laminates due to the tow-drop areas. Parametric studies were subsequently conducted to investigate the effects of the fiber angle, tow width, and laminate thickness.

Using this concept, Fayazbakhsh et al. [41] developed MATLAB® subroutines that could be used to predict the distribution of AFP defects in a finished AFP product. In a later paper [42], the same authors introduced a defected layer to quantify the impact of the AFP defects on the elastic properties of variable-stiffness panels. This defected layer consists of a regular composite layer whose thickness and elastic properties can be modified to simulate a gap or overlap in a variable-stiffness laminate.

Based on these previous studies [40,41], optimal panels designed with constant-curvature fiber paths were considered in this work. These panels were manufactured using two different manufacturing strategies: complete overlaps and complete gaps. They were then mechanically tested under compressive load. The primary objective of this work was to quantify the real effects of the defects (i.e., overlaps and gaps) introduced during manufacturing on the stiffness and buckling properties of the panels. The work presented in this paper was performed as part of a CRIAQ project (COMP-413 [4,6,24,38,41–44]) toward optimizing the designs of aeronautical structures manufactured using the AFP process.

2. Panel description

2.1. Panel design and optimization

The composite panels tested in this work were designed and optimized as reported in [24] as part of the CRIAQ project COMP-413. The objective of the design process was to determine the fiber paths that simultaneously maximized both the in-plane stiffness and the buckling load of the composite laminates. This multi-objective optimization problem was solved using the surrogate-based NSGA-II (NSGA+PR) optimization algorithm. For a more detailed description of the optimization algorithm, the reader is referred to [24,44]. The performance of the optimized laminates was compared with that of a quasi-isotropic laminate with a $[45/0/-45/90]_{2s}$ lay-up configuration, which served as the reference design. The composite panels were fabricated using G40-800/Cycom 5276-1 prepreg slit tape. The mechanical properties of the constituent materials are listed in Tables 1 and 2.

In this work, a fiber path with a constant curvature was used; it can be expressed as follows [40]:

$$\cos(\varphi) = \cos(T_0) - \kappa|x| \tag{1}$$

where φ represents the fiber orientation angle at any point along the width of the plate in the x direction, T_0 represents the fiber angle at $x = 0$, and κ represents the curvature of the reference fiber path [40].

A schematic representation of this equation is illustrated in Fig. 1, where the fiber orientation angle along the reference path changes from T_0 (at $x = 0$) to T_1 (at $x = \pm a/2$). Between these points, the curvature (which is equal to the reciprocal of the radius) of the reference fiber path remains constant. The notation $[(T_0, \kappa)]$ is mostly used to define a single lamina with a variable fiber orientation according to a constant-curvature path. Particularly, $\kappa = 0$ denotes the case of a straight fiber lamina [40].

During the design process, the following design requirements were applied [24]:

- The radius of curvature of the reference fiber path is kept constant.
- The shifted method was selected as the manufacturing strategy [10].
- The stacking sequence for the panel was chosen to be symmetric and balanced: 16 layers $[(T_0, \kappa)]$ of carbon/epoxy prepreg slit tape; each with a thickness of 0.1545 mm.

In addition to the preceding requirements, the panel characteristics were limited by the following conditions:

- The minimum turning radius of the AFP machine was 625 mm (the minimum radius of curvature required for laying the material down on a flat surface without wrinkles or micro-buckling [1]).
- The dimensions (width × length) of the panels were fixed at 254 mm × 406 mm. This limitation was dictated by the testing fixture.

Table 1
Elastic properties of G40-800/Cycom 5276-1 unidirectional carbon/epoxy prepreg.

Elastic properties	Values
Longitudinal modulus $E1$ (GPa)	142.7
Transverse modulus $E2$ (GPa)	9.1
Shear modulus $G12$ (GPa)	4.82
Poisson's ratio ν_{12}	0.3