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Buckling behavior of variable-stiffness composite laminates manufactured by the tow-drop method

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ABSTRACT

The current investigation deals with the buckling behavior of variable-stiffness composite panels manufactured by the automated fiber placement (AFP) process. In order to minimize the occurrence of AFP-inherent defects as gaps and overlaps, the so-called tow-drop method was adopted. Compression-buckling tests were performed on large panels containing gaps or overlaps under simply-supported boundary conditions. The specific responses of the out-of-plane deflections, which were tracked by four laser sensors focused on the axial centerline of the panels during compression loading, were explained by the measured initial geometric curvatures, which were characteristic of variable-stiffness panels. The tracking of the in-plane strains using sixteen strain gauges located strategically on the panels confirmed that the presence of gaps and overlaps does not affect the symmetry of variable-stiffness panels. Finally, it was established that the tow-drop method significantly improved the structural performance in terms of the pre-buckling stiffness, buckling load, and the failure load while keeping minimal geometric disturbances.

1. Introduction

Automated fiber placement (AFP) is a leading technology for manufacturing large and complex aerospace composite structures and is presently the preferred process for producing modern aircraft, such as the Boeing 787, the Airbus 350 XWB, and the Bombardier C-Series. A recent review paper [1] discussed the development of the automated prepreg processes used for manufacturing composites, including the AFP process. Although the AFP process is primarily used for manufacturing composite structures with straight fibers (i.e., constant-stiffness laminates), it offers the possibility of steering individual fiber tows along curvilinear paths. This manufacturing feature has widely opened the way to what are known as variable-stiffness laminates [2]. Variable-stiffness laminates allow designers to reinforce and enhance the structural properties against the load direction, which is significantly desirable to produce aircraft structures. Several research studies on the design and optimization of composite materials have demonstrated the potential of the variable-stiffness design to improve the in-plane stiffness (e.g. [3–5]), buckling resistance (e.g. [6–8]), strength (e.g. [9–11]), vibration response (e.g. [12–14]) and bending properties (e.g. [15–17]). However, the manufacturing of the variable-stiffness laminates reveals misgivings associated with specific inherent defects induced by the fiber steering, referred to as gaps and overlaps; the effects of these defects on the structural performance of composite laminates are not yet well understood. Therefore, elucidating the effects of these defects is essential for the development of this promising design.

In the open-literature, there are numerous experimental and numerical studies which address the effects of gaps and/or overlaps on the mechanical properties of constant-stiffness laminates. Among them, Sawicki and Minguet [18] investigated the decrease in the compressive strength of straight-fiber laminates with intra-ply overlap and gap defects. Turoski [19] performed numerical and experimental analyses to investigate the effects of the number of gaps on the ultimate strength of 32-ply carbon/epoxy composite plates under uniaxial tensile and compressive loads. Croft et al. [20] addressed an experimental approach to understand the effects of four different defect configurations, namely, gaps, overlaps, twisted tows, and half gaps/overlaps, on the mechanical performance of laminate composites. Legay et al. [21] examined the effects of gaps and overlaps on the low-velocity impact response of AFP-manufactured 24-ply quasi-isotropic carbon/epoxy laminates. They examined the damage-initiation load, the peak impact load, the absorbed energy, the damage area, and the compression-

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after-impact strength. Fayazbakhsh et al. [22] performed a finite element analysis to investigate the effects of gaps and overlaps on the compressive strength of a quasi-isotropic laminate with a $[45/0/-45/90]_{3s}$ lay-up. They used the experimental data available in the literature to validate the FE model and results. A reasonable agreement between the experimental and numerical results was reported.

Although it is fairly easy to find experimental data on the effects of the AFP process-induced defects on the mechanical characteristics of constant-stiffness composites, most published studies on variable-stiffness composite laminates have involved numerical simulations (e.g. [10,23,24]), and there is a lack of experimental data related to these inherent defects (i.e., gaps and overlaps), as reported in Ref. [25]. Wu et al. [26,27] performed numerical and experimental analyses on the buckling behavior of two-steered composite panels (i.e., with and without overlaps) subjected to uniaxial compression. Jegley et al. [28,29] performed compression and shear tests on tow-steered panels with a central circular cutout. The results of these studies indicated that the overall elastic properties of variable-stiffness panels with gaps and overlaps were significantly better than those of their constant-stiffness counterparts. However, it should be pointed out that, in the previous studies[26–29], the strategy adopted for manufacturing the tested panels, referred to as the tow-overlapping method [30], led to a significant amount of overlaps within the panels. The manufactured panels were quite unsymmetrical, since they had one smooth side (the one that was against the mold surface) and one bumpy side, owing to the excessive amount of overlaps and thickness build-up. Such geometry is generally undesirable for aerodynamic control surfaces in aeronautical applications, like in aircraft wings, which control the air flow rate and aircraft lift. Previous authors [26–29] have used the staggering technique, which involves offsetting the origin of the main path for each ply by a small distance, during the manufacturing process, in order to prevent the clustering of the AFP defects. Nevertheless, after consolidation, the cured variables-stiffness panels presented large initial geometrical imperfections compared to the constant-stiffness panel used as the baseline panel. To counter this, Wu et al. [26] forced the supported panels' edges straight during the compression test. This interference during testing probably affects the buckling behavior of the panels, as the performance of variable-stiffness panels is highly dependent on the boundary conditions [5].

In contrast with the tow-overlapping method, another manufacturing method can be used to reduce the geometrical anomalies and minimize the amount of defects induced in the AFP-manufactured variable-stiffness panels. This method, which involves cutting the fiber-tows to avoid the formation of an excessive amount of AFP defects, referred to as tow-drop method. In practice, several design strategies can be adopted when the tow-drop method is employed. These strategies can be classified on the basis of the «coverage percentage» parameter [31]. In the strategy corresponding to 0% coverage (i.e., complete gap), the tow is dropped as soon as one edge of the tow reaches the limiting curve (e.g. an adjacent course or the bounding edge of the laminate); this results in small triangular resin-rich areas (i.e., gaps). In opposite, in the strategy corresponding to 100% coverage (i.e., complete overlap), the tow is dropped when both edges of the tow cross the limiting curve; this results in small areas of triangular overlap. Furthermore, intermediate scenarios are also possible, in which the coverage percentage lies between 0% and 100% (see [31] for details).

The current investigation aimed to quantify the effects of the AFP process-induced defects on the buckling and post-buckling characteristics of rectangular, simply-supported, variable-stiffness panels subjected to uniform in-plane displacement. For this purpose, two optimal variable-stiffness panels with the lowest possible amount of AFP defects were manufactured using the tow-drop method: one corresponded to 0% coverage (i.e., with complete gaps) and the other corresponded to 100% coverage (i.e., with complete overlaps). A special fixture was designed and manufactured to ensure the simply-supported boundary conditions at all of the panels' edges during experiment. The buckling characteristics of the variable-stiffness panels were determined, and the results were compared with those obtained for a constant-stiffness panel (i.e., defect-free quasi-isotropic baseline panel). This experimental work is part of the COMP-413 project [5,20,23,24], intended to optimize the design of steered-tow composite structures by taking into account the AFP process-induced defects. Ref. [5] examined the multi-objective optimization of the in-plane stiffness and buckling load of a flat composite plate with variable stiffness using the surrogated NSGA-II approach (NSGA-II: Non-dominated Sorting Genetic Algorithm-II). The flow chart of the surrogate-based optimization defined in Ref. [5] served to propose two optimized variable-stiffness composite panels intended to be manufactured using a Viper 4000 AFP machine.

2. Experimental procedures

2.1. Material and test panel manufacturing

Three types of panels were manufactured: (i) a quasi-isotropic panel with constant-stiffness, which served as the baseline, (ii) a variable-stiffness panel with complete overlaps (i.e., with 100% coverage) and (iii) a variable-stiffness panel with complete gaps (i.e., with 0% coverage). The stacking sequences for these tested panels are listed in Table 1. The fiber orientation notation used in Table 1 is that proposed by Gürdal and Olmedo [3]. One should note here that the studied variable-stiffness panels were optimized using the methodology and flow chart described in Ref. [5] to achieve a maximum buckling load compared to the baseline panel.

The fiber-steered panels were manufactured using a VIPER ® 4000 fiber placement machine. This AFP machine has the capability to lay-up any even number of 3.175 mm wide slit tape, up to 32 tows, and allows for individual tow cut/restart control. To manufacture the variable-stiffness composite laminates, each fiber-tow in the AFP process was laid up by following a predefined curvilinear-fiber path. To simulate the fiber paths, the ACE programming/simulation software was used. This software can also simulate the distribution of the AFP process-induced defects (see Fig. 1) and foresee the potential areas that might exhibit quality-related problems, resulted when the constraint of the minimum fiber radius of curvatures is violated. For a 3.175 mm wide prepreg tow, the minimum required radius of curvature, as recommended in the literature [32], is 635 mm for laying prepreg tows onto a surface free of wrinkles and micro-buckling.

All the tested panels were manufactured using G40-800/5276-1 carbon/epoxy slit tape from Cytec Engineered Materials. The panels were then cured at 177 °C in an autoclave for 2 h under a pressure of 0.58 MPa. The nominal material properties are listed in Table 2.

After being cured in the autoclave, the panels were cut into specimens with dimensions of 254 mm × 406 mm using a diamond saw under running water. Subsequently, the shorter edges of the trimmed specimens were machined flat and parallel to

Table 1
Stacking sequences of the tested panels.

Panel design	Stacking sequence
Quasi-isotropic design	$[+45/0/-45/90]_{2s}$
Overlaps design	$[\pm\langle 49\vert 41\rangle/\pm\langle 48\vert 61\rangle/\pm\langle 57\vert 73\rangle/\pm\langle 72\vert 77\rangle/]_s$
Gaps design	$[\pm\langle 49\vert 41\rangle/\pm\langle 48\vert 61\rangle/\pm\langle 57\vert 73\rangle/\pm\langle 72\vert 77\rangle/]_s$