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Design, manufacturing, and testing of a variable stiffness composite cylinder

Mohammad Rouhi*, Hossein Ghayoor, Jeffrey Fortin-Simpson, Tom T. Zacchia, Suong V. Hoa, Mehdi Hojjati

Department of Mechanical and Industrial Engineering, Concordia Center for Composites, Concordia University, Montreal, Quebec H3G 1M8, Canada

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ABSTRACT

Fiber steering is one of the promising capabilities of Automated Fiber Placement (AFP) technology in manufacturing of advanced composite structures with spatially tailored properties. The so-called variable stiffness (VS) composites have considerable scope to outperform their traditionally made constant stiffness (CS) counterparts. However, there are several design and manufacturing challenges to be addressed before practically using them as structural components. In this work we demonstrate the design, manufacturing and testing procedure of a variable stiffness (VS) composite cylinder made by fiber steering. The improved bending-induced buckling performance is the objective of the VS cylinder to be compared with its CS counterpart. The experimental results show that the buckling capacity of the VS cylinder is about 18.5% higher than its CS counterpart.

1. Introduction

Laminated fiber-reinforced composites are usually made by stacking plies with straight fibers and mostly limited to 0°, 90°, and ± 45°. Using straight fibers limits the tailorability of the composite structure to tailoring the stacking sequence of the laminate. This design space can be further extended by using curvilinear fibers in the composite plies, e.g., allowing the plies to have continuously varying fiber orientation angles. Automated fiber placement (AFP) machines have made it possible to steer the fibers in individual plies to manufacture such laminates. The resulting variable stiffness (VS) laminate is capable of creating a more efficient load path between the loading points and the supports that allows harnessing the full potential of directional properties of composite materials. As a result, the VS composites made by fiber steering offer significantly improved performance compared with their constant stiffness (CS) counterparts [1–6].

The most common manufacturing defects within fiber/tow steering are tow buckling, tow pull-up and tow misalignment [7]. Tow buckling occurs on the inside of the highly curved steering radius where the compressive force is too high. Likewise, tow pull-up may occur on the outside of highly curved steered fiber due to excessive tensile force. Tow misalignment can occur due to variability in the layup control or prepreg material. Tow gaps/laps are also other important steering-induced defects in VS composites of which the impact on the mechanical performance of the final products has not been extensively investigated.

The increased number of design variables introduces more challenges in the design optimization of VS composites such as modeling complexities and computational cost. Moreover, there are manufacturing issues associated with the VS composites to be taken into account such as gaps/overlaps, process efficiency, product quality, and manufacturability. Several review papers focused on different aspects of the VS composites potentials and challenges including the optimization methods [8], manufacturability [9], mechanical behavior of VS designs [10], and recently the maturity of VS designs [11]. The potential structural improvement that can be harnessed by fiber steering has been extensively studied [3,12–16]. They all demonstrated that through stiffness tailoring, the loads are more efficiently redistributed that results in an optimum load path from the loading points to the supports. For a VS composite cylinder under bending-buckling load, Blom et al. [3,17] predicted improvements of up to 17 percent compared to its baseline laminate. Khani et al. [12] showed that the buckling capacity of a VS cylinder can get about 24% higher than its CS counterpart. This improvement was about 21% for an elliptical cylinder. Rouhi et al. [18] showed that for elliptical cylinders under axial buckling there is about 118% improvement for VS over CS design. Ghayoor et al. [19] also investigated this potential improvement for bending-buckling of elliptical cylinders. Their results showed about 70% improvement in bending buckling of elliptical VS cylinders with cross-sectional aspect ratio of 0.7. Among several works reporting the potential improvement of composite structures' performance by fiber steering, a few of them have experimentally validated such improvements [3,20–22]. Failure load of composite flat panels with and without cutouts [20], and with large cutouts [21] were experimentally shown to be improved using fiber steering. Blom et al. [3] performed experimental testing for

* Corresponding author.
E-mail address: m.rouhi@gmail.com (M. Rouhi).

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bending of a VS cylinder and compared their results with a QI baseline cylinder. They predicted the buckling improvement for VS cylinder, but did not go up to the buckling point to experimentally validate their prediction. White et al. [22] also performed axial buckling test and validated their results predicted by FEA in both buckling and post-buckling regions.

In this work a VS composite cylinder was designed and optimized for improved bending-induced buckling capacity over its CS counterpart which is a quasi-isotropic (QI) cylinder in this study. The experimental validation of the results for bending-buckling is performed for the first time. To this end, a multi-step metamodeling-based design optimization (MBDO) approach [23] combined with finite element analysis (FEA) were used. After finding the optimum fiber paths of the VS design, both QI and VS composite cylinders were manufactured by AFP machine and cured. The cylinders were thereafter prepared, installed on a bending machine and tested to assess their bending-buckling performance. The design, manufacturing, and testing procedures along with the experimental results were explained and discussed in details in the rest of this manuscript.

2. Modeling and design optimization

A composite cylinder with the gauge length and inside diameter of 381 mm was considered in this study. The material system of the composite plies were those of cured Carbon/Epoxy prepreg tows of which the mechanical properties of unidirectional layers are given in Table 1. The stacking sequence of $[\pm\theta/0/90]_s$ was considered in this study in which θ is kept unchanged and limited to 45° for QI cylinder, whereas for VS laminate it can vary in circumferential direction as shown in Fig. 1a.

The bending load is applied on the ends of the cylinder and the buckling load is computed by using the commercial FEA software ABAQUS™. The FE model was generated using S8R5 shell elements and followed by a mesh convergence study, the cylinder was discretized into 100 points around the circumference. For the VS plies, the continuous variation of the fiber orientation angle in the circumferential direction was approximated by a piece-wise constant model in which the circumference is divided into a limited number (=100 in this study) of axial narrow bands with constant fiber orientation angles as shown in Fig. 1b. Therefore, stiffness tailoring was made by finding the orientation angle (θ_i) in each narrow band of the piece-wise constant model. To further reduce the number of the design variables, the orientation angles of certain equally-spaced narrow bands in each ply (T_i's) are considered to be the design variables (Fig. 1c). The orientation angles in other narrow bands were calculated by the linear interpolation between the design variables. Considering the symmetry about the vertical axis and the above mentioned definition of the design variables, 5 design variables were considered for a θ_i-ply to represent it as a VS lamina: $T_1,\ldots,T_5$. Therefore, the orientation angle of the kth narrow band located between α_i and α_{i+1} is calculated by:

$$\theta_k = T_i + \frac{\alpha_k-\alpha_i}{\alpha_{i+1}-\alpha_i}(T_{i+1}-T_i) \quad i = 1,\ldots,5 \text{ and } k = 1,\ldots,10 \tag{1}$$

Table 1
Material properties of each unidirectional carbon/epoxy composite ply (tow properties).

Property	Value
E_1 (GPa)	134
$E_2 = E_3$ (GPa)	7.71
$G_{12} = G_{13}$ (GPa)	4.31
G_{23} (GPa)	2.76
$\nu_{12} = \nu_{13}$	0.301
ν_{23}	0.396
V_f	0.55
Thickness (mm)	0.127

The effects of gaps/laps were not considered in this model and, as will be described in the manufacturing section in more details, the gauge length of the cylinders were manufactured so that there is no gap between the adjacent curvilinear tows but overlap was allowed.

Calculating the buckling load via FEA is computationally expensive. On the other hand, the design optimization usually is an iterative process that requires numerous function calls, i.e., FEA in this case. One way to overcome this problem is using a computationally efficient surrogate model on behalf of the FEA. Therefore, a metamodel-based design optimization (MBDO) was used for the VS cylinder. To reduce the error associated with the metamodeling and enhance the computational efficiency, a multi-step MBDO [23] was used in which the design domain is narrowed down step-by-step around the previously found optimum design point until the optimum design is converged.

The MBDO resulted in the optimum orientation angle distribution of VS plies as shown in Fig. 2. As observed, the tensile portion of the cylinder was stiffened because of small orientation angles of the fiber tows whereas the compressive portion was softened due to large orientation angles of the tows. As a result, the compressive load is partially transferred to the tensile part of the VS cylinder and the buckling capacity is expected to increase. The bending-buckling capacities of VS and QI cylinders calculated by FEA are listed in Table 2 in which the VS design shows about 28% improvement over its QI counterpart. The buckling mode shapes of the two cylinders were also shown in Fig. 3. It reveals that via stiffness tailoring the section loads are redistributed in a more efficient way. As a result, the compressive section load is partially transferred to the tensile part [3,14,15], a larger area in VS cylinder carries the compressive section load and the buckling capacity is improved.

3. Manufacturing and experimental setup for testing

The orientation angle (OA) distribution over the circumference of VS plies was transformed to fiber paths using a finite difference method. Starting from any circumferential point at one end of the cylinder, any subsequent point of the tow path center line is determined by having the OA and a prescribed small differential distance from the preceding point. A spline passing through the resulted points from one end to the other end of the cylinder length defines the center line of each tow path. Therefore, starting from a different circumferential location results in a different path in a VS ply. The adjacent tow has to be placed so that there is no gap between the two tows in the gauge length of the cylinder (the middle 15-in long part). To this end, the starting point of the succeeding tow is calculated with the above mentioned constraint. Eq. (2) shows how the gap distance is calculated between the two adjacent tows along the length of the cylinder:

$$GD = SD - \frac{TW}{2}\left(\frac{1}{\cos\theta_1} + \frac{1}{\cos\theta_2}\right) \tag{2}$$

where GD, SD, and TW are gap distance, shift distance and tow width, respectively, as shown in Fig. 4. The placement of a tow on the final path calculated via this method leaves a small gap with the first placed tow just before covering the whole surface of the cylinder in the gauge area of a VS ply. This gap is equally distributed between all the tows (distance between the starting points) to have the surface of the cylinder fully covered with negligible gap (less than 0.01 mm) between the adjacent tows at its gauge area.

The generated splines were converted to a commercial software SolidWorks (part) file readable by the AFP machine's computer console. The AFP machine placed the tows on a 1067-mm long steel mandrel with a diameter of 381 mm as shown in Fig. 5. To improve the tackiness between the tows and the substrate, the mandrel was preheated before the first ply tows were placed on the mandrel. The total length of the composite cylinder made by AFP was set to 762 mm: the 381-mm middle part as the gauge length and two 190.5-mm side parts to be held