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Effect of structural parameters on design of variable-stiffness composite cylinders made by fiber steering

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ABSTRACT

A variable stiffness composite cylinder made by fiber steering is optimized for maximum buckling load due to pure bending. A multistep design optimization procedure is developed to get the maximum potential improvement in structural performance. To improve the computational efficiency, low-cost and computationally inexpensive surrogate models based on radial basis functions (RBF) are used as approximate for the high fidelity finite element (FE) analyzes. Different RBF formulations are also studied and compared with each other in terms of their accuracy.

The effects of radius (R) and aspect ratio (L/R), as two structural parameters, on the structural improvement of the variable stiffness cylinders are also investigated. Keeping the thickness (t) constant, radius (R) is shown to have no considerable effect on the buckling load improvement of the variable stiffness cylinders whereas the aspect ratio (L/R) has a substantial effect on the buckling load improvement. Improvements up to 38.5% are obtained for cylinders with low aspect ratio.

1. Introduction

Fiber-reinforced polymer composite (FRPC) materials have been increasingly used in aerospace structures due to their high stiffness- and strength-to-weight ratios. Tailorability of the stiffness and strength properties and substantial reduction in part count offered by such material systems are other advantages that made them superior compared with metals in aerospace applications. FRPC's can also be manufactured in very complex geometric shapes resulting in both higher product performance and manufacturability. However, the full potential of these materials has not been realized yet. This is, mainly, because of the fact that they have traditionally been designed and manufactured as multi-ply laminates consisting of unidirectional layers in which the fiber orientation angle in each layer is typically held fixed and usually limited to 0°, 90°, and ±45°. Limiting each layer to have a single orientation angle over the entire structural component does not let the designer to fully exploit the directional material properties offered by composite layers. On the other hand, sophisticated manufacturing equipment is needed to accommodate spatial variation of fiber orientation angles in the individual layers. The advent of Automated Fiber Placement (AFP) machines made it possible to steer the fibers/tows to manufacture composite laminates with continuously varying fiber orientation angles. The resulting variable-stiffness (VS) composite component has spatial stiffness properties that can create an optimum load path between the loading points and the supports. These VS laminates allow the designer to exploit the full potential of composite materials by extending the design space resulting in structural components with significantly higher performance and/or lower weight compared with constant stiffness structures [1–11].

Research efforts on fiber/tow placement technology started in the literature when AFP machines were introduced to the market in the late 1980s [12]. The first reported engineering studies were made to build stiffened panels using AFP machines [13,14]. Thereafter, a number of aircraft parts, such as the F/A-18E/F horizontal stabilizer skins, the Bell/Boeing V-22 Osprey aft fuselage [15], and the V-22 grip [16,17] were made using AFP technology. As AFP was becoming more accepted in aerospace applications, other aircraft parts were made by this technology such as the Boeing JSF inlet duct, the C17 landing gear pod fairings and engine nacelle doors [18], and the fuselage sections of Raytheon Premier I and Hawker Horizon business jets [19]. On a large scale, AFP technology has recently been used in the production of Boeing 787 Dreamliner and the aft fuselage sections of Airbus A380 and A350 XWB [20,21]. In all cases, using AFP technology resulted in lower labor costs, reduced amount of scrap materials, and improved product quality.

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Fiber steering capability of AFP technology has been shown to be very promising in structural performance improvement of composite structures. However, there are still several design and manufacturing challenges that need to be addressed to reach its full potential in production of high performance composite structures. The effect of fiber steering in improving both structural performance and reducing weight of plates and panels [2,5,22] and cylindrical shells [23,24] were extensively studied. By fiber steering, Blom et al. [4,23] could improve the bending induced buckling load of a composite cylinder up to 17 percent with respect to its constant stiffness (baseline $[\pm 45, 0_2, \pm 45, 0_2, 90, \pm 45, 90]_s$ laminate) counterpart. Fiber steering allowed them to design a VS composite cylinder with a stiff laminate at the tension side and a soft laminate at the compression side so that the load is relieved from the buckling critical compression side resulting in a more efficient load path and consequently an improvement in buckling load. Khani et al. [24] also presented a method for circumferential tailoring of circular and elliptical cylinders for buckling load improvement under axial compression, bending and torsion with consideration of strength constraints. By steering the fibers in all of the plies in a 24-ply circular cylinder and an 8-ply elliptical cylinder they could improve the buckling load by 29.6% (bending buckling) and 18% (axial buckling) for circular and elliptical cylinders respectively.

One of the issues that need to be addressed in design optimization of VS structures is the effect of geometric parameters on the improvement in structural performance. In other words, will the potential improvement percentage be higher for larger VS structures or lower? To the knowledge of the authors, the effect of the geometric parameters on the structural performance of VS composite structures has not been studied and quantified yet. In this paper, the effect of radius (R) and aspect ratio (L/R) on the buckling performance of VS composite cylinders are investigated.

The design optimization procedure of VS structures usually includes metamodeling. This is to reduce the computational expense (simulation runtime) which is a major obstacle in optimization procedures. In many cases, hundreds or thousands of function evaluations may be required in a design optimization procedure. This problem poses a big challenge when computationally expensive high fidelity finite element (FE) simulations are required for each function evaluation. Metamodels are computationally efficient surrogate models that are widely used in a diverse set of engineering design optimization problems [25,26] to provide approximate responses (function values) at a design point. By performing comparative studies of metamodeling techniques under multiple modeling criteria, Jin et al. [27] concluded that radial basis functions (RBF) is the most dependable method in most situations in terms of accuracy and robustness. Likewise, Arian Nik et al. [28] compared different metamodeling methods in design optimization of VS composites and concluded that RBF and Kriging are the best ones in terms of their performance criteria. RBF was also successfully used in design optimization of structures made of multi-scale composite materials for both buckling [29] and energy absorption [30]. Followed by choosing RBF as the metamodeling method in this work, four different formulations of RBF metamodels including Gauss, Inverse Multiquadric (IMQ), Multiquadric (MQ), and Thin Plate are also compared in terms of their accuracy and reliability.

In aerospace structures any weight savings through reduction of skin thickness must be balanced against the requirement for structural stability. Therefore, bending-induced buckling strength is considered as the metric for structural performance. The material system considered in this study is carbon/epoxy which is commonly used for aerospace applications because of its high weight efficiency and structural performance.

2. Modeling of variable stiffness composite cylinder

A 16-ply laminated composite cylinder with the length and diameter of 18 in. is considered in this study. The plies are made of AS4D/9310 carbon/epoxy materials for which the mechanical properties are given in Table 1.

As illustrated in Fig. 1, a pure bending load is applied to the cylinder and it is analyzed for buckling. Fig. 1 also shows how the boundary conditions are applied on two ends of the cylinder. Multipoint constraint (MPC) option in ABAQUS [31] made it possible to tie the circular ends (edges) of the cylinder to their associated center points with rigid bars, so that both edges remain circular during the deformation. Simply supported BC's were applied by fixing one end (left hand side MPC reference point) of the cylinder and allowing the other end (right hand side MPC reference point) to move along the centerline of the cylinder. S8R5 shell elements of ABAQUS having 8 nodes and 5 degrees of freedom in each node [31] were used in this study.

As a baseline, quasi-isotropic (QI) laminate containing 0°, ±45°, and 90° plies is defined to be symmetric and balanced. Followed by a full factorial design analysis, $[0/+45/90/-45/-45/90/+45/0]_s$ ply schedule is selected as the baseline laminate satisfying the design criteria and requirements recommended in [32]. The buckling performance of VS composite cylinders were compared with those with the baseline laminate. For VS laminates plies having ±45° orientation angles were considered as candidate for fiber steering. Therefore, the VS composite cylinders have $[0/+\theta/90/-\theta/-\theta/90/+\theta/0]_s$ ply schedule in which θ varies in circumferential direction. That means only 50% of the whole laminate is steered to improving the structural performance. In order to make sure that $\theta = 45°$ is an appropriate orientation angle for a constant stiffness (CS) laminate to compare with its VS counterpart, θ is varied from 0° to 90° in the CS laminate. The variation of the bending-induced buckling load for CS cylinder in terms of θ is shown in Fig. 2 that reveals the optimum orientation angle for θ-plies to be 45°. Aside from this CS laminate, a general $[\pm\theta_1/\pm\theta_2/\pm\theta_3/\pm\theta_4]_s$ ply schedule was also

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

Property	AS4D/9310
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

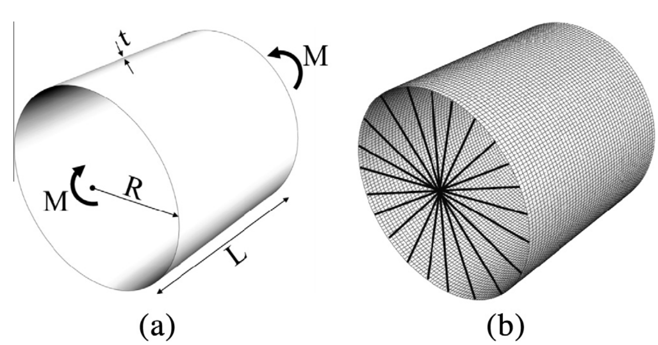

Fig. 1. (a) Loading and BC's of the composite cylinder subject to bending induced buckling and (b) finite element model with multipoint constraint (MPC) in ABAQUS to implement simply supported BC's.