Composites: Part B 69 (2015) 249–255

Contents lists available at ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Multi-objective design optimization of variable stiffness composite cylinders

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ARTICLE INFO

Article history:
Received 3 July 2014
Received in revised form 2 October 2014
Accepted 4 October 2014
Available online 16 October 2014

Keywords:
B. Buckling
C. Computational modelling
C. Finite element analysis (FEA)
Variable stiffness

ABSTRACT

The bending-induced buckling improvement in a variable stiffness (VS) composite cylinder (made by fiber steering) is studied. For such a cylinder, the effect of the variation of the direction of the load on its buckling performance of the cylinder is also examined. Compromise programming, as a multi-objective optimization method, is used to design for buckling of the VS cylinder subjected to bending load in either of the two opposite directions. Different combinations of weight factors for the structural performance in the two opposite directions were also applied to obtain the Pareto frontier as the main decision making tool for the designers in a multi-objective design problem.

1. Introduction

Fiber-reinforced polymer composite (FRPC) materials have been used increasingly over the past few decades in aircraft structures due to their high specific stiffness and strength properties. These superior characteristics as well as tailorability of the stiffness and strength properties and substantial reduction in part count offered by such material systems primarily fueled their dramatic growth in aerospace applications. However, FRPC materials' full potential has not been realized yet due to the limitations associated with the traditional techniques used to design and manufacture components made of these materials. They have traditionally been designed and manufactured as multi-ply laminates consisting of several unidirectional layers resulting in a material with spatially uniform stiffness/strength properties. The fiber orientation angle in each layer is typically held fixed and mostly limited to 0°, 90°, and ±45°. By limiting each layer to have a constant orientation angle over the entire structural component, the designer cannot fully exploit the directional material properties offered by composite layers. On the other hand, accommodating spatial variation of the orientation angles in the individual plies would be nearly impossible without sophisticated manufacturing equipments. Automated fiber placement (AFP) machines have made it possible to steer the fibers in individual plies to manufacture composite parts with continuously varying fiber orientation angles. The resulting variable stiffness (VS) laminate is capable of creating an optimum load path between the loading points and the supports that allows the full potential of composite materials to be harnessed. As a result, the VS composites made by fiber steering offer considerably higher performance and/or lower weight compared with their constant-stiffness counterparts [1–6]. Having been reported since the late 1980s, the research efforts show that the overall program labor costs and the amount of scrap materials were reduced by using AFP technology, while the product quality was increased [7–13]. However, there are still several design and manufacturing challenges to be addressed for this technology, particularly for VS composites made by fiber steering, to reach its full potential in production of high performance aerospace structures.

The effect of fiber steering on the structural improvement of composite conical [14] and circular [3,15–17] cylinders has been extensively studied. Axial and circumferential stiffness tailoring of composite cylinders was first studied by Tatting [18]. Tatting concluded that the buckling load can be improved through load and stiffness redistribution by stiffness tailoring that results in an optimum load path between loading points and the supports. Blom et al. [3,19] reported improvements of up to 17% with respect to a baseline laminate at the same weight. Khani et al. [15] used a two-step optimization framework to include both the theoretical and manufacturing issues in design of a VS circular cylinder under bending and an elliptical cylinder under axial compression. They could improve the buckling load of a

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http://dx.doi.org/10.1016/j.compositesb.2014.10.011
1359-8368/

VS cylinder over a constant-stiffness design about 29.6% using linear and 23.9% using nonlinear analysis. For the elliptical cylinder, these improvements were 17.9% and 21.3%, respectively. In all cases, the structures were subjected to a single loading condition and designed for a single objective. Therefore, changing the load direction may result in a decreased structural performance compared with their baseline laminate. Improved by about 25% compared with its quasi-isotropic counterpart, Rouhi et al. [20] reported about 57% reduction in bending buckling load of a VS composite cylinder when it is subjected to a reverse loading.

In general, structures are subjected to multiple load scenarios that must be considered in the design process. To this end, the design optimization process must systematically and simultaneously consider a collection of objective functions. This process is called multi-objective optimization (MOO) or vector optimization [21]. One of the most common methods for MOO is compromise programming in which a weighted combination of all objective functions is used as the objective function. On the application side, buckling strength is considered as a metric for structural performance in aerospace structures since any weight savings through reduction of skin thickness must be balanced against the requirement for structural stability. Since buckling is a stiffness-driven phenomenon, this is a perfect candidate for the variable stiffness design optimization problem for aerospace application. In this paper, compromise programming is used to buckling design of a VS composite cylinder subjected to bending in either of the two opposite directions. The corresponding Pareto frontier for different combinations of weight factors for the loadings is represented. In addition, the effects of variation of the load direction on the buckling performance of the VS composite cylinders are studied for both single and multi-objective designs.

2. Modeling and analysis of VS composite cylinder

A 16-ply laminated composite cylinder with the length and diameter of 18 inches and stacking sequence of $[0/\theta/90/-\theta/-\theta/90/\theta/0]_s$ was considered in this study. The plies are made of Carbon/Epoxy (AS4D/9310) material system which is commonly used for aerospace applications because of its high weight efficiency and structural performance. The mechanical properties of the plies are given in Table 1. For quasi-isotropic (QI) laminate which is considered as a baseline, θ is kept unchanged and limited to 45°, whereas for VS laminate, θ can vary in circumferential direction as shown in Fig. 1. Therefore, for the ply schedule considering in this study, only 50% of the whole laminate is steered to improve the structural performance. Eq. (1) along with Fig. 1 shows the variation of orientation angle of θ-plies in QI and VS laminates.

$$\begin{aligned} &\theta = 45^\circ \quad \text{for QI laminate} \\ &\theta = \theta(\alpha) \quad \text{for VS laminate} \end{aligned} \tag{1}$$

The bending load is applied in either of the two opposite directions on the ends of the cylinder which is analyzed for buckling. The buckling load is computed using the commercial finite element

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

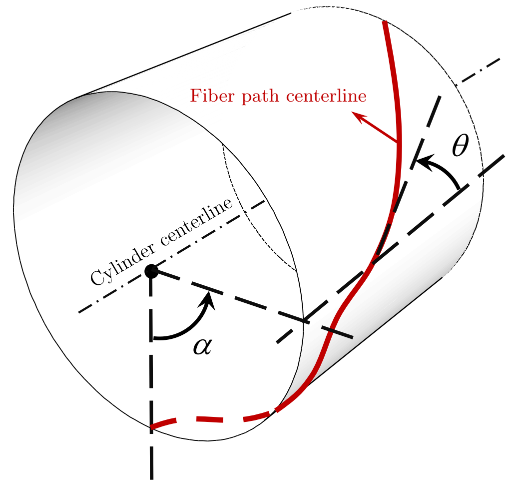

Fig. 1. Fiber path centerline for θ-plies in VS composite cylinder.

(FE) software ABAQUS™. S8R5 shell elements of ABAQUS™ having 8 nodes and 5 degrees of freedom in each node [22] are used in FE models. After a mesh convergence study, the cylinder is discretized into 134 points around the circumference. To approximate the continuous variation of the fiber orientation angle in the circumferential direction for VS laminates, a piece-wise constant model is used. In this model, as shown in Fig. 2, the cylinder is divided into a number (=134 in this study) of axial narrow bands in which the fiber orientation angle of steered plies is assumed to be constant. Stiffness tailoring for VS laminate is made by finding the orientation angle (θ_i) of each narrow band shown in Fig. 2. In order to reduce the number of the design variables, the orientation angle in VS plies is assumed to vary in 6 steps from the keel to the crown of the cylinder. The symmetry about the vertical axis and the defined step by step variation of orientation angles result in 7 design variables per each VS ply: $T_1, \ldots, T_7$, as shown in Fig. 2. Assuming a linear variation in between two adjacent design variables, the orientation angle of the kth narrow band laying between α_i and α_{i+1} is calculated by:

$$\theta_k = T_i + \frac{\alpha_k - \alpha_i}{\alpha_{i+1} - \alpha_i}(T_{i+1} - T_i) \quad i = 1, \ldots, 7 \quad \text{and} \quad k = 1, \ldots, 10 \tag{2}$$

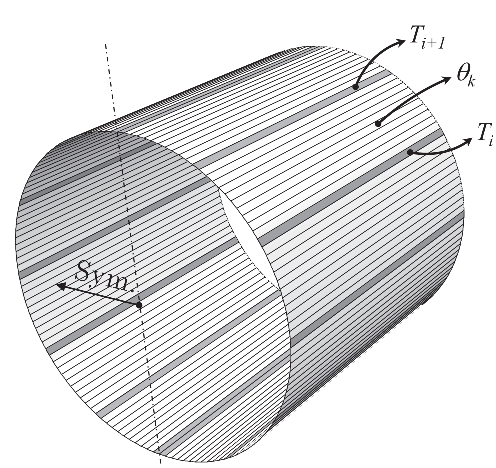

Fig. 2. Piece-wise constant model used as a substitution for continuously varying fiber orientation angle of θ-plies in $[0/\theta/90/-\theta/-\theta/90/\theta/0]_s$ stacking sequence. θ_k's are calculated from Eq. (2).