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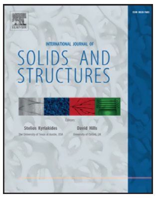

Use of curvilinear fibers for improved bending-induced buckling capacity of elliptical composite cylinders

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ABSTRACT

In this work, the bending-induced buckling of elliptical composite cylinders is significantly improved by using curvilinear fiber paths. The orientation angle in the composite plies are designed to circumferentially vary in elliptical multi-layered composite cylinders for the best bending-buckling performance. To this end, a metamodeling based design optimization approach is successfully employed. The resulting elliptical cylinders with so-called variable stiffness (VS) laminates are shown to have bending buckling capacities up to 70% higher than their constant stiffness (CS) counterparts made with traditional straight-fiber laminates. Unlike the circular cylinders, the non-uniform curvature of the elliptical cylinders adds more complexity to the buckling behavior when the direction of the bending moment is changed. The effect of loading direction on the buckling performance of VS and CS elliptical cylinders is then investigated. Finally, a VS elliptical composite cylinder is designed for having maximum bending buckling capacity in two opposite directions simultaneously, and its buckling performance in different directions is compared with its CS counterpart.

1. Introduction

Aerospace structures are required to be strong but lightweight at the same time, because of which fiber reinforced polymer (FRP) composites are largely used in aerospace applications. Traditional methods for FRP composite manufacturing such as hand layup are being replaced by advanced technologies such as Automated Fiber Placement (AFP) and Automated Tape Laying (ATL) in which computer-guided robotics are used to lay one or several fiber tapes or tows onto a mold to create a laminated composite part. The advantages of AFP/ATL technology include but not limited to higher throughput, improved quality, reduced waste material, reduced labor costs, not requiring high operator skills as needed in traditional methods such as hand layup, reduced manufacturing time, accuracy and repeatability of the production process, and software solutions that allow complex shapes to be programmed quickly. Another benefit that is exclusive to AFP technology is its capability to steer the fibre/tows on the plane of a ply to create controlled curvilinear paths. It gives the designers more scope to take advantage of the directional properties of the composite materials and create optimum path between the loading points and supports in a structural component. The resulting so-called variable stiffness (VS) composites have been shown to have considerably higher structural performance compared to their constant stiffness (CS) counterparts. Followed by investigating the buckling (Hyer and Lee, 1991) and in-plane stiffness (Gürdal and Olmedo, 1993) responses of VS square panels, several researches were conducted to demonstrate the superiority of VS composites over their CS counterparts. The structures studied and designed to this end include but not limited to flat plates and panels for buckling (Ribeiro and Akhavan, 2012; Stanford et al., 2014; Wu et al., 2015) and progressive damage and failure (Lopes et al., 2007), circular cylinders for bending-induced buckling (Blom et al., 2010; Rouhi et al., 2014), and elliptical cylinders for axial buckling (Sun and Hyer, 2008; Khani et al., 2012; 2015; Rouhi et al., 2016). In all cases, the improvement in the structural performance were studied for almost the ideal case in which there is no defect (gap/overlap) due to fiber/tow steering in the manufacturing process. To avoid such defects due to steering, continuous tow shearing (CTS) manufacturing technique was introduced by Kim et al. (2012) in which, however, the thickness of the produced VS laminate is not uniform due to preservation of the volume of tow elements before and after shear deformation resulting from tow steering. The manufacturing characteristics of this method have been discussed in Kim et al. (2014). Since CTS tries to force the tow to slide in a direction perpendicular to the steering direction, it introduces some defects in the final product. Despite having potential for improving tow steering

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technologies, as stated in Kim et al. (2014), it is still immature compared to current AFP technologies in terms of productivity and reliability of the process.

For the CS cylindrical structures, the first study on the pure bending-induced buckling behavior of cylindrical shells was done by Brazier (1927). By disregarding a local buckling, Brazier found the theoretical upper limit of the bending-induced buckling capacity for infinitely long isotropic circular cylinders. Heck (1937) followed the work by investigating the bending buckling behavior of an orthotropic cylindrical shell of elliptical cross section for the first time. He assumed that the cylinder is of infinite length, there are no local instabilities, and the stresses remain below the linear elastic limit of the material. His theoretical results showed a good agreement with experiment for bending load applied about major axis of the elliptical cylinder, but markedly higher than experimental values for bending about the minor cross-sectional axis. Heck (1937) concluded that the local wrinkling of the shell wall resulted in material failure and consequently significant drop in the buckling load. However, this was not the case for the circular cylinders and the elliptical cylinder in bending about its major cross-sectional axis. In other words, the sensitivity of the bending buckling capacity of an elliptical cylinder to the local wrinkling is higher when the load being applied about minor axis than about major axis.

The buckling of finite length VS composite circular cylinders was first studied by Tatting (1998). He examined both axial and circumferential stiffness tailoring by fiber steering. His results showed that the most significant improvements in buckling load was found for bending and shear loadings that involve circumferential variation of loading.

VS structures with optimum curvilinear fiber paths can create more efficient load path, however, at the expense of increasing the number of design variables and consequently adding more complexity to the design process. Therefore, it is worth to note that one should not choose a VS design unless there is a considerable scope for structural improvement due to, for instance, inhomogeneity in the geometry of a structure and/or non-uniformity in the loading distribution or boundary conditions. For example, buckling performance of an axisymmetric structure (e.g. circular cylinder) can be improved over a non-uniform loading condition (e.g. bending), or buckling performance of a non-axisymmetric structure (e.g. elliptical cylinder) can be improved over a homogeneous loading (e.g. axial compression). This, of course, does not imply that the structural performance of an elliptical VS cylinder cannot be improved when it is subjected to bending, rather means there is no scope for improvement for a circular cylinder subjected to a uniform load such as torsion or axial compression.

Efficient aerodynamic design often dictates using structures with cross sections different from a circle, such as in fuel tanks or launch vehicles. As a consequence, due to the variation in the radius of curvature with circumferential location, there are structural disadvantages to a noncircular geometry. For instance, if an elliptical cylinder is subjected to an axial load, the flatter portions of the cross section are less stable than the highly curved portions resulting in occurrence of buckling failure in the flatter portions with no considerable deformation in the more highly curved portions. Sun and Hyer (2008) showed that this structural inefficiency can be compensated to a great extent by stiffness tailoring (use of curved fibers) for elliptical composite cylinders subjected to axial buckling. The redistribution of stiffness by varying fiber orientations resulted in redistribution of the compressive load so that it is partially transferred from the flatter portions of an elliptical cylinder to the more highly curved portions that are geometrically more stable. As a consequence, the axial buckling load is considerably increased (30-35%) compared with its CS counterpart (Sun and Hyer, 2008). In another load case scenario, White and Weaver (2012) studied the potential of using curved fibers to design bend-free pressurized elliptical cylinders and revolved ellipsoids. Their results showed that completely bend-free states are achievable only for elliptical cylinders with particular stacking sequence and geometric properties.

Although aerospace structures are subjected to numerous combined load cases, VS structures are commonly designed for one primary loading scenario to showcase the superiority of this type of design over CS. As a result, design optimization for one load case may lead to loss in structural performance in other load scenarios. To include multiple load scenarios and design for simultaneous improvement for all objectives, performing a multi-objective design optimization is necessary.

To the best knowledge of the authors, bending-induced buckling design of VS elliptical cylinders have not been performed yet. For circular cylinders, however, single objective (Blom et al., 2010; Khani et al., 2012; Tatting, 1998) and multi-objective (Rouhi et al., 2015b) bending buckling improvement of composite cylinders via fiber steering was previously studied. The potential buckling improvements were shown to be dependent to the structural geometry (Rouhi et al., 2014) and the percentage of the plies candidate for fiber steering in a composite laminate (Rouhi et al., 2015a).

In this research, potential improvement of bending-induced buckling capacity of VS elliptical composite cylinders compared with their CS counterparts is studied. The bending load is applied about major and minor axes of the elliptical cylinders to investigate the potential improvement by fiber steering in each case. In addition, the direction of the bending moment is changed to investigate the buckling performance of the VS elliptical cylinders in all directions. The elliptical cylinders are also designed for a special case of having the maximum bending-induced buckling capacity in two opposite directions at the same time. In all cases, the optimum orientation angle distributions over the circumference of the elliptical cylinders are found and the results are discussed. It is worth noting that manufacturing limitations of fiber steering process have not been considered in this work. Therefore, the term “potential improvement” is used instead of “improvement” in many places in the manuscript.

2. Modeling of elliptical composite cylinders for bending buckling design

Structural analysis for calculation of buckling capacity is part of the design optimization process. Since there is no closed-form solution for the buckling capacity of elliptical composite cylinders, we used finite element analysis (FEA). The commercial software Abaqus (Aba, 2011) was used to perform FEA for each cylinder. The number of finite elements (S8R5 in this study) was determined by performing a convergence study to make sure that the analyzes are not mesh size dependent. Fig. 1 shows the geometry of the elliptical cylinders along with the applied loads considered in this study. The continuous circumferential variation of the fiber orientation angles for VS laminates was approximated by assuming a piece-wise constant model. In this method, it was assumed that the surface of the elliptical cylinder is divided into a limited number of narrow bands in which the fiber orientation angle for a ply is constant but different from its neighboring narrow bands (Blom et al., 2010; Rouhi et al., 2014). To further reduce the number of design variables in VS cases, a number of equally spaced narrow bands were considered as control points for which the orientation angles of VS plies in these regions are considered as the design variables (T_i’s). Fiber orientation angles for other narrow bands are calculated from a linear interpolation between these control points. Fig. 2 shows the piece-wise constant orientation angle assumption for VS plies. As shown in Fig. 2, the elliptical cylinders were modeled so that the symmetry of the orientation angle distribution

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