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Natural frequency optimization of braided bistable carbon/epoxy tubes: Analysis of braid angles and stacking sequences

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ABSTRACT

The natural frequency of cantilevered bistable carbon/epoxy reeled composite (BRC) slit tubes constructed from combinations of braided and unidirectional (UD) plies is optimized with respect to fiber orientation angles and laminate stacking sequences. BRC tubes have the same geometry as a carpenter's tape; however, they also have a second stable configuration in the coiled state, and it is considered likely that the coiled state diameter will be fixed by the geometry of the deployment mechanism or its housing. The optimization process uses the BRC coiled diameter as a constraint, and the maximum and minimum physically achievable braid angles as bounds. Both individual tubes, and a simple deployable solar array concept are analyzed. It is observed that the braid angle, rather than ply location in the stack is of greater importance when optimizing long slender or shallow BRCs, whereas both factors must be considered in shorter BRCs. The sensitivity of natural frequency and coiled diameter to braid angle perturbations indicates the importance of precision during manufacture.

1. Introduction

Fiber braided composite materials have high specific stiffness and outstanding performance in fatigue, corrosion and thermal protective characteristics. Carbon/epoxy braided slit tubes have the same geometry as a carpenter's tape [1], but they also can be stable in a coiled state (see Fig. 1(a)), compared to a carpenter's tape which is stable only when extended (Fig. 1(b)). This behavior makes bistable slit tubes suitable candidates for use in a variety of deployable structures for space applications. However, one of the main challenges in using BRC tubes for very large deployable structures is maintaining a sufficiently high natural frequency. One possible application for BRC tubes in space is a deployable "roll-up" photovoltaic (PV) solar array (see Fig. 2(a)) consisting of two bistable carbon-fiber reinforced polymer (CFRP) tubes and a flexible PV cell covered blanket in between. This structure essentially consists of two parallel cantilever beams side by side. If this structure is to be deployed from a spacecraft, the stiffness of the BRC tubes must be sufficiently high to avoid significant coupling between the spacecraft's control system and the solar array's structural modes. For example, Campbell [2] describes a rollable solar array design, and recommends that the natural frequency be kept above 0.2 Hz. While the precise requirements for the vibration characteristics of a BRC based deployable structure will vary from mission to mission, it is desirable to increase the frequency of the first mode to the greatest extent possible without excessive sacrifice of performance in other areas. The natural frequency of the BRC tube supported "roll-up" solar array decreases dramatically with increase in tube length [3]. This paper presents an analysis of the effect that altering the braid fiber angles within a carbon/epoxy BRC tube has on the first "cantilever" mode, while keeping the coiled diameter of the second stable state constant. An approach to optimizing this frequency while keeping the coiled diameter constant is also given, followed by a discussion of the sensitivity of the optimized frequency and the coiled diameter to potential small fiber misalignments encountered during manufacture.

The maximization of the fundamental frequency of laminates has been an area of intensive research. Bert [6] first put forward the idea of maximizing the natural frequency by arranging the lamination of symmetric balanced angle-ply (SBAP) laminates on the basis of practical feasibility and manufacturing costs. Careful selection of the orientation angles of the fibers within the SBAP laminate to optimize the natural frequency was addressed in his paper. Fukunaga et al. [7] examined the optimal design of a laminate to maximize the fundamental frequencies of symmetric laminated plates on the basis of the concept of lamination parameters, which was introduced by Miki [8,9] to define a set geometric properties of a laminate such as ply angles, the number of plies, stacking sequences, and unit ply thickness. A 'Layer-wise Optimization

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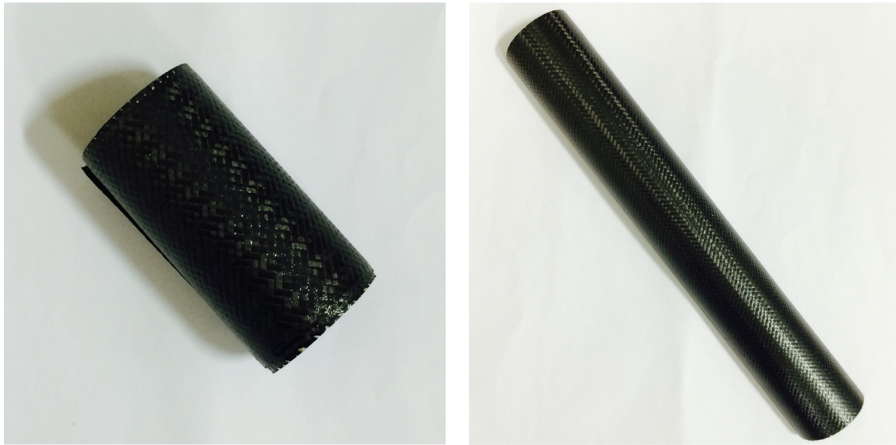
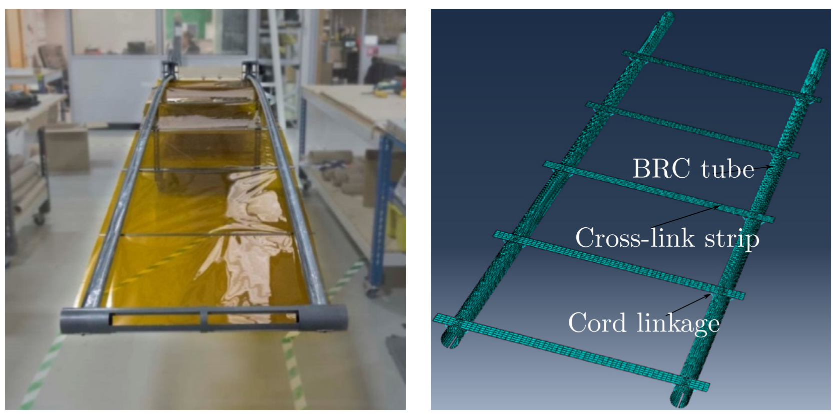


(a) Coiled stable state (b) Extended stable state

Fig. 1. Carbon/epoxy BRC tubes at two stable configurations [4].



(a) Deployable “roll-up” PV solar array developed for DeployTech (b) Assembly of a deployable “roll-up” solar array with no PV blanket in ABAQUS

Fig. 2. Deployed “roll-up” PV solar array.

Approach’ (LOA) for maximizing the fundamental frequencies of laminated composite plates or shallow cylindrical shells has also been proposed [10,11]. This approach took the orientation angles of fibers in each ply as variables and utilized an iterative procedure to find a solution for the optimal natural frequency of the entire laminate. Betts [12] defined an optimization method using stability as a constraint, with an objective function based on a ratio of laminate stiffness in two specified directions. More research related to the dynamic response of shells can be found in literature [13–15]. Note, however, that very few of these publications discuss the effect of uncertainties or small perturbations in fiber angles within the composite laminate.

The effects of other types of uncertainty in the mechanical response of composite structures has been analyzed in a number of articles [16–18]. The sensitivity of bistable laminates has also been examined [19]. The main sources of uncertainty in composite materials [20–23] include variability in material properties due to indeterminate fiber and matrix properties, geometric aspects at macroscopic level, and the manufacturing process itself [24]. The dynamic response of structures with uncertainties in the composite material was studied using a parametric probabilistic approach by assigning random variables to certain parameters [25]. The uncertainty in fiber angles in each ply of a composite laminate is an important concern in the dynamic response of BRC tubes.

This paper presents an analysis of natural frequency and coiled diameter with respect to braid fiber angles. The nonlinear constrained vibration optimization procedure [26,4] combining a Finite Element (FE) numerical model in FE commercial code ABAQUS [27] with Matlab [28] optimization functions is briefly described. A stability margin constraint, the natural frequency and the coiled diameter are studied for different laminate stacking sequences. A deployable “roll-up” solar array with no PV membrane is also modeled in ABAQUS (see Fig. 2(b)) for the purpose of validating the feasibility of analyzing one single BRC tube instead of the whole solar array structure. The natural frequencies of several BRC tubes with various dimensions, constraints and stacking sequences are optimized with respect to braid angles within the laminates. The effects of longitudinal and transverse stiffness on the natural frequency of a slender BRC tube are computationally investigated. Finally, concluding remarks are outlined.

2. Model development

2.1. Description of a BRC tube model

A simple sketch of the BRC tube cross-section is shown in Fig. 3. The BRC tube model is based on the following assumptions: