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Mechanically-prestressed bistable composite laminates with weakly coupled equilibrium shapes

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Fiber-reinforced asymmetric laminates fabricated at elevated temperatures may exhibit bistability at room temperature. The magnitude of deformation in each shape depends primarily on the curing temperature. This paper presents a novel asymmetric bistable laminate that is fabricated at room temperature and whose stable shapes are analogous to those of a thermally cured fiber-reinforced polymeric composite. The proposed laminate is composed of a stress-free isotropic core layer sandwiched between two asymmetric, mechanically-prestressed, fiber-reinforced elastomeric layers. Its stable shapes can be independently tuned by varying the prestress in each elastomeric layer. The mechanics of the laminate are studied using an analytical laminated-plate model that includes the geometric and material nonlinearities associated with large deformations caused by highly-strained elastomers. The effects of core modulus, core thickness, elastomer-core width ratio, and laminate size are examined through a parametric study. Laminate samples are fabricated in the 90°/core/0° configuration for model validation. The simulated stable shapes of the laminate are in agreement with the measured shapes. The dynamic response of the laminate during shape transition is measured using a motion capture system.

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1. Introduction

Multistable composite laminates exhibit multiple stable shapes and require actuation only for shape transition. Due to the potential offered by these laminates for reduction in weight and complexity, they are candidates for adaptive structures in automotive body panels [1], aircraft control surfaces [2], and wind turbine blades [3]. The basic requirement in the design of a multistable laminate is to incorporate residual stress into the structure such that multiple strain energy minima are possible. The methods available for inducing multistability in a panel can be classified into two categories, viz., mechanical and thermal.

Residual stress can be mechanically induced in isotropic panels using plastic deformation techniques like plastic forming [4], and creating dimples [5] and corrugations [6]. Forcing an initial curvature in a stress-free plate or beam by designing the appropriate boundary conditions results in pseudo-bistable structures [7,8]. Designs with mechanically-induced multistability are compatible with isotropic panels, but the resting shape is sensitive to the actuation force applied.

The most extensively studied multistable behavior involves asymmetric fiber-reinforced polymeric (FRP) laminates which are cured in a pre-impregnated form at high temperature and pressure. This processing ensures geometric precision and optimal strength [9]. Cooling the cured laminates to room temperature results in an intrinsic residual stress induced by a mismatch between the thermal contraction of the matrix and fiber. At room temperature, FRP laminates exhibit two stable shapes that are curved in opposite directions [10]. The magnitude of curvature is primarily influenced by the curing temperature and its direction is governed by the orientation of fiber layers [11–13]. The stable shapes of an asymmetric FRP laminate can be augmented by sandwiching an isotropic core [14]. Daynes et al. [15] selectively applied mechanical prestress to fiber layers to create a buckled region in the laminate in order to achieve symmetric curvatures. Li et al. [16] developed hybrid symmetric laminates without the need for a buckled region by including two symmetric metallic layers whose thermal expansion coefficient is much higher than that of the fibers and the matrix. In laminates with thermally induced bistability, the presence of a continuous matrix material results in fully coupled shapes at room temperature, leaving little scope for tailoring individual shapes. By virtue of the thermo-mechanical process involved in fabricating

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FRP laminates, they are sensitive to operating temperature and humidity [17].

This paper presents a room temperature-cured asymmetric bistable laminate with stable shapes that are analogous to those of an asymmetric FRP laminate (Fig. 1). The laminate consists of a stress-free isotropic core sandwiched between two mechanically-prestressed elastomeric matrix composites (EMCs). EMCs are fiber-reinforced elastomeric layers that are intrinsically anisotropic. In the proposed laminate, they are thin elastomeric strips reinforced with fibers oriented along the width in order to achieve near-zero in-plane Poisson's ratio [18]. Chillara et al. [19] demonstrated that a cylindrical curvature can be created in an isotropic plate by bonding it to an EMC that is mechanically-prestressed in the matrix-dominated direction. The resulting geometry is such that the prestressed EMC is on the concave face. Two prestressed EMC strips are aligned with fibers in the 90° and 0° orientations and are bonded on opposite faces of the core to form a bistable laminate (Fig. 1 (a)). The stable cylindrical shapes in this configuration have curvatures that are 90° apart (Fig. 1(b) and (c)).

When the modulus of the core is much higher (10^3 times) than the modulus of an EMC in the prestressed direction, a weakly-coupled condition is possible, where the stable cylindrical shapes are independent of the prestress in the EMC on the convex face. This condition exists when the relative angle between two transversely-reinforced EMCs is 90°. Only the EMC on the concave face is associated with curvature since the orthogonal EMC (on the convex face) has near-zero in-plane Poisson's ratio. Therefore, it is possible to tune each shape independently during laminate fabrication by varying the prestress in the corresponding EMC. The magnitude of each curvature depends on the modulus and thickness of the core, and the width of each EMC. The width of an EMC is restricted to a fraction of the core width since the fibers in the EMCs can have a modulus comparable to that of the core and therefore restrict curvature in the laminate.

Varying the relative angle between the two EMCs results in complex laminate shapes consisting of twist and curvature. The proposed bistable laminate design offers opportunities for the control of motion and vibration of a continuous surface through the incorporation of localized bistability. Also, the prestressed EMCs serve as damping elements that suppress vibrations persisting after snap-through from one shape to another. Mechanically-prestressed bistable laminates are fabricated at room temperature and their performance is expected to be insensitive to temperature and humidity variations.

A nonlinear analytical laminated-plate model inspired by the model for thermally cured bistable laminates by Hyer [20] is developed to calculate the stable shapes of a mechanically-prestressed bistable laminate (section 2). A Lagrangian strain formulation based on classical laminate plate theory is used to describe the laminate in a large deflection context. Large prestrain applied to a hyperelastic material such as an EMC requires the incorporation of material and geometric nonlinearities in the model [21]. The stable shapes of a bistable laminate are computed as a function of prestress in each of the EMCs. A fabrication method is presented and laminate samples with various magnitudes of EMC prestrain are fabricated for model validation (section 3). The calculated stable shapes of the laminate are in accordance with the measured shapes (section 4). A model-based parametric study is conducted to determine the effects of parameters such as the ratio of EMC width to core width, core modulus, core thickness, and laminate size (section 5). The response of the laminate during shape transition is measured using a motion capture system (section 6).

2. Analytical model

The equilibrium shapes of an asymmetric mechanically-prestressed bistable laminate can be calculated analytically by minimizing its total potential energy to obtain the coefficients of the assumed strain and displacement functions. Hyer [20] presented an analytical model based on energy minimization to calculate the room temperature shapes of thermally-cured asymmetric laminates. In-plane strain functions were assumed to be polynomials of second degree containing only the terms with an even power. Dano and Hyer [22] improved this model using third degree polynomials for strain and proposed a method for the computation of in-plane shear strain from axial strains. However, the snap-through phenomenon and certain bistability effects could not be accurately estimated with this model. Pirrera et al. [23] developed higher order models to accurately reflect the geometric nonlinearity in slender laminates (high aspect ratio); the multi-event snap-through phenomenon, experimentally observed by Potter et al. [24], was explained using 11th degree polynomials.

Hyer's model was successfully employed as the basis for the development of thermally-cured bistable laminate designs like adaptive [25], symmetric [15], anti-symmetric [26], and unsymmetric metal-hybrid laminates [27]. In these designs, the thermal input applied to the laminate is linearly related to strain through the coefficient of thermal expansion of the constituent layers. The model for a mechanically-prestressed bistable laminate incorporates the nonlinear mechanics of a hyperelastic material such as a prestressed fiber-reinforced elastomer (Fig. 2). The detailed

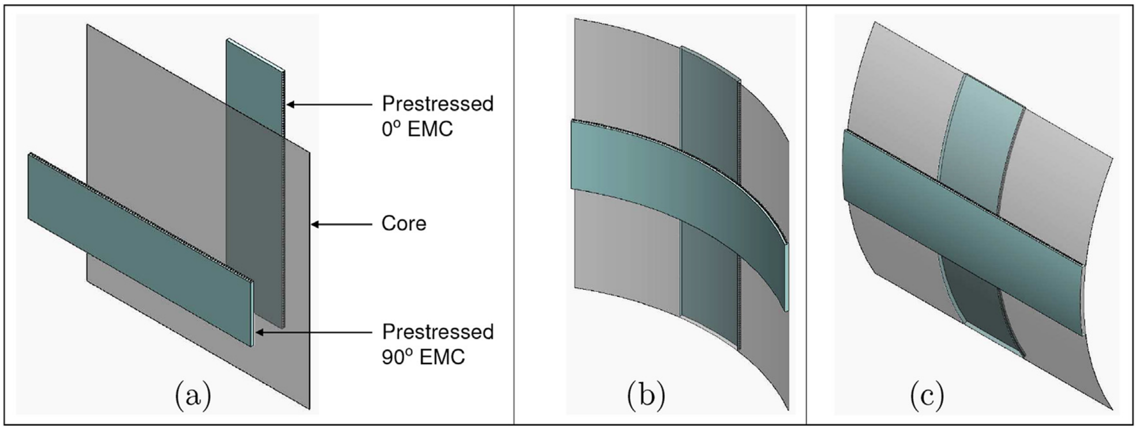

Fig. 1. (a) Configuration of a mechanically-prestressed bistable laminate, (b) curved laminate due to a deformed 90° EMC, and (c) curved laminate due to a deformed 0° EMC.

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