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Bistable hybrid symmetric laminates

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ABSTRACT

Bistable laminates with unsymmetric lay-ups have been studied extensively. In this work a novel type of bistable hybrid laminate with symmetric lay-up is presented. The two stable configurations of the bistable hybrid symmetric laminate are doubly-curved. The two stable configurations have identical curvatures with opposite signs. The bistability of hybrid symmetric laminates derives from the thermal strain mismatch between the metal ply and the 0° composite ply. Finite element analyses (FEA) are performed using ABAQUS and results are compared with a new analytical model which employs piecewise continuous displacement functions. Two bistable hybrid symmetric laminates are manufactured and the stable configurations are measured in experiments. Both FEA and analytical results match experimental results reasonably well. In addition, the influences of various laminates' lay-ups, dimensions and material properties are investigated to gain a thorough understanding of the bistable characteristics of bistable hybrid symmetric laminates (BHSLs).

1. Introduction

The interest in bistable or multistable structures arises due to their ability to sustain significant changes in shape without a continuous power supply. Recent studies illustrate that multistable structures provide a solution to the problems of mass penalties and high maintenance costs of mechanical deployable devices. These advantages offer potential for multistable structures in deployable and morphing structures [1–3].

Bistability or multistability can be achieved by a variety, or combination, of means such as residual thermal stress [4–11], curvature effects [12–17], boundary conditions [18], mechanical connections [19–21] and prestress [22,23]. The residual thermal stress method exploits the thermal stress in the structure and has already been extensively studied for more than 30 years. In recent years, curvature effects, pinned boundary conditions, mechanical connections as well as prestress have also been shown to be effective methods to achieve bistability or multistability. Guest and Pellegrino proved that cylindrically curved strips are bistable when made from anisotropic materials such as composites [17]. Brinkmeyer et al. recently put forward the concept of pseudo-bistable which relies on curvature and viscoelastic effects [13,14]. Coburn et al. show that an orthotropic doubly-curved shell exhibits tristability [15]. Eckstein et al. experimentally and analytically studied a cross-ply laminate with initial curvature, and found that the laminate exhibits multistability at different temperatures [16]. Daynes et al. proposed a bistable composite air inlet structure by carefully designing the pinned boundary condition [18]. Dai et al. achieved tristable and multistable structures by connecting bistable structures together [19–21]. By adding prestress to the symmetric laminate before curing, Daynes et al. showed that symmetric laminates may buckle and have two stable configurations [22].

Up until now, most of the studies concerning bi-stable structure were based on residual thermal stress within composite laminates generated from unsymmetric lay-ups. Early in the 1980s, Hyer found that the $[0_n/90_n]_T$ laminates exhibit two stable cylindrical states instead of the saddle shape predicted by the Classic Lamination Theory [4]. The configurations of such unsymmetric composite laminates are illustrated in Fig. 1, where (a) shows the saddle configuration predicted by Classic Lamination Theory and (b) and (c) show the two cylindrical stable configurations. Later, it was analytically and experimentally shown by Hyer that the bistability of such unsymmetric laminates is due to geometrical nonlinearity and resultant unsymmetric residual thermal stresses [4,6]. To predict both cylindrical configurations, Hyer extended classical lamination theory to include effects of geometric nonlinearity. By using assumed displacement functions in conjunction with a Rayleigh–Ritz minimization of the total potential energy, Hyer's model predicts the overall shape of stable configurations of square cross-ply composite laminates well [5,6].

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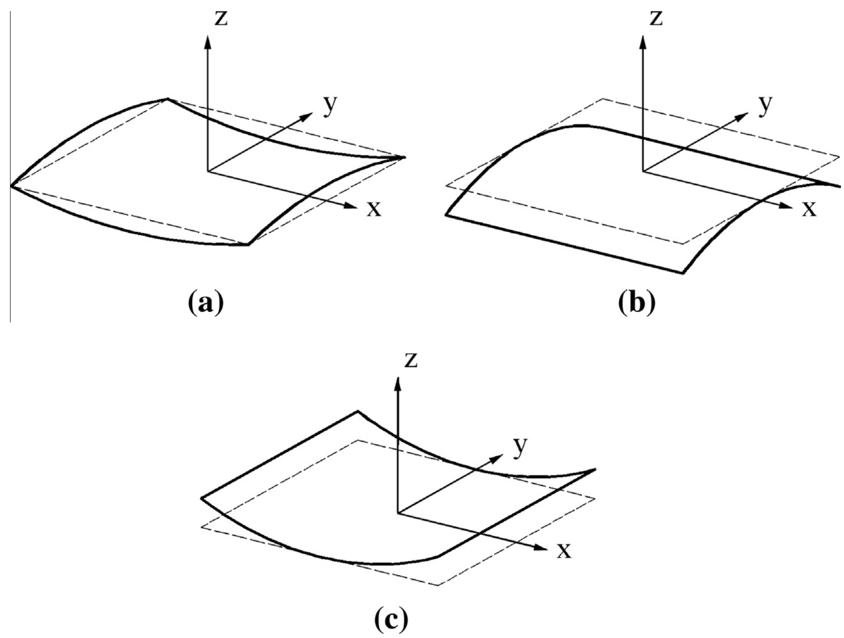

Fig. 1. Basic configurations of bistable cross-ply laminates: (a) unstable saddle configuration, (b) stable cylindrical configuration, (c) the second stable cylindrical configuration.

Later work by Daynes et al. indicates that a symmetric composite laminate can buckle and have two stable configurations if the central region is compressed by the side regions. In their study they accomplished this goal by adding prestress to the side regions before curing [22]. A disadvantage of prestressing the symmetric composite laminates is the requirement for a special prestressing technique throughout the curing process. As a result, the manufacturing process is complicated and it is difficult to assure laminate quality. Inspired by the prestress method, the current study presents a new type of hybrid symmetric composite laminate which also has two stable configurations. This bistable laminate is termed as BHSL (bi-stable hybrid symmetric laminate) in this study. The lay-up of a BHSL is illustrated in Fig. 2, which is $[90_n/\mathrm{Al}/90_n]_T \cup [90_n/0_m/90_n]_T \cup [90_n/\mathrm{Al}/90_n]_T$. The two rectangular side regions of the middle ply are aluminum plies with thickness identical to the 0° ply. The manufacturing process of BHSLs is similar to the bistable unsymmetric laminates. As the thermal expansion coefficient of aluminum is much higher than that of carbon fiber, the aluminum ply shrinks much more than the 0° ply when the laminate cools down to room temperature. Consequently, the aluminum ply is stressed in tension and imposes compressive stress to the 0° ply. The stable and unstable configurations of a BHSL are presented in Fig. 3 where (a) shows the unstable flat configuration, and (b) and (c) are the stable cylindrical configurations. In the current work, BHSLs are first analyzed by the finite element method, and the basic distinguishing characteristics of BHSLs are presented. Subsequently, a simple analytical shape prediction model using assumed piecewise displacement functions and Rayleigh–Ritz minimization of the total potential energy is established. The FEA and analytical data are validated by experimental results of two specimens. Further, FEA and the simple analytical model are used to investigate the bistable characteristics of BHSLs via changing the geometric dimensions, lay-ups and material properties.

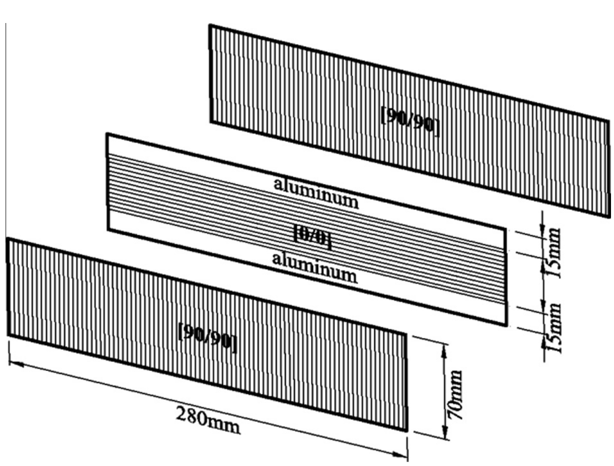

Fig. 2. Symmetric stacking sequence $[90_2/\mathrm{Al}/90_2]_T \cup [90_2/0_2/90_2]_T \cup [90_2/\mathrm{Al}/90_2]_T$ of a BHSL.

2. Finite element analysis

To understand the basic characteristics of BHSLs, a FEA is done with the lay-up $[90_2/\mathrm{Al}/90_2]_T \cup [90_2/0_2/90_2]_T \cup [90_2/\mathrm{Al}/90_2]_T$ using commercial finite element code ABAQUS. The dimensions of the FEA model is 280 mm × 70 mm, and the dimension of each aluminum ply is 280 mm × 15 mm. The material properties used are listed in Table 1.

In FEA the shell element S4R (4-node general-purpose shell, reduced integration with hourglass control, finite membrane strains) is employed. The FEA model is meshed by 784 square shell elements. Large deformation effects are considered. The model is clamped at the center point. First, a temperature field reflecting the elevated curing temperature is applied to the FEA model in the initial step. Subsequently, the temperature of the model decreases to the room temperature in the first "Static" analysis step. The temperature gradient ΔT is −120 °C. As the FE model captures ideal response, the FEA predicts a flat configuration as illustrated in Fig. 4(a). In which, the contour map is the stress σ_x^0 at the middle plane. It shows that the side of the laminate, i.e. hybrid area, is in tension while the central area is in compression. The underlying reason for this is that the thermal expansion coefficient of the aluminum ply is much larger than the 0° composite ply in