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Effect of initial tool-plate curvature on snap-through load of unsymmetric laminated cross-ply bistable composites

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ABSTRACT

In this study, the effect of the initial curvature of a tool plate on the snap-through load of square cross-ply bistable composites was analyzed. The snap-through load is a function of the cured curvature and residual moment. In the curing process, both these physical quantities are affected by the initial tool-plate curvature. As a result, the snap-through load can also be changed by adjusting the initial tool-plate curvature. Then, for evaluating its effect on the snap-through load, a snap-through process was simulated by minimizing the total potential energy of the bistable composites through the Rayleigh–Ritz approximation method. The simulation results show that the snap-through load changes linearly with the initial tool-plate curvature. The simulation results are compared with those obtained experimentally and by a finite element analysis (FEA) in order to verify the pre-identified effect of the initial tool-plate curvature.

1. Introduction

Bistable composites have two stable shape (cylindrical shapes [1–7] or saddle shapes [8]) as a result of the coupling effect between their residual stress and geometric nonlinearity. These composites can be snapped through (i.e. from one stable shape to the other at a specific mechanical load) [9–11]. During this snap-through action, a large out-of-plane deflection occurs at a fast time scale with respect to quasi-static phenomena. After snap-through, the bistable composites remain in a stable state without requiring any additional energy supply to maintain a constant shape. Owing to these interesting properties, bistable composites have attracted research attention in the fields of aerodynamics, energy harvesting and robotics for developing a high-energy-efficiency morphing structure or device [12–21].

In the field of aerodynamics, the concept of a morphing airfoil was proposed on the basis of bistable composites [12–16]. Furthermore, analytical models were developed to design and control the morphing airfoil based on bi-stable composites [17,18]. Further, in the field of energy harvesting, an energy harvesting device was first developed by combining bistable composite plates with a piezoelectric patch for effective energy harvesting and subsequently analyzed [19,20]. In the field of biomimetics, a flytrap-inspired robot was developed by employing a cross-ply laminated bistable composite. This robot was found to well mimic the prey capture behavior of the Venus flytrap owing to the snap-through action of the bistable composite [21].

Generally, morphing structures such as a morphing wing or a flytrap-inspired robot require different stable shapes and different structural stabilities depending on the circumstances (e.g., the flight condition or the open and closed states of a flytrap) [13,17]. For this reason, the cured curvatures or the snap-through load of bistable composites should be adjusted differently in each stable state depending on the design requirement.

Unfortunately, this adjustment is not easy to perform, because unsymmetric cross-ply laminates are ordinarily cured on a flat tool plate. Moreover, if the laminates have an alternating layers of orthotropic laminae with equal thickness and identical material properties on both sides of the mid-plane axis, e.g., [90°/0°], [90°/0°/90°/0°], or [90°/90°/0°/0°], the cured curvatures of both the stable states are forced to be identical to each other, and so are the snap-through loads of these states.

Although the desired result is expected to be obtained by the modification of the lay-up sequence of laminates, e.g., [90°/90°/90°/0°/0°], this approach results in alteration of other design-dependent variables (e.g., the thickness and stiffness of laminates). As a result, this design approach of bistable composites results in a structurally overweight or a mechanically over-stiff composite. Therefore, to be able to apply the design of bistable

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composites more flexibly to morphing structures, it would be desirable to consider a method for adjusting the cured curvature or the snap-through load while minimizing the change in the design-dependent variables.

Several strategies were introduced to address this problem. These can be categorized into three strategies. One strategy is to connect the different angle-ply laminated composites with each other in parallel or series [22–24]. From this strategy, the multi-stable shape of bi-stable composite was attained and controlled without changing the thickness of composite. Another strategy is to prestress the selected plies of symmetric laminates before curing process by means of the specifically manufactured prestress machine [25,26]. The snap-through load and curvature of the symmetric laminated composites was tailored by unsymmetrically prestressing on the basis of the neutral axis. Other approach is to apply an initial curvature to unsymmetric laminated composites by using an initially curved tool plate [5,27]. In this approach, the initial curvature of the tool plate affects the cured curvature while keeping the thickness and stiffness of the composites.

Although the previous paper [5,27] did not focus on the snap-through load, it is an important design factor in the practical application of morphing structures that are based on the snap-through action of bistable composites. Accordingly, in addition to curvature tailoring, the snap-through load of bistable composites also needs to be adjusted.

On the basis of the logic explained below, we expect that the snap-through load can be adjusted by tailoring the initial tool-plate curvature. The initial tool-plate curvature affects the cured curvature; this cured curvature is closely related to the bending deformation energy of the bistable composite, which is required to be supplied until a snap-through occurs. Consequently, because the snap-through load is also related to the bending deformation energy, this load will also be affected by a change in the cured curvature induced by a change in the initial tool-plate curvature.

If the effect of the initial tool-plate curvature on the snap-through load can be evaluated, the snap-through load of bistable composites could also be adjusted to meet various design requirements. Then, it would be possible to effectively apply bistable composites as morphing structures, which require different structural shapes and different structural stabilities depending on the circumstances. The present study therefore aims to estimate the effect of the initial tool-plate curvature on the snap-through load of unsymmetric cross-ply laminated composites. First, a snap-through process is simulated by minimizing the total potential energy of the square cross-ply bistable composites, by employing the Rayleigh–Ritz approximation method. The simulation results show that the snap-through load changes linearly with the initial tool-plate curvature. These results are compared with those obtained experimentally and by a finite element analysis (FEA) in order to validate the pre-identified effect of the initial tool-plate curvature on the snap-through load.

2. Snap-through of bistable composite and its driving mechanism

Two stable shapes of the square cross-ply bistable composite are defined as Mode 1 and Mode 2 depending on the orientation of the curvature of the bistable composite with respect to the initial tool-plate curvature, as illustrated in Fig. 1. Specifically, Mode 1 is defined as a cylindrical shape in which the dominant curvature is parallel to the initial tool-plate curvature, i.e., the x-directional curvature κ_{xx}. On the other hand, Mode 2 is defined as a cylindrical shape in which the dominant curvature is perpendicular to the initial tool-plate curvature, i.e., the y-directional curvature κ_{yy}.

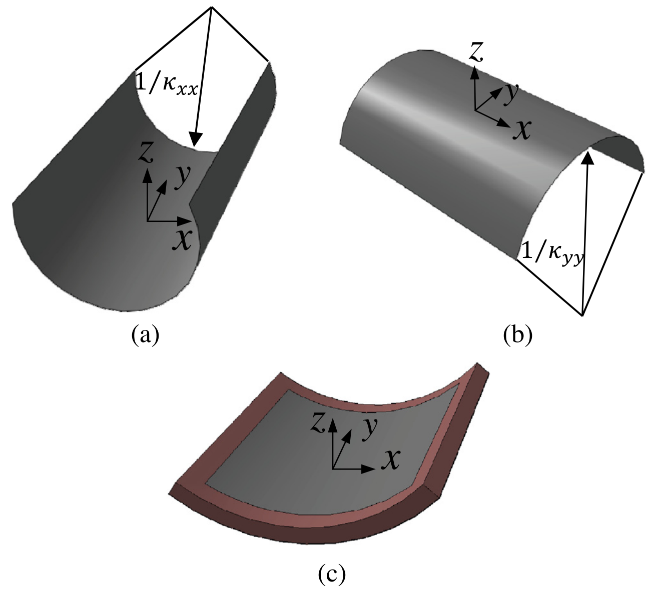

Fig. 1. Two stable configurations of square cross-ply bistable composites: (a) Mode 1: $\kappa_{xx} > 0$, $\kappa_{yy} \approx 0$; (b) Mode 2: $\kappa_{xx} \approx 0$, $\kappa_{yy} < 0$; and (c) tool plate: $\kappa_{xx} \neq 0$, $\kappa_{yy} = 0$.

The snap-through process is separately categorized into a snap-forth process and a snap-back process depending on the sequence of mode change. Specifically, snap-forth refers to snap-through from Mode 1 to Mode 2, and snap-back refers to snap-through from Mode 2 to Mode 1, as illustrated in Fig. 2.

In order to induce snap-through, a mechanical load should be applied with the aim of unrolling the bistable composite. For example, if an x-directional moment is applied to the bistable composite in Mode 1, it will just unroll while maintaining the x-directionally curved cylindrical shape at the beginning of deformation. However, when the dominant curvature of the bistable composite reaches a certain x-directional deformation curvature (henceforth referred to as the "snap-forth starting curvature"), the composite starts transforming from Mode 1 to Mode 2 (i.e., snap-forth) by itself. In other words, at the snap-forth starting curvature, the direction of the dominant curvature starts changing from the x-direction to the y-direction, which is perpendicular to the direction of the external moment and direction of the dominant curvature.

In order to explain the above phenomenon, we make the following two assumptions:

1. A driving mechanism exists that is acting perpendicular to the direction of the dominant curvature of each mode.
2. The snap-through starting curvature is the minimum or critical curvature at which the driving mechanism is sustained.

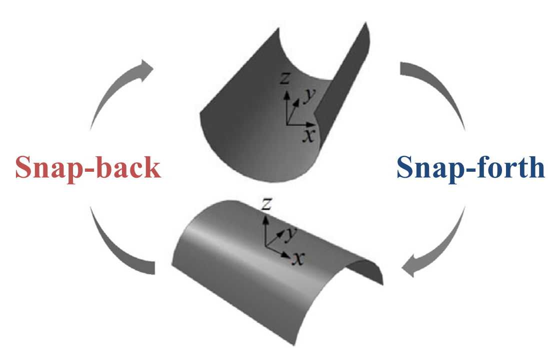

Fig. 2. Schematic of snap-forth and snap-back processes.