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A novel design method of bistable structures with required snap-through properties

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ABSTRACT

To simplify the design process characterized by complex computation and repeated tests for pre-compressed bistable structures, a novel method is proposed for quickly designing bistable structures with required snap-through properties. The bistable structures are pre-compressed arch-shaped beams with local reinforcements, which are formed through axially compressing the corresponded straight beams into post-buckling states. The post-buckling shape, inertial stress state and the required snap-through properties such as the snapping force, the maintaining force and the snapping distance, can be well controlled by adjusting the control parameters including the position and dimensions of local reinforcements and the compressed length of the beam. Based on the finite element method, the relationship between the snap-through properties and the control parameters is numerically analyzed. Furthermore, the model spectrum describing the variation of snap-through properties with control parameters is delineated. By traversing the model spectrum, all design schemes can be obtained for achieving desired bistable properties, which greatly enlarges the design domain for pre-compressed bistable structures. A design example is provided to illustrate the utility of the method of designing a bistable structure with required snap-through properties. Meanwhile, the manufacturability of the designed bistable structure is taken into account. The experimental results show that the measured snap-through properties are in good agreement with the design objectives, which sufficiently validates the effectiveness of the proposed design method.

1. Introduction

Bistable structures are extensively used in industrial devices, such as switches [1,2] which sizes can vary from the macro-world to the micro-world [3], constant-force mechanisms [4–6] taking full advantage of negative stiffness characteristics of bistable configurations, energy harvesting devices [7–11] transforming ambient kinetic energy into electric power, actuators [12–16], and positioners [17]. Furthermore, the attractive characteristics of bistable structures include less power consumption [18], increased reliability, the precise positioning, structural simplicity [19], chaotic behavior [20,21], negative extensibility [22], etc.

Snap-through properties of bistable structures, mainly including the snapping force, the maintaining force and the snapping distance from one steady state snapping to another, are significantly dependent on many factors, such as the section shape, pre-compression [23], the actuation position [3], the apex height, boundary conditions [24] and the internal stress of the curved beams. Because of the complex coupling relationships between snap-through properties and influencing factors, it is often difficult to design a bistable structure with required snap-through properties. Thus, how to efficiently design and fabricate bistable structures with required properties has become an urgent problem in engineering applications.

Many efforts for designing bistable structures have been done, among them, one important type of bistable structures is based on the pre-shaped and/or pre-compressed beams [23–32]. For examples, based on the relationships between the axial force, the axial displacement and the apex height in [23,25,26], pre-compressed bistable beams with uniform section are designed. Wu et al. [27] proposed a design criterion of a V-shaped bistable beam to investigate if the bistability can occur. Vangbo [28] theoretically analyzed bistable mechanics of a compressed bistable buckled beam for modeling the snap-through of a double-clamped bistable beam. Based on the generalized variation principle and meromorphic function method, Zhao et al. [29] modified the analytical solution of the snapping force in [28], improving the accuracy. Cazottes et al. [3] explored the influence of the actuation position on the snap-through of a pre-compressed bistable beam, and results showed a shifted actuation caused difficulties for a monolithic design. Huang

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et al. [30] modified local segment's geometry of a pre-shaped bistable beam for optimizing the ratio of the snapping force and the maintaining force. Aiming at the pre-shaped bistable configurations with the equal section, Qiu et al. [31] proposed the analytical solution of the lateral force and the center deflection in the case of neglecting higher modes, which was developed in [32]. Rafsanjani et al. [33] analyzed the effects of the snap-through instabilities on the tensile stress–strain curve of the proposed mechanical metamaterial comprising the bistable mechanism in [32]. The above contents illustrate that the snapping force, the maintaining force and the snapping distance are determined by the shape and the pre-stress distribution of the bistable structures, and it is a challenge to exactly control the pre-stress distribution in fabricating bistable structures. Besides, owing to the complex non-linear relationship between snap-through properties and the influence factors, it is also difficult to efficiently obtain bistable structures with required snap-through properties.

In this paper, a novel method is presented for designing and fabricating the bistable structures with required snap-through properties. The bistable structures are pre-compressed arch-shaped beams with local reinforcements, which are formed through compressing the corresponding straight beams into post-buckling state. The required shape and pre-stress distribution of the beams are exactly controlled through the post-buckling states. The post-buckling states are adjusted through the compressed length of the beam and the position and sizes of the local reinforcements. The rest of this paper is outlined as follows. In Section 2, the configuration of the bistable structure is proposed and the fabrication process is introduced. Then, in Section 3, the mechanical model of the proposed bistable structure is presented for analyzing the snap-through properties. In Section 4, the novel design method of bistable structures with required snap-through properties is put forward. In Section 5, the design and fabrication process of a design example is illustrated in detail, and the snap-through properties of the designed bistable beam are verified by the experiment. In the last section, some conclusions are summarized.

2. Configuration design and fabrication process

The configuration of the bistable structure proposed in this paper is a pre-compressed arch-shaped beam with local reinforcements, as shown in Fig.1. The snap-through properties can be adjusted through cooperatively controlling the position x_0 and sizes (length l_0, width w_0 and thickness t_0) of the local reinforcements and the axial compressed length, namely, the pre-compressed length ΔL, shown in Fig. 2. Under the action of the lateral force F, the designed bistable beam can jump to the second steady-state position from the first steady-state position.

The proposed bistable structure is formed through axially compressing a straight beam with local reinforcements shown in Fig. 2(a) into the post-buckling state in Fig. 2(b). The span $\bar{L}$ of the designed bistable structure is determined by the pre-compression ΔL adjusted to achieve the required snap-through properties.

In Fig. 2, W denotes the width of the basic beam. T and t_0 are the thickness of the basic beam and the local reinforcement, respectively. H_s is the apex height. In fact, the snapping distance is equal to $2H_s$. Thus, the apex height H_s can be used as the description of the snapping distance property.

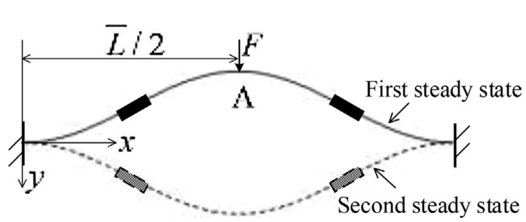

Fig. 1. The proposed bistable structure subjected to the actuation force/transverse force F at the midpoint A.

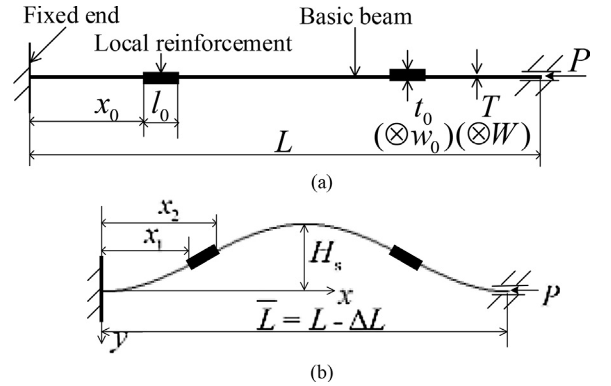

Fig. 2. The fabrication process: (a) an axial force P is applied to the end of a straight beam with symmetrical local reinforcements, (b) the post-buckling deformation of the beam.

3. Snap-through analysis

3.1. Mechanical model and control equation

According to Figs. 1 and 2, the equilibrium equation of a pre-compressed bistable beam with local reinforcements satisfies:

$$EI_z(x)w^{(4)}(x) + Pw''(x) = F\delta(x - \bar{L}/2)(0 \le x \le \bar{L}) \quad (1)$$

where $w(x)$ is the deflection of the beam; $\delta(x)$ is Dirac delta function; E is the Young modulus; $\bar{L}$ is the span of the bistable beam and $\bar{L} = L - \Delta L$; $I_z(x)$ is the beam's inertial moment, written as

$$I_z(x) = \begin{cases} \dfrac{Wt_0^3}{12} x \in [x_1, x_2] \cup [\bar{L} - x_2, \bar{L} - x_1] \\ \dfrac{WT^3}{12} x \in [0, x_1) \cup (x_2, \bar{L} - x_2) \cup (\bar{L} - x_1, \bar{L}] \end{cases} \quad (2)$$

where, x_1 and x_2 can be obtained by deformation coordination equations, expressed as

$$x_0 - \frac{Px_1}{EWT} = \int_0^{x_1} \sqrt{1 + [w'(x)]^2} dx \quad (3)$$

$$l_0 - \frac{P(x_2 - x_1)}{Ew_0t_0} = \int_{x_1}^{x_2} \sqrt{1 + [w'(x)]^2} dx \quad (4)$$

The boundary conditions of the fixed-fixed bistable structure are

$$\begin{cases} w(x)|_{x=0} = w(x)\big|_{x=\bar{L}} = 0 \\ w'(x)|_{x=0} = w'(x)\big|_{x=\bar{L}} = 0 \end{cases} \quad (5)$$

When P is applied to one end of the beam, the shorten length of the beam d_p is

$$d_p = \frac{P\bar{L}}{EWT} + \frac{2P(x_2 - x_1)}{E}\left(\frac{1}{w_0t_0} - \frac{1}{WT}\right) \quad (6)$$

and another deformation coordination equation is

$$L - d_p - \int_0^{\bar{L}} \sqrt{1 + [w'(x)]^2} dx \approx (\Delta L - d_p) - \frac{1}{2}\int_0^{\bar{L}} [w'(x)]^2 dx = 0 \quad (7)$$