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A novel gardenia-shaped structure materials with variable stiffness under elastic tension

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ABSTRACT

Nature's creatures often have unique behaviors that have inspired humans to create many bionic structures to meet engineering needs. In previous work, we reported a Gardenia-shaped structure (GSS) materials. Then an optimal GSS materials is developed in this paper. The optimal GSS materials shows its easily available variable stiffness characteristics from the testing in the homemade experimental bench. The variable stiffness characteristics of the optimal GSS materials were investigated by using both experimental and finite element methods in this paper. The experimental results show good agreement with the numerical results. The excellent performance of the optimal GSS materials has the potential for engineering applications to meet multi-stiffness requirements.

1. Introduction

The extraordinary physical properties of metamaterials have attracted scholars from all over the world [1]. They tend to have higher strength, lighter mass, and excellent energy absorption properties [2]. The negative Poisson's ratio (NPR) [3] and the zero Poisson's ratio (ZPR) [4–6] are representatives of the many properties of metamaterials. When the NPR material is compressed along the longitudinal direction, the transverse direction will shrink rather than expand. When ZPR materials are compressed, their transverse dimensions remain in their initial state and do not shrink or expand. The special properties of metamaterials have a good potential for engineering applications. They are also widely used in research in the fields of mechanics [7], acoustics [8], and optics [9].

The variable stiffness properties of metamaterials have also received scholarly attention. Leissa and Martin [10] first introduced the concept of variable stiffness. Waldhart [11] analyzed the buckling and in-plane response of variable stiffness plates. Gupta and Pradyumna [12] investigated the geometrically nonlinear dynamics of variable stiffness composite laminates (VSCL) and sandwich shell plates. The nonlinear dynamic behavior of VSCL and sandwich shell plates was investigated for the first time.

This paper is a further study of the GSS materials, that have been investigated through experimental and FE methods. Interestingly, we find that the optimal GSS materials has easily available variable stiffness characteristics and has the potential for engineering applications to meet multi-stiffness requirements.

2. Material and methods

2.1. Structure origin

In previous work, we proposed a structure similar to the gardenia by mimicking the gardenia, as shown in Fig. 1(a) [13]. We found that the GSS materials has good deformability and a zero Poisson's ratio effect. In subsequent work, we have designed an optimal GSS materials with easily available variable stiffness characteristics and derived the Young's modulus equation (Supplementary), as shown in Fig. 1(b). We have changed the rules of variation of the originally given structural parameters, initially, the GSS materials always remained three-axis symmetric and now the GSS materials always remains biaxially symmetric. In Fig. 1(b) the yellow dots remain unchanged and the GSS

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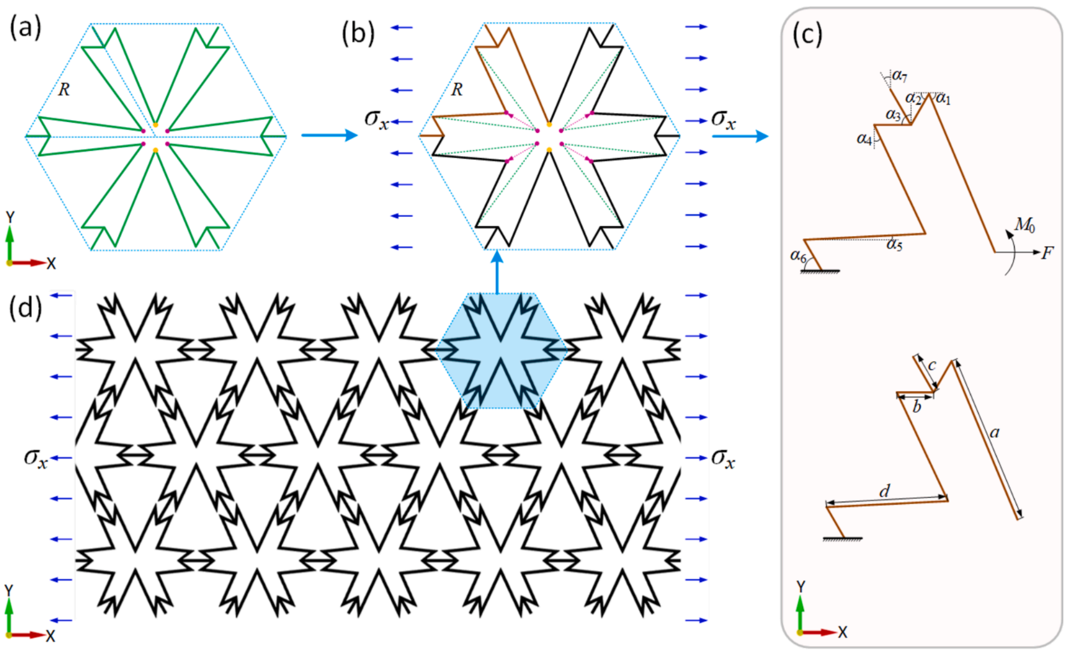

Fig.1. Schematic of the (a) GSS unit cell [13]; (b) an optimal GSS unit cell; (c) the geometric parameters of GSS; (d) array rules.

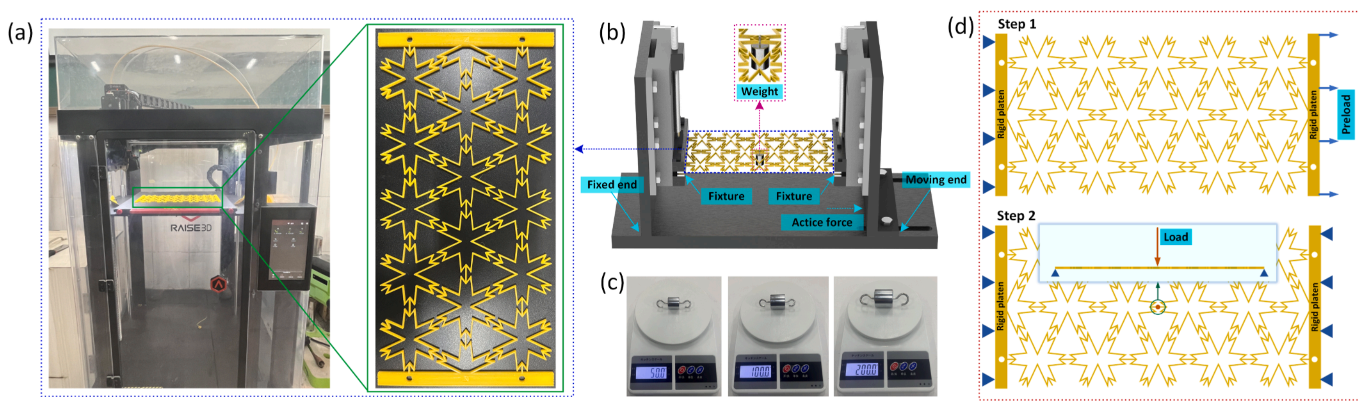

Fig. 2. (a) Model printing process; (b) the homemade experimental bench; (c) weights; (d) boundary setting steps in FE.

materials is changed by moving the red dots. According to the symmetry of the structure, the cell of 1/4 and its geometrical parameters are shown in Fig. 1(c). The array rules for the GSS materials are shown in Fig. 1(d).

2.2. Fabrication, experiments and simulations

In this paper, the sample is produced by the fusion deposition modeling (FDM) 3D printing method, with polylactic acid (PLA) as the processing material for print production. PLA has Young's modulus of about 3.23GPA and the Poisson's ratio is 0.33 [14]. The printer used is Raise3D pro2 plus, as shown in Fig. 2(a). Fig. 2(b) shows a rendering of the experimental stand. The two ends of the sample shown are fixed by the fixture. The left end of the fixture is the fixed end and the right end is the moving end. As shown in Fig. 2(c), the weights used in the experiment are all standard pieces. This paper is simulated using the commercial finite element software HyperWorks (version 2017, Altair Engineering, Inc.). The boundary conditions in FE as shown in Fig. 2(d).

3. Results and discussions

As can be seen in Fig. 3, the numerical and experimental images are deformed in agreement. This paper has conducted four sets of experiments. In each set of experiments, the weight is kept constant and only the preload is increased to raise the stiffness of the sample. In the figure ε_x is the strain when no weights are hung and only the preload is applied. In Fig. 3(a)–(d) when the preload is all 0 N, the maximum displacement of the sample becomes larger and larger as the weight of the weight increases. However, as the preload increases, the stiffness of the sample increases and the maximum displacement of the sample becomes smaller and smaller. At the same time, it is also clear from Fig. 3 that the maximum stress in the sample decreases as the preload increases.

Fig. 4 shows a good agreement between the experimental results and the FE results. Fig. 4(a)–(d) shows that that the maximum displacement of FE and experiment decreases almost linearly as the ε_x increases. When εx reaches 3.8%, the experimental maximum displacements in Fig. 4(a)–(d) are reduced by 60.49%, 59.38%, 55.56%, and 49.62%, respectively. As shown in Fig. 4(e) and (f), when the strain is 0 and the weight is 300 g, the optimal GSS materials is concave down very significantly. When preload is applied to the structure, the optimal GSS materials reaches ε_x of 7.4% and the stiffness increases, at which point it deforms insignificantly.

The variation of the maximum displacement in the experiments and FE reflects the variation in the stiffness of the optimal GSS materials.

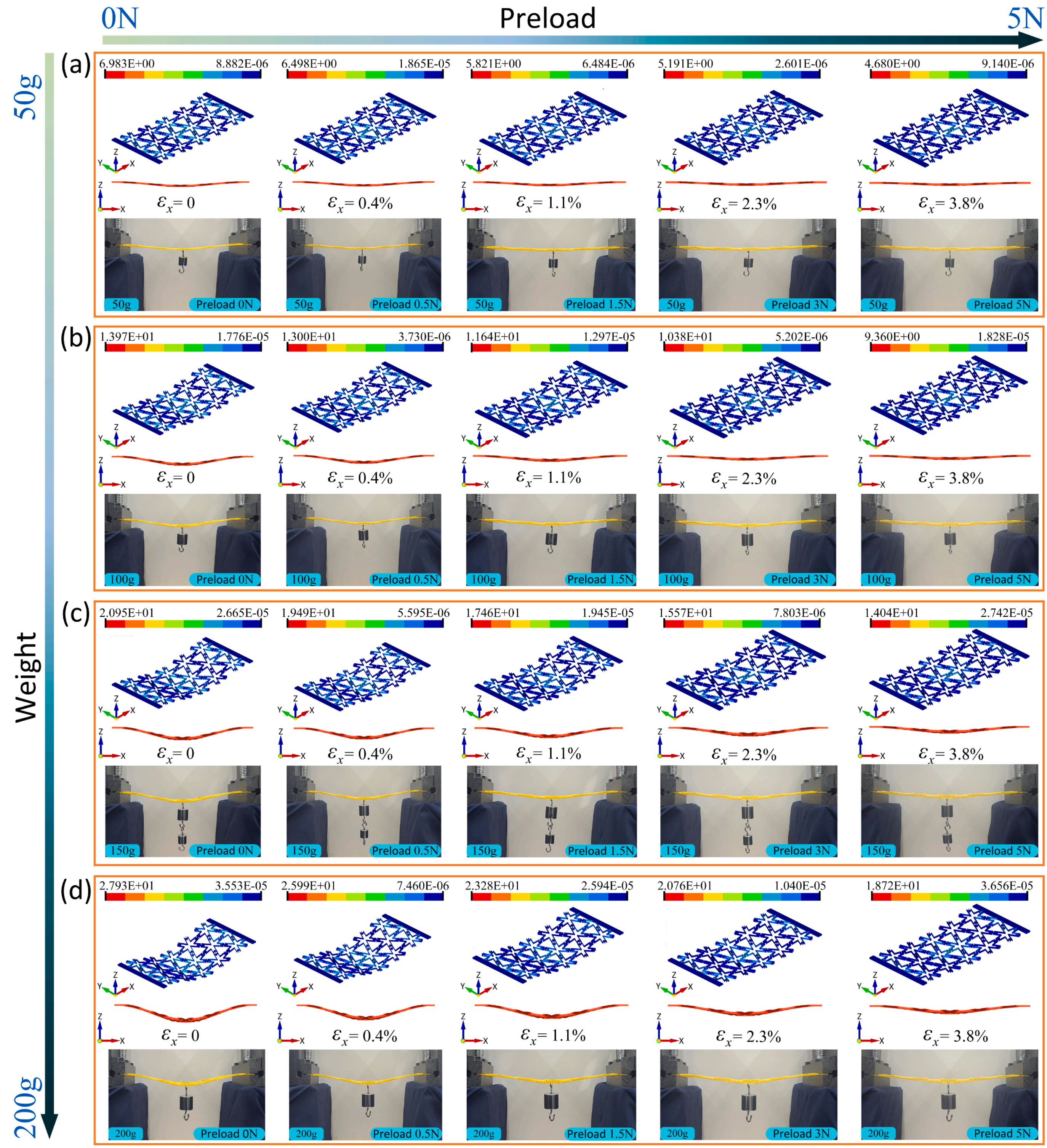

Fig. 3. Schematic diagram of the experiment and numerical deformation of the sample when 0 N < preload < 5 N and the weight = (a) 50 g; (b) 100 g; (c) 150 g; (d) 200 g.

This exhibits the variable stiffness characteristics that are easily obtained with the optimal GSS materials. It can be noted that the maximum displacement in the four sets of experiments decreases almost linearly as ε_x becomes larger, indicating an almost linear increase in the stiffness of the sample. At the same time, the maximum displacement is almost always reduced to as much as two times that at $\varepsilon_x = 0$. It is also found that the variable stiffness characteristics of the sample diminish slightly as the weight becomes greater.

4. Conclusions

In this paper, an optimal GSS materials is proposed and investigated. The variable stiffness characteristics of the GSS within the elastic strain phase are investigated using experimental and FE methods. The accuracy of this study is confirmed by the good agreement between the experimental and numerical results. The following conclusions can be drawn from the present work.

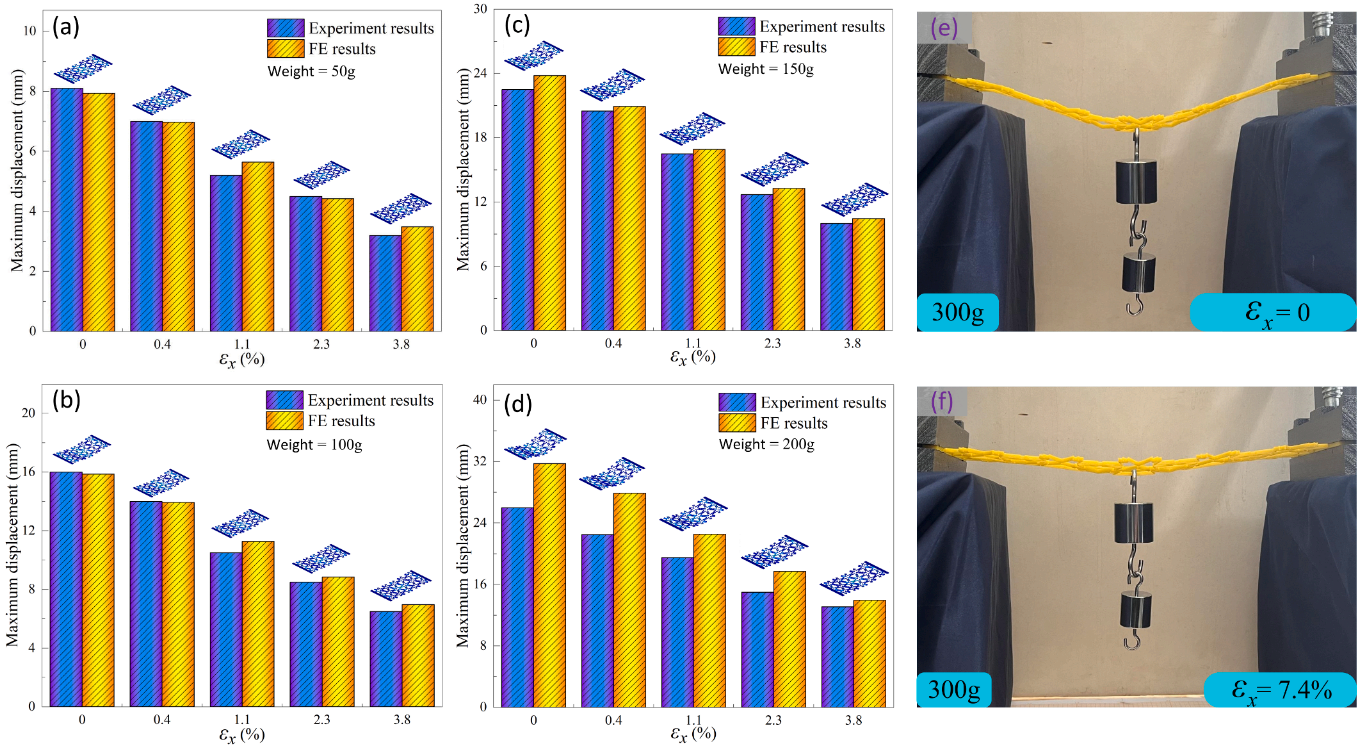

Fig. 4. Comparison of numerical models and experimental predictions of maximum displacement when the weight = (a) 50 g; (b) 100 g; (c) 150 g; (d) 200 g; The deformation when the weight = 300 g and ε_x = (e) 0; (f) 7.4%.

The stiffness of the optimal GSS materials increases linearly with increasing preload, but the maximum stress decreases. In all four sets of experiments, the maximum displacement at $\varepsilon_x = 0$ is almost more than twice as large as at $\varepsilon_x = 3.8\%$. When the preload is increased from 0 N to 5 N, the maximum reduction of the displacement can reach to 60.94%. When the loads are 100 g, 150 g, and 200 g, the maximum displacement is reduced by 59.38%, 55.56%, and 49.62% respectively. And it also demonstrates that the variable stiffness capacity of the optimal GSS materials decreases slightly as the load increases.

This paper presents a detailed study on the variable stiffness characteristics of GSS materials, that have the potential for engineering applications to meet multi-stiffness requirements.

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CRediT authorship contribution statement

Ning Feng: Conceptualization, Writing – original draft, Methodology. **Yuanhao Tie:** Visualization, Methodology, Writing – review & editing. **Shangbin Wang:** Writing – review & editing. **Chongfu Huang:** Methodology. **Liwen Lv:** Methodology, Writing – review & editing. **Weibo Xie:** Conceptualization, Methodology. **Jingze Wang:** Conceptualization, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.matlet.2023.134821.

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