Concepts for morphing airfoil using novel auxetic lattices

Zeyao Chen, Xian Wu*, Zhe Wang, and Jianwang Shao

School of Automotive Studies, Tongji University, China;

+86-138-1650-1824

chenzeyao@tongji.edu.cn (Z.C.); *wuxain@tongji.edu.cn (X.W., corresponding author); wangzhe@tongji.edu.cn (Z.W.); shaojianwang@tongji.edu.cn (S.J.).

Abstract

In nature, the wings shape of a bird can be adjusted to be suitable for all flight situations providing optimal aerodynamic performance. Unfortunately, wings of traditional aircraft are optimized for only a few conditions, not for the entire flight envelope. Therefore, it is necessary to develop the morphing airfoil with smart structures for the next generation excellent aircraft. Combined with the actuators, sensors and controller techniques, the smart airfoil will bring a revolution for aircraft. Hence, the design of smart structure which is applicable for the morphing airfoil is the first step, especially the flexible airfoil which exhibit many more changeable degrees than rigid structures. In this paper, the composite structure based on re-entrant quadrangular is designed to be applied in the deformable aircraft. The re-entrance structure can show negative Poisson's ratio performance, also called auxetic, which can offer a great advantage in morphing mechanism. Based on fundamental work about re-entrant quadrangular lattices, the scheme of morphing airfoil is firstly given. Firstly, as shown in the FFT-based homogenization analysis, the enhanced re-entrant lattice outperforms remarkably the original one in stiffness and have similar flexibility. The mechanical characteristics of morphing airfoil with auxetic lattice core are the focus of our paper, which are investigated by using the finite element model. The design loads are extracted from the aerodynamic loads, which are converted to effective nodal loads distributed in the airfoils. The estimated natural model frequencies are given using the model analysis method, which accords with the limits. Furthermore, the compliance performances of the airfoil are investigated under passive and active morphing respectively. The morphing airfoil with auxetic lattices have the advantages of high deformable, ease of control, variable stiffness, and the ability to bear large amounts of stress. These works offer researchers and designers novel ideas for designing morphing aircraft.

Keywords: Morphing airfoil; re-entrance lattices; Auxetic; Stiffness;

1. Introduction

In the aerospace field, many research on investigating the morphing aircraft to accommodate the complex flight envelopes have emerged in recent years [1]. The idea is inspired by the nature in which bird, fly or bee can adjust the shape of wings for different flying conditions. Morphing structures can expand the flight envelopes with eliminating flap-type mechanisms, reducing aerodynamic drag and controlling vibration [2]. A variety of methods by using special materials and structures have been developed to provide the capability of morphing airfoil. The morphing materials or structures should easily deform when subjected to driving load with low amplitude and carry the aerostatic or aerodynamic load simultaneously [3], and therefore cannot be made by simply using conventional and readily available materials. “Smart” materials and structures with high flexibility including the cellular material have played a significant role in morphing airfoil [4, 5].

Material with negative Poisson’s ratio (NPR), also be named as auxetic material, contracts in compression but expands in tension, which is counterintuitive as most of the natural materials show positive Poisson’s ratio [6]. NPR property has been used to enhanced mechanical properties like resilience [7], crack resistance [8], fracture toughness [9, 10], sound absorption capacity [11]and energy absorption capability [12, 13], etc. When Poisson's ratio approaches -1.0, its bulk modulus is much less than its shear modulus which means the material becomes highly compressible [6]. And, skins with large in-plane Poisson’s ratio would show anticlastic shapes, however, skins with negative in-plane Poisson’s ratio would induce synclastic behavior when bent out of plane [14]. Such characteristics and high strain-energy capability would provide a potential application for morphing structures.

Because of the stiffness and mechanism of cellular materials especially bending-dominated, it is readily applied in morphing structures [15]. A lot of studies about morphing airfoil with cellular material core have been reported [16-19]. The re-entrant hexagonal core shows the highest shear flexibility compare to other cellular materials with positive Poisson’s ratio which have been proposed in [20, 21]. However, there is a dilemma between the high stiffness and flexibility which are necessary for morphing airfoil. Therefore, how to obtain flexibility while maintaining the stiffness to carry load is necessary to be further investigated. There are a lot of research on passive morphing, yet there are few reports about the concept of active morphing using cellular material. In this paper, we introduced the active concept for the morphing airfoil with auxetic lattice core.

The paper is categorized into three sections including this introduction. Section 2 shows the homogenized mechanical properties of re-entrant quadrangular lattice and its enhanced form. Section 3 reports how to construct a morphing airfoil using the auxetic lattice. The morphing properties of an airfoil with auxetic lattice core are investigated in Section 3. Besides the passive morphing properties, the active morphing mechanism also preliminarily discussed in this section. Concluding remarks are finally exhibited in Section 4.

2. The characteristics of re-entrant quadrangle

While designing the morphing structures for engineering, both stiffness and flexibility should be considered, however they are always the conflicting requirements. In this section, the re-entrant quadrangular lattices are investigated whose structures and corresponding unit cell have been depicted in Fig. 1. New developed FFT-based homogenization method was applied to study both cells. From the homogenized computing, the constitutive stiffness matrix C^H can be obtained. Because of the cubic symmetry of these structures, there are only three independent elastic constants in the homogenized elastic tensor presented in the following.

$$C^H = \begin{bmatrix} C_{11}^H & C_{12}^H & 0 \\ C_{21}^H & C_{22}^H & 0 \\ 0 & 0 & C_{33}^H \end{bmatrix} \tag{1}$$

From the stiffness tensor (Voigt matrix notation) C, the shear modulus and bulk modulus can be derived as following considering the symmetry of the matrix:

$$G^H = C_{33}^H \tag{2}$$

$$S^H = \begin{bmatrix} S_{11}^H & S_{12}^H & 0 \\ S_{21}^H & S_{22}^H & 0 \\ 0 & 0 & S_{33}^H \end{bmatrix} \tag{3}$$

And the effective Poisson's ratio and Young's modulus can be obtained by:

$$v_{yx}^{H} = -S_{12}^{H} / S_{11}^{H}, \quad v_{xy}^{H} = -S_{21}^{H} / S_{22}^{H} \tag{4}$$

$$E_{x}^{H} = 1 / S_{11}^{H}, \quad E_{y}^{H} = 1 / S_{22}^{H} \tag{5}$$

By varying the width of a strut, we can extend the relative density. At relative density range from 0.05 to 065, the mechanical properties of both cells have been shown in Fig. 2. As shown in Fig. 2(a), v_{yx} of the enhanced structure increase drastically which means the weakness of negative Poisson's ratio. Fortunately, v_{xy} of the enhanced structure is similar to the original one. For this re-entrant quadrangular lattice, the principal direction is *x*, and thus the negative value of v_{xy} will be used to implement the morphing mechanism. Simultaneously, as shown in Fig. 2(b), E_x of the enhanced structure increase ~8 times than the original one. And, the E_y also have been improved obviously. Therefore, the enhanced form of re-entrant quadrangular lattice, maintaining a balance between stiffness and flexibility, is adopted to design the morphing core of the airfoil. The structure is capable of providing good flexibility while maintaining a carrying capability for aerostatic loading.

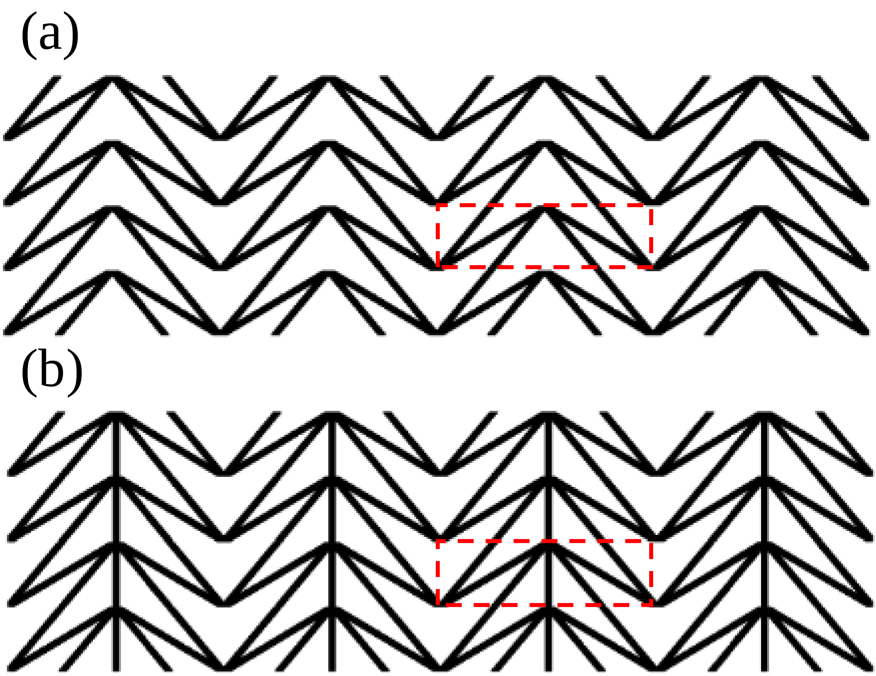

Fig.1 The re-entrant quadrangle 4x4 lattice and its unit cell: (a) original; (b) enhanced.

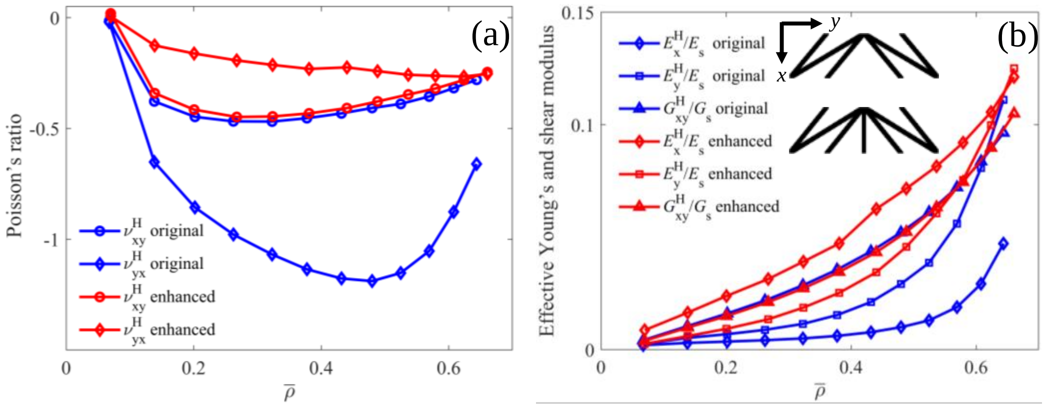

Fig. 2 The homogenized elastic constants of re-entrant quadrangle lattices: (a) Poisson’s ratio; (b) Young’s modulus and shear modulus.

3. Analysis of the morphing airfoil

Based on the unit cell of re-entrant quadrangle in Section 2, the lattice is mapped into an airfoil profile (NACA-0009 9.0% smoothed). The chord length of airfoil is 1000 mm shown in Fig. 3. The airfoil comprises of the core and frame. The material of core is Carbon-fiber (CC90/ET443 SEAL) material whose Young’s modulus is 56.6 GPa and Poisson’s ratio is 0.0514, Poisson’s ratio is 0.06. The material of frame is aluminum alloy (Al 6061-T051) whose Young’s modulus is 70 GPa and Poisson’s ratio is 0.33. The finite element model (FEM) in this paper is developed by utilizing the commercially available software Abaqus. The frame of the airfoil is discretized by the 2D solid element (CPS4R). The cellular structure is modeling by the beam element (B21).

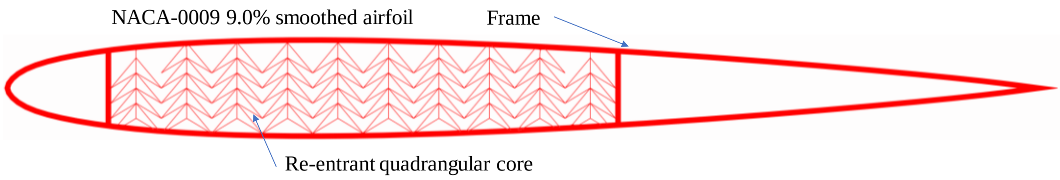

Fig. 3 The scheme of airfoil with re-entrant quadrangular core.

3.1 Modal analysis

We conducted modal analysis for this model. The results can be used to evaluate the dynamic properties of structure. And, by comparing to the modal experiment, the finite element model can be validated. Unfortunately, we have not performed the experiment so far. Furthermore, the modal analysis can be utilized to determine the connectivity of FEM model. Fig. 4 shows five normal modes of this morphing airfoil and Fig. 5 exhibits the constrained modes. As shown in both figures, the FEM model is in a good connection. As known, the resonant deformation of 2D airfoil will not be motivated before that of the whole wing as the first modal frequency of 2D airfoil is remarkably higher. It should be noted that the trailing part shows large deformation in every mode. In practical design, the trailing part should be strengthened, yet it is not considered in this paper.

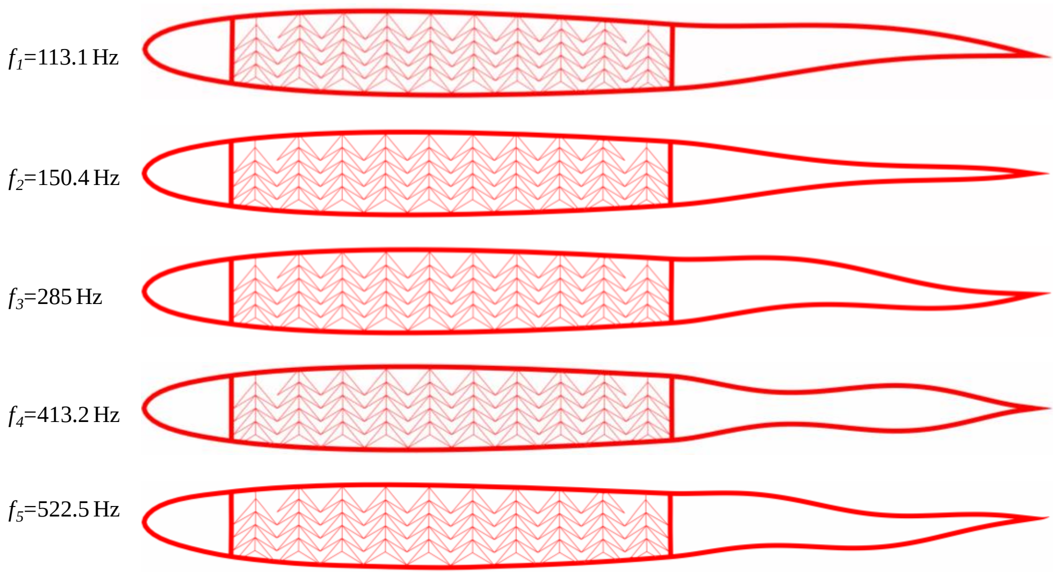

Fig. 4. The normal modes of morphing airfoil (10 times deformation)

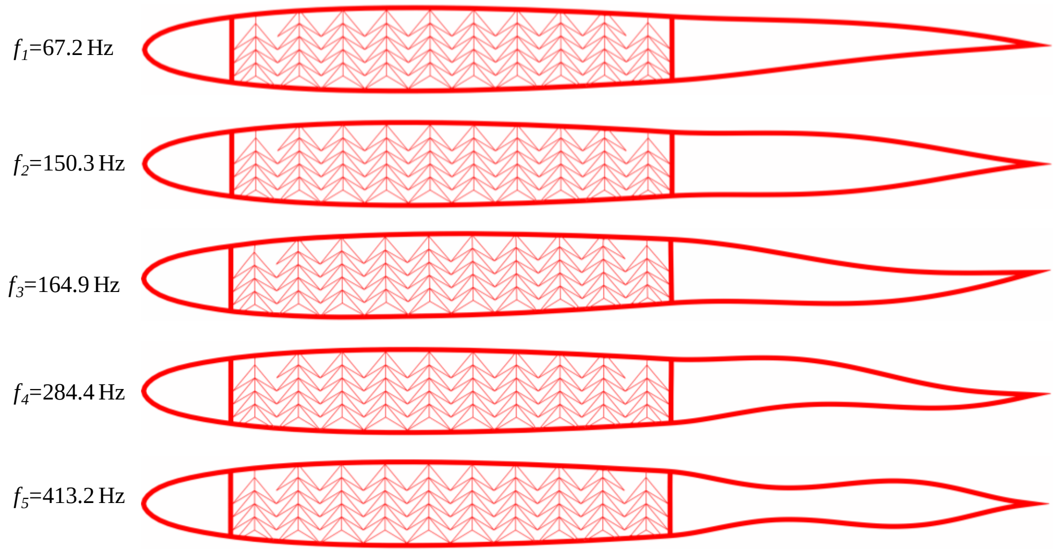

Fig. 5. The constrained modes of morphing airfoil (10 times deformation)

3.2 Passive morphing

For simplicity, the model is completely clamped at the leading edge shown in Fig. 6(a). The airfoil is imposed a concentrated force at the trailing edge shown in Fig. 6(a) while such conditions do not represent the typical aerodynamic load but accord with the experiments carried out in [20, 21]. The linear load respect to the trailing edge displacement is reported in Fig. 6. It is worth noting that the applied load- trailing edge displacement curves were generated within the elastic range of the constituent material. The high flexibility in shear of the auxetic lattice while maintaining shear stiffness is good for a passive morphing airfoil application. As shown in Fig. 7, the morphing airfoil with auxetic lattice core exhibits high elastic flexibility when it is imposed by the concentrated force. When the passive load is 400N, the airfoil has a significant deformation in shape.

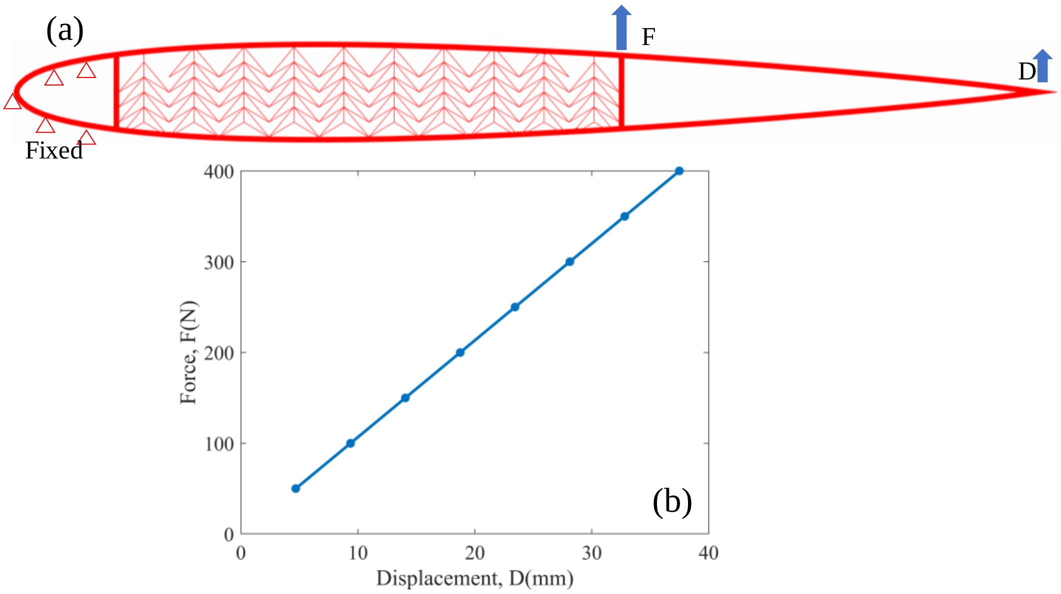

Fig. 6 Condition and results. (a) The loading and constraints of the airfoil; (b)Applied load vs. trailing-edge displacement

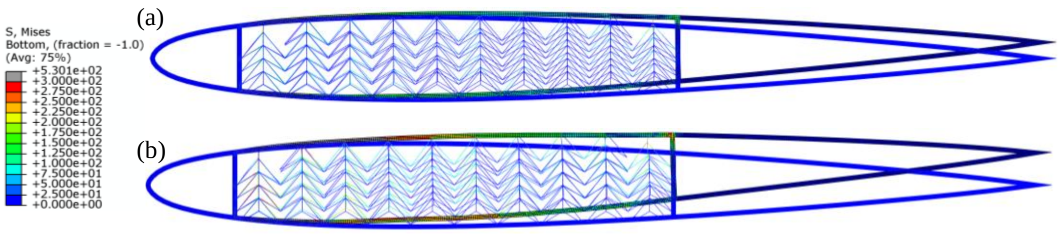

Fig. 7 Stress distribution (a) 200 N (b) 400N.

3.3 Active morphing

The core of the morphing airfoil is fabricated by the lattice. Therefore, it is easy to replace struts with actuators in this scheme to implement the active morphing. Four actuators are arranged in this model to drive morphing shown in Fig. 8. Here, two cases are conducted including case 1: all actuators have 6 mm elongation; case 2: 4, 6, 8, 10 mm elongation respectively for No.1, 2, 3, 4 actuators. As shown in Fig. 9, case 2 achieve the better property of morphing than case 1 within the same strain limitation. Hence, we use case 2 as the working condition. Simulations under different driven scopes are conducted to analysis the morphing properties of the active airfoil under case 2. Here, the elongation of No.1 actuator is utilized as base and elongations of other actuators are proportionate to it as case 2. The linear relationship between the active elongation of No.1 actuator and trailing-edge displacement is depicted in Fig. 10 which allow identifying the maximum displacement that can be reached without exceeding the linear strain limits. The deformation and stress distribution of the morphing airfoil under 3 mm and 5 mm elongation of No.1 actuator have been exhibited in Fig. 11. As shown, the deformation patterns are similar to the passive condition in the above Section.

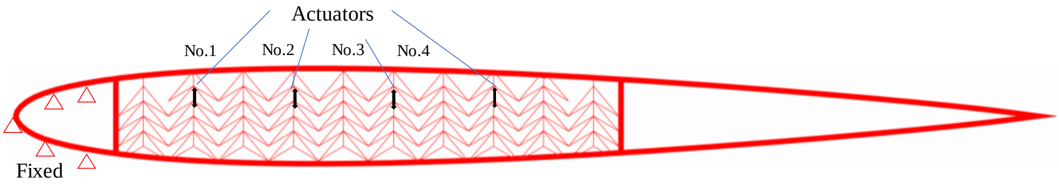

Fig. 8. Morphing airfoil with four actuators.

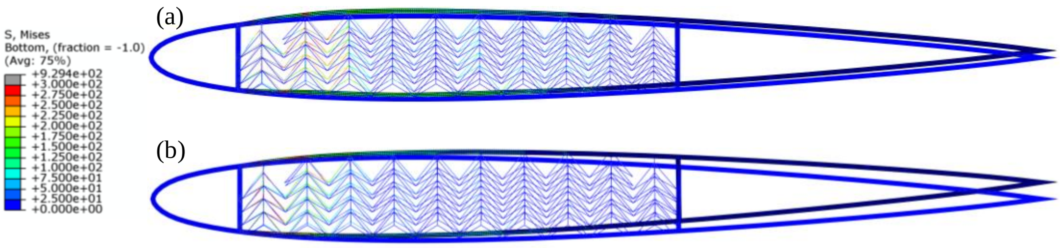

Fig. 9. Deformation and stress distribution under: (a) case 1; (b) case 2.

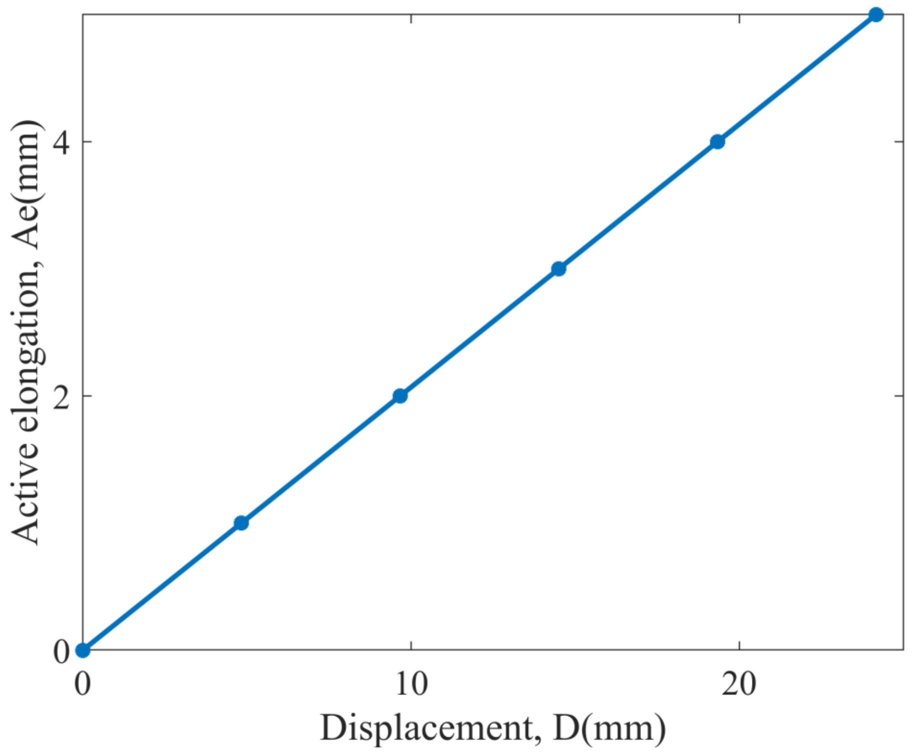

Fig. 10. Applied active elongation vs. trailing-edge displacement

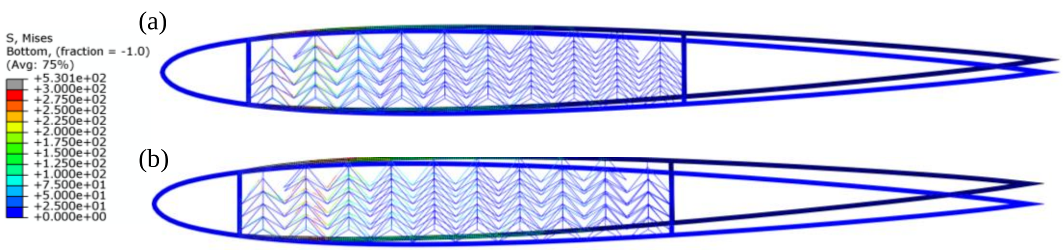

Fig. 11 Deformation and stress distribution under: (a) 3 mm; (b) 5 mm

4. Conclusion

In this paper, we investigated the in-plane mechanical properties of re-entrant quadrangular lattices and its application to the morphing airfoil with flexible cores. The enhanced re-entrant lattice shows remarkable superior to the original one in stiffness and has similar flexibility. The morphing airfoil with auxetic lattice was studied under an aero-static load. The re-entrant lattice core shows high shear flexibility. Besides the passive morphing, the active morphing also has been investigated in this paper. The actuator is readily arranged in a re-entrant quadrangular lattice to implement active control for morphing airfoil. By lengthening actuator in the right way, the airfoil can achieve deformation like the passive morphing generated by the concentrated force. The elementary result of this paper provides ideas for the design of passive and active morphing airfoil.

Acknowledgments

The authors are grateful for the support provided by National Key R&D Program of China (No. 2017YFB0103204), Natural Science Foundation of Shanghai (No. 18ZR1440900) and Chinese Scholarship Council (No. 201706260056).

References

[1] Barbarino S, Bilgen O, Ajaj RM, Friswell MI, Inman DJJJoims, structures. A review of morphing aircraft. 2011;22(9):823-77.
[2] Rodriguez A. Morphing aircraft technology survey. 45th AIAA aerospace sciences meeting and exhibit2007. p. 1258.
[3] Thill C, Etches J, Bond I, Potter K, Weaver PJTaj. Morphing skins. 2008;112(1129):117-39.
[4] Weisshaar TAJJoA. Morphing aircraft systems: historical perspectives and future challenges. 2013;50(2):337-53.
[5] Liu Y, Hu HJSR, Essays. A review on auxetic structures and polymeric materials. 2010;5(10):1052-63.
[6] Lakes R. Foam structures with a negative Poisson's ratio. Science. 1987;235:1038-41.
[7] Prawoto Y. Seeing auxetic materials from the mechanics point of view: a structural review on the negative Poisson’s ratio. Computational Materials Science. 2012;58:140-53.
[8] Liu Q. Literature review: materials with negative Poisson's ratios and potential applications to aerospace and defence. DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION VICTORIA (AUSTRALIA) AIR VEHICLES DIV; 2006.
[9] Choi J, Lakes R. Fracture toughness of re-entrant foam materials with a negative Poisson's ratio: experiment and analysis. International Journal of fracture. 1996;80(1):73-83.
[10] Donoghue J, Alderson K, Evans K. The fracture toughness of composite laminates with a negative Poisson's ratio. physica status solidi (b). 2009;246(9):2011-7.
[11] Chen C, Lakes R. Micromechanical analysis of dynamic behavior of conventional and negative Poisson’s ratio foams. Journal of Engineering Materials and Technology. 1996;118(3):285-8.
[12] Allen T, Martinello N, Zampieri D, Hewage T, Senior T, Foster L, et al. Auxetic foams for sport safety applications. Procedia Engineering. 2015;112:104-9.
[13] Chen Z, Wang Z, Zhou S, Shao J, Wu XJM. Novel Negative Poisson’s Ratio Lattice Structures with Enhanced Stiffness and Energy Absorption Capacity. 2018;11(7):1095.
[14] Peel LD, Mejia J, Narvaez B, Thompson K, Lingala MJJoMD. Development of a simple morphing wing using elastomeric composites as skins and actuators. 2009;131(9):091003.

[15] Fleck N, Deshpande V, Ashby MJPotRSAM, Physical, Sciences E. Micro-architectured materials: past, present and future. 2010;466(2121):2495-516.
[16] Olympio KR, Gandhi FJJoims, structures. Flexible skins for morphing aircraft using cellular honeycomb cores. 2010;21(17):1719-35.
[17] Ramrakhyani DS, Lesieutre GA, Frecker MI, Bharti SJJoa. Aircraft structural morphing using tendon-actuated compliant cellular trusses. 2005;42(6):1614-20.
[18] Bharti S, Frecker M, Lesieutre G, Browne J. Tendon actuated cellular mechanisms for morphing aircraft wing. Modeling, Signal Processing, and Control for Smart Structures 2007: International Society for Optics and Photonics; 2007. p. 652307.
[19] Olympio KR, Gandhi FJJoims, structures. Zero Poisson's ratio cellular honeycombs for flex skins undergoing one-dimensional morphing. 2010;21(17):1737-53.
[20] Heo H, Ju J, Kim D-MJCS. Compliant cellular structures: application to a passive morphing airfoil. 2013;106:560-9.
[21] Bettini P, Airoldi A, Sala G, Di Landro L, Ruzzene M, Spadoni A. Composite chiral structures for morphing airfoils: Numerical analyses and development of a manufacturing process. Composites Part B: Engineering. 2010;41(2):133-47.