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Compliant cellular structures: Application to a passive morphing airfoil

Hyeonu Heo [a], Jaehyung Ju [b,*], Doo-Man Kim [a]

[a] School of Aerospace and Mechanical Engineering, Korea Aerospace University, Goyang, Republic of Korea
[b] Department of Mechanical and Energy Engineering, University of North Texas, 1155 Union Circle, #3311098, Denton, TX 76203-5017, USA

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ABSTRACT

Cellular materials are known to have two properties; structures and mechanisms. Therefore, one may design structures with cellular materials while controlling stiffness and flexibility depending on the struts' connectivity. The objectives of this study are to investigate in-plane flexible properties of bending dominated cellular materials under macroscopic deformation and to secure a method to design a passive morphing airfoil with flexible cellular cores. The airfoil with three cellular cores (chiral, regular and re-entrant hexagonal honeycombs) is investigated under a static load through the deformation gradient of the cellular cores under an aerostatic load. The structural performance of the airfoil with the designed compliant cellular cores is validated through the fluid–structure interaction through which a structural finite element analysis is combined with fluid statics. Considering the deformation of the airfoil with flexible cellular cores under an aerostatic load, shear is the dominant deformation mode of the cores of the airfoil. The re-entrant hexagonal honeycomb core shows the highest flexibility in shear and causes a lower stress in local cell walls in shear than the other cellular cores when the cellular mesostructures are designed to have the same shear modulus. This implies that the re-entrant hexagonal honeycomb core has the potential to be used as a structure with a passive morphing airfoil.

1. Introduction

Cellular materials, often called lattice materials, are made up of an interconnected network of solid struts or plates and have complex architectures with voids [1]. They include two-dimensional (2D) honeycombs, three-dimensional (3D) lattice truss structures, randomly structured foams, porous materials, etc. Cellular materials have received great attention due to their high stiffness to weight ratio. In addition to the light weight property, cellular materials were found to be either stiff or flexible depending on the struts' connectivity [2,3]. For example, according to Maxwell's stability criteria [4], the condition for a pin-jointed frame made up of b struts and j joints to be both statically and kinematically determinate in 2D is

$$M = b - 2j + 3 = 0 \tag{1}$$

In 3D, the equivalent equation is

$$M = b - 3j + 6 = 0 \tag{2}$$

If $M < 0$, as in Fig. 1(a), the frame is a mechanism; it does not have stiffness or strength. If the joints are locked, the bars of the frame bend when the structure is loaded. If $M = 0$, as in Fig. 1(b), the frame is not a mechanism any more. Its members carry tension or compression; it becomes a stretching dominated structure. Maxwell's criteria gives insight into the design of cellular materials to distinguish bending dominated structures from stretching dominated ones.

From the criteria, we may categorize the cellular structures with bending or stretching dominated ones and they are shown in Figs. 2 and 3. Triangular topologies have high macroscopic stiffness with stretching dominated properties of the cell members [3,4]. Cellular structures with bending dominated topologies such as hexagonal topologies have low macroscopic stiffness and high flexibility. One may tailor material properties by properly selecting cell topologies associated with struts' connectivity depending on their structural functions.

As mentioned, cellular materials have two properties – stiffness and mechanism – at the same time. Most studies on cellular materials have focused on the first properties with mass [5–10]. However, one may use the second property for tailoring flexible cellular solids. Ju and his co-workers investigated the hexagonal structures to identify the struts to decompose the stiffness and mechanism for different loading conditions [11–17]. The hexagonal honeycombs with negative cell angles were found to be highly flexible in shear due to the larger deflection of the vertical cell struts perpendicular to the loading [11,13–17]. On the other hand, the hexagonal honeycombs with the long inclined cell strut was found be flexible in uniaxial loading [12]. Observing the deformation of hexagonal cellular solids, some struts are

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* Corresponding author. Tel.: +1 940 565 2118; fax: +1 940 369 8675.
E-mail addresses: jaehyung.ju@unt.edu (J. Ju), dmkim@kau.ac.kr (D.-M. Kim).

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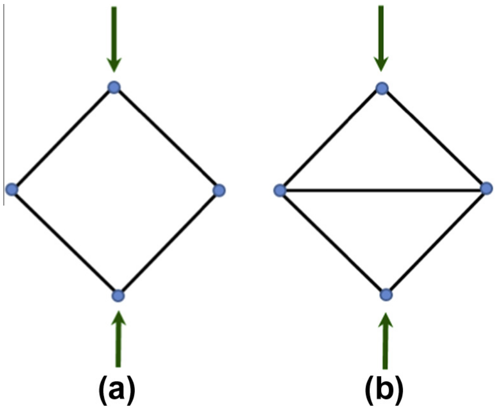

Fig. 1. Pin-jointed frames: (a) mechanism – bending dominated and (b) structure – stretching dominated.

primarily used for a structural purpose (stiffness) and some are mainly used for a mechanism purpose (strain) depending on directions and modes of external loads applied to cellular structures. The concept on the flexible cellular materials was applied to design flexible components of non-pneumatic tires [12,14,15].

Some research groups tried to use the flexible property of cellular materials for other structural applications. They investigated a chiral honeycomb's application to a passive morphing airfoil structure. Using its flexible property associated with ligament bending, an aeroelastic performance was investigated with fluid–structure interaction [18,19]. It was found that the chiral core's flexible property might be favorably used for a passive airfoil morphing design, yet no direct comparison with other cellular topologies on the application has been made.

We may use hexagonal honeycombs that are known to be bending dominated for the flexible structural design of a passive morphing airfoil. In this study, an airfoil with hexagonal (regular and re-entrant) honeycomb cores are designed to have both a load carrying capability and flexibility at the trailing-edge under aerostatic loading and their aeroelastic performance will be compared with that of the airfoil with a chiral honeycomb core. From a prescribed static load determined by the deformation gradient of the core region by an aerostatic load, the honeycomb cores are designed then their aeroelastic performance is validated through fluid–structure interaction. The primary deformation mode of the cellular core under the aerostatic load turns out to be shear, which will be covered in Section 2. The re-entrant hexagonal honeycomb core shows the best aeroelastic performance for the passive morphing capability among the three cellular cores, which will be discussed in Section 3.

2. Design of an airfoil with compliant cellular cores

While designing the compliant cellular structures, both stiffness and flexibility, which are the conflicting requirements, should be considered. In this section, considering a deformation mode, compliant cellular cores of a passive morphing airfoil are designed while maintaining the required stiffness associated with an aerostatic loading. Three cellular geometries are considered for the core design in this study: a chiral honeycomb, regular and re-entrant hexagonal honeycombs. Each core is designed to have the same effective stiffness for the applied aerostatic loading. The displacements of cellular airfoils are compared with one another and the maximum allowable strains are investigated while checking local stresses of the constituent material.

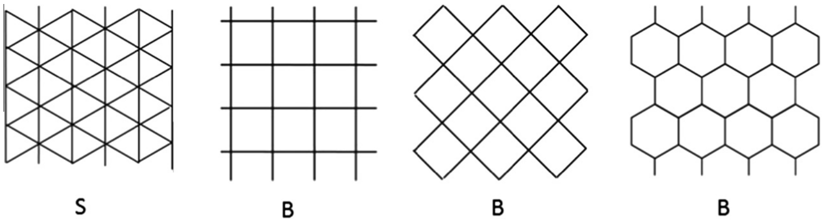

Fig. 2. 2D honeycomb cells; stretching (S) and bending (B) dominated structures.

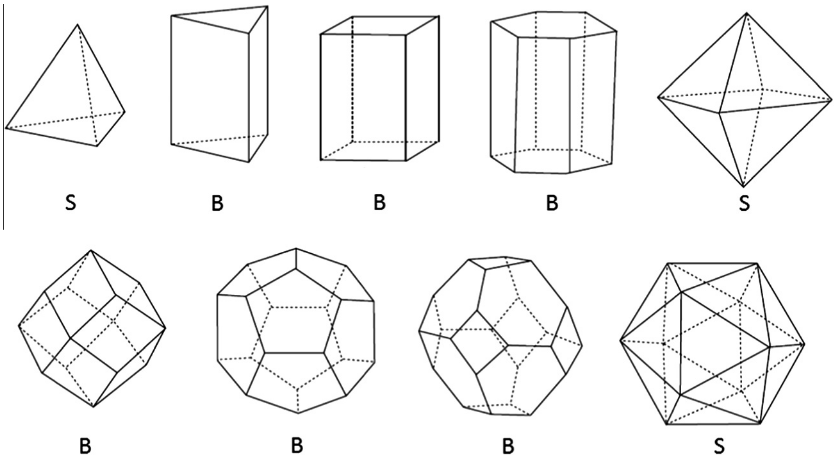

Fig. 3. 3D Polyhedral cells; stretching (S) and bending (B) dominated structures.