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Damping behavior investigation and optimization of the structural layout of load-bearing biological materials

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ABSTRACT

Load-bearing biological materials, such as bone and nacre, exhibit superior mechanical properties to support and/or protect biological functionalities. To achieve this, an important ability of such materials is to effectively shield external dynamic impacts. The damping behavior of the biological materials mostly stems from their architecture and also the organic portion which intrinsically shows viscoelastic-plastic behavior. The loss modulus, a crucial representative of dynamic behavior, is a key index on how strong the bio-composite is able to damp the dynamic energy within its structure. This work aims to study the damping behavior of mostly seen staggered architectures of biological materials such as regular, offset, stairwise, herringbone and random staggering patterns to highlight the optimal layout, geometry, and feature sizes of the bio-composite in which the energy dissipation within the structure is maximal. Our studies show that not only the stairwise staggering arrangement overall offers the highest loss modulus amongst other existing architectures but also the aspect ratio of the platelet leading to the maximum loss modulus is remarkably in excellent agreement with experimental observations which might explain why this kind of arrangements is extensively observed in nature. Our findings here not only gain valuable insights into the dynamic behavior of load-bearing biological materials, but also provide useful guidelines to the design of bio-inspired engineering materials.

1. Introduction

Load-bearing biological materials, such as bone, sea shell, tooth, antler and mineralized tendon, are bio-composites consisting of simple soft organic and hard inorganic materials [1–6]. This class of biological materials often possesses internal levels of structural hierarchy with length scales ranging from the nanoscale to the macroscale [4,5,7–10]. For instance, it is known that the sea shell structure typically has been formed of two to three hierarchical levels with a mineral volume fraction of 95% [8,11], while bone possesses seven structural levels with the 45% mineral volume fraction [4,5].

Thus far, great efforts have been made to understand complicated hierarchical structures and establish structure-property relations for this class of biological materials [6,12–17]. For example, it was shown that the micro/nanostructures of such materials have dictated their mechanical properties [5,18–28]. With regard to the tensile behavior of biological materials [26,29], Ji and Gao developed a continuum model (well-known as tension-shear chain model) to explain how such materials were able to achieve superb mechanical properties such as high stiffness and toughness [13,14,21,30,31]. Interestingly, Zhang et al. recently studied the effects of non-uniform or random staggering alignments of the mineral platelets on the mechanical properties of bio-composites from the static point of view and found that some of the staggered patterns like regular and stairwise staggering show optimal mechanical properties compared to other platelet distributions [32].

It is noted that most of previous works were done under static loading conditions. In reality, load-bearing biological materials are often exposed to dynamic loading like external impacts [6,33], which implies that they should be able to effectively shield dynamic impacts to protect their inside soft organs. Many investigations studied the damping behavior of the composite structures [34–42]. Therefore, it is crucial to understand how biological materials are able to dissipate dynamic energy and damp the stresses within their structures caused by dynamic loads [34,37,43–46]. In recognition of the importance of the shielding role, several studies have been performed recently to understand the dynamic energy dissipation and stress wave decay within the structure of biological materials [47–52]. For instance, it was shown that the nanostructure of biological materials could efficiently attenuate the stress waves passing through their structure by reflecting and refracting the stress waves at the hard and soft phase interfaces [48].

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Furthermore, the synergistic effects of the viscoelastic properties of the protein and structure of biological composites were studied on the stress wave attenuation of a regular staggered architecture [49]. We note, however, that there exist different patterns of the staggered architecture in nature, such as stairwise, herringbone, mortar-brick and random staggering [4,6,20,53–55]; therefore, it is crucial to study how efficient these staggering architectures are able to absorb and dissipate the dynamic energy.

Then, a few important questions arise: why has nature designed different staggered architectures like offset, stairwise, and herringbone staggering patterns for the structure of load-bearing biological composites? Furthermore, in such different staggered patterns, what are the feature sizes and layout of the bio-composite leading to the maximum dynamic energy dissipation? Moreover, does the intrinsically built-in hierarchical architecture of the biological composites play a significant role in improving the damping properties of the bio-composites with different staggered arrangements?

This paper aims to investigate the effects of several staggering patterns of natural bio-composites on the damping properties (loss moduli) of these materials. First, we would like to develop a theoretical model to identify the dynamic properties of well-known mostly seen architectures of load-bearing biological materials. Then, we use a self-similar multi-level structure to investigate the effects of the hierarchy number on the damping behavior of the bio-composite with different staggering patterns. Next, we perform finite element method (FEM) calculations to validate the theoretical derivations. Through this investigation, we would like to explain why different types of staggering architectures are often observed in nature and also answer how these bio-composites select particular layout with specific feature sizes at different length scales.

2. Mathematical modeling

Load-bearing biological materials are known to possess complicated layouts and built-in structures, which give rise to their superior mechanical properties. As such, they have become an exceptional source of inspiration to develop engineering materials with excellent mechanical properties and extraordinary functionalities. Apparently, their multi-level structure is the product of nature during a long era of the evolution process. Remarkably, regardless of various types of structural hierarchy in this class of biological materials, all of them have something in common; that is, a mixture of soft proteins and hard mineral inclusions, with the latter being embedded into the former as the matrix at the nanoscale [6,12].

Mechanically, the damping properties of the biological composites are believed to be related to their structural architecture which is built hierarchically with specific combination of hard mineral and soft protein. However, it is known that biopolymers like protein play the most important role in dictating the damping properties of biological materials with usually exhibiting significant viscoelastic-plastic features [9,56–58]. Therefore, a synergistic source of energy damping in biological materials can be expected. Zhang and To also calculated the damping figure of merit of the bio-composites with a hierarchical regular staggering pattern and found that the hierarchical structure was able to efficiently increase the damping figure of merit [52]. Their formulations ignored the high-order terms of loss modulus and consequently obtained the loss modulus of the bio-composite in such small frequencies near static loading conditions. However, in real circumstances most of the loads applied on biological structures are dynamic with an extensive range of loading frequencies. Furthermore, by considering hierarchical effects of the biological materials in a self-similar multi-level model, a recent study obtained the storage and loss moduli of bio-composites with the regular staggering architecture for a wide range of load frequencies [47].

Fig. 1 schematizes various staggering patterns seen in nature for biological materials. The offset staggering pattern contains the hard

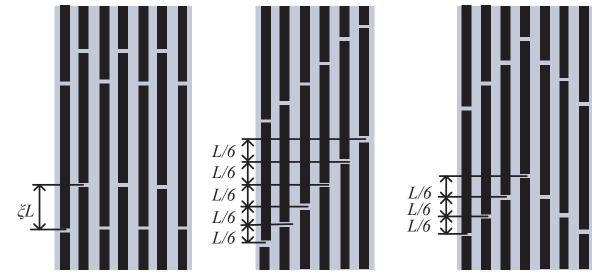

Fig. 1. Different staggering patterns in biological composites: (a) offset staggering, (b) stairwise staggering ($n = 6$), and (c) herringbone staggering ($n = 6$).

inclusions that can be shifted to the neighboring inclusions by a distance of ξL, where ξ is the offset parameter ($0 \le \xi < 1$) and L is the length of the mineral inclusion (Fig. 1(a)). For $\xi = 0.5$, the offset staggering pattern will simply change to the regular staggering structure which has been mostly used to find the structure-property relation of the load-bearing biological materials [14,30]. The stairwise staggering pattern of the bio-composite with (here with $n = 6$) contains the unit cell composed of 6 aligned platelets and each platelet has an upward shift of 1/6 of the length of the platelet relative to its left neighbor platelet (Fig. 1(b)). By selecting $n = 2$, the stairwise staggering pattern will be similar to the regular staggered structure. The herringbone structure is one of the well-known arbitrary patterns for the staggered arrangement (here with $n = 6$) (Fig. 1(c)).

In this section, the principles of complementary energy as well as the correspondence principles are applied to briefly calculate the effective elastic modulus of the regular staggered nanocomposite (here $\xi = 0.5$ for offset staggering or $n = 2$ for stairwise staggering pattern) of load-bearing biological materials as a simple instance. It should be noted that the derived elastic modulus is due to static perspective and to be used as the material properties of the bottom level of the self-similar hierarchical structure of biological materials. Of the detailed calculation of the effective modulus (based on the static standpoint) for other staggering patterns like offset, stairwise, herringbone and random architecture refers to [32]. In a self-similar hierarchical model, each level consists of mineral inclusions arranged in a staggered pattern within the soft protein matrix. It should be noted that the hard inclusions in higher levels (Level 2 and above) are heterogeneous, made of the composites of their immediate neighbors of lower levels. At the primary level, the structure is composed of a protein matrix and a staggering distribution of elastic mineral platelets; however, at the higher levels, it is formed of the homogeneous composite of a lower level, and both of the hard and soft counterparts have viscous characteristics. The staggered pattern, the mineral volume fraction and the aspect ratio of the hard reinforcements are exactly the same through different structural hierarchies, which is just what the “self-similarity” means.

Fig. 2 shows the regular staggering pattern of the nanostructure in which the unit cell is composed of two aligned platelets.

Fig. 2 shows the unit cell of the regular staggering pattern as well as its stress and stain fields due to a small longitudinal elongation Δ applied to it. L is the hard inclusion length, h_m is the hard inclusion thickness and h_p is the soft matrix thickness. It should be noted that the mineral volume fraction is $\phi = h_m/(h_p + h_m)$. In deriving the effective modulus, the deformation of the mineral inclusions is assumed to be just one-dimensional along the axial direction z. To do so, the length of the mineral inclusions is to be at least one order of magnitude larger than their thickness within the unit cell. Furthermore, the Young's modulus of the mineral platelets should be at least two orders of magnitude greater than that of the protein matrix, making the soft matrix to be able to transfer the axial loading in the z direction via shear mechanism. Furthermore, τ^U and τ^L are the shear stresses within the