Propagation properties of elastic waves in the 3D nacreous composite material

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Abstract

Inspired by natural nacreous materials with the excellent performance, a kind of 3D nacreous composite material is designed based on the thought of staggered and combined soft and hard materials. In the 3D band structure analysis, the designed material generates an ultrawide low frequency band gap. Additionally, the influences on the band gap with different material parameters of the model are examined. Furthermore, the numerical tests for the transmission characteristics reveal the significant vibration attenuation effect of the nacreous material which fit remarkably well with the band gap.

Keywords: Nacreous composite material, Phononic crystal, Band gap, Vibration isolation, Multi-level substructure.

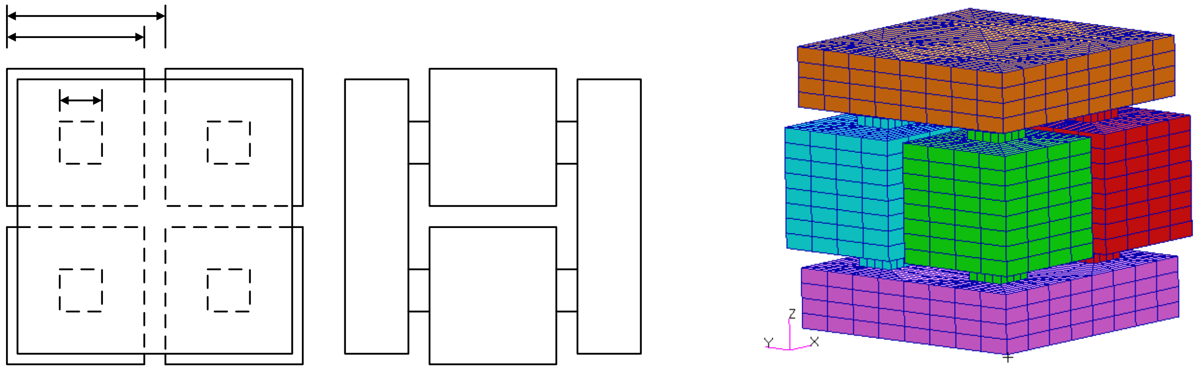
Introduction

Mother nature is the best designer. This belief enlightens people to set foot on the way to mimic and understand nature. In the exploration of nature, people find out that many biological materials feature excellent mechanical or physical properties compared with engineering materials people usually use [1]. The feet of geckos and insects possess remarkably strong adhesion contact ability; cobwebs boast considerably high toughness and strength; animal bones are shaped in multi-scale and porous structures with light weight and high strength; nacreous composite materials exhibit the strength stronger than any member of single-phase material. All of these have prompted the flourish of biomimetic materials. Nacre is composed of 95% mineral substance (which is relatively hard material) and 5% protein (which is relatively soft biological material). This material, however, is more than several times strength than the single-phase mineral material [2]. Taking this into consideration, Gao *et al.* [3] proposed an explanation that the microstructures of nacreous composite materials are insensitive to flaw, and then built a Brick-and-Mortar (B-and-M) model to describe nacreous materials. Yao’s study [4] showed that nacreous composite materials are not only insensitive to flaw under the micro scale, but perform well to restrain the stress concentration.

It should be noticed that nacreous composite materials exhibit periodicity in the soft and hard hierarchical structures, which is the basic characteristic of phononic crystals [5]. They are capable of tailoring the wave propagation through some frequency ranges (band gaps) in which the propagation of sound and elastic waves is forbidden [6]. Inspired by nacreous composite materials with the excellent performance, the elastic wave propagation in the 3D nacreous composite material is studied.

Three-dimensional Band Strucuture

Most researchers spare much less time for the dynamic characteristics of the B-and-M composite structure. As our attention in this paper is mainly paid to the band structure and wave propagation characteristics of the designed 3D B-and-M composite material. The geometric parameters of the 3D finite element model (FEM) are shown in Fig. 1(a). The model is divided into six basic substructures [Fig. 1(b)] based on a multi-level substructure technique [7] to improve computational efficiency and reduce memory usage significantly which has the same accuracy with the traditional FEM. The material of the Brick is aluminum, and that of the Mortar is silicone rubber (material parameters shown in Table 1).



(a) Geometric parameters (b) Substructure model

Figure 1. The unit cell of a 3D nacreous composite material

Table 1. Two-phase parameters of nacreous material

Material	Density /kg/m^3	Elastic modulus /MPa	Poisson's ratio
Aluminum (Brick)	2700	70000	0.3
Silicone rubber (Mortar)	1300	0.1175	0.4688

The band structure of the designed 3D nacreous material (Fig. 2) illustrates that this material opens up an ultrawide band gap in the low frequency regime (84.4155Hz ~ 467.5685Hz). This kind of nacreous composite material, however, is a typical kind of Bragg phononic crystal rather than the locally resonant phononic crystal, which can be verified from its reduced frequency of the central gap frequency. Owing to its band characteristics, this material is suitable for the engineering application in the vibration isolation in the low frequency range. Foreseeably, this material will have a remarkable effect on the vibration isolation if elastic waves' frequencies locate in the band gap regime.

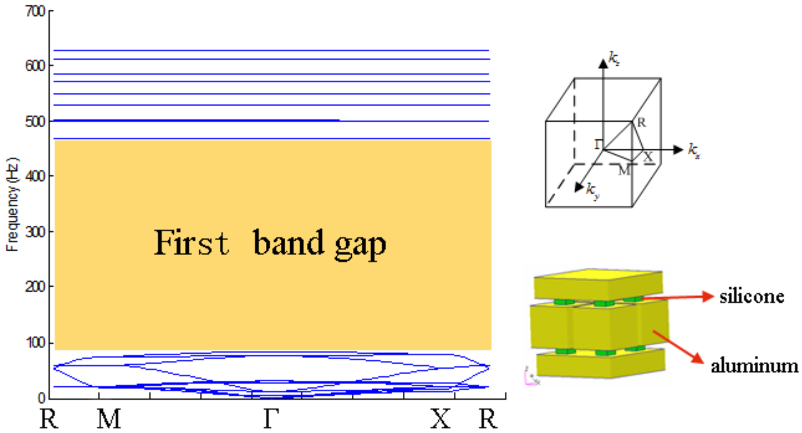


Figure 2. The band structure of the 3D nacreous material

It is known that the scaling law [8] uniformly expanding or shrinking the physical sizes of phononic crystals by a factor β results in the frequency spectrum being scaled by $1/\beta$. This law can also be explained by a view of finite element method. The generalized eigenvalue problem of the phononic crystal with finite element method can be written as,

$$[\boldsymbol{K}]\{\boldsymbol{u}\} = \omega^2[\boldsymbol{M}]\{\boldsymbol{u}\}\,. \tag{1}$$

When the physical size of the phononic crystal is expanded or shrinked by a factor β, the new generalized eigenvalue equations with the constant density and elasticity can be written as,

$$\beta[\boldsymbol{K}]\{\boldsymbol{u}\} = \varpi^2\beta^3[\boldsymbol{M}]\{\boldsymbol{u}\},\ \varpi = \frac{1}{\beta}\omega\,. \tag{2}$$

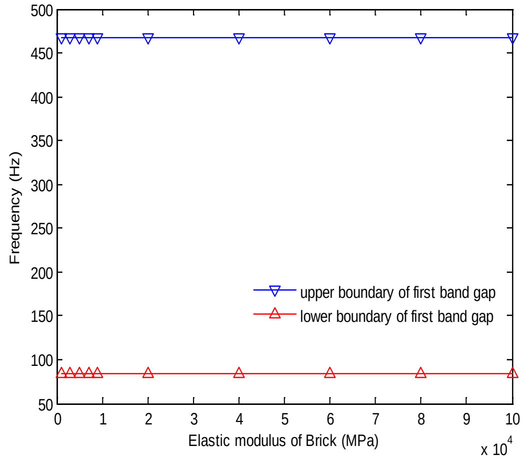
In addition, Chen's study [9] showed that the size-effect becomes more important and the non-classical elastic continuum should be taken into account when a system is in the dimension of several nanometers. The results illustrated that the classical elastic continuum is still applicative above the dimension of ten nanometers, otherwise the size-effect should be considered. Therefore, the analysis of nacreous material with the B-and-M pattern is reasonable in the classical elastic continuum. Moreover, a lot of researches using the classical elastic continuum to discuss phononic crystals in the micron scale and nano scale were found in Ref. [10][11]. The vibration isolation performance for a given B-and-M structure is dependent on the length scale, but the B-and-M structures at macroscale and microscale have similar vibration isolation performance. According to the scaling law, the first band gap of the 3D nacreous composite material (Fig. 1) has a range of 16.88MHz～93.51MHz, if the length of the unit cell is 350nm.

Influences of Material Parameters on the Band Gap

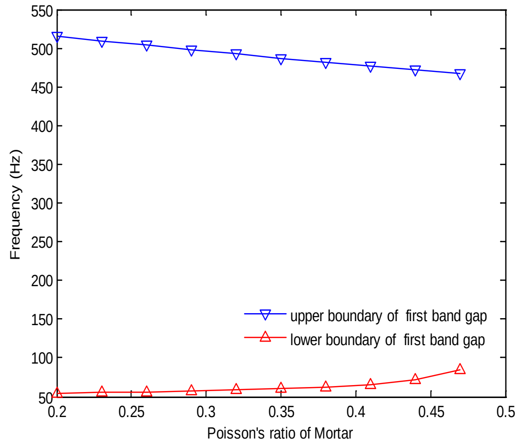
In order to design the nacreous composite material for vibration reduction in the low frequency regime, four material parameters of the 3D B-and-M model are studied to examine their influence on the band gap. The four material parameters are the elastic modulus and density of Brick, the elastic modulus and Poisson's ratio of Mortar (with corresponding ranges shown in Table 2).

Table 2. The range of parameters of four materials with two-phase model

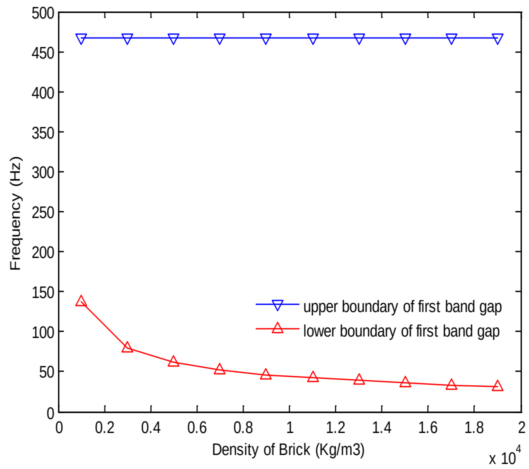
	Brick		Mortar	
	Elastic modulus (GPa)	Density (kg/m^3)	Elastic modulus (MPa)	Poisson's ratio
Lower limit	1	1000	0.1	0.2
Upper limit	100	20000	100	0.49



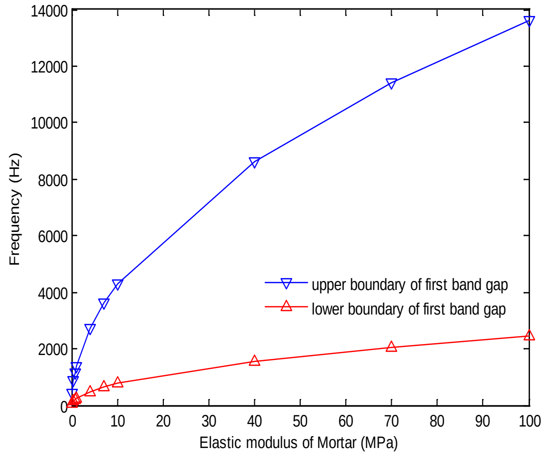
(a) Elastic modulus of Brick



(b) Poisson’s ratio of Mortar



(c) Density of Brick



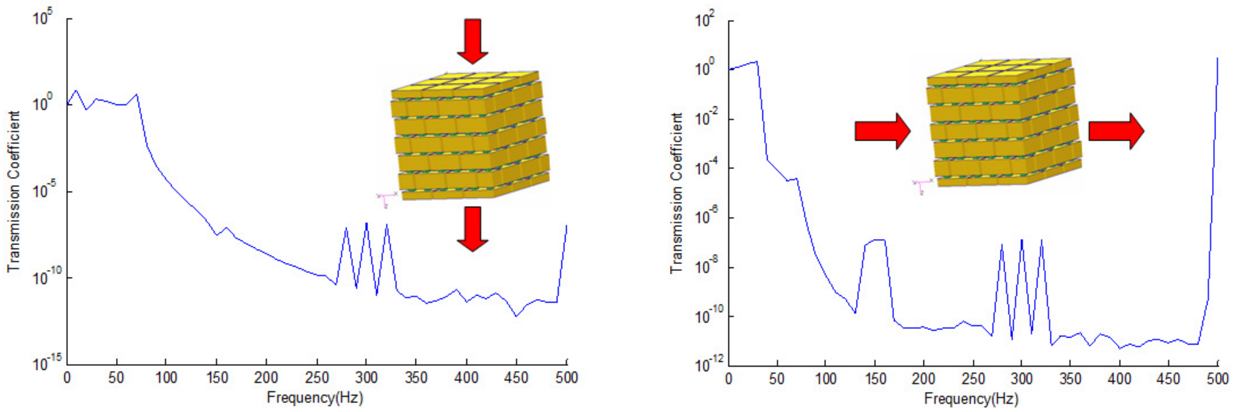
(d) Elastic modulus of Mortar

Figure 3. The influence of the four material parameters on the first band gap

The influence exerted by the four material parameters is shown in Fig. 3. The band gap results demonstrate that the elastic modulus of Brick and the Poisson’s ratio of Mortar exert little influence on the first band gap. However, a larger density of Brick, which leads to a larger mass, contributes to a wider first band gap. Moreover, a smaller elasticity modulus of Mortar, which makes the shear stiffness of Mortar smaller, leads to the lower boundaries of the first band gap with a narrower first band gap.

Transmission Characteristics

To verify the vibration isolation effect of the 3D nacreous composite material, the transmission characteristics of the designed material are studied in this paper. A finite periodic structure of 3×3 ×3 cells is modeled for the numerical analysis with the help of the software MSC.Nastran. We are interested in the *x*-directional (horizontal) and *z*-directional (vertical) displacement transmission characteristics, which are valued by the ratio between the output displacement and the input displacement. The response curves are usually described in the logarithmic form.



(a) Horizontal direction (b) Vertical direction

Figure 4. The transmission characteristics of the designed material

The horizontal and vertical transmission characteristics of the designed material are shown in Fig. 4. According to the results, the 3D nacreous composite material isolates the vibration effectively within an ultrawide frequency regime in both horizontal and vertical directions. Given that the frequency range of the elastic wave attenuation and the band gap regime are consistent with each other, the correctness of the computed results is verified from an additional aspect. The results also show that the 3D nacreous composite material is a kind of Bragg phononic crystals which do not present the Fano-like interference phenomenon [12] found in locally resonant phononic crystals, thus benefiting the application in the engineering vibration reduction.

Conclusions

Enlightened by the nacreous composite material with the excellent performance, a 3D phononic crystal material is designed based on the idea of staggered and combined soft and hard materials. The results demonstrate that the material generates an ultrawide first band gap in the low frequency regime, and that its size makes it suitable to be applied to the engineering vibration reduction and isolation. Moreover, the band gap could be furtherly changed via adjusting material parameters. In the numerical tests for transmission characteristics, this material boasts remarkable effect on vibration reduction and isolation, which is in consistency with the band gap results.

Acknowledgments

The supports of the National Natural Science Foundation of China (11232003, 91315302), the National 111 Project of China (No.B08014, No.B14013), and the Doctoral Fund of Ministry of Education of China (20130041110050) are gratefully acknowledged.

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