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Microgeometrical design of lightweight bioinspired nacre-like composite materials for wave attenuation tuning

Andrea PRANNO[1,a], Fabrizio GRECO[1,b*], Raimondo LUCIANO[2,c] and Umberto DE MAIO[1,d]

[1]Department of Civil Engineering, Via P. Bucci Cubo 39B, Rende, Italy

[2]Department of Engineering, Parthenope University of Naples, Naples, Italy

[a]andrea.pranno@unicall.it, [b]fabrizio.greco@unical.it, [c]raimondo.luciano@uniparthenope.it, [d]umberto.demaio@unical.it.

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Abstract. Numerical simulations give the opportunity for designing periodic microstructured materials by tuning and manipulating their dynamic properties in terms of vibration control by varying their main micro-geometrical parameters. Specifically, the bandgap formation in 2D nacre-like composites characterized by a brick-and-mortar arrangement of stiff platelets and a soft matrix containing periodically arranged cavities was investigated through the Bloch-wave analysis. The numerical outcomes highlighted that, by varying the microstructural topology of the void inclusions and the stiff platelets, enhanced wave absorption capabilities can be obtained providing new opportunities to design periodic lightweight bioinspired composite metamaterials with elastic wave attenuation properties.

Introduction

As engineering requirements have become more strict, composite materials are increasingly being used in many applications [1,2] to meet advanced mechanical, chemical, thermal and vibrational [3,4] requirements. The research community is also constantly interested in developing advanced materials inspired by nature that can reach excellent properties. Thus nacre, also known as the mother of pearl, is among the most examined because of its excellent mechanical properties [5] related to the “brick-and-mortar” pattern characterizing its microstructural arrangement. Due to recent advancements in additive manufacturing, numerous researchers are exploring the high potential for designing nacre-like bioinspired materials with advanced properties finding applications in a wide range of engineering fields [6–8]. Due to their complex microstructure, composite materials are heterogeneous media that are susceptible to various nonlinear phenomena, especially if subjected to large deformation, such as instabilities at the microscopic and macroscopic scale [9] or damage mechanisms involving the microscopic scale such as matrix cracking or debonding of the fiber-matrix interfaces [10–13]. It is widely known that there is a strict correlation between these microscopic mechanisms and macroscopic fracture phenomena such as delamination, interfacial debonding, and multiple crack propagation which are generally considered the most frequent precursors of damage in microstructured composites [14–17]. By adopting hyperelastic constitutive models, numerous advanced numerical modeling techniques, including homogenization [18,19] and multiscale techniques [20,21], have been developed over the past decade to predict the mechanical behavior of composite materials subjected to large deformations and to reduce the computational effort needed to model complex microstructural geometries. Recent research has shown that nacre-like composite materials are capable of influencing wave propagation through their intrinsic periodic microstructure, which has led to an increase in interest in the study of their dynamic and wave propagation properties [22–25]. In this regard, materials with periodic structures, exhibiting physical properties not available in nature such as noise and vibration attenuation, are commonly referred to as metamaterials. They have experienced tremendous growth during the last decade, but they still have a few limitations. In mechanically demanding processes, for example, the mechanical properties of such materials can conflict with the demand for high energy dissipation needed to guarantee the vibration and noise attenuation characteristics. In this work, the Floquet-Bloch analysis is used to investigate the elastic waves propagation in lightened nacre-like composites with alternating stiff platelets and void inclusions in a finite element code (COMSOL Multiphysics 5.6). As a result, we will be able to increase our understanding of this growing area of research by exploring how by varying the main geometrical parameters and the voids inclusion arrangement affect vibration control and band gap phenomena of periodic nacre-like composite materials. Specifically, two void inclusion arrangements were investigated, and a parametric study was conducted by varying the main geometrical parameters, such as void volume fraction, platelets aspect ratio, and the thickness ratio between the horizontal and vertical matrix interfaces. The numerical outcomes have shown that by varying the void inclusion arrangements we are able to provide new opportunities for designing lightened bioinspired composite metamaterials with advanced wave absorption capabilities.

Numerical Results

The 2D unit cells investigated are reported in Fig.1 together with an example of mesh discretization highlighting the main geometrical parameters characterizing the results of the parametric analysis reported in the following. In this work, the matrix interphases are characterized by two different thicknesses b_h and b_v, related to the horizontal and vertical interfaces respectively. The unit cell and the platelets length are denoted by L and L_p, respectively, while the unit cell and the platelets height are denoted by H and H_p, respectively.

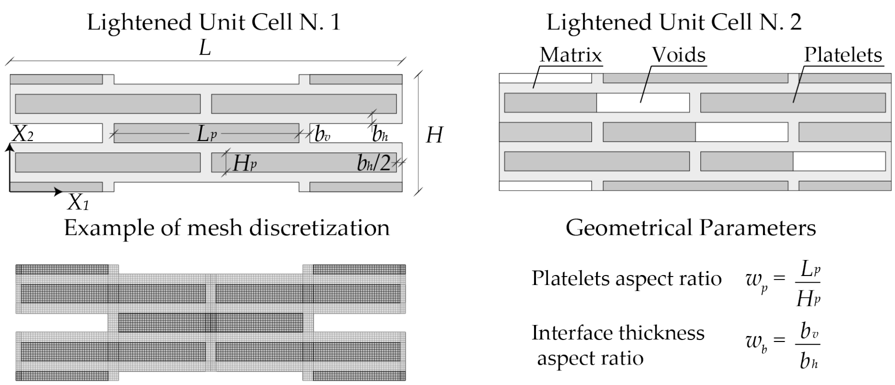

Fig.1 Investigated lightened nacre-like metamaterial with the main geometrical parameters.

The parametric analyses were performed by varying the geometrical parameters in terms of volume fraction $v_f = (8L_pH_p)/[(2L_p + 2b_v)(4H_p + 4b_h)]$, platelets aspect ratio $w_p = L_p / H_p$, with $L_p = 10\mu m$ and interface thickness aspect ratio $w_b = b_v / b_h$. The parameter v_f, ranging from 0.91 to 0.99 , is evaluated considering both the volume occupied by the platelets $v_f^p = (3/4)v_f$ and the one occupied by the voids $v_f^v = (1/4)v_f$. Based on the following neo-Hookean hyperelastic strain energy density function, the constitutive law for each microstructural material phase (matrix and platelets) is defined:

$$W = \frac{1}{2}\mu_{(m,p)}(\mathrm{tr}(C)-3) - \mu_{(m,p)}\ln(J) + \frac{1}{2}\lambda_{(m,p)}\ln(J)^2, \tag{1}$$

Where the material parameters with subscript m and p are related to the matrix and platelets, respectively. Here μ is the initial shear modulus, C is the right elastic Cauchy-Green tensor, J

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is the Jacobian of the transformation and λ is the first Lamé parameter which is able to control the material compressibility. With the aim to model the incompressible behavior of material phases $\lambda_{(m,p)}$ was considered equal to $1000\mu_{(m,p)}$. The initial shear modules are equal to $\mu_m = 2.5$ MPa and $\mu_p = k\mu_m$ with k equal to 10000. The Floquet-Bloch analysis was performed by imposing the Floquet-Bloch boundary conditions on the periodic unit cells and by opportunely varying the k-wave vector inside the first Brillouin zone obtaining the corresponding frequency dispersion (additional information about the numerical implementation can be found in the following research works [23,26,27]). Then, by analyzing the obtained dispersion curves the complete bandgap found were stored for each geometrical configuration investigated and then reported in Figures 1 and 2 in order to show the bandgap evolution as a function of the volume fraction parameter for different platelets and interface thickness aspect ratio.

Fig. 2 shows the evolution of the complete bandgaps with reference to the first lightened unit cell as a function of the volume fraction v_f. The figure highlights that numerous bandgaps were obtained for the case in Fig.2a with $w_b = 1$ and that they become slightly wider as the volume fraction increases. Specifically, with $91\% \leq v_f \leq 95\%$ only two bandgaps were found for the cases with $w_p = 0.5$ and $w_p = 4$ in a range of frequency below 60 [MHz], while with $95\% \leq v_f \leq 99\%$ we found that numerous bandgaps appear at higher frequency ranges and with different platelets aspect ratios reaching the highest attenuated frequency equal to 250[Mhz].

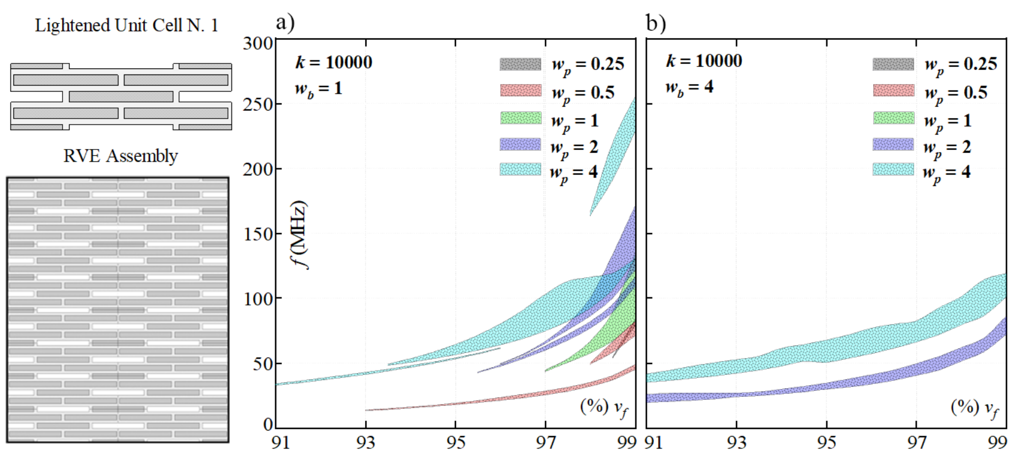

Fig.2 Bandgap evolution with reference to the lightened unit cell n.1

The numerical results with reference to a thickness aspect ratio $w_b = 4$ were reported in Fig.2b, in which it is clear that a higher thickness aspect ratio leads to a change in the wave absorption properties in terms (lowering the attenuated frequency ranges). In fact, only two bandgaps were found for the cases with $w_p = 2$ and $w_p = 4$ reaching the highest attenuated frequency equal to 110 [MHz]. To investigate the influence of different void inclusion arrangements, a second unit cell was proposed considering the same amount of void volume fraction and the obtained results were reported in Fig. 3. Compared with the unit cell n.1, in this case, it is clear that greater bandgaps were observed at lower frequency ranges and that the bandgaps become slightly wider as the volume fraction increases. In Fig.3a the most bandgaps were found for the cases with a volume fraction $94\% \leq v_f \leq 99\%$, while in Fig.3b the most band gaps were found for $97\% \leq v_f \leq 99\%$. However, in both Fig.3a and Fig.3b the bandgaps with the highest and widest frequency range were found for the case with a platelets aspect ratio $w_p = 4$ while the bandgaps with the lowest frequency range were found with $w_p = 0.25$. Thus, in general, we observed that a higher volume fraction leads to wider bandgaps with higher attenuated frequency ranges and that a higher platelets aspect ratio leads to higher attenuated frequency ranges.

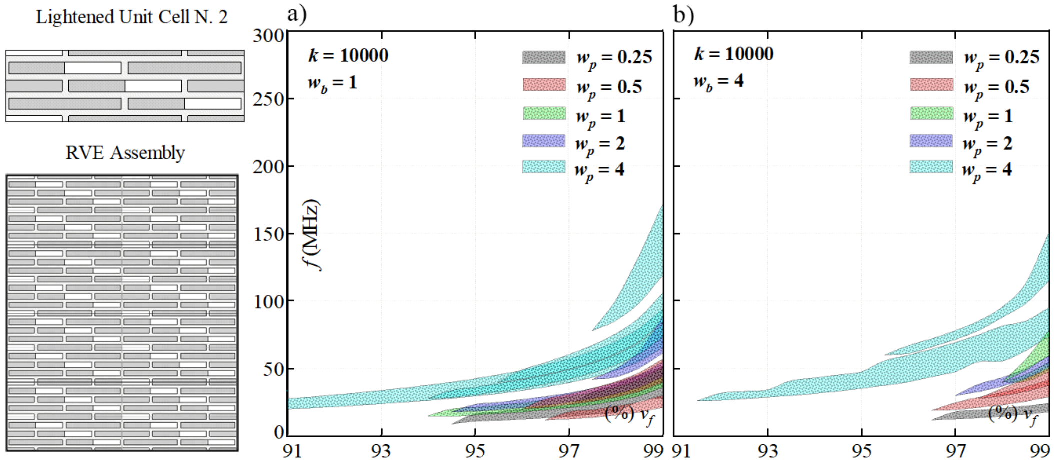

Fig.3 Bandgap evolution with reference to the lightened unit cell n.2

Conclusions

In this study, we investigated the wave propagation properties in two different lightened bioinspired metamaterials by varying the main geometrical parameters. The proposed microstructured metamaterials were lightened by inserting void inclusions in place of some reinforcing platelets in order to promote wave attenuation property. Comprehensive parametric analyses were performed to investigate the influence of the void volume fraction, the platelets aspect and the interface thickness aspect ratios. Based on the numerical results, void inclusions and stiff platelets with different microstructural topologies were found to experience enhanced wave absorption capabilities, thereby providing new opportunities to design periodic lightweight bioinspired composite metamaterials able to attenuate specific frequency ranges of propagating elastic waves.

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