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Analytical and numerical modeling on resonant response of particles in polymer matrix under blast wave

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ABSTRACT

A novel methodology is proposed in this paper to design polymer matrix with particles for protecting against the blast wave. Through the adoption of vibration analysis, two kinds of basic equivalent unit cell models introducing the massive springs are developed and the corresponding relations for structural parameters considering the Poisson effects are derived. The resonant frequencies of particles are obtained by theoretical prediction and compared with the results of finite element analysis, in which a good agreement is achieved. Based on the theoretical analysis, two types of composite materials with different geometry configurations are proposed and the 3D periodic models are established to investigate the dynamic performance under blast wave. The energy history of system is calculated to study the energy transfer effect among components. Additionally, the numerical parametric studies are conducted to investigate the effects of coating properties and particle volume fraction on the wave propagating in these two unit cell models. The acquired results show that the attenuation of blast wave is caused by the interaction between the elastic wave motion and the resonant particles. The coating properties and particle volume fraction are significant factors to affect the wave propagation and attenuation. The dominant frequencies of spectrum obtained by the simulations are well coincident with the theoretical solutions.

1. Introduction

As a new type of artificially designed composite material, meta-material may exhibit excellent performance such as negative mass density [1–3], enhanced absorption [4,5], negative refractive index [6,7] and zero rigidity [8] when subjects to ultrasound, acoustic, electromagnetic and even elastic wave. These exotic physical properties have great potential applications in practical engineering, yet are not observable in the natural materials. With the rapid development of science and technology, the research of meta-material attracts the more attention. The great achievements have been obtained on the structural design and performance study of the materials [9–15].

For the acoustic elastic meta-material, local resonance and Bragg scattering physical phenomena are two significant influence factors for the exotic properties of these materials [16]. Bragg scattering behavior plays an important role for the attenuation of incident wave when the wavelength is the same order as the size of microstructural inclusion, but local resonance behavior operates at larger wavelength. Kushwaha et al. [17] proposed the first full band-structure calculations for the periodic elastic composite material and obtained a "phononic" band gap extending throughout the Brillouin zone. They did not calculate the band structures for the mixed transverse-longitudinal mode, so the gaps found were not independent on polarization. Klironomos and Economou [18] calculated the scattering cross section for a vertical incident elastic plane wave on the circular cylinder and found that the resonances were necessary for the band gap creation. The incident elastic or acoustic wave cannot propagate in these meta-materials within the Bragg-type band gap frequency ranges [19–23]. Based on the idea of localized resonant structures, Liu et al. [1] developed a novel elastic meta-material with locally resonant structural unites. When the incident sonic wave passes through the material, the resonance of lead inclusion can be activated at certain frequency ranges resulting in resonance induced low-frequency band gaps. Li and Chan [24] first demonstrated theoretically the existence of elastic/acoustic meta-materials and showed that both the effective bulk modulus and mass density may be simultaneously negative in an effective medium which was derived from the low-frequency resonances. Wang et al. [25] studied the longitudinal elastic waves propagating in a quasi-one-dimensional slender beam attached periodic harmonic oscillators. The transmission frequency response function (FRF) was computed based

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on the theoretical model and compared with the experimental data with a good agreement achieved. An effective medium theory for investigating the unusual properties of two-dimensional elastic meta-material was presented by Wu et al. [26]. Zhou and Hu [27] proposed a unified analytic model to predict the dynamic effective bulk modulus, shear modulus and mass density for elastic meta-material by averaging physical fields from local stress, strain and momentum. They found that the negative total momentum of materials with a positive velocity field is responsible for the negative effective mass density.

A rigorous theoretical relation for the effective dynamic mass density of elastic meta-material was proposed by Milton and Willis [28]. The generalized equations of motion for a rigid bar were obtained by using Newton's second law, which was found that the effective dynamic mass density was a function of the oscillation frequency. Nemat-Nasser et al. [29] expanded the solution of Floquet-Bloch problem in Fourier series and obtained the Bloch-type waves. In addition, the frequency-dependent dynamic effective elastic moduli and mass density were acquired via the adoption of the mixed variational method [30]. To further investigate the locally resonant meta-material, Zhu et al. [31] introduced a quite general approach to derive the field equations for a microstructure continuum model (MCM) to study the dynamic performance of an elastic material with the resonator microstructures. The material constants used in MCM can be expressed by the properties of resonator and host medium which do not need to be determined by the experiments. Huang et al. [32] extended this work, proposing two continuum methods (the homogeneous classical and multi-displacement continuum models) to investigate the dynamic performance of 2D meta-composite with internal resonators. They showed that two continuum models were capable of describing the accurate dispersion behavior and the band-gap structure. They further confirmed that the multi-displacement continuum model could be used to model the more complex microstructures within a meta-composite. Recently, a new type of meta-material is proposed to reduce the energy transmission and damage caused by the blast load [33,34]. The internal spherical inclusions consisting of a heavy lead core with a soft coating replace the sand, stone and gravel aggregates for standard concrete. Based on the light spring-mass model, Mithcell et al. [33] presented a simple relationship between the main geometry parameters and the coating stiffness to define the range of resonant frequencies. The finite element models were established to investigate the dynamic behavior of meta-material slab under blast load and the energy histories of system were computed. These analyses show that there was an energy transfer between the aggregates and host mortar, as well as the heavy lead core of aggregates can absorb a major portion of total energy to further reduce the amount of stress carried by the host mortar component.

We propose a novel methodology in this paper to design locally resonant particle/polymer composite material for the explosion protection structures, and establish the 3 D periodic finite models to investigate dynamic performance of the material subjected to blast wave. In Section 2, the geometry and structure of aggregate consisting of a glass sphere core with a coating is described. Two kinds of basic equivalent unit cell models introducing the massive springs are developed and the corresponding relations for structural parameters considering the Poisson effects are derived. Based on the proposed theoretical prediction approach, two types of particle/polymer composite materials are designed with different geometry configurations. The corresponding finite element models and the application of periodic boundary conditions are presented in Section 3. The energy history of system is calculated in Section 4 to study the energy transfer between components. Furthermore, the numerical parametric studies are carried out for the effects of coating properties and inclusion volume fractions on the elastic wave propagating in these two composite materials. Some valuable conclusions are obtained in Section 5.

2. Analytical models

2.1. Analytical inclusion resonant frequency

The composite material consists of polyurea (PU) elastomer and aggregates. The aggregate is composed of a glass inclusion core coated with a soft layer. The properties of corresponding component materials are listed in Table 1. Because the difference in density between inclusion and elastomer is not remarkable, the simple theoretical analysis model proposed in Ref. [33] cannot be used to define the resonant frequency range of the inclusion for current study. To obtain the accurate resonant frequency of the inclusion, two kinds of basic equivalent unit cell models (with and without coating) introducing the massive springs are developed, as shown in Fig. 1, and the corresponding relations are derived for structural parameters via the adoption of vibration analysis.

2.1.1. The particle/polymer material without coating

For the particle/polymer composite material without coating, an equivalent unit cell model is proposed to calculate the resonant frequency of inclusion, as shown in Fig.1(a). Here, it is assumed that the inclusion is coated with a layer of PU elastomer, and the thickness of equivalent elastomer layer is equal to a half of inclusion spacing. So the local resonant system in the composites consists of inclusion and equivalent elastomer layer. The equivalent massive spring-mass model with a single inclusion is considered as shown in Fig.1(c).

The classical single massive spring-mass system is given in Fig.2 (a) and the wave equation can be derived as [35],

$$\frac{\partial^2 u}{\partial x^2} = \frac{m}{Kt_s^2}\frac{\partial^2 u}{\partial t^2}, \tag{1}$$

where u denotes the displacement of a point on the massive spring. m and K are the mass and stiffness of spring, respectively. The stable particular solution of wave equation is

$$u = F(x) \cdot \cos\omega_1 t, \tag{2}$$

which can describe a series of standing wave on the massive spring. Substituting Eq. (2) into Eq. (1), we obtain the ordinary differential equation,

$$\frac{d^2F}{dx^2} = -F \cdot \frac{m\omega_1^2}{Kt_s^2}. \tag{3}$$

The solution can be given by

$$F(x) = A\sin\frac{\omega_1}{t_s}\sqrt{\frac{m}{K}}x + B\cos\frac{\omega_1}{t_s}\sqrt{\frac{m}{K}}x. \tag{4}$$

Substituting the boundary conditions ($x = 0,\ u = 0$) into Eq. (4), the result is simplified by

$$u = A\sin\frac{\omega_1}{t_s}\sqrt{\frac{m}{K}}x \cdot \cos\omega_1 t. \tag{5}$$

Table 1
Material properties for all components.

Material	E (GPa)	ν	ρ (kg/m^3)
Glass ball	64.89	0.30	2470
Polyurea	0.0649	0.465	1129
Nylon	1.0	0.40	1150
Silicone	0.001	0.47	1100