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Experimental investigation of the dynamic behavior of metaconcrete

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ABSTRACT

A study investigating the dynamic material behavior of a new type of heterogeneous composite called metaconcrete is presented. Instead of sand, stone and gravel in a conventional concrete, the metaconcrete mortar is filled with heavy, spherical aggregates that are encapsulated in a soft coating. This locally resonant metamaterial exhibits band gaps that lead to the attenuation of applied stress waves at the inclusion's eigenfrequencies. Plate impact experiments are conducted to investigate the viability of the underlying physical concepts for the attenuation of stress waves. To reduce the effects of porosity and inhomogeneity, the mortar material is substituted by an epoxy matrix and a lead core encapsulated in polyurethane serves as the aggregate. Strain gauges applied between the aggregates on the specimen surface are used to evaluate the performance of the metaconcrete microstructure. Initial conditions were varied with respect to impact velocities (18 m/s–100 m/s) and flyer plate thickness (0.8 mm–25.4 mm) to study the dependence of the attenuation properties for a range of impact configurations. Moreover, the resonant frequency of the aggregates was measured using high-speed photography and digital image correlation (DIC) and shown to be in good agreement with analytical predictions. The metaconcrete microstructure lead to a reduction in maximum strain of up to 72% compared to a homogeneous epoxy specimen, showing the potential for metaconcrete to be used in damage mitigation of structures subjected to dynamic stress wave loading.

1. Introduction

Heterogeneous multi-phase and layered materials can be used to mitigate damage to structures under highly transient loading such as impact and blast [1–5]. The concept of engineered metamaterials has emerged as a new paradigm with wide ranging applications [3–8]. At present, there has been limited progress towards the selection and geometry of materials to promote stress wave attenuation. In this study, we consider the recently proposed concept of metaconcrete, which can significantly attenuate stress waves arising from dynamic loading conditions [3–5].

There have been numerous efforts to study engineered microstructures (metamaterials) that exhibit enhanced properties when subjected to electromagnetic or acoustic waves (e.g., photonic [9–16] and phononic crystals [17–20]). Their interesting behavior (negative refractive index [21,22], electromagnetic cloaking [6–8], waveguides [23] etc.) stems from a designed microstructure rather than the chemical composition of their constituents. The unit cell length-scale of these materials is on the order of the wavelength they aim to manipulate, typically hundreds of nanometers to millimeters. This design strategy becomes problematic for low-frequency acoustic or elastic waves with wavelengths on the order of several meters. As a result, structures attenuating these waves using crystal arrangements would need to be prohibitively large. Liu et al. [20] proposed the use of locally resonant inclusions, which consist of heavy spheres coated in a soft coating, that affect low-frequency acoustic waves with unit cells orders of magnitude smaller than the acoustic wavelength. Milton and Willis [24] derived a one dimensional, analytical framework to relate the resonant frequency f_{res} of the heavy aggregate cores to the Young's modulus E_c and the thickness t of the soft coating as well as the radius R_l and density ρ_l of the aggregates by:

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{3E_c}{R_l t \rho_l}}, \tag{1}$$

For frequencies above resonance ($f > f_{res}$), a negative effective mass is obtained due to the out of phase motion of the heavy aggregates, which results in favorable wave attenuation properties. Therefore it is important to design the inclusions such that their resonant frequency is contained within the frequency content of the loading wave.

Mitchell et al. [4] pioneered the concept of using metaconcrete for stress wave attenuation and damage mitigation in structures that are subjected to transient loading arising from explosions and impact. They studied the response of a metaconcrete slab under blast wave loading using a finite element model. They observed that the stress reduction in the mortar phase strongly depends on the elastic modulus of the

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aggregate coating (E_c), but only to a small degree on the geometrical properties of the inclusions such as R_l and t. It was found that E_c should be approximately one order of magnitude lower than the Young's modulus of the matrix material. They showed that choosing E_c to be 2–3 orders of magnitude lower, increases the stress inside the mortar as the soft coating fails to transfer energy to the resonant aggregates. Mitchell et al. extended their modeling to include failure of the matrix and showed that damage from transient blast loading can be significantly mitigated through the use of metaconcrete [5].

A simple mechanical model is outlined in Section 2 to illustrate the concept of resonant metamaterials and estimate the transmission ratio that characterizes the attenuation. Section 3 describes the finite element modeling used to design the metaconcrete specimen for the experimental investigation. The experimental details including metaconcrete specimen preparation, plate impact experimental setup, high-speed imaging and digital image correlation are presented in Section 4. The experimental results are presented in Section 5 and discussed in Section 6. The conclusions of the study are summarized in Section 7.

2. Wave transmission in metaconcrete

A model developed by Huang et al. [25] is used to evaluate the locally resonant behavior of the metaconcrete microstructure. Their problem formulation is illustrated in Fig. 2. The equations of motion derived from this one-dimensional mass-in-mass system are given by

$$m_1^j \ddot{u}_1^j + k_1(2u_1^j - u_1^{j-1} - u_1^{j+1}) + 2k_2(u_1^j - u_2^j) = 0 \tag{2}$$

$$m_2^j \ddot{u}_2^j + 2k_2(u_2^j - u_1^j) = 0, \tag{3}$$

where m_1, m_2 and u_1^j, u_2^j represent the mass and displacement in the jth unit cell associated with the matrix (subscript 1) and aggregates (subscript 2), respectively. The spring constant of the matrix k_1 and soft coating k_2 can be derived as

$$k_1 = \frac{E_m A}{L}, \qquad k_2 = \frac{\pi R_l^2 E_c}{t}, \tag{4}$$

with the equivalent length L defined as the ratio of the matrix volume V_m to the specimen cross-sectional area A [3]. Substituting the harmonic wave solution $u^j = Ce^{i(jqL - \omega t)}$ with wave number q in Eqs. (2) and (3), results in an eigenvalue problem of the form $[\mathbf{K}(\mathbf{q}) - \omega^2\mathbf{M}]\mathbf{u} = \mathbf{0}$. The solution of this problem

$$\omega^2 = 4\frac{k_1}{m_{eff}}\sin^2(qL/2) \tag{5}$$

with

$$m_{eff} = m_1 + \omega_0^2 m_2/(\omega_0^2 - \omega^2), \qquad \omega_0^2 = 2k_2/m_2, \tag{6}$$

is commonly referred to as the dispersion relation [25,26]. The effective mass m_{eff} in Eq. (6) recovers the static mass $m_1 + m_2$ in the low-frequency limit as $\omega \to 0$. Frequencies above resonance of the inner spring-mass system $\omega > \omega_0$ lead to a negative effective mass, which gives rise to the favorable wave attenuation properties of the metaconcrete microstructure.

The dispersion relation, based on the metaconcrete specimen used in the experimental study, is plotted for values of $-\pi < qL < \pi$ (i.e., the first Brillouin zone) in Fig. 3(a). Due to its periodicity, this range describes the behavior of the spring-mass system for all wave numbers. The optical (solid line) and acoustic (dashed line) vibrational modes represent the out-of-phase and in-phase motion of the lead aggregates and matrix, respectively. Frequencies, for which no solution of the dispersion relation exists, are prevented from propagating through the microstructure. The associated frequency range is called a band gap and is indicated by the gray region between the acoustic and optical mode in Fig. 3(a).

The transmission ratio T, shown in Fig. 3(b), is used to evaluate the frequency dependent attenuation properties of the metaconcrete specimen used in the following experiments. It is defined by the ratio of the time-independent displacement amplitude $\bar{u}_1^j = C_1 e^{jqL}$ of the last unit cell to the excitation displacement [26]. Rewriting the equations of motion in terms of $\bar{u}_1^j$ results in a transmission ratio T of

$$T = \left| \prod_{j=1}^{N} T_j \right| = \left| \prod_{j=1}^{N} \frac{k_1}{k_1(2 - T_{j+1}) - m_{eff}\,\omega^2} \right|, \tag{7}$$

with $T_{N+1} = 1$. On a decibel scale, an attenuation of the excitation displacement leads to a negative and an amplification to a positive transmission ratio T.

The transmission ratio is the key parameter for the design of metaconcrete materials and was used to tune the locally resonant inclusions to attenuate a significant part of the frequency spectrum of the incident stress waves in the following experiments.

3. Finite element modeling

The purpose of this numerical study is to provide insight into the design of the experimental technique and a suitable metaconcrete microstructure for the investigated specimen. No attempt has been made in our work to explicitly correlate results as predicted by finite element theory with the measured response from the experiments.

In order to observe the attenuation of elastic waves, the bandgap structure of the specimen microstructure requires a significant overlap with the frequency content of the loading wave. A finite element model created in Abaqus/Explicit is used to investigate the relationship between the frequency content of the loading wave and the microstructure of the specimen. The specimen design is based on the geometrical (see Table 1) and material properties (see Table 3) employed by Mitchell et al. in their numerical study of metaconcrete [4]. A mesh of 10-node tetrahedral elements (C3D10M) with an average element size of 2.5 mm was used.

The effect of frequency content and pulse duration of the loading wave is investigated by applying three incident waves with equal rise time, in order to preserve high-frequency content, while the rest of the pulse is stretched in time by a factor of 2 or 5. Fig. 4 shows the simulated incident pressure-time histories in time and frequency space. The original stress pulse is based on the blast wave simulated by Mitchell et al. [4], generated by a 10 kg TNT detonation, located 0.015 m away from the front surface of the metaconcrete specimen. A detailed description of blasts in air can be found in Kinney [27].

The attenuation properties of the metaconcrete microstructure are evaluated based on the maximum, absolute strain that results from a simulation with a metaconcrete $||\varepsilon_{meta}||_{\max}$ and a homogeneous epoxy specimen $||\varepsilon_{epoxy}||_{\max}$. Table 2 shows the reduction of the maximum, longitudinal strain R_ε defined as:

$$R_\varepsilon = 1 - \frac{||\varepsilon_{meta}||_{max}}{||\varepsilon_{epoxy}||_{max}}, \tag{8}$$

obtained at 180 mm distance from the loading surface (see Fig. 1). The

Table 1
Geometric parameters of the finite element model (see Fig. 1(b)), resonant frequency of the metaconcrete (Concrete/Nylon/Lead) specimen and its inclusion volume V_i and mass fraction m_i.

Inclusions	l [mm]	b [mm]	R_l [mm]	t [mm]	a [mm]	V_i [%]	m_i [%]	f_{res} [kHz]
8	240	30	11	1	30	26.8	56.8	17.4