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Investigation of elastic wave transmission in a metaconcrete slab

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ABSTRACT

A new type of modified concrete, termed *metaconcrete*, has been shown to exhibit trapping of wave energy and a reduction in mortar stress when subjected to dynamic loading. Metaconcrete replaces the standard stone and gravel aggregates of regular concrete with spherical inclusions consisting of a heavy core coated with a compliant outer layer. These new layered aggregates resonate at designed frequencies by allowing for relative motion between the heavy core and the mortar matrix, which causes the aggregate to absorb energy and therefore reduce stress within the mortar phase of the composite material. The transmission of wave energy through a metaconcrete slab can be used to visualize the effect of resonant behavior within the metaconcrete aggregates. To quantify this behavior we compute a transmission coefficient, which is a method of measuring the absorption of wave energy as an applied forcing of known frequency travels through the material. The transmission coefficient is plotted against forcing frequency for four different aggregate material and geometry configurations. A reduction in transmission ratio is observed at or near the computed natural modes of the aggregate, indicating the activation of resonance within the inclusions. This behavior is consistent with observations from studies on sonic metamaterials containing resonant inclusions with a similar layered structure. The frequency location and width of the dip in transmission coefficient will aid in the design of metaconcrete aggregates for specific forcing applications.

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1. Introduction

Recently, the design and construction of metamaterials with unconventional properties has become an area of active research. Metamaterials are complex composites consisting of an engineered microstructure which is specifically designed to manipulate an applied wave or loading, allowing these materials to display unusual properties such as negative refractive index, negative shear modulus, or negative effective mass. These properties are often desired in applications that deal with electromagnetic, acoustic, or elastic waves, yet are not readily achievable with traditional materials.

Many earlier studies consider the use of metamaterials for the manipulation of electromagnetic waves. There has been significant investigation into the propagation of electromagnetic waves in both one and two-dimensional systems, where analyses include an examination of the photonic band structure of periodic metamaterials utilizing, for example, dielectric scatterers (Sigalas et al., 1993; Smith et al., 1993) and metal cylinders (Smith et al., 1994). Additionally, there has several studies into the use of materials with negative refractive index at optical wavelengths, where examples include the superlenses proposed by Pendry (2000) and the invisibility properties

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demonstrated by Kundtz and Smith (2010) and Urzhumov et al. (2011). This has influenced the development of acoustic metamaterials, and there has been considerable attention placed on the design of sonic or phononic crystals (Kushwaha et al., 1993; Klironomos and Economou, 1998; Psarobas et al., 2000; Goffaux and Sánchez-Dehesa, 2003; Jensen, 2003; Hirsekorn, 2004; Wang et al., 2004a,b,c). Simple phononic crystals involving periodic arrays of cylinders have been shown to exhibit wave filtering behavior. Mártinez-Sala et al. (1995) introduced an investigation into the sound attenuation achieved by a sculpture in Madrid, and this was more formally presented by Sánchez-Pérez et al. (1998) with an experimental analysis of a two-dimensional periodic array of rigid stainless steel cylinders. When these periodic composite materials interact with acoustic waves, they exhibit wave filtering behavior, creating band gaps or stop bands within the frequency spectrum. Within the band gap frequency range, the applied acoustic waves cannot propagate and the incident energy is dispersed or scattered from the medium. These materials often utilize the periodicity of the internal structure to create Bragg-type band gaps (Goffaux and Sánchez-Dehesa, 2003; Hirsekorn, 2004; Wang et al., 2004c). However, certain size restrictions on the dimensions of the acoustic barrier are required to make use of Bragg gaps. To overcome this constraint, Liu et al. (2000) developed an array of locally resonant inclusions, consisting of silicone coated lead spheres in an epoxy matrix. As the sonic wave passes through the material, resonance of the heavy lead core can be activated at chosen frequencies resulting in resonance-induced band gaps.

The wave attenuation behavior of materials with these resonant inclusions is derived from the unusual material properties that these composites display, such as negative effective mass. Mass density is typically considered to be the volume average of the mass of the constituents. However, in the case of resonant inclusions under dynamic excitation, there is relative motion between the constituents and the matrix, which causes the dynamic effective mass density to be different from that found in the static case. Milton and Willis (2007) derive a simple relation for the effective dynamic mass density by considering a rigid bar with hidden voids, each containing a spring-mass system. The effective mass density for this system is found to be a function of the oscillation frequency and when resonance of the heavy internal mass is activated, the effective mass can become very large and negative in value. This ‘negative effective mass’ induced by resonance enables systems of this structure to manipulate and reduce the effect of wave energy.

Metaconcrete, recently introduced in Mitchell et al. (2014), represents an example of such a system. Metaconcrete is a modified concrete developed for the purpose of reducing the damage and propagation of energy caused by dynamic loading, such as the blast loading profile generated by an explosion. In a similar way to the extension of hollow cylinder phononic crystals to earthquake mitigation by Brûlé et al. (2014), metaconcrete utilizes the concept of resonance induced negative effective mass that has been successfully used in locally resonant sonic crystals. Metaconcrete employs bi-material spherical inclusions as a replacement for the standard stone and gravel aggregates of regular concrete. These new aggregates modify the response of the system at or near the resonant frequency of the aggregate. Each aggregate contains a heavy core coated in a thin compliant outer layer a few millimeters in thickness. By adjusting the geometry of the aggregate and the coating stiffness we can modify the resonant behavior of the aggregate so that it occurs within a desired frequency range.

Finite element studies of shock loading in metaconcrete slabs consisting of purely elastic constituents have shown that there is a beneficial transfer of energy between the mortar phase and the inclusions when a section of slab is subjected to blast loading, as described in Mitchell et al. (2014). These analyses showed that a significant portion of the total mechanical energy is absorbed by the lead phase of the aggregates in the form of kinetic energy, whereas a much smaller fraction is carried by the mortar component of the metaconcrete slab. This behavior was seen particularly for the aggregate configurations with higher coating elastic moduli, where resonance of the aggregates could be activated under the considered shock loading. For example, in the case of nylon coated lead spheres, approximately 60% of the total mechanical energy was carried by lead cores while only 30% was attributed to the mortar. These characteristics of metaconcrete were also seen in the computation of maximum longitudinal stress within the slab, where a significant reduction in mortar stress was seen in the samples with high coating stiffness.

The beneficial transfer of energy and the implication of resonance induced negative effective mass suggest the need to investigate the behavior of a metaconcrete slab at fixed frequencies of applied loading. Transmission ratio plots have been used to quantify the band gap and resonance induced behavior of phononic crystals with an analogously layered structure (Liu et al., 2000; Sheng et al., 2003). These crystals have been shown to exhibit resonant behavior when experimentally tested with sound waves of varying frequencies, where the ratio of the change in wave amplitude across the crystal is measured and plotted against input wave frequency. A similar ratio can be computed for metaconcrete by considering the amount of energy transmitted through a slab and we investigate the effect of resonance by considering this ratio at different forcing frequencies. To this end, we examine the transmission behavior and resonance activation of metaconcrete by considering a slab containing a periodic array of aggregates subjected to a displacement loading over a range of chosen frequencies. The information gained from these analyses allows us to more accurately determine the appropriate aggregate properties for specific loading applications.

The paper is structured as follows. In Section 2 we describe the geometry and material properties used for the modeled aggregates, and two approaches, analytical and numerical, for the computation of aggregate resonant frequencies. The method for computing the transmission ratio from a metaconcrete slab finite element model is presented in Section 3, along with results from the analysis of four aggregate configurations. Concluding remarks are given in Section 4, where we outline other work being

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