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Vibration attenuation properties of periodic rubber concrete panels

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HIGHLIGHTS

- Periodic rubber concrete panels can produce attenuation zones below 20 Hz.
- Directional attenuation zones can be designed in Bragg-scattering panels.
- Vibration can be reduced significantly by using only three periodic units.

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ABSTRACT

In this paper, attenuation zones of two-dimensional periodic rubber concrete panels are investigated. Both the Bragg-scattering periodic panels and the Local-resonant periodic panels are studied. It is found that complete attenuation zones in the low frequency region can be obtained in the considered panels by proper design. Further, parameter studies show that non-symmetric periodic panels with directional attenuation zones are much suitable for engineering applications. Numerical simulation shows that vibration attenuation is possible if the frequency of an excitation falls within the attenuation zones. The present investigation also shows that vibration can be reduced significantly by using a periodic structure with only three units. The results of the study provide valuable information for a better understanding of dynamic properties of periodic rubber concrete panels.

1. Introduction

Concrete has served as a construction material in civil engineering field for more than two millennia. Numerous efforts have been devoted to improve the performance of concrete since the ancient roman period. With the needs of sustainable development for human being and some special requirements for construction materials, rubberized concrete has become an emerging research topic in recent years and a lot of achievements have been obtained. Zheng et al. [1,2] and Skripkiūnas et al. [3,4] experimentally studied the damping ratio, dynamic and static modulus, strength and brittleness index of rubberized concrete. It was found that the crushed rubberized concrete had better damping properties but lower dynamic and static modulus of elasticity than ground rubberized concrete [1,2], and the compressive and flexural strength of concrete decrease with increasing tires rubber waste additives [3,4]. Sukontasukkul and Chaikaew investigated the properties such as thermal conductivity, strength, sound absorption of concrete mixed with crumb rubber at different frequency and noise reduction [5,6], results indicated that crumb rubber concrete was not only lighter but had higher sound absorption and lower heat transfer properties than the conventional concrete. Ling experimentally investigated the influence of rubber content within the range of 5–50% on the density and compressive strength and proposed the linear and logarithm equations to predict these two parameters of rubberized concrete blocks [7]. In addition, Ling also studied the effects of compaction method on the properties of concrete paving blocks [8].

Different from above works, this study does not focus on the use of waste tires, but on the use of the periodic theory to rubber concrete composites. Investigations in the field of solid state physics show that the phononic crystal (one kind of periodic material or periodic structure) can produce bands of frequency gaps. If the excitation frequencies fall within the frequency gaps, the waves cannot propagate in, or through, the material. Therefore, periodic materials may be designed with one or more band of frequency gaps in order to block wave propagation or reduce vibration, which has many potential applications, such as reducing engine noise, suppressing vibrations in civil structures, isolating seismic vibrations, and reducing traffic noise [9–11]. In the following discussion, the term "band of frequency gap(s)" will be replaced by the term "attenuation zone(s)", and the attention is going to focus on the use of periodic theory to rubber concrete panels.

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In fact, the property of attenuation zone existing in periodic materials has been used in civil engineering field. By using the idea of the local resonant unit, Li and Chen developed a new concrete [12], incorporated the coated lead balls into a short fiber reinforced cementitious composite. Their experimental results showed that the new concrete has much better sound proofing capability and has good potential in engineering applications. Based on vibration theory, Zhang and Li developed a new approach to calculate the effective mass density for a composite modeled as consisting of a hard spherical core, with a soft shell layer surrounding the core and embedded in a stiff host medium [13]. By the use of finite-difference schemes, Redondo et al. [14,15] evaluated the potential of sonic crystals as sound diffusers, which showed that the performance of sonic crystals as sound diffusers could be improved. Guided by the achievements in the field of solid-state physics and the concept of band of frequency gaps, Shi and his co-workers [16–19] proposed a new and innovative method for seismic base isolation. Their works demonstrated that periodic foundations have a great potential in future applications for seismic isolation.

Though the periodic theory has been established in the solid-state-physics for many decades, it has been introduced into civil engineering field only recently. Lots of attentions have been paid to search possible application of periodic structures in civil engineering structure at the present. Meanwhile some problems have begun to emerge. Specially, the fundamental frequencies of most engineering structures and the frequencies of the main components of external excisions in civil engineering are usually below 50 Hz. For engineering application, periodic panels of small size are much applicable. Therefore, periodic rubber-concrete panels with limited size are always hoped to have low-frequency attenuation zones. To meet these requirements, this paper will give a comprehensive study on the attenuation zones of two-directional periodic rubber concrete panels. Attenuation zones of both the Bragg-scattering periodic panels and the Local-resonant periodic panels are studied comparatively. The influences of geometrical parameters on the complete attenuation zone are particularly discussed. In addition, the directional attenuation zones for periodic panels with non-symmetric unit cells are investigated. Finally, the dynamic responses of periodic structures with finite units to external excitations are investigated.

2. Basic theory

As illustrated in Fig. 1, a periodic panel containing inner scatters of any shape is considered. For two-component periodic panels, the inner scatters are made of concrete and the matrix is rubber; for three-component periodic structure, both the matrix and the core are made of concrete and the coating is rubber. Material parameters are given in Table 1. The periodic constant is assumed to be A. In this section, the basic theory for waves propagating in infinite periodic panels is presented.

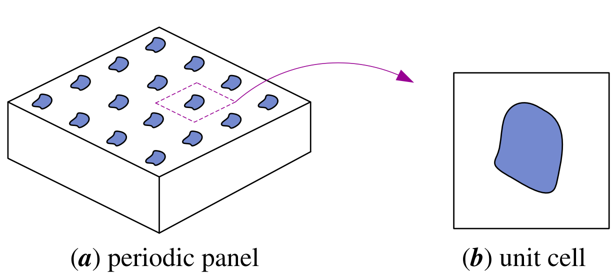

Fig. 1. Illustration of a periodic panel and its unit cell.

Table 1
Material component properties [16].

Material	Young modulus E (Pa)	Poisson ratio ν	Density ρ (kg/m^3)
Rubber	1.37×10^5	0.463	1300
Concrete	3.00×10^{10}	0.2	2500

2.1. Governing equations

Under the assumption of a continuous, isotropic, perfectly elastic and small deformation as well as without consideration of material damping, the governing equation for the in-plane waves propagating in a two-dimensional inhomogeneous solid can be given as:

$$\begin{cases} \rho(\boldsymbol{r})\frac{\partial^2 u}{\partial t^2} = \frac{\partial}{\partial x}\left[C_{11}(\boldsymbol{r})\frac{\partial u}{\partial x} + C_{12}(\boldsymbol{r})\frac{\partial v}{\partial y}\right] + \frac{\partial}{\partial y}\left[C_{44}(\boldsymbol{r})\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right] \\ \rho(\boldsymbol{r})\frac{\partial^2 v}{\partial t^2} = \frac{\partial}{\partial x}\left[C_{44}(\boldsymbol{r})\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right] + \frac{\partial}{\partial y}\left[C_{21}(\boldsymbol{r})\frac{\partial u}{\partial x} + C_{22}(\boldsymbol{r})\frac{\partial v}{\partial y}\right] \end{cases}. \quad (1)$$

where (u, v) is the displacement vector, $\boldsymbol{r} = \{x, y\}$ the coordinate vector, $C_{11}, C_{12}, C_{21}, C_{22}, C_{44}$ are the elastic parameters, ρ the density and t the time parameter.

For simplicity, concrete and rubber can be taken as isotropic material, whose elastic parameters are:

$$\mathbf{C} = \begin{bmatrix} \frac{E(1-v)}{(1+v)(1-2v)} & \frac{vE}{(1+v)(1-2v)} & 0 \\ \frac{vE}{(1+v)(1-2v)} & \frac{E(1-v)}{(1+v)(1-2v)} & 0 \\ 0 & 0 & \frac{E}{2(1+v)} \end{bmatrix} \quad (2)$$

where E and v are the Young modulus and the Poisson ratios, respectively.

2.2. Periodic boundary conditions

According to the periodic theory, solutions of Eq. (1) can be expressed as:

$$\boldsymbol{u}(\boldsymbol{r}, t) = e^{i(\boldsymbol{K}\cdot\boldsymbol{r} - \omega t)}\boldsymbol{u}_{\boldsymbol{K}}(\boldsymbol{r}) \quad (3)$$

in which, $\boldsymbol{K}$ denotes the wave vector in the reciprocal space, ω the angular frequency, and $u_{\boldsymbol{K}}(\boldsymbol{r})$ the wave amplitude, which is a periodic function:

$$u_{\boldsymbol{K}}(\boldsymbol{r}) = u_{\boldsymbol{K}}(\boldsymbol{r} + \mathrm{A}) \quad (4)$$

in which $\boldsymbol{A}$ is a constant vector.

Due to periodicity, the dispersion relationships of an infinite periodic structure can be investigated by using a typical periodic unit with periodic boundary conditions. Substituting Eq. (4) into Eq. (3), periodic boundary conditions can be obtained as follow and shown in Fig. 2:

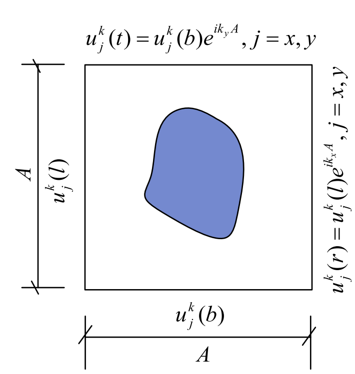

Fig. 2. Periodic boundary conditions for two-dimensional periodic panels.