Experimental Investigation on Flexural Vibration Control of Large-scale Reinforced Concrete Metaplates

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ABSTRACT

In this study, the vibration control performance of a large-scale reinforced concrete (RC) metaplate is experimentally validated and investigated. The local resonance frequency of plate-type LRM unit is numerically estimated. 4,200 x 3,000 x 210 mm RC metaplate, embedded with 165 LRM units measuring 200 x 200 x 85 mm each, is excited to heavy-weight impact to measure its acceleration responses. The experimental results showed that the generation of a local resonance bandgap in metaplate, leading to vibration control within the bandgap frequency range. The acceleration response of the metaplate is attenuated by up to 85.39 % at the local resonance frequency (42.51 Hz) compared to an RC plate without LRMs. The amplitude of modal peak within the bandgap frequency range is attenuated by up to 71.22 %. Based on the two indicators used to analyzed vibration control performance, The influence of both the local resonance and modal characteristics of the metaplate on its bandgap behavior is analyzed.

INTRODUCTION

Since the pioneering work of Liu et al. [1] on locally resonant phononic crystals (LRPCs), research on locally resonant metastructures has evolved into an active area over the past 20 years. The wave control mechanism of locally resonant metamaterials (LRMs) produce the bandgap, which generate evanescent waves and dissipate energy around the local resonance frequency of the resonators [2]. The safety and serviceability of structures could be easily hindered by vibrations, rendering LRMs a focal point of extensive research for various engineering applications.

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In particular, on plate structures, Al ba'ba'a et al. [3] conducted structural intensity analysis on an aluminum plate measuring 270 x 243 x 2.54 mm, composed of 100-unit cells of 24 x 24 mm. The experimental results demonstrated that metaplates effectively attenuated the propagating waves within the bandgap frequency ranges of 1550-2275 Hz. Liu et al. [4] proposed LRM sandwich plates and validated their performance using finite element (FE) analysis. The influence of the radiated sound from the resonators is investigated within frequency regions above 600 Hz. Peng et al. [5] proposed acoustic multi-stopband metaplates and presented design guidelines for broadband vibration control. The infinite metaplates were modeled using the extended Hamilton's principle based on FE analysis, and bandgap behaviors were observed for frequencies above 700 Hz. However, literature reviews indicated that most of the research on metaplates with LRMs has been verified through FE analysis or small- and laboratory-scale experiments. Moreover, the majority of studies on metaplates have primarily focused on the mid- to high-frequency ranges above 100 Hz.

To address these limitations, recently, the authors analyzed the bandgap behavior by applying LRPCs to the floors of a 20-story residential building [6]. A total of 50 LRPCs, each with a cube shape and a side length of 150 mm, were installed on a floating floor system measuring 9,810 x 4,700 mm. Experimental results confirmed that flexural vibrations and sound radiation were attenuated within the local resonance bandgap frequency regions of 36.13-51.00 Hz. Furthermore, to consider the ease of design, installation, and workability, plate-type LRMs were proposed and applied to a 5 m steel beam to observe the bandgap behavior [7]. Three indicators were introduced to evaluate the vibration control performance. The maximum reduction of 98.58 % in acceleration response was achieved near 40 Hz. However, it should be noted that such types of LRMs may require additional spaces or installation strategies outside the host structures for stable maintenance and installation. Furthermore, surface-mounted LRMs on the host structure are more likely to exhibit lower control performance compared to embedded-type LRMs [4].

Therefore, This study experimentally investigates the flexural vibration control performance of a large-scale metaplate embedded with LRMs. The local resonance frequency of the LRM unit is estimated based on the material properties, such as mass density, Young's modulus. To validate the proposed approach, the acceleration response of the 4,200 x 3,000 x 210 mm RC metaplate excited to heavy-weight impact are compared and analyzed with those of an RC plate without LRMs. Furthermore, the vibration control performance of the metaplate is quantitatively presented using two indicators, which enables for an analysis of the relationship between modal characteristics and bandgap behaviors.

EXPERIMENTAL SETUP

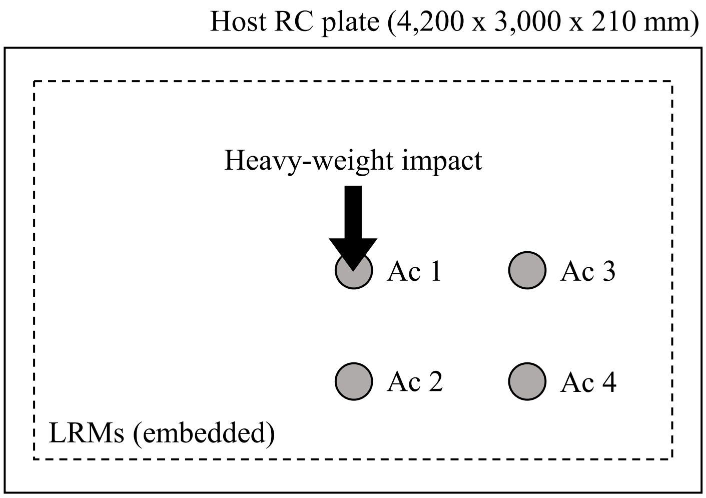
In this study, the LRM unit consisted of plate-type structures incorporating both hard and soft materials. The hard material was sandwiched between two layers of soft material. Since both sides of the LRM unit were composed of soft material, the hard material could freely oscillate even when the unit was embedded in the host structure. The local resonance frequency of this plate-type LRM unit could be calculated as [7]:

$$f_r = \frac{1}{2\pi}\sqrt{2k/m} = \frac{1}{2\pi}\sqrt{2E_s/l_h l_s \rho_h}. \quad (1)$$

Here, m and k represent the mass and stiffness of the local resonator, respectively. E, l, and ρ correspond to Young's modulus, thickness, and mass density, respectively. The subscripts s and h denote the soft and hard materials. In this study, steel was used as the hard material, while graphite-embedded expanded polystyrene (EPS) foam was employed as the soft material to control structural vibrations within the frequency range of 30-60 Hz. The mass density of steel is 7,850 kg/m^3, and the dynamic stiffness of EPS foam is 7MN/m^3. The thickness of steel and EPS foam is 25 and 30 mm, respectively. Finally, the dimensions of the LRM unit are 200 x 200 x 85 mm. The local resonance frequency of the LRM unit, calculated using Eq. (1), is 42.51 Hz. Therefore, based on the vibration control mechanism of the local resonance bandgap, it is estimated that the flexural vibration of the metaplate will be attenuated around this frequency.

Figure 1 illustrates the experimental setup to validate and analyze the vibration control of the large-scale metaplate using the fabricated LRM units. A total of 165 LRM units were embedded in the metaplate, which measured 4,200 x 3,000 x 210 mm. The dimensions of the plate are commonly used in various civil and infrastructure applications, including walls, slabs, bridges, and towers, as well as aerospace, automotive, marine structures. Considering these, RC was used as the host medium. To measure the acceleration response of the metaplate, as shown in Fig. 1(a), the metaplate was lifted and supported at four points using a crane. This setup can be considered similar to a completely free boundary condition. The positions for measuring the acceleration responses and excitation are indicated in Fig. 1(b). Considering the local resonance characteristics of the LRM unit, the metaplate was excited using a standard rubber ball, which corresponds to the standard impact source specified in ISO 10140-5 [8]. The standard rubber ball is a well-known device to replicate heavy-weight impact source with reliable similarity. Acceleration responses were measured at four locations to analyze the modal response of the structure with the bandgap behavior. Additionally, to fairly analyze the bandgap behavior of the metaplate, the acceleration response of an RC slab without LRM units was measured through the identical procedure.

(a)



(b)

Figure 1. Experimental setup for measuring flexural vibration of metaplate:
(a) a photograph, (b) impact and measurement locations.

RESULTS AND DISCUSSION

Figure 2 compares the frequency spectra of the acceleration responses of the metaplate and the plate without LRMs, measured at Ac 1-4. The experimental results clearly indicate that the acceleration response of the metaplate is significantly attenuated around the local resonance frequency (35-55 Hz) of the LRM units at all measurement points. This observation suggests that the attenuation is attributed to the presence of the local resonance bandgap. The metaplate exhibits upper and lower peaks at 25.2 and 67.4 Hz, respectively, which are not present in the plate without LRMs. This phenomenon could be attributed to the anti-resonance effect provide by the LRM units, similar to conventional vibration absorbers [5]. The generation of new peaks in metastructures has been reported in analytical and experimental results on previous studies [7]. Meanwhile, since LRMs have a minimum effective mass density with a negative value in the immediate upper frequency region of the local resonance frequency [9], metastructures can exhibit a sharp decrease in structural response in that range. However, this phenomenon was not observed in this study, consistent with previous research [7] that applied similar plate-type LRMs to beam structures. These multiple experimental findings suggest that metastructures incorporated plate-type LRMs may exhibit a strong anti-resonance effect in addition to the local resonance bandgap effect. This could improve vibration control performance of metastructures with plate-type LRMs at specific frequencies.

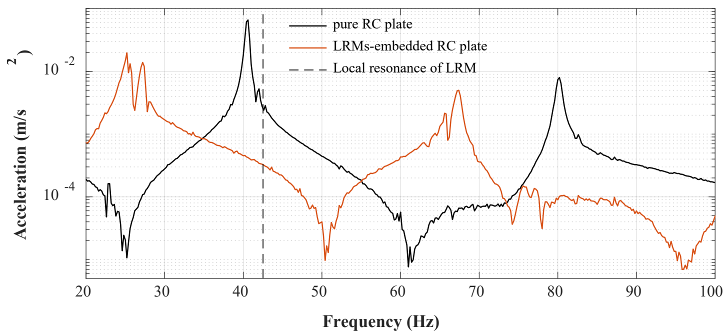


Figure 2. Bandgap behaviors of metaplate for vibration control measured at Ac 1.

The bandgap behavior of the metaplate also attenuated the maximum acceleration response of its second mode (40.6 Hz). The maximum response of a structure is one of the most common indicators used to assess its safety and serviceability [10]. Therefore, Choi et al. [7] evaluated the response control performance of the metastructures using the response suppression ratio in the local resonance frequency (RSiR) and the peak (or maximum) response suppression ratio (PRSR). RSiR and PRSR are calculated as:

$$RSiR = {(P_b - P_c)}/{P_b} \times 100(\%), \text{ and} \tag{2}$$

$$PRSR = {\left(P_p - max(P_l, P_u)\right)}/{P_p} \times 100(\%) \tag{3}$$

Here, P_b and P_c represent the responses of the plate without LRMs and the metaplate at the resonance frequency of the LRM units, respectively. P_u, P_l and P_p denote the amplitudes of the upper and lower peaks generated in the metaplate, and the maximum response of the plate without LRMs, respectively. RSiR evaluates the response suppression at the target frequency in design process, while PRSR aims to assess the maximum response suppression of the metaplate due to tis bandgap behavior.

TABLE I. RSiR calculated at each measurement locations.

Ac 1	**Ac 2**	**Ac 3**	**Ac 4**
86.66 %	72.23 %	85.39 %	66.19 %

TABLE II. PRSR calculated at each measurement locations.

Ac 1	**Ac 2**	**Ac 3**	**Ac 4**
70.08 %	71.22 %	26.10 %	21.06 %

The calculated RSiR and PRSR for each location of the metaplate are presented in Table I and II. The PRSR for Ac 1-2 is consistently above 70 %, while for Ac 3-4, it ranges from 21 % to 26 %. The significant difference in PRSR between Ac 1-2 and Ac 3-4 is attributed to the influence of the modal characteristics of metaplate on its bandgap behavior. As the modal energy decreases, the bandgap behavior becomes weaker [6]. The second modal vector of the metaplate under completely free boundary conditions is maximum at Ac 1-2 and approaches a minimum value near Ac 3-4. Therefore, these results further support that bandgap behavior is influenced by the modal characteristics of metastructures. On the other hand, in Table I, RSiR showed consistently high values of 66 % or above at all measurement locations.

CONCLUSIONS

In this study, the vibration control performance of a large-scale RC metaplate with embedded LRM units was experimentally investigated. To this end, the local resonance frequency of the fabricated LRM units were numerically estimated, and the bandgap behavior of the metaplate near the frequency was observed. From the perspective of structural safety and serviceability evaluation, the vibration control performance of the metaplate was analyzed using two indicators.

The experimental results on the 4,200 x 3,000 x 210 mm RC metaplate clearly demonstrated that the acceleration responses were reduced by the local resonance bandgap. The additionally observed anti-resonance effect of the LRM units further enhances the vibration control performance of the metaplate. Based on the calculated RSiR and PRSR, the acceleration response of the metaplate was reduced by up to 85.39 % at the local resonance frequency. The maximum response of the structure was reduced by up to 71.22 % in the bandgap frequency range. Moreover, it is notable that the maximum response reduction of the structure is influenced not only by bandgap frequency range but also by the modal characteristics of the metaplate. Therefore, for efficient metaplate design, while the vibration at the target frequency could be controlled based on local resonance estimation, achieving optimal control of maximum structural response may also require the consideration of the modal characteristics.

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