Conceptual Design of Novel Locally Resonant Meta-Basement for Seismic Protection of High-rise Buildings

Wen Zhou[1], Kaiming Bi[1*], Hong Hao[1]

Centre for Infrastructure Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Bentley, WA 6102, Australia

kaiming.bi@curtin.edu.au

Abstract

The recent advances in solid-state physics revealed that periodic structures, termed elastic metamaterials, can block the propagation of acoustic/elastic waves when the frequencies of input waves fall within the bandgaps. On this basis, researchers have developed meta-based techniques for structural vibration control, and it was found that the locally resonant metamaterials can attenuate waves with wavelengths much greater than their geometric size. On the other hand, floating floor structure (FFS), in which the floor is isolated from the supporting beam, has been used to control the vibrations of buildings. Inspired by the two techniques, in the present study, a novel locally resonant meta-basement is formed by modifying the conventional underground basement of high-rise building to mitigate structural vibrations during earthquake excitations. The feasibility of the proposed method is demonstrated by analytical study on the infinite number of unit cells, and the control effectiveness is evaluated by finite element modelling.

Keywords: High-rise building; vibration control; meta-basement.

1 Introduction

Many high-rise buildings exist in modern cities. The fundamental vibration frequency of high-rise buildings is normally low, which makes them likely to resonate with earthquake ground motions and thus be damaged in a severe earthquake. Various vibration control techniques have been proposed in the past decades to control the adverse excessive vibrations, and they can be broadly classified into passive, active, and semi-active control methods (Parulekar and Reddy 2009). However, some inherent shortcomings exist for these traditional methods. For example, passive control techniques usually require large additional mass; active and semi-active control methods require a continuous supply of power (Abdelraheem Farghaly 2012, Yang et al. 2017). It is therefore necessary to develop some other vibration control techniques to overcome these limitations.

Metamaterial is an artificial material which can be used to manipulate the propagation patterns of elastic waves. The Locally Resonant Metamaterials (LRM) is found to be able to attenuate elastic waves at a wavelength much longer than its geometrical dimension, making it practical for civil structural vibration control. Xiang et al. (2012) and Bao et al. (2012) proposed the concept of meta-foundation and developed a one-dimensional (1D) meta-foundation with concrete and rubber. Cheng and Shi (2014) extended the above researches and discussed the influences of the key parameters on the bandgap properties through systematic parametric studies. Yan et al. (2014) further developed the 2D and 3D (Yan et al. 2015) meta-foundations, and validated their effectiveness through experimental studies. It should be noted that the size of the above proposed meta-foundation was extremely large in order to create low frequency bandgaps for mitigating seismic ground excitation effect, their application potential is therefore questionable. Basone et al. (2019) proposed a new type of locally resonant meta-foundation for fuel storage tank vibration control. In which, a shear frame was used to replace the hosting material in the conventional meta-foundation, and a concrete mass block was connected to the shear frame and performed as the local resonator. The effectiveness of the proposed method was validated through numerical studies. However, this design is impractical for high-rise buildings because no space is available for the additional mass blocks as the basement is normally reserved for parking bays. On the other hand, the "strong-column weak-beam (SCWB)" philosophy is widely adopted in the seismic resistant design of frame structures to prevent the collapse of buildings (Kirk and Hao 2009, Nie et al. 2020). When an earthquake occurs, the beam is expected to yield prior to the column, and thus to prevent the collapse of the column. The concept of floating floor structure (FFS) is an alternative method to realize SCWB. In FFS, instead of rigidly connecting the floor slab and beam, the entire or partial floor slab is isolated from the beam, the flexural strength of the beam is thus significantly reduced. Moreover, the isolated part is free to vibrate from the primary structure and can serve as an energy absorption device. The effectiveness of FFS has been widely investigated (Taflanidis and Jia 2011, Jia et al. 2014).

Inspired by the previous studies, a novel meta-basement is proposed in the present study. By introducing FFS into meta-foundation, the basement floor slab is separated from the supporting beam and serves as the local resonator in metamaterial. Through careful design, bandgaps can be formed and the energy of seismic wave with frequencies in the meta-foundation bandgap can be filtered, the vibration of the super-structure is thus expected to be mitigated. The effectiveness of the proposed method is examined in the present study.

2 Conceptual Design

Fig. 1(a) shows the layout of a typical high-rise building. Since this study focuses on the basement, the super-structure is simplified as a one-storey structure just to reflect its first mode. The building consists of an *N*-level basement and a one-storey super-structure. Fig. 1(b) shows the schematic view of the building with proposed meta-basement. As shown, the basement floor slab is isolated from the beam by using the isolation bearings. With such a design, the floor slab can vibrate freely with respect to the main structure in the horizontal direction.

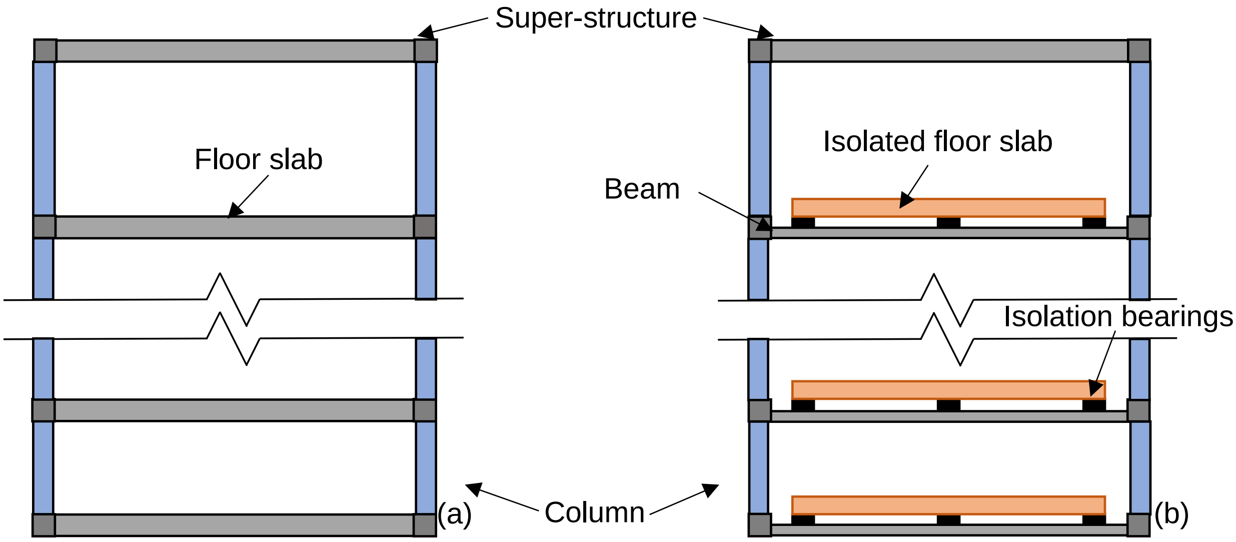

Figure 1. Elevation view of a structure with (a) conventional basement and (b) meta-basement.

3 Analytical Model

Fig. 2 shows the analytical model of a building with the proposed meta-basement. As shown, the mass and lateral stiffness of super-structure are m^S and k^S, respectively. The super-structure is supported by an *N*-level meta-basement, the height of each level is *h,* and the lateral stiffness is k_0. The mass of the basement floor slab is m_1 and that of the beam is m_0. The slab and beam are connected by a spring with stiffness k_1 in the horizontal direction.

In the metamaterial concept, the dispersion curve normally needs to be derived to show the bandgap. To obtain the dispersion curve of the meta-basement, one unit cell, i.e., one-storey of meta-basement, is taken out for analysis. Fig. 3 shows the mass-spring model of the *jth* unit cell. The corresponding equations of motion can be expressed as

$$\begin{cases} m_0\ddot{u}_0^j + k_0\left(2u_0^j - u_0^{j-1} - u_0^{j+1}\right) + k_1\left(u_0^j - u_1^j\right) = 0 \\ m_1\ddot{u}_1^j + k_1\left(u_1^j - u_0^j\right) = 0 \end{cases} \tag{1}$$

where u_0 and u_1 represent the displacements of the isolated floor slab and beam, respectively. The superscripts j, $j-1$ and $j+1$ denote the counts of the unit cell or basement floor level. The over dot represents the differentiation with respect to time. Based on Floquet-Block theory, the propagation of elastic waves in a periodic structure can be expressed by Eq. (2)

$$\boldsymbol{u}(\boldsymbol{r},t) = e^{i(q\cdot r-\omega t)}\boldsymbol{u_k}(\boldsymbol{r}) \tag{2}$$

in which q denotes the wave vector in reciprocal space; ω is the angular frequency; $\boldsymbol{u_k}(\boldsymbol{r})$ is the vector of wave amplitude, which is a periodic function about the periodic constant $\boldsymbol{A}$, namely

$$\boldsymbol{u_k}(\boldsymbol{r}) = \boldsymbol{u_k}(\boldsymbol{r}+\boldsymbol{A}) \tag{3}$$

Substituting Eq. (3) into Eq. (2), the periodic boundary condition can be obtained as follows

$$\boldsymbol{u}(\boldsymbol{r}+\boldsymbol{A},t) = e^{iq\cdot\boldsymbol{A}}\boldsymbol{u}(\boldsymbol{r},t) \tag{4}$$

Obviously the periodic constant $\boldsymbol{A}$ in uniaxial state is h in the present study. Applying the periodic boundary condition to Eq. (1), the dispersion relation can be obtained by solving the following equation:

$$m_0m_1\omega^4 - \{2k_0m_1[1-\cos(q\times h)] + k_1(m_0+m_1)\}\omega^2 + 2k_0k_1(1-\cos(q\times h))=0 \tag{5}$$

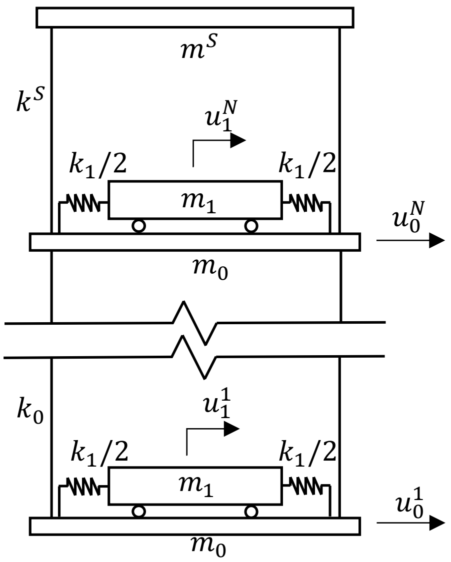

Fig. 2. Analytical model of a structure with a meta-basement.

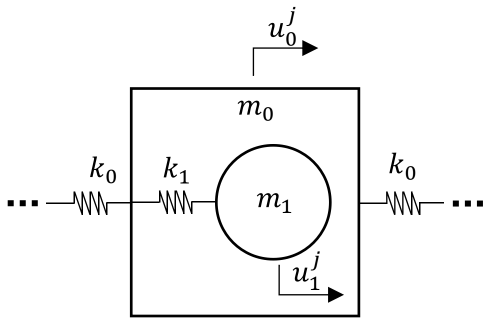

Fig. 3. Mass-spring model of the jth unit cell of the meta-basement.

4 Development of Finite Element (FE) Model

Commercially available software ANSYS is used to model the buildings with conventional basement and meta-basement as shown in Fig. 1. Only the horizontal vibration is considered in the present study, the building is therefore simplified as a 2D one-bay structure as shown in Fig. 4. Beam4 element in ANSYS is adopted to simulate all the components. In order to have a direct comparison with the analytical model (see Fig. 3), the mass of each column is lumped to its two ends and is considered together with the mass of the beam. Fig. 4(a) shows the FE model of the conventional building, and Fig. 4(b) shows that of the building with meta-basement. The modelling techniques for the two buildings are exactly the same. The difference is that the floor slab and supporting beam are separated with each other, and two springs with a stiffness of $k_1/2$ are used to connect the beam and slab in the meta-basement as shown in Fig. 4(b), the springs are modelled by Combine14 element in ANSYS.

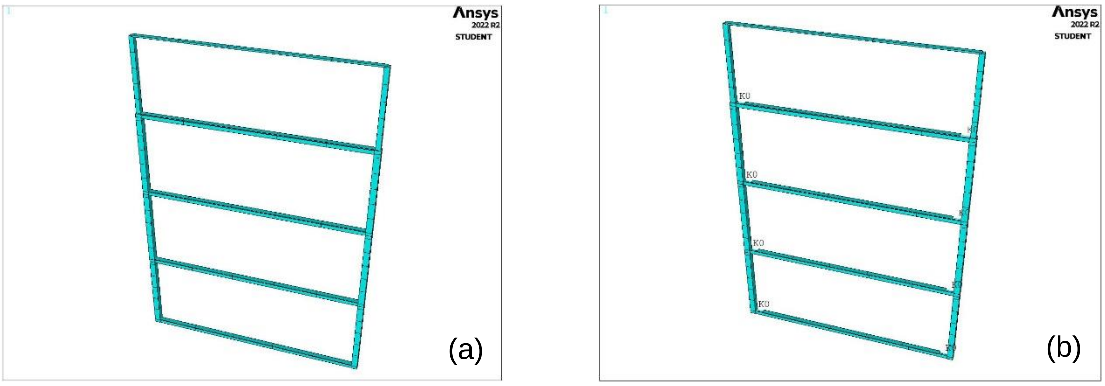

Fig. 4. FE models of the buildings with (a) conventional basement and (b) meta-basement.

5 Bandgap of Uncoupled Systems

The theoretical bandgap of an uncoupled meta-basement (i.e., without considering super-structure) is calculated by solving Eq. (5), and the bandgap of a 4-storey meta-basement is also calculated with the FE model as developed in Section 4 (without the super-structure). A real building is selected as the prototype building, and the parameters of the basement are $[m_0, m_1, m^S, k_0, k^S, h] = [9.98 \times 10^5 \text{ kg}, 9.38 \times 10^5 \text{ kg}, 2.50 \times 10^7 \text{ kg}, 2.81 \times 10^{10}\ N/m, 5.63 \times 10^9\ N/m, 3.8 \text{ m}]$. The bandgap is designed to cover the fundamental vibration frequency of the building (i.e., 2.25 Hz), k_1 is therefore set as 1.7×10^{10} N/m. With the above parameters, the analytical dispersion relation curve is calculated and shown in Fig. 5. It can be seen that the meta-basement has a bandgap between 2.14 Hz and 2.98 Hz. For the 4-storey meta-basement shown in Fig. 4(b), a harmonic displacement excitation with a sweeping frequency between 0 and 6 Hz is applied to the bottom nodes of the structure in the horizontal direction, while the response of a node on the top of the basement is collected as output. The averaged response function (ARF), which is defined as $\tau = 20\log(u_0^N/u_0^1)$, is normally used to assess the control effectiveness (Cheng et al. 2013), where u_0^N and u_0^1 are the displacement amplitudes of the last cell and the first cell (i.e., the excitation displacement), respectively. The calculated ARF is shown in Fig. 6. It can be observed that the ARF falls into negative region in the shaded area, i.e., a bandgap between 2.14 Hz and 3.10 Hz is observed. The results clearly show that a bandgap exists in the proposed novel meta-basement, which demonstrates the feasibility of the proposed system for vibration mitigation. Moreover, these results also validate the accuracy of the developed FE model. It can also be seen that the bandgap obtained from the FE model is slightly different from that obtained from the analytical result. This is because the analytical model is based on the assumption of infinite number of unit cells, while there are only four unit cells in the FE model.

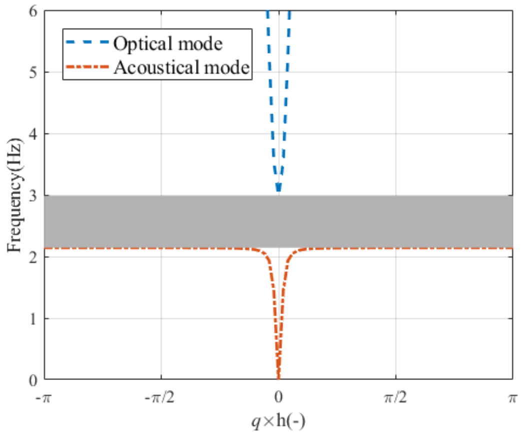

Fig. 5. Dispersion relation curve obtained based on the analytical model.

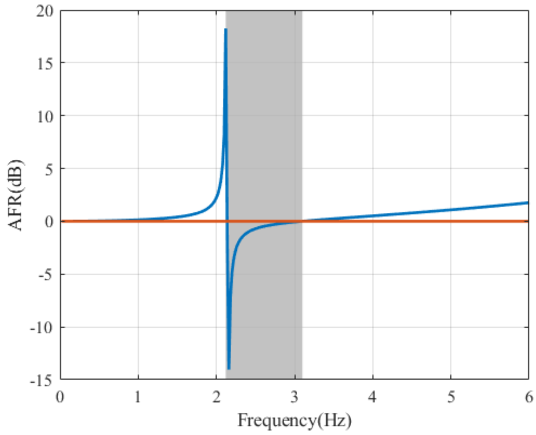

Fig. 6. Averaged response function (ARF) obtained based on the FE model.

6 Numerical Simulation of Coupled Systems

The above derivation is based on uncoupled system (i.e., only the foundation is considered). For a high-rise building, coupling effect between the super-structure and the foundation is significant. According to the studies in (La Salandra et al. 2017) and (Xiao et al. 2020), coupling can cause structural vibration frequency shift and obviously influence the control effectiveness. To explicitly demonstrate the control effectiveness of the proposed method, time history analyses on the high-rise building (a coupled system) are performed in this section. Three typical earthquake ground motion records, with dominant frequency contents below (GM1 in Table 1), within (GM2) and higher (GM3) than the designed bandgap, are applied to the building. More detailed information can be found from Table 1 and Fig. 7.

Table 1. Selected earthquake ground motions.

No.	Ground Motion	Year	Record Station	Magnitude	PGA (m/s^2)
GM1	Loma Prieta	1989	APEEL 2 - Redwood City	6.9	2.7
GM2	San Fernando	1971	Anza Post Office	6.6	0.3
GM3	San Fernando	1971	Lake Hughes #12	6.6	3.7

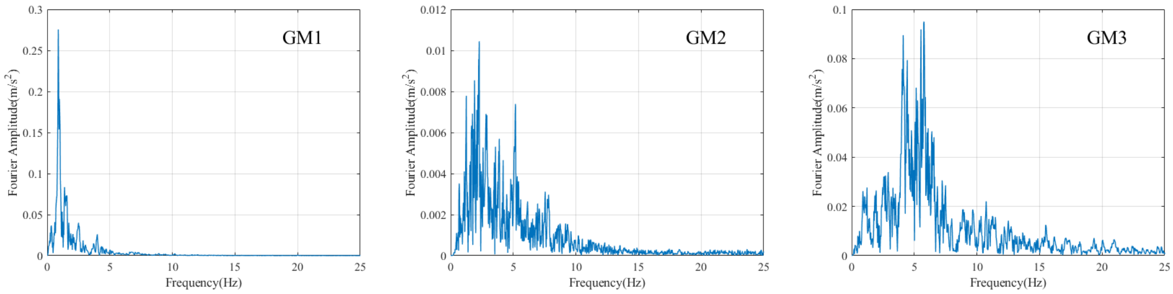

Fig. 7. Fourier spectra of the selected earthquake ground motions.

The dynamic responses of the buildings with conventional basement and meta-basement are calculated in this section. Fig. 8 shows the relative displacement time histories between the top of the super-structure and the bottom of the foundation. To quantitatively evaluate the control effectiveness, a reduction ratio $\alpha = (RMS^C - RMS^M)/RMS^C$ is defined, in which RMS^C and RMS^M are the Root Mean Square displacements of the conventional and meta-basement buildings, respectively. The results are summarized in Table 2. It can be seen that for all the three ground motions, meta-basement results in the smaller responses compared to the conventional basement, which demonstrates the effectiveness of the proposed method. The results also show that the control effectiveness is highly influenced by the relationship between the energy contents of input wave. As can be read from Table 2, the reduction ratio of GM2 (with the dominant energy in the designed bandgap) is 24.9%, which is much larger compared to the other two cases (with the dominant energy outside of the designed bandgap) with an average reduction of 4.5%. That is because most of the seismic energy of GM2 is within the designed bandgap, the meta-basement is expected to filter out the energy of input wave with frequency in the meta-basement bandgap, which leads to the most evident control effectiveness. While at the same time, the dominant frequency contents of GM1 and GM3 are outside the designed bandgap, the meta-basement can only filter out limited energy, the control effectiveness is thus not pronounced.

In summary, the meta-basement can mitigate the vibration of the structure. The control effectiveness is, however, significantly influenced by the frequency contents of the ground motions. The most evident control effectiveness can be obtained when the bandgap covers both the frequency range of the dominant ground motion energy and the fundamental vibration frequency of the super-structure. Therefore, designs to extend the width of bandgap to cover a wide frequency range are needed.

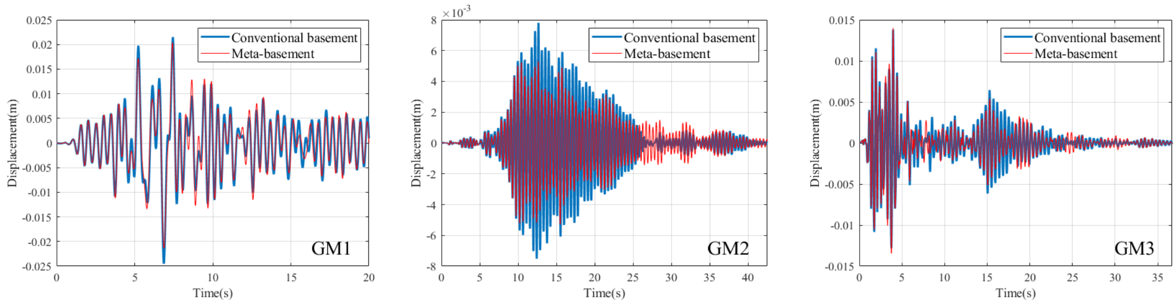

Fig. 8. Relative displacement responses of the buildings with conventional basement and meta-basement.

Table 2. RMS displacements and reduction ratios of the buildings under the selected earthquakes.

No.	Ground motion (GM)	Record Station	RMS^M(m)	RMS^C(m)	α(%)
GM1	Loma Prieta	APEEL 2 - Redwood City	0.0057	0.0059	3.5
GM2	San Fernando	Anza Post Office	0.0015	0.0020	24.9
GM3	San Fernando	Lake Hughes #12	0.0023	0.0025	5.5

7 Conclusion

A novel locally resonant meta-basement, which is developed based on the combined metamaterial and FFS concepts, is proposed in the present study for seismic induced vibration control of high-rise buildings. The meta-basement can perform the same as a normal basement under static loads because no change is needed to be made on the columns. Its effectiveness is examined through analytical and numerical analyses, respectively. The results show that with properly selected parameters (i.e. the connecting stiffness and geometric dimension of isolated floor slab), the proposed locally resonant meta-basement shows an obvious bandgap, which therefore has the application potential for seismic induced vibration control. However, the control effectiveness is significantly influenced by the frequency contents of the ground motions. The most evident control effectiveness can be obtained when both the fundamental vibration frequency of the building and the frequency range of the dominant energy of the ground motions are within the meta-basement bandgap.

The results presented in this manuscript are based on a conceptual study of modifying the conventional basement of building structures to achieve a bandgap for vibration mitigation of structures subjected to earthquake ground motions. Further studies are deemed necessary to consider modification techniques of the basement to achieve a wider frequency bandgap that covers the frequency range of dominant ground motion energy as well as the frequencies of multiple vibration modes of building structures. Detailed parametric studies are also required to determine the key influencing factors on structural performance.

Acknowledgements

The support from Australian Research Council Future Fellowship FT200100183 is acknowledged.

References

Abdelraheem Farghaly, A. (2012). "Optimum design of TMD system for tall buildings." Iran University of Science & Technology Vol 2, No 4, pp: 511-532.

Bao, J., Z. Shi and H. Xiang (2012). "Dynamic Responses of a Structure with Periodic Foundations." Journal of Engineering Mechanics Vol 138, No 7, pp: 761-769.

Basone, F., M. Wenzel, O. S. Bursi and M. Fossetti (2019). "Finite locally resonant Metafoundations for the seismic protection of fuel storage tanks." Earthquake Engineering & Structural Dynamics Vol 48, No 2, pp: 232-252.

Cheng, Z. and Z. Shi (2014). "Vibration attenuation properties of periodic rubber concrete panels." Construction and Building Materials Vol 50, pp: 257-265.

Cheng, Z., Z. Shi, Y. Mo and H. Xiang (2013). "Locally resonant periodic structures with low-frequency band gaps." Journal of Applied Physics Vol 114, No 3, pp: 033532.

Jia, G., I. Gidaris, A. A. Taflanidis and G. P. Mavroeidis (2014). "Reliability-based assessment/design of floor isolation systems." Engineering Structures Vol 78, pp: 41-56.

Kirk, J. and H. Hao (2009). Numerical Investigation of Floor Isolation for Passive Earthquake Energy Dissipation, The Australian Earthquake Engineering Society.

La Salandra, V., M. Wenzel, O. S. Bursi, G. Carta and A. B. Movchan (2017). "Conception of a 3D metamaterial-based foundation for static and seismic protection of fuel storage tanks." Frontiers in Materials Vol 4, pp: 30.

Nie, X., S. Zhang, T. Jiang and T. Yu (2020). "The strong column–weak beam design philosophy in reinforced concrete frame structures: A literature review." Advances in Structural Engineering Vol 23, No 16, pp: 3566-3591.

Parulekar, Y. and G. Reddy (2009). "Passive response control systems for seismic response reduction: A state-of-the-art review." International Journal of Structural Stability and Dynamics Vol 9, No 01, pp: 151-177.

Taflanidis, A. A. and G. Jia (2011). "A simulation-based framework for risk assessment and probabilistic sensitivity analysis of base - isolated structures." Earthquake Engineering & Structural Dynamics Vol 40, No 14, pp: 1629-1651.

Xiang, H., Z. Shi, S. Wang and Y. Mo (2012). "Periodic materials-based vibration attenuation in layered foundations: experimental validation." Smart Materials and Structures Vol 21, No 11, pp: 112003.

Xiao, L., F. Sun and O. S. Bursi (2020). "Vibration attenuation and amplification of one-dimensional uncoupled and coupled systems with optimal metafoundations." Journal of Engineering Mechanics Vol 146, No 7, pp: 04020058.

Yan, Y., Z. Cheng, F. Menq, Y. Mo, Y. Tang and Z. Shi (2015). "Three dimensional periodic foundations for base seismic isolation." Smart Materials and Structures Vol 24, No 7, pp: 075006.

Yan, Y., A. Laskar, Z. Cheng, F. Menq, Y. Tang, Y. Mo and Z. Shi (2014). "Seismic isolation of two dimensional periodic foundations." Journal of Applied Physics Vol 116, No 4, pp: 044908.

Yang, D.-H., J.-H. Shin, H. Lee, S.-K. Kim and M. K. Kwak (2017). "Active vibration control of structure by active mass damper and multi-modal negative acceleration feedback control algorithm." Journal of Sound and Vibration Vol 392, pp: 18-30.