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Seismic Performance and Vibration Control of Urban Over-track High-rise Buildings

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Abstract During the structural design of urban over-track high-rise buildings, two problems are most likely encountered: the abrupt change of story stiffness between the podium and the upper towers, as well as the demand for train-induced vibration control. Traditional earthquake-resistant structures have to be particularly designed with transfer stories to meet the requirement of seismic control under earthquakes, and thus horizontal seismic isolation techniques are recommended to solve the transfer problem. The function of mitigating the vertical subway-induced vibration can be integrated into the isolation system including thick rubber bearings and 3D composite vibration control devices. Engineering project cases are presented in this paper for a more comprehensive understanding of the engineering practice and research frontiers of urban over-track high-rise buildings in China.

Keywords Urban over-track building, high-rise building, seismic isolation, train-induced vibration, 3D isolation device.

1. Introduction

The requirement of land resources being efficiently used brings about the inevitable outcome of gathering of population and growth of metropolises. Urbanization rates in developed countries have already exceeded 80%, and the authorized statistical data of China is 64.72% by the end of 2021 (National Bureau of Statistics, 2022). For instance, the urbanization rates of Beijing and Shanghai in China are approaching 90%. However, social problems are more likely to appear along with the process of urbanization, including the lack of land resources, which leads to possible solutions in different directions. Upwards, the design and construction techniques of tall buildings are increasingly maturing, enabling the development of commercial districts where skyscrapers are integrated. Downwards, underground spaces are explored and utilized, and newly constructed commercial buildings are completed with two or three functional stories underground. Outwards, since rare lands are available in the cities, suburban areas are generally planned for residential usage, which develops the necessity of convenient urban rail transit systems. As a consequence, the intensive mode of city development requires various functional spaces to coincide at the same plane position, and the integration of business and traffic land uses becomes the leading trend. Buildings are not only constructed near the urban rail transit systems, but also above them, which increases the need for urban over-track high-rise buildings.

Although construction of underground rail transit operation sections can be realized through the new Austrian tunneling method (NATM) or tunnel boring machines (TBM) to mitigate the influence of excavation on the surface buildings, the open-cut method is still broadly adopted for the construction of rail transit stations, and thus integrated planning and design of the station and its corresponding surface buildings are recommended. Besides, generally placed on the ground floor, urban rail transit depots take up massive land spaces for parking and maintenance of

Figure 1. Visualization of over-track development of Xinzhuang Metro Station.

Figure 2. Visualization of over-track development of Beianhe Depot.

vehicles, and the upper spaces should not be wasted. In both cases, over-track buildings are the best choices for property developers. Starting in 2007, over-track comprehensive development of Xinzhuang Metro Station in Shanghai is the first transit-oriented-development (TOD) project in the mainland of China, as shown in Figure 1, and has entered its third development phase (Lv, 2012) (Wang, 2016). The urban planning of Beianhe Deport of Metro Line 16 in Beijing reserves areas of 170,000 m^2 for over-track developments, and the whole project is honored as "urban park above the parking garage" (He and Zhou, 2017) (Liang, 2018), as shown in Figure 2. More and more over-track development projects are emerging, along with the expansion of their sizes, heights, and structural complexities. In addition, the Standard for Structural Design of Urban Over-track Buildings (T/CECS 1035-2022, 2022) in China was released as guidance for structural engineers.

Structural safety and residential comfort are two dominant considerations for buildings in the operation stages. These two aspects are critical for urban over-track high-rise buildings. Multi-tower-large-podium architectural topology is generally selected as the elevation layout to meet the functional requirements, as demonstrated in Figure 3. The substructure, i.e. the large podium, is adopted for the accommodation of passengers or rail transit vehicles, under circumstances of stations or depots, respectively, as well as operation of the urban rail transit systems. A larger inner space is required and thus frame structures are used. While for the high-rise superstructures, i.e. the upper towers, seismic wall structures are usually chosen based on the engineering practice in China. As a consequence, transfer members between the podium and upper towers should be carefully designed in order not to violate the load paths of the gravity loads. Moreover, functional requirements result in various story heights of the podium, and the formation of weak or soft stories should be avoided. Especially for over-track high-rise buildings, global bending of the superstructure about the wall base may lead to an overturning vibration mode. Since in these scenarios basement foundations are no longer accessible, the interaction between the podium and upper towers under seismic actions should be verified.

Concerning residential comfort, train-induced vibration has already been widely recognized as a public nuisance.

Figure 3. Multi-tower-large-podium architectural topology for TOD projects.

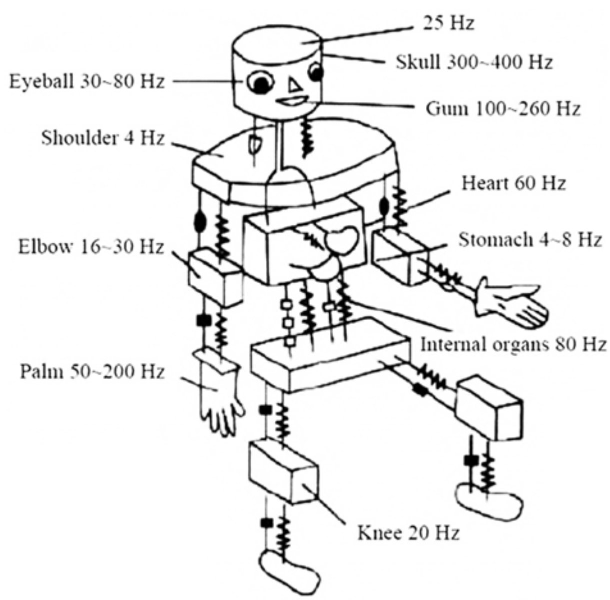


Figure 4. Simplified mechanical models and natural frequencies of human body parts.

As an extraordinarily sophisticated biological system, the human body may be simplified into a mechanical system composed of mass particles, springs, and damping components, as seen in Figure 4. The human body is able to sense mechanical vibrations of 1 ~ 1,000 Hz, but is only allergic to those below 80 Hz, since the high-frequency components attenuate rapidly affected by damping (Zhu, Qian, Pan, and Zhou, 2017). In-situ test results indicated that rail train-induced vibrations transmitted to the upper floors were usually concentrated in the frequency band of 20~50 Hz, dominated by the vertical vibrational component, which was proved to be the worst scenario for human health. Although it was generally considered that vibration attenuates along the elevation of the superstructure, relevant research showed that a first-attenuation-then-amplification trend should be the real case, which could be disadvantageous for the upper floors of high-rise buildings. Apart from seismic vibration control, train-induced ambient vibration control is catching increasing attention these days, and relative measures must be taken to ease the unfavorable corresponding social influences.

Based on relevant engineering practices and research frontiers in China, this paper presents various solutions to the above-mentioned problems in urban over-track high-rise buildings. First, seismic performances of over-track buildings are discussed, including traditional earthquake-resistant structures and isolated structures. Then, control measures for the train-induced vibration are summarized, and the applications of two newly developed isolation bearings are introduced. Finally, suggestions are provided for future research.

2. Earthquake-resistant design of over-track high-rise buildings

As a traditional solution to seismic problems, earthquake-resistant structures are still popular among designers for over-track high-rise buildings. The transfer members play a significant part in the mechanical interaction between the substructure and superstructures. Not only does the transfer story serve as the direct foundation of the upper high-rise buildings, but also acts as the direct load sources for the podium beneath, both vertically and horizontally. As shown in Figure 5, typical transfer members include girders, trusses, inclined columns, deep beams, transition plates, etc. (Ribeiro, 2018). On the one hand, the structural grids above and beneath the transfer story are generally altered to fulfill different operation functions of each part. The load path of gravity loads is no longer direct to the foundation. As a result, the transfer members should be able to bear additional shear forces and bending moments induced in case of the local or global failure of these members. Provided with a larger story height, the lateral stiffness of the podium stories may be weakened. The extra constraint at the top of vertical structural members caused by the enhanced transfer stories restricts the lateral deformation, and thus the inter-story strength and stiffness must be carefully determined in case of the formation of weak or soft stories. Numerical simulations with finite element method and physical experiments of structural models using shaking tables are both recommended for

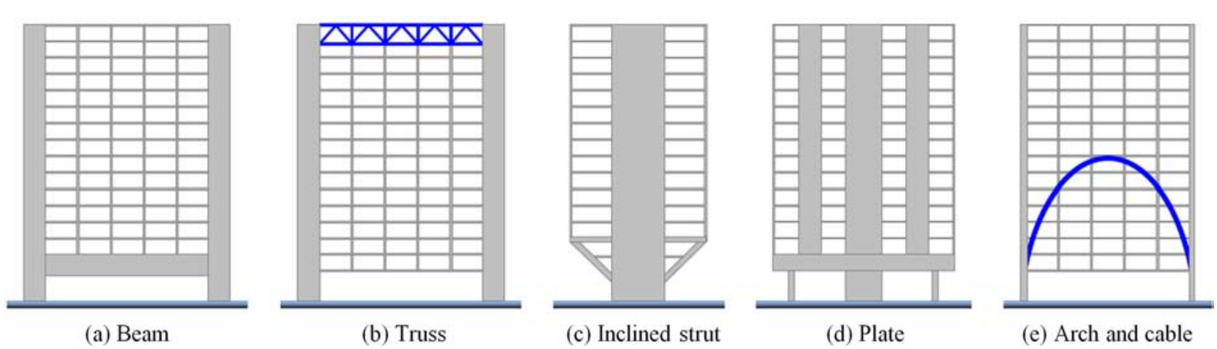


Figure 5. Types of transfer members.

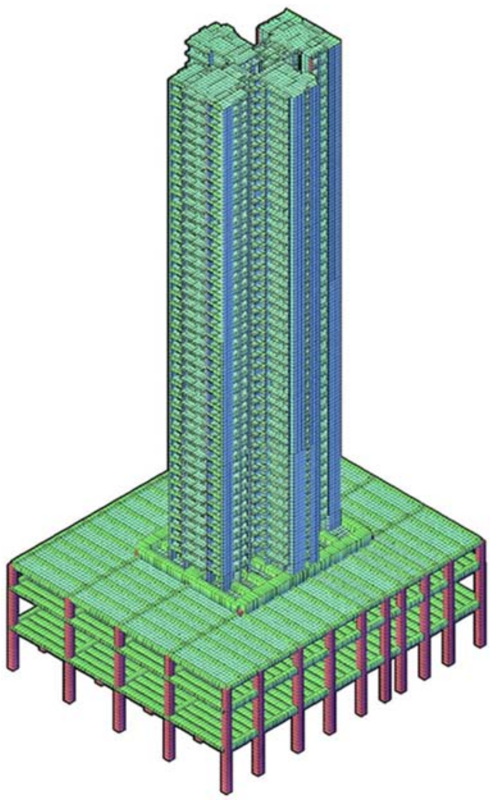


Figure 6. Structural model of fully frame-supported seismic wall structure.

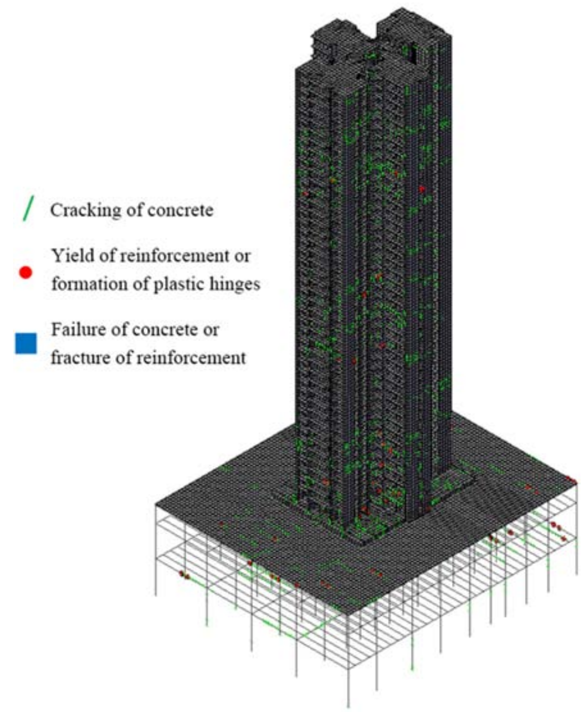
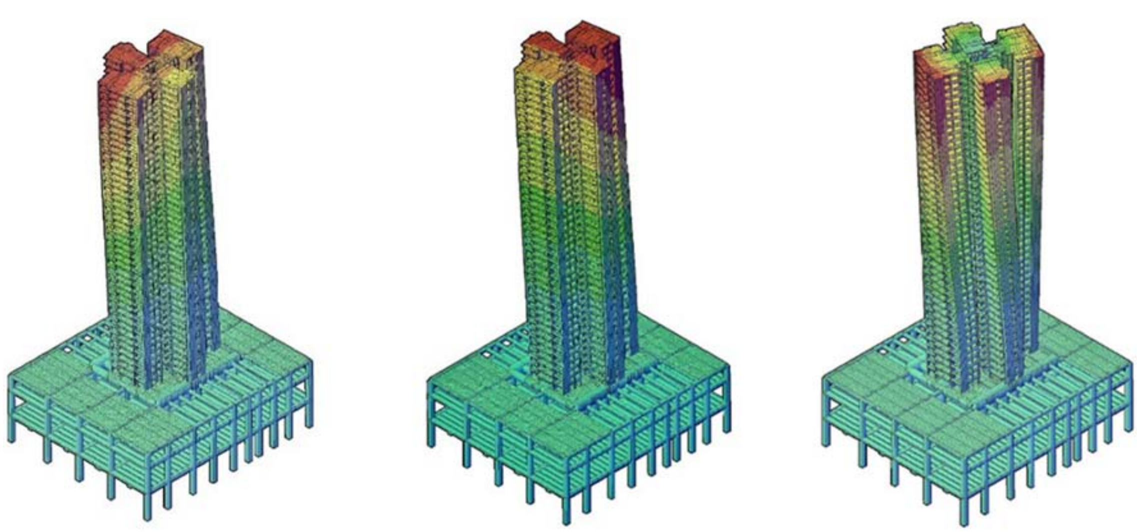


Figure 8. Typical damage pattern of the numerical model under rare earthquakes.

the verification of earthquake-resistant structural systems.

In Figure 6, the frame-supported seismic wall structure with a prefabricated cover plane in Chisha Metro Depot, Guangzhou, is the tallest over-track building developed in China, and the thick plate is adopted as the transfer member (Zhou, Wen, Wu and Xiao, 2022). The podium is composed of three stories with a total height of 29.2 m, and the superstructure is 131.4 m in height, exceeding the height limit of 120 m, regularized by the current Chinese code (GB 50011-2010, 2016). A numerical model of this structure was established and dynamic analysis by the finite element method was performed, including modal analysis and time history analysis under earthquake excitation. The first three vibration modes are depicted in Figure 7, and the damage state of this structure under rare earthquake excitation is shown in Figure 8. Considering the plasticity



(a) 1st order (4.0 s) (b) 2nd order (3.5 s) (c) 3rd order (3.4 s)

Figure 7. First three vibration modes of numerical model.

Figure 9. 1/10 scaled physical model for shaking table tests.

and fracture characteristics of steel and concrete materials, the elastoplastic structural behaviors could be simulated. Primary damages included the yield of reinforcement at the base of the superstructure, the formation of plastic hinges on several beams, as well as the formation of plastic hinges on particular columns of the substructure. Limit states of structural failure and collapse did not happen under rare earthquakes.

In addition, a distinguished large-scale shaking table test of the structural model was conducted in the structural laboratory of Tongji University in 2021, to provide the experimental knowledge base for the over-track building using the transfer member of thick plate, as shown in Figure 9. The tested model was 1:10 scaled with an outskirt plane size of 6.90 m × 9.16 m. Three seismic records were selected and scaled to different levels based on peak ground accelerations (PGA), and 13 loading cases were performed in total. Dynamic responses of the prototype structure were deduced according to similarity criteria and the frequency and damping ratio results are plotted in Figure 10, reflecting accumulated damages to the structure. Although the whiplash effect was observed during tests, lateral deformation of the structure and damage of structural members are within the limit of relevant codes, and weak or soft stories were not formed. Thus, the feasibility of the high-rise fully frame-supported seismic wall structure using the transfer member of the thick plate is verified numerically and experimentally.

3. Adoption of seismic isolation technique in structural design

Although traditional earthquake-resistant structures are proved viable for urban over-track high-rise buildings, the design and evaluation of transfer members are of extreme complexity and require a great amount of labor work,

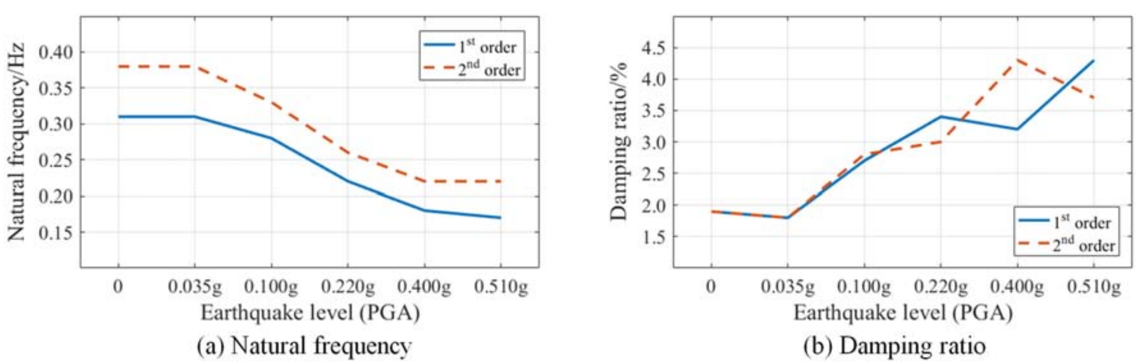


Figure 10. Dynamic characteristics of prototype structure under different levels of earthquakes.

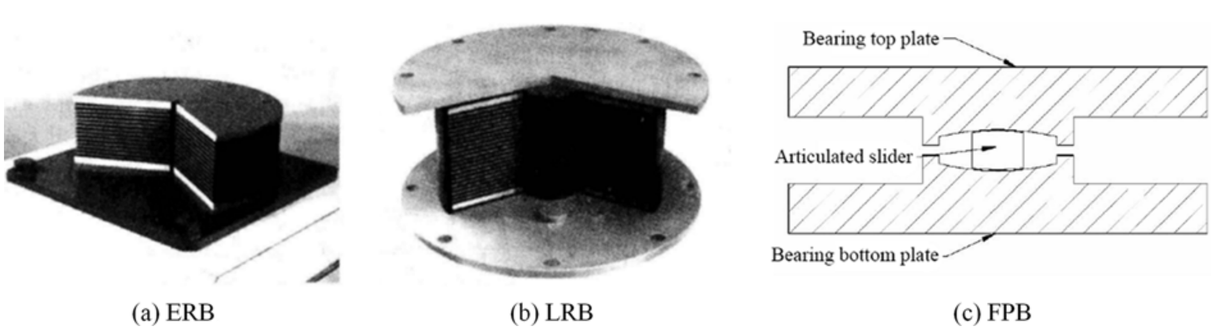
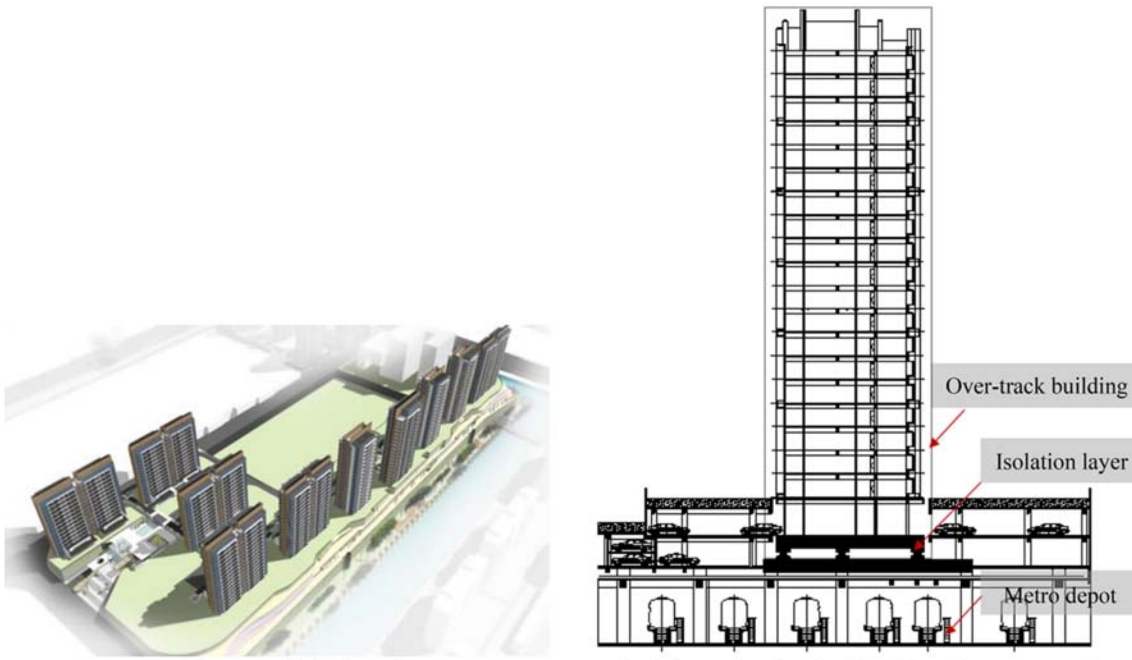


Figure 11. Conventional seismic isolation devices.



(a) Aerial view of whole project (b) Schematic sketch of building for a case study

Figure 12. Over-track development project in Xujing, Shanghai.

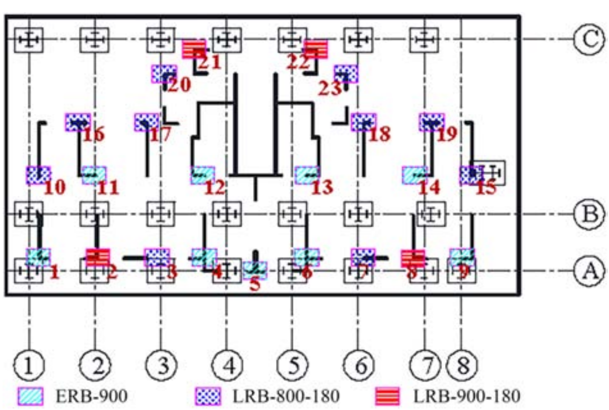


Figure 13. Plan layout of isolation layer composed of conventional rubber bearings.

numerically or experimentally. Besides, rigid connection between substructure and superstructures enables continuous transmission of seismic energy, generally leading to amplification of vibration responses of upper stories and causing structural or non-structural damages. In order to alleviate seismic responses of superstructures and safeguard lives and property as much as possible, the seismic isolation technique is innovatively developed and popularized around the world (Zhou, 2020). Based on this, seismic responses would be concentrated at the isolation layer, i.e. relatively large inter-story deformation, and superstructures would be protected, with security and reliability guaranteed.

Conventional base isolation devices shown in Figure 11 include elastomeric rubber bearings (ERB), lead rubber bearings (LRB), and friction pendulum bearings (FPB). The

Table 1. Natural periods of earthquake-resistant model and seismic isolated model (s)

Modal	Earthquake-resistant model		Seismic isolated model	
	Horizontal	Vertical	Horizontal	Vertical
1st order	1.258	0.118	3.148	0.159
2nd order	1.070	0.117	3.098	0.114
3rd order	0.906	0.111	2.629	0.109

massive over-track development project of UNICITY in Xujing Metro Depot, Shanghai, adopted the technique of seismic isolation with LRBs and ERBs (Zhou, Ma, Chen, Lu and Wu, 2022). The elevation layout of a typical over-track high-rise building is depicted in Figure 12. The height of the podium is 13.7 m, reserved for maintenance and storage of rail transit vehicles, while the height of the upper parts of residential buildings is 62.0 m, with an aspect ratio of 3.8. Twenty-three rubber bearings are utilized in total and the plan layout of the isolation layer is depicted in Figure 13. The dynamic characteristics and seismic responses of this isolated structure are compared to those of the fixed structure. Through Table 1, natural periods in the horizontal directions are approximately three times elongated, providing a promising isolation effect for horizontal earthquakes. Although natural periods in the vertical direction are not altered as much, vertical components of earthquakes are not of dominance to the structure studied, and the security of upper stories is not greatly affected. An index β is introduced to evaluate the efficiency of seismic isolation, defined as the ratios of

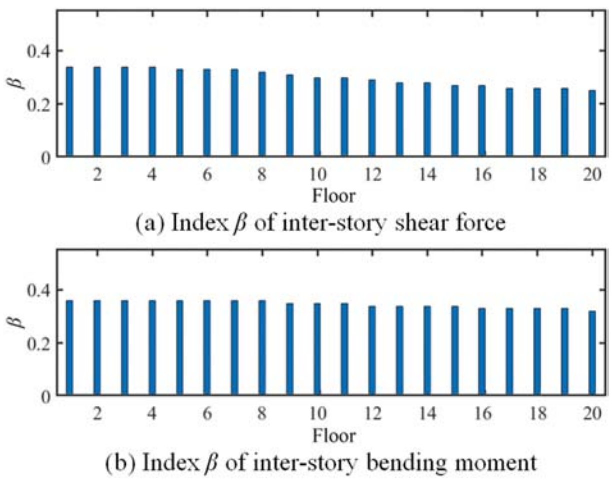


Figure 14. Evaluation of the efficiency of seismic isolation under earthquakes.

inter-story shear forces or bending moments of the isolated structure to those of the traditional earthquake-resistant structure, and the results are shown in Figure 14. The indices β of all stories are below 40%, indicating a brilliant isolation effect for earthquakes.

4. Train-induced vibration control in over-track buildings

The design of transfer members (thick plate or isolation devices) between the podium and the upper towers solves the problem of structural damage mitigation during earthquakes and enhances the security and reliability of the over-track buildings. However, the same conclusion cannot be drawn when it comes to the aspect of residential comfort. Earthquakes are extreme natural events that rarely occur, but the operation of rail transit in over-track buildings can be a daily routine, which may cause the persistent discomfort to inhabitants nearby. Thus, train-induced vibration control techniques should be introduced (Zou, Wang, Zhang and Tao, 2020). From the vibration sources, ballast mats or floating slab tracks can be placed along the rail transit lines to alleviate the impact of the vehicles. From the transmission path, trackside wave barriers can consume and absorb the vibration energy. Also, installing isolation layers can avoid the superstructures from the dominant frequency band of train-induced vibration. All of these methods are proved effective in train-induced vibration control, while track isolation techniques (ballast mats, floating slab tracks, and trackside wave barriers) cannot isolate horizontal earthquakes. For urban over-track high-rise buildings, using three-dimensional isolation devices is recommended for mitigating earthquakes and train-induced vibrations simultaneously.

Research has shown that the vertical component of train-induced vibration has the dominant influence on human bodies. From a theoretical point of view, the transmissibility curve of a single-degree-of-freedom (SDOF) system under base excitation in the vertical direction is depicted in Figure 15 (Zhou and Zhang, 2022). The frequency ratio is defined as the ratio of the frequency of forced vibration excitation to the natural frequency of the SDOF system, and the goal of vibration control can be achieved when the frequency ratio is larger than $\sqrt{2}$. However, for isolation layers composed of conventional rubber bearings (CRBs), including LRBs and ERBs, the stiffness in the vertical direction is not significantly reduced. The working frequency range of over-track buildings using CRBs is 11 ~13 Hz, while the dominant frequency band of train-induced vibration is 20~50 Hz, resulting in a frequency ratio very close to $\sqrt{2}$, providing little effect of train-induced vibration control. Thus, novel techniques must be developed to mitigate the train-induced vibrations, either by improving the existing devices or by developing new devices.

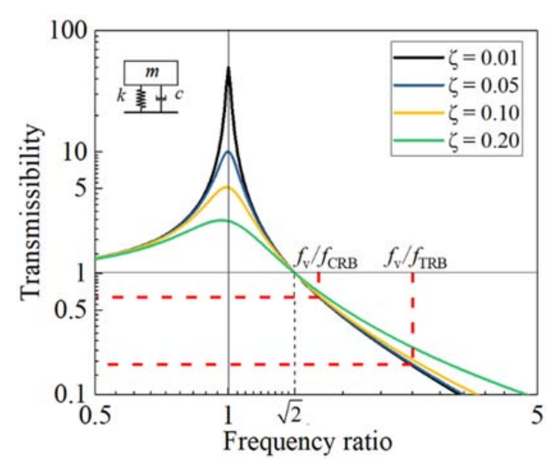


Figure 15. Vibration transmissibility curves.

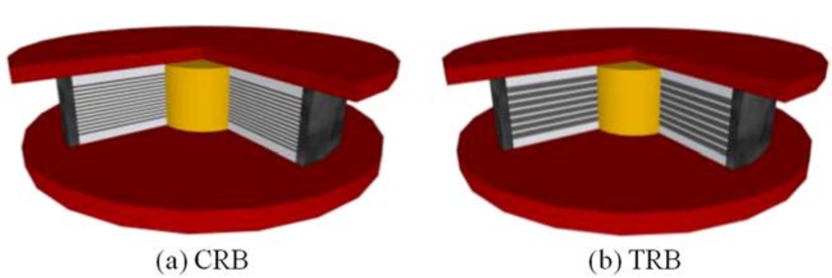


Figure 16. Comparison of conventional rubber bearings and thick rubber bearings.

5. Train-induced vibration control with thick rubber bearings

In order to fulfill the vertical vibration control, one of the most promising solutions is to reduce the vertical stiffness of conventional rubber bearings, which can be achieved through increasing the thicknesses of rubber layers of bearings. Such an improved type of rubber bearings is called thick rubber bearings (TRB), as shown in Figure 16. One important index of rubber bearings, the first shape factor S_1, is defined as the ratio of the constrained area of rubber materials in each plane to the unconstrained perimeter area of rubber materials through the height. For conventional rubber bearings, the first shape factors normally exceed 30, while for thick rubber bearings the indices can be between 2 to 20. Similarly, lead cores can also be added to enhance the wind load resistance and earthquake energy consumption, composing lead thick rubber bearings (LTRB) (Zhou and Zhang, 2022).

Thick rubber bearings are proved efficient in train-induced vibration control, and have already been applied in the construction of an over-track elementary school building. The analytical model of the structure is depicted in Figure 17, and the plan layout of the isolation layer is shown in Figure 18. Eighty-eight thick rubber bearings with or without lead cores are utilized in total. The in-situ test results in an over-track building were adopted as the input excitation and dynamic responses of the structure were calculated through time history analysis. Various indices have been proposed to evaluate vibration responses, e.g. Z vibration level, 1/3 octave vibration level, etc. (GB 10071-88, 1988) (ISO 2631-1, 1997) (ISO 2631-2, 2003). According to the calculation results, the average values of Z vibration levels of each story can be reduced by 6.0 ~ 7.1 dB when TRBs are adopted, and the Z vibration levels can be reduced by 9.2 dB at most. Hence, the isolation effect of TRBs on the train-induced vibration is proved significant.

The application of TRBs in over-track high-rise buildings has been numerically verified using the same structural model as in Section 3 (Zhou, Ma, Chen, Lu, and Wu, 2022). The plan layout of the isolation layer is depicted in Figure 19. The lateral stiffness of the isolation layer is comparable to the structural scheme of CRBs to ensure similar seismic performances in earthquake scenarios. In-situ test results of train-induced vibration were adopted as the input excitation and results of time history analysis were used to evaluate Z vibration levels of the superstructure, as shown in Figure 20. The train-induced vibration can be reduced by 2~5 dB with CRBs, while it can be reduced by 4~6 dB with TRBs. Moreover, through the trend of the Z vibration level curve, TRBs provide a better vibration control effect at the bottom stories, where train-induced vibration is more sensitive. Thus, TRBs are more effective than CRBs in train-induced vibration control of over-track high-rise buildings.

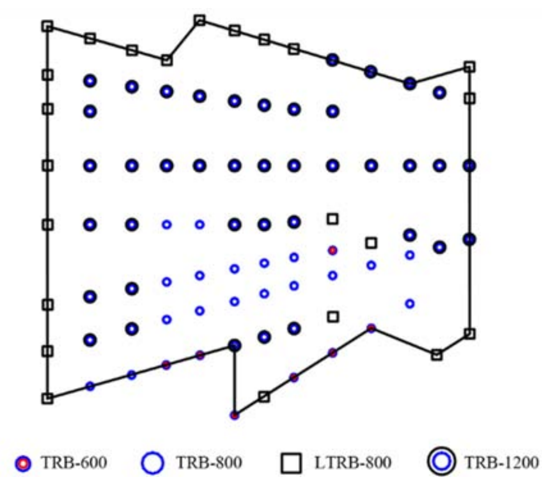


Figure 18. Plan layout of the isolation layer of the elementary school building.

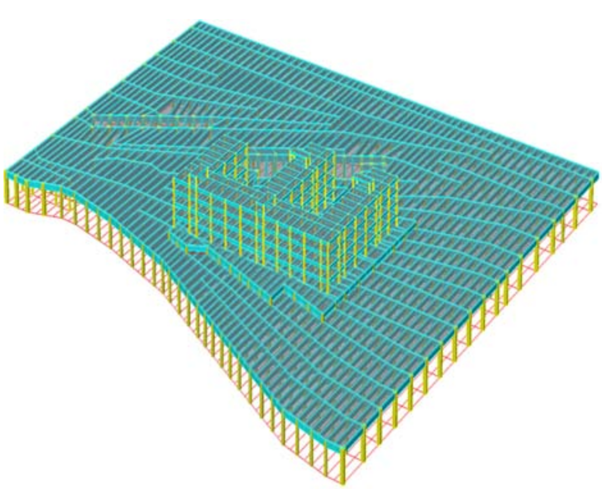


Figure 17. Structural model of the over-track elementary school building.

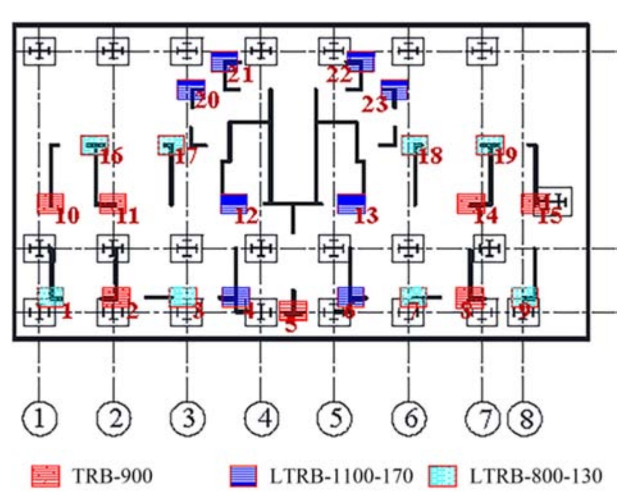


Figure 19. Plan layout of the isolation layer composed of thick rubber bearings.

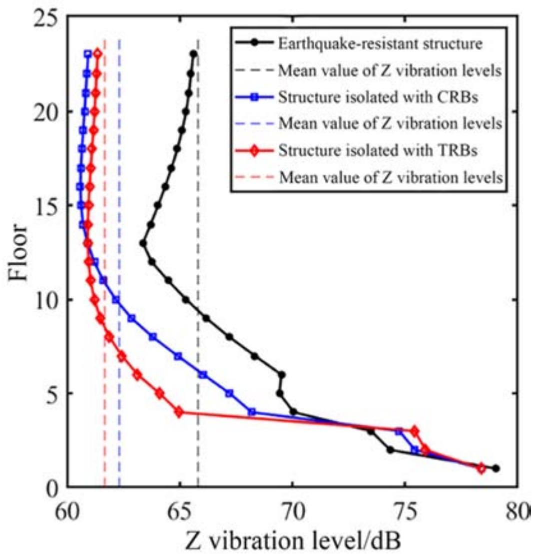


Figure 20. Evaluation of vertical vibration control effect using Z vibration levels.

6. Train-induced vibration control with 3D composite vibration control devices

Another possible solution to reduce the vertical stiffness of the isolation layer is to add decoupled horizontal and vertical isolation devices. The horizontal and vertical vibration control devices should be connected in series, and the horizontal deformation of vertical vibration control devices should be strictly restricted to ensure the seismic isolation effect. Such devices are called 3D composite vibration control devices, as demonstrated in Figure 21 (Liu, 2022). In this case, horizontal and vertical movements of the superstructure are decoupled to the utmost extent, and the design complexity can be greatly simplified. Helical springs and disk springs are possible choices for the vertical vibration control devices, with linear and nonlinear elastic mechanical behaviors respectively. One of the research frontiers of vertical vibration control devices is the quasi-zero stiffness (QZS) systems (Chen, 2019) (Zhou, Chen, and Mosqueda, 2019). The basic idea of QZS is to connect two vertical components in parallel to form a platform on the force-displacement curve of the device. Take helical springs and disk springs as an example, as is shown in Figure 22. The helical spring has a linear positive stiffness, while the disk spring has a nonlinear force-displacement curve with a negative stiffness section. The parallel connection of these two devices leads to a nonlinear force-displacement curve with a platform of quasi-zero stiffness, which serves as the working state of the device, as shown in Figure 23. Since the initial stiffness

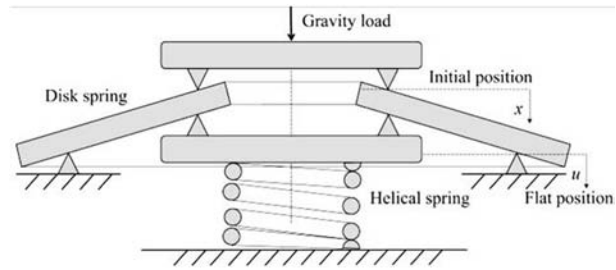


Figure 22. Configuration of vertical isolation systems with quasi-zero stiffness property.

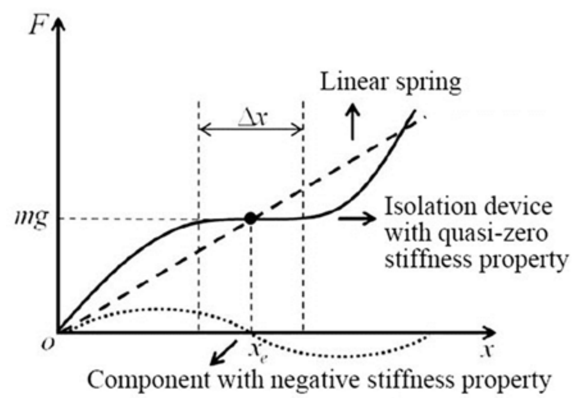


Figure 23. Theoretical basis for quasi-zero stiffness property.

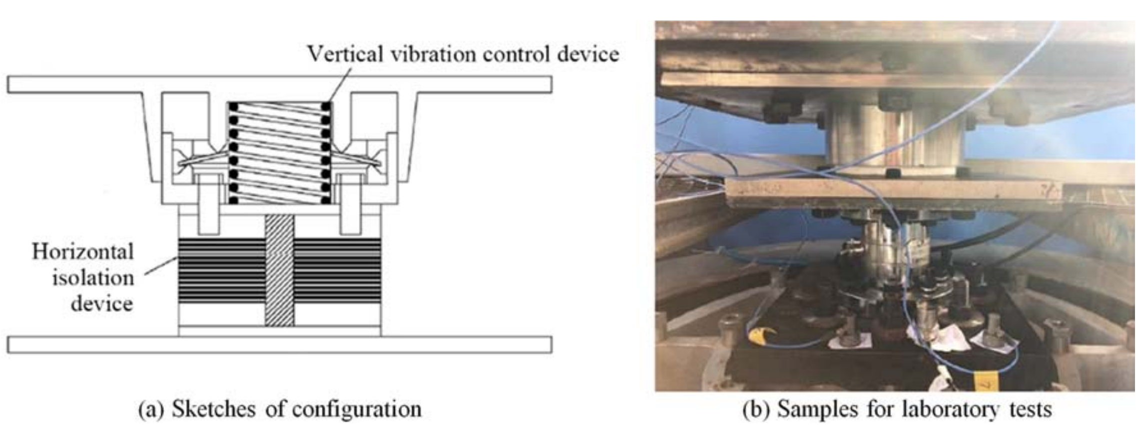


Figure 21. Sketches and samples of 3D composite vibration control devices.

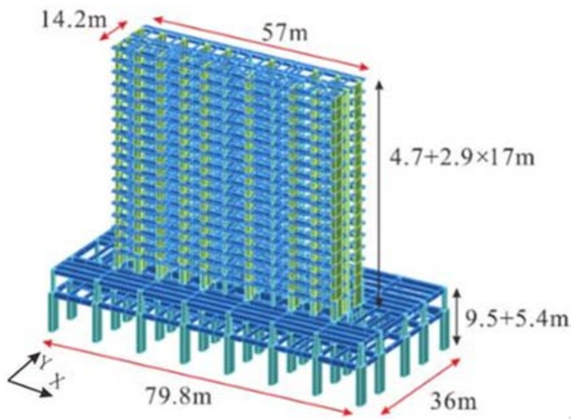


Figure 24. Structural model of the over-track high-rise building in Jinqiao, Shanghai.

of the device is high, excessive static deformation of the device under gravity loads from the superstructure can be

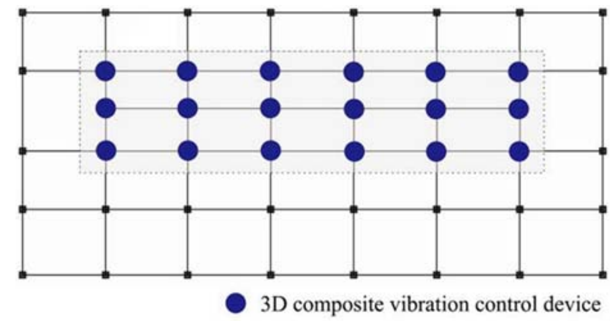


Figure 25. Plan layout of the isolation layer composed of 3D composite vibration control devices.

limited. The ideal axial load exerted on the device should be located on the platform of the force-displacement curve so that the dynamic stiffness of the device is close to zero, which means the frequency ratio in the vertical direction is approaching infinite, and thus the vertical

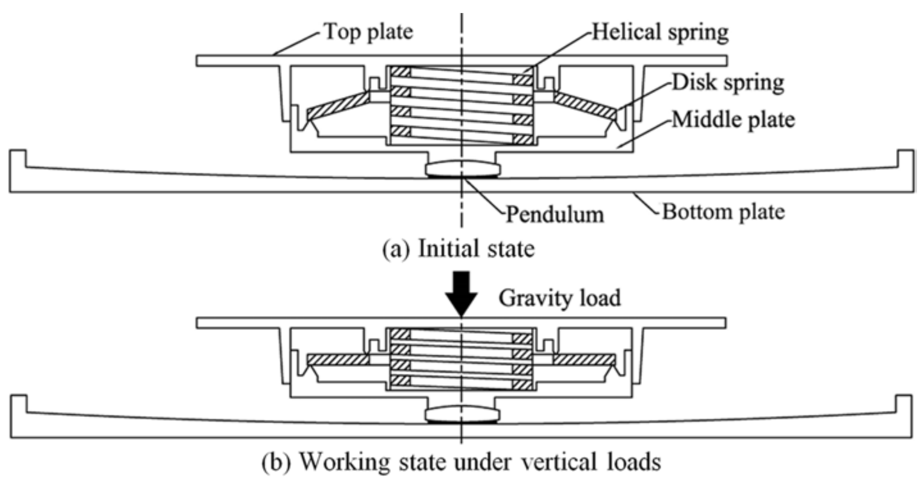


Figure 26. 3D composite vibration control device adopted for the design example.

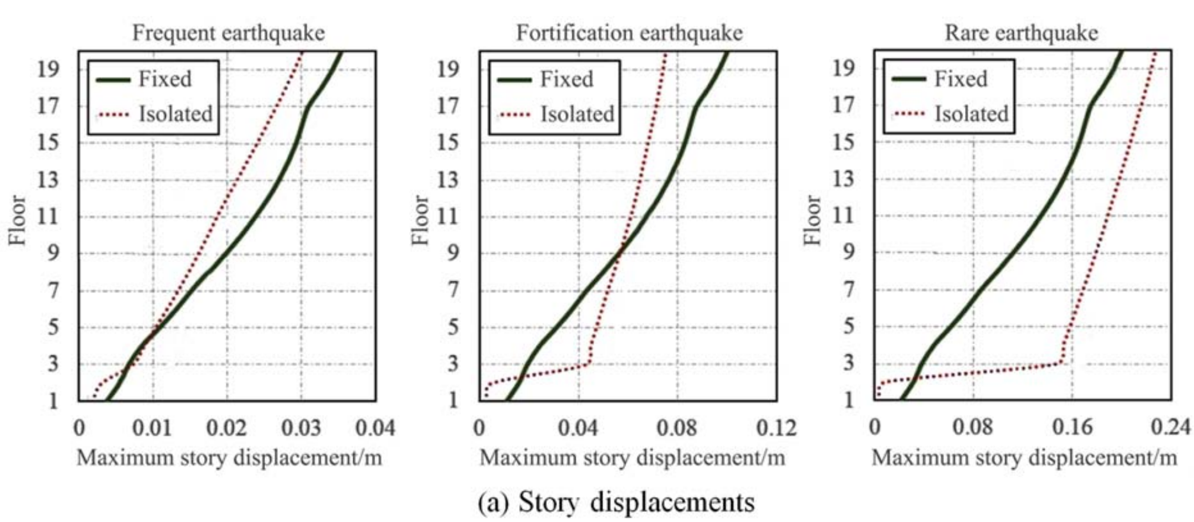


Figure 27. Seismic responses of the structure under earthquake excitations.

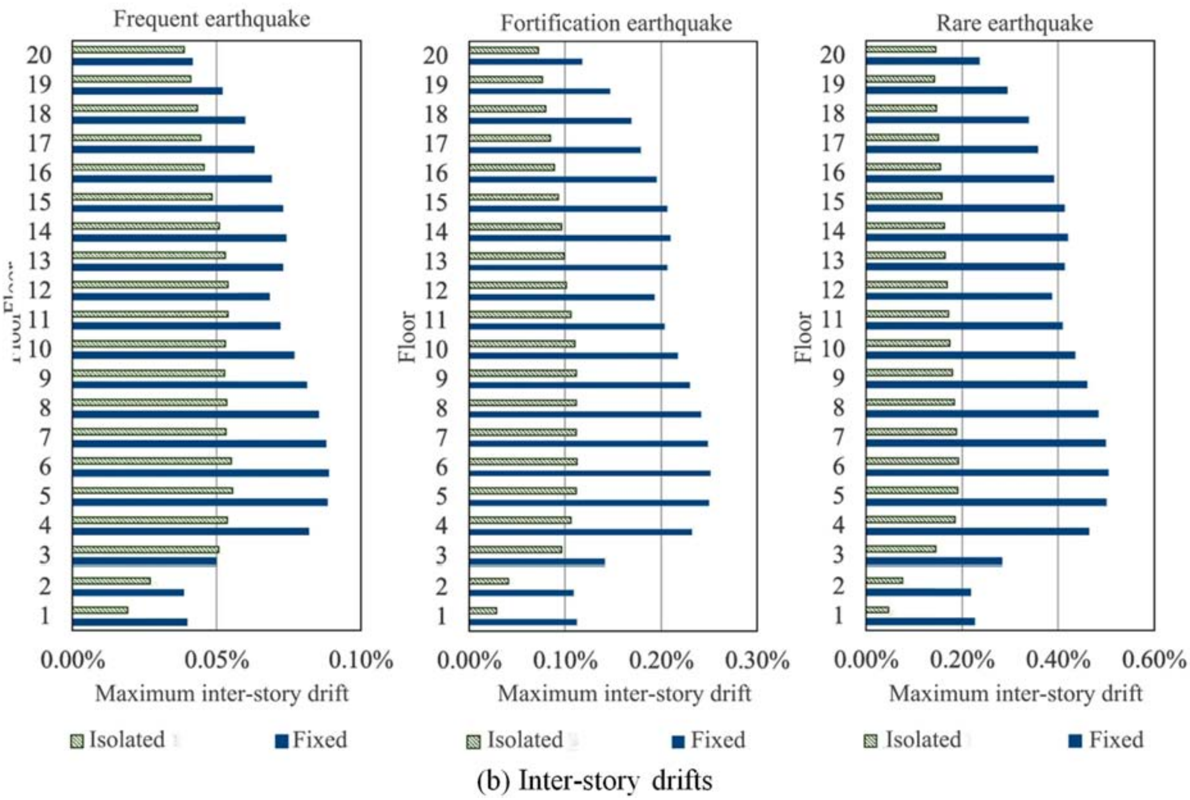


Figure 27. Continued.

component of train-induced vibration is unable to be transmitted to the upper stories.

Numerical simulations have been performed to study the effect of 3D composite vibration control devices (Zhou, Chen, and Mosqueda, 2022). The building model depicted in Figure 24 was established based on the comprehensive over-track development project of Jinqiao Metro Depot in Shanghai, and the heights of the substructure and the superstructure are 14.9 m (2 stories) and 54.0 m (18 stories), respectively. Plan layout of the isolation layer is depicted in Figure 25, with 18 isolation devices applied. The 3D composite vibration control device adopted is composed of a friction pendulum bearing for the horizontal direction and a vertical quasi-zero stiffness system, as shown in Figure 26. Through time history analysis, three earthquake records are selected and scaled to verify the seismic isolation effect of 3D composite vibration control devices in the horizontal direction, and in-situ test results of train-induced vibration are used for evaluating the vertical vibration control effect. Structural responses during one of the rare earthquake loading cases are depicted in Figure 27, with maximum story displacement responses and maximum inter-story drift responses plotted. Deformation is concentrated at the isolation layer and the seismic effects of the upper stories are significantly reduced. For evaluating the train-induced vibration control, the weighted root mean square (RMS) acceleration index is calculated, as shown in Figure 28.

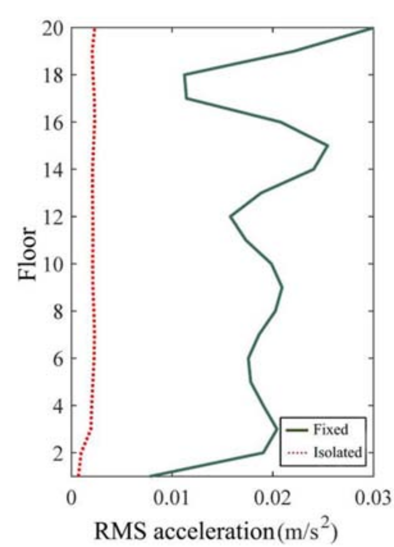


Figure 28. Evaluation of the vertical vibration control effect using the index of RMS acceleration.

Adoption of 3D composite vibration control devices successfully reduces the RMS acceleration from the sensible 0.01~0.02 m/s^2 to an insensible level, suggesting a promising application prospect.

Conclusions

This paper offers a global overview of the engineering practice and research frontiers of structural design for urban over-track high-rise buildings in China. Two main problems are pointed out, including the abrupt change of story stiffness between the podium and the upper towers, which is related to the safety and security of the structure during earthquakes, and the urgent demand for train-induced vibration control, which corresponds to the residential comfort.

As for the solutions, satisfying structural responses of earthquake-resistant structures under earthquakes can be achieved if properly designed. However, the complexity of transfer members adds to the uncertainty during the design as well as the operation phase, and thus seismic isolation techniques are strongly recommended. Seismic isolation layers composed of CRBs are able to accommodate concentrated inter-story deformation and absorb earthquake energy, so that the superstructures can be protected from earthquake damages. Moreover, the function of train-induced vibration control can be integrated into conventional isolation systems through the application of 3D isolation devices. First, TRBs designed with a low first shape factor have a relatively small vertical stiffness to mitigate the vertical vibration. Then, 3D composite vibration control devices are able to decouple the horizontal and vertical movements of the superstructure and significantly reduce the horizontal and vertical vibrations. The quasi-zero stiffness systems are proved to be prospective in the area of micro-vibration control of structures. Therefore, isolation devices including TRBs and 3D composite isolators are recommended to mitigate the train-induced vibration and improve the seismic safety of over-track buildings.

For the future study of urban over-track high-rise buildings, the mechanism of the train-induced vibration transmission should be investigated to provide a theoretical basis for the evaluation of the vertical vibration control effect. The train-induced vibration responses of earthquake-resistant over-track buildings should be carefully examined. Furthermore, novel vibration control devices can be developed to efficiently isolate both earthquakes and train-induced vibrations. Engineering practice should be advanced as well so that state-of-the-art technologies can be applied in production.

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