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Engineering Modular Building Towers for Improving Earthquake Safety

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Abstract

A modular building is formed by modules that are prefabricated in a factory and then transported and assembled on site. A building which is constructed in this manner and without any structural walls, nor frames, to provide the lateral bracing is called a pure modular building. This form of construction has the merit of minimising site work, thereby saving construction time. The lateral stability of a pure modular building relies fully on bolted connections which secure the modules in position. With a building tower which is constructed by the method as described, failure of the inter-modular bolted connections in a rare earthquake event may trigger wholesale overturning of the tower. An inexpensive, non-intrusive and effective method of improving the seismic performance of this type of building is to apply prestress to the tower using a vertical superelastic tendon. Shaker table testing demonstrating the potential effectiveness of the rocking mechanism in mitigating damage caused to the building when subject to strong ground shaking is carried out. Importantly, the effectiveness of the use of a superelastic tendon in further enhancing the seismic performance of the building tower is demonstrated.

Keywords: modular building, seismic protection, superelastic tendon, shaker table testing

1 Introduction

Steel modular buildings are built by prefabricated prefinished modules that are manufactured in a factory and then assembled on-site by using inter-module connectors. The construction time is shortened, environmental impact is alleviated and energy efficiency is improved. Modular buildings are used as residential apartments, hotels, healthcare buildings, educational sector buildings and the like, as shown in Fig.1. The market share of modular construction is predicted to increase to 5%–10% by year 2030 (Ferdous et al., 2019). As this form of construction is relatively new, no post-earthquake damage report can be sourced from the literature. Consequently, the seismic performance, or robustness, of steel modular buildings is largely uncertain.

 

Fig. 1 Murray Grove project building in London, U.K., and the Ibis Hotel East Perth building in Australia (Noordzy et al., 2021)

The connection between modular units is an important part of the lateral load resistance system of a self-supported modular building. Both the stiffness and strength of the inter-modular connections have a significant influence on the seismic performance of the structure (Chua et al., 2020; Feng et al., 2020). There are dozens of types of connectors (Lacey et al., 2018, 2019) adopted for modular buildings, and most of them are bolted connections. In addition to controlling the stiffness and strength of the building, the connectors are also designed to meet the requirements of fast on-site assembly and limited operational space (Chen et al., 2017; Cho et al., 2019; Dai et al., 2019). In a former testing study (Muhinadeen et al., 2019), connection failure during an earthquake may trigger the collapse or overturning of the modular building, which is catastrophic. Instead of simply strengthening the connections, the building system should be designed to respond to strong ground shaking in a robust, and reliable, manner which put the building at very low risk of overturning in a severe earthquake event, and avoid sustaining significant damage in a mild or moderate earthquake event.

Large rotation of the building in the vertical plane (known as rocking) (Housner, 1963) can be described as a method of seismic isolation for slender structures. Rocking of a modular building is expected when the base of the building is not fixed to the foundation. Note, rocking of a modular building as a whole, or a major part of the building, in an earthquake is different to rocking of only the structural walls. With the latter scenario, the beams and columns surrounding the rocking wall would prevent the building from overturning or excessive rotation. With whole building rocking, no such restraints are available to control the overturning risk. A better controlled rocking system is desirable. In the study by Aslam et al. (1978), the design of the rocking system of radiation shielding blocks featured central vertical prestressing for controlling the risk of overturning. In the study by Eatherton et al. (2014), a design concept for controlling the rocking of steel-braced frames was proposed.

This paper aims to introduce the use of an alloy material to form a particular tendon restraint to allow the modular building to rock in a controlled manner. This kind of material is known as 'superelastic' behaviour (Ozbulut et al., 2011; San Juan & Nó, 2013; Xia et al., 2020). Many alloy systems exhibit superelasticity. The Nickel-Titanium (NiTi) alloy is widely used because of its high strength, ductility, and corrosion resistance (Ozbulut et al., 2011). Other kinds of superelastic material such as Iron-based superelastic alloys may also apply. This design scheme is introduced in Section 2, and then a testing validation by shaker table testing is reported in Section 3.

2 Designing superelastic tendons in modular buildings

The self-supported pure modular building is highly prefabricated. Formed by modular units with connectors distributed at the corner or middle of the unit, the modular building relies on the connectors to form an integrated structure. The lateral force resistance system of this structure has obvious discontinuous characteristics. The modular boxes are strong, but the connections between the modules are weak. Failure of a small number of connections in an earthquake can trigger severe damage or even progressive collapse. With the form of bolted connection considered in this study, which uses four M24 Category 8.8/S structural bolts connecting the adjacent corners of four modular units as shown in Fig. 2, dislocation motion at the connection is possible following the failure of two bolts. Should one connector snaps, the force demand on the nearby connectors can increase significantly. Triggering a chain of connection failure in an earthquake may result in the wholesale collapse of the building in a rare earthquake event.

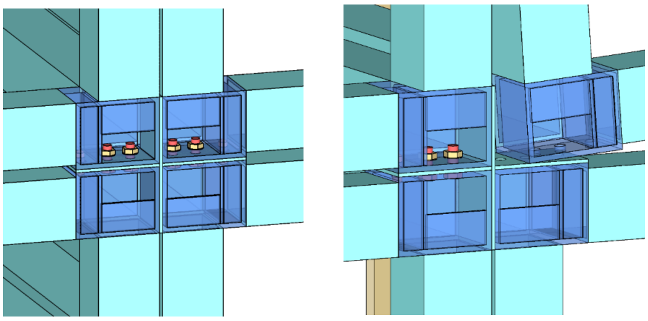

Fig. 2 Inter-modular connection and possible behaviour after bolting failure

Envisaging possible brittle failure of the inter-modular connections as mentioned in the foregoing has prevented the widespread adoption in practice of the design of pure modular high-rise buildings. Contrary to the common practice of strengthening the modular connections, the authors advocate the concept of using rocking to isolate the modular building for enhancing the potential seismic performance. Incorporating superelastic tendons into the rocking system is beneficial for achieving a balance between mitigating internal force demand within the building and controlling the overturning risk (Li et al., 2022). If a steel tendon is used instead, the amount of elongation would be restricted to the yield limit of about 0.2% - 0.4%. In contrast, a tendon made of NiTi alloy can elongate by up to 10% with full recovery potential, making it ideal for facilitating large rocking motion. The proposed superelastic tendon is different from short-length superelastic material bars installed at the base of columns (Rele et al., 2021; Roh & Reinhorn, 2010). For the latter one, the short length bar may not impose effective prestressing force on the structure by itself. The analytical model of the proposed system and the hysteretic curve are shown in Fig. 3.

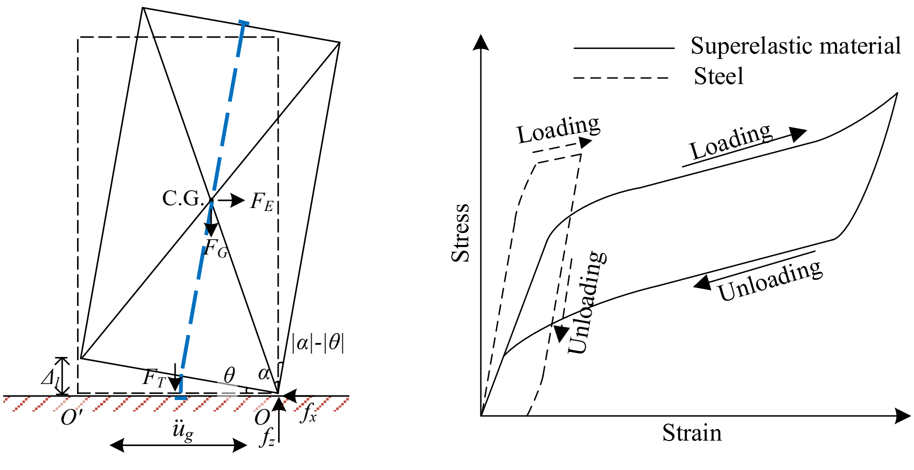

Fig. 3 Proposed rocking control system by superelastic tendon (left) and analytical model of superelastic material (right) (Li et al., 2022)

3 Testing validation of a scaled modular building with superelastic tendons

3.1 Design of the scaled building model and test set-up

In this study, a scaled-down building model was designed and tested on the shaker table to validate the proposed system of controlled rocking. With the prototype building, the dimension of a modular unit was 10.5 m in length, 2.78 m in width and 2.78 m in height, and the weight of the unit was 26.5 tons. Each floor contained ten units in an array, and the building was 18 storeys tall, with the following gross dimensions: 10.5 m in width, 27.8 m in length and 50.04 m in height. The fundamental natural period of vibration of the building was 0.85s. Ground shaking was applied along the smaller plan dimension of the building to excite the building into rocking motion. The floor plan of the scaled model was made up of four modular units. With the scaled-down model to be tested on the shaking table, the length scaling ratio, λ_L, was 1:33. The model was 0.32 m in width, 0.34 m in length and 1.52 m in height, with a total weight of 53.1 kg. With 1-g gravity field, the similitude ratio of acceleration, λ_a, was 1.0. The similitude ratio of time is accordingly equal to $\lambda_L^{-0.5}$, resulting in a targeted fundamental natural period of vibration of 0.15 s.

The test model of the building is shown in Fig. 4. The foundation plate which was made of aluminium was fixed to the surface of the shaking table. The building model was made of steel plates of 0.9 mm in thickness. Metal sheet fabrication with laser cutting method was adopted to process the steel plate into the modular unit boxes. To satisfy the dynamic similitude ratio of mass, dummy masses made of bricks were placed on the floors, resulting in a total mass of 53.5 kg. The built model had a period of 0.146 s, which was close to the desired natural period mentioned before.Two superelastic tendons were installed at the centre of the building model. The tendon was made of 1 m length of NiTi string which was connected in series to a 0.5 m long steel wire. The diameter of the NiTi string was 1 mm, and that of the steel wire was 2 mm. Much of the elongation of the tendon occurred within the NiTi string segment.

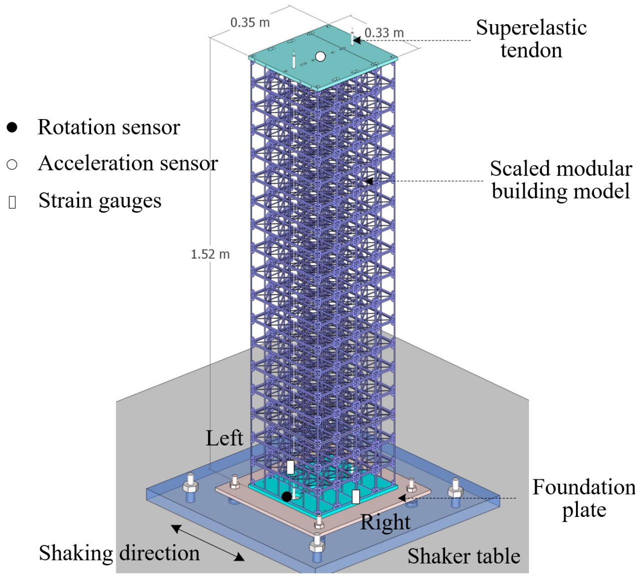

Fig. 4 The 3D view of the scaled building model and test set-up

The sensor for monitoring rotation of the building was installed at the base of the scaled model for measuring the rocking angle. The acceleration sensor was fixed at the top of the model, and strain gauges were set at the base of the columns of the ground floor. Static push testing on the building was used to calibrate the moment–strain relationship in each test set-up.

3.2 Testing results

Tests were carried out in three groups: fixed-based specimen testing, free rocking (no tendon) specimen testing and superelastic tendon restrained specimen testing. In each set-up, two test cases were carried out: free release test and base excitation test. In the free release test, a pull force was applied horizontally at the top of the model to give the model an initial deformation or rotation, and then the force was suddenly removed to result in the model responding to the abrupt change. In the base excitation test, a single impulsive wave was applied on the shaking table. The period of the impulsive wave was 0.63 s, representing a 3.6 s period major impulse in a typical near-fault earthquake, such as the 1992 Turkey Erizican earthquake. Identical histories of base motion were applied to the three different test set-ups.

Test results for the fixed-base specimen, free rocking specimen and superelastic tendon restrained specimen testing were obtained. The maximum base moment of the three test specimens was 246 Nm, 41 Nm and 158 Nm. The seismic internal force of the model with the superelastic tendon restrained specimen was 36% lower than that of the fixed base model. At the same time, the amount of rotation of the tendon restrained specimen was 61% lower than that of the free rocking specimen. With the tendon restrained specimen, the amount of tensile stress in the columns was lower than the fixed base specimen, but the compression stress was higher, and some limited rocking motions were recorded. The beneficial effects of the superelastic tendon restraints were evident.

4 Conclusions

A high-rise modular building with a large height-to-width ratio and limited structural redundancy was investigated. Response to seismic actions was characterised by a high risk of brittle style failure of the inter-modular connections. Failure of one connection in a rare earthquake could trigger progressive failure leading to the wholesale overturning of the building. This paper presents a new design approach which allows the building to experience rocking motion when subject to vertical partial restraint imposed by a prestressed superelastic tendon. This arrangement serves to reduce internal forces generated in the structural elements while controlling the risk of overturning. The proper functionality of the proposed system of controlled rocking was confirmed in observations taken from shaker table testing that was carried out on the fixed base building specimen, the free rocking specimen and the superelastic tendon restrained specimen.

5 References

Aslam, M., Godden, W. G., & Scalise, D. T. (1978). Earthquake rocking response of rigid bodies. *Lawrence Berkeley National Laboratory*, *LBL-7983*.

Chen, Z., Liu, J., & Yu, Y. (2017). Experimental study on interior connections in modular steel buildings. *Engineering Structures*, *147*, 625–638. https://doi.org/10.1016/j.engstruct.2017.06.002

Cho, B., Lee, J., Kim, H., & Kim, D. (2019). Structural Performance of a New Blind-Bolted Frame Modular Beam-Column Connection under Lateral Loading. *Applied Sciences*, *9*, 1929.

Chua, Y. S., Liew, J. Y. R., & Pang, S. D. (2020). Modelling of connections and lateral behavior of high-rise modular steel buildings. *Journal of Constructional Steel Research*, *166*, 105901. https://doi.org/10.1016/j.jcsr.2019.105901

Dai, X., Zong, L., Ding, Y., & Li, Z. (2019). Experimental study on seismic behavior of a novel plug-in self-lock joint for modular steel construction. *Engineering Structures*, *181*(May 2018), 143–164. https://doi.org/10.1016/j.engstruct.2018.11.075

Eatherton, M. R., Ma, X., Krawinkler, H., Mar, D., Billington, S., Hajjar, J. F., & Deierlein, G. G. (2014). Design Concepts for Controlled Rocking of Self-Centering Steel-Braced Frames.

Journal of Structural Engineering, *140*(11), 04014082. https://doi.org/10.1061/(asce)st.1943-541x.0001047

Feng, R., Shen, L., & Yun, Q. (2020). Seismic performance of multi-story modular box buildings. *Journal of Constructional Steel Research*, *168*, 106002. https://doi.org/10.1016/j.jcsr.2020.106002

Housner, G. W. (1963). The behavior of inverted pendulum structures during earthquakes. *Bulletin of the Seismological Society of America*, *53*(2), 403–417. https://doi.org/10.1785/BSSA0530020403

Lacey, A. W., Chen, W., Hao, H., & Bi, K. (2018). Structural response of modular buildings – An overview. *Journal of Building Engineering*, *16*(July 2017), 45–56. https://doi.org/10.1016/j.jobe.2017.12.008

Lacey, A. W., Chen, W., Hao, H., & Bi, K. (2019). Review of bolted inter-module connections in modular steel buildings. *Journal of Building Engineering*, *23*(September 2018), 207–219. https://doi.org/10.1016/j.jobe.2019.01.035

Li, S., Tsang, H. H., & Lam, N. (2022). Seismic protection by rocking with superelastic tendon restraint. *Earthquake Engineering & Structural Dynamics*, *51*(June), 1718–1737. https://doi.org/10.1002/eqe.3635

M, M. M. M., Lam, N. T. K., Godbole, S., & Rajeev, P. (2019). *Safety of Modular Buildings in Seismic conditions*.

Noordzy, G., Whitfield, R., Saliot, G., & Ricaurte, E. (2021). Modular Construction: An Important Alternative Approach for New Hotel Development Projects. *Journal of Modern Project Management*, *10*(1), 217–235. https://doi.org/10.19255/JMPM02715

Ozbulut, O. E., Hurlebaus, S., & Desroches, R. (2011). Seismic response control using shape memory alloys: A review. *Journal of Intelligent Material Systems and Structures*, *22*(14), 1531–1549. https://doi.org/10.1177/1045389X11411220

Rele, R., Balmukund, R., Bhattacharya, S., Cui, L., & Mitoulis, S. A. (2021). Application of controlled-rocking isolation with shape memory alloys for an overpass bridge. *Soil Dynamics and Earthquake Engineering*, *149*. https://doi.org/10.1016/j.soildyn.2021.106827

Roh, H., & Reinhorn, A. M. (2010). Hysteretic behavior of precast segmental bridge piers with superelastic shape memory alloy bars. *Engineering Structures*, *32*(10), 3394–3403. https://doi.org/10.1016/j.engstruct.2010.07.013

San Juan, J., & Nó, M. L. (2013). Superelasticity and shape memory at nano-scale: Size effects on the martensitic transformation. *Journal of Alloys and Compounds*, *577*(SUPPL. 1), 25–29. https://doi.org/10.1016/j.jallcom.2011.10.110

Xia, J., Noguchi, Y., Xu, X., Odaira, T., Kimura, Y., Nagasako, M., Omori, T., & Kainuma, R. (2020). Iron-based superelastic alloys with near-constant critical stress temperature dependence. *Science*, *369*(6505), 855–858. https://doi.org/10.1126/science.abc1590