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Preliminary Assessment of Self-Centring Steel Frame Systems with Energy Dissipation Devices

Michelle Gualdi[a], Andrea Belleri[a,*], Alessandra Marini[a], Simone Labò[a]

[a]*University of Bergamo, Department of Engineering and Applied Sciences, V.le Marconi 5, Dalmine 24044, Italy*

Abstract

The increasing emphasis on the resilience and sustainability of the built environment in modern building construction has led to the development of low-damage solutions such as rocking systems. In this context, the Life Cycle Thinking approach is essential to ensure both structural performance and the long-term environmental and economic sustainability of design decisions. Self-centring rocking systems minimize residual deformations and structural damage, enabling rapid post-earthquake recovery while reducing repair costs and resource consumption. This study investigates the application of re-centring rocking systems in lightweight steel structures. The focus is on the analysis of in-plane frames with controlled rocking mechanisms that include post-tensioned members and energy dissipators such as friction or viscous devices. A sensitivity analysis is performed to evaluate the structural response when different energy dissipation devices are integrated into the frame.

Keywords: Rocking Systems; Lightweight Steel Structures; Life Cycle Thinking

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1. Introduction

Current seismic building codes aim to ensure structural safety, functionality and damage control across different limit states. However, conventional design approaches that achieve energy dissipation through damage in ductile elements often result in significant repair costs, downtime and material waste, which complicates post-earthquake

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* Corresponding author. Tel.: +39 035 2052 007; fax: +39 2052 077.
E-mail address: andrea.belleri@unibg.it

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recovery and increases losses. In response, the concept of structural resilience has emerged, promoting systems that can withstand strong earthquakes with minimal damage, negligible residual deformation and rapid post-event functionality. Among the most promising solutions are self-centring rocking systems that allow controlled uplift and re-centring through post-tensioned (PT) elements. Energy dissipation is enhanced by hysteretic or viscous devices, resulting in flag-shaped hysteresis loops. Several self-centring systems have been developed for both new and existing structures. In reinforced concrete structures, rocking walls, either precast or cast-in-place, are designed without continuous longitudinal reinforcement at the base, allowing them to rock and re-centre during seismic events (Priestley et al., 1962; Restrepo and Rahman, 2007; Schoettler et al., 2009; Belleri et al., 2014; Belleri, Torquati and Riva, 2013; Mpampatsikos et al., 2020; Casprini et al., 2022; Labò et al., 2025). In steel structures, several innovative configurations have emerged, including moment-resisting frames (MRFs) with post-tensioned rods (Ricles et al., 2001; Christopoulos et al., 2002) or with self-centring components (Freddi, Dimopoulos and Karavasilis, 2017; Elettore et al., 2021) and controlled rocking steel braced frames (CRSBFs) equipped with energy dissipation (ED) devices (Pollino, 2015; Wiebe and Christopoulos, 2015). A notable solution applicable to both RC and steel systems is the rocking podium structure, which was first implemented in the Soviet Union in the 1980s (Zhong and Christopoulos, 2021). This concept allows the columns at the base level to rock and re-center during seismic events, effectively decoupling the seismic demands on the superstructure and increasing the overall resilience of the system. These structures have demonstrated their seismic performance in various real events and have attracted renewed interest and further research in recent years (Zaki, Zhong and Christopoulos, 2025; Vassiliou et al., 2021; Bachmann, Vassiliou and Stojadinović, 2017, Belleri et al., 2023).

In parallel, the growing attention to sustainability has led to the extension of Life Cycle Thinking (LCT) in building design. LCT promotes the holistic assessment of impacts from raw material extraction to the end-of-life. Rocking systems naturally align with this philosophy due to their low-damage, easily repairable nature of repair and potential for reuse and disassembly. This study focuses on lightweight steel (LWS) frames incorporating controlled rocking mechanisms, with particular attention to the implementation of hysteretic energy dissipation devices located at two different points on the structure. Initial numerical analyses carried out by Gualdi et al. (2025) have already shown the potential of this system in terms of seismic performance and low-damage behaviour, thus laying the foundation for the present investigation. A detailed finite element model was developed to evaluate the response of the system through nonlinear static, cyclic and time-history analyses.

2. Proposed structural system and LCT principles

2.1. Geometry

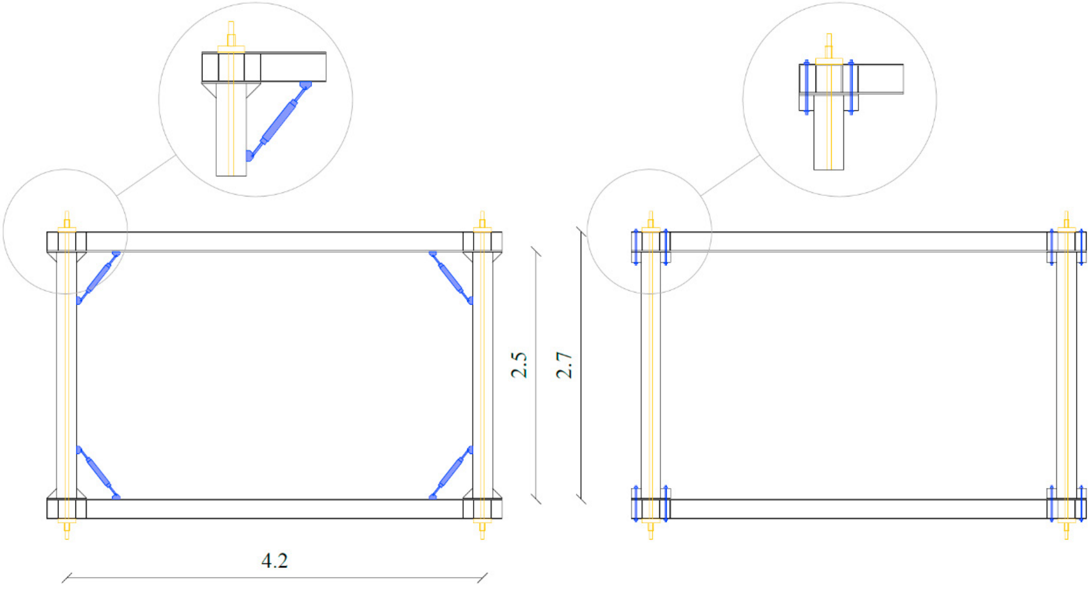
The analysis of the proposed re-centring rocking system is performed on the same three-story residential building of lightweight steel construction previously presented in Gualdi et al. (2025). The structure uses a lightweight steel platform frame system for the upper floors, while the seismically induced displacements are concentrated on the first level, where six rocking frames are installed in each direction. For clarity, Table 1 summarizes the main geometric and structural features.

Table 1. Summary of the main characteristics of the case study structure.

Component	Description / Specification
Superstructure (platform-frame)	
Floor system	C-shaped steel joists (250x50x20x2.5 mm) spaced 0.6 m topped by 22 mm CLT panels
Wall system	Vertical stud-connected columns (100x50x20x1 mm) with horizontal C-shaped rails (100x40x1 mm)
Lateral bracing	X-shaped steel diagonal strips (100x1 mm)
Dead loads / live loads	0.86 kN/m^2 (intermediate floors), 0.70 kN/m^2 (roof) / 2 kN/m^2 (according to Italian Code NTC18)

Substructure (rocking frames)	
Frame elements	S235 hot-rolled (HR) hollow-square columns and double-C beams (f_y=235 N/mm^2, f_u=360 N/mm^2, E=210000 N/mm^2)
Re-centering system	DYWIDAG threaded rods Φ26.5 mm (f_y=950 N/mm^2, f_u=1050 N/mm^2) pre-stressed to 60% f_y

The hysteretic energy dissipation devices were built into the frame and arranged in two different configurations, as shown in Figure 1: diagonally in the corners and vertically at the rocking interfaces. These configurations are referred to below as the Oblique-Corner configuration (OC) and Vertical-Interface configuration (VI) respectively. In the OC configuration, four dissipators are used, one at each corner of the frame, while the VI configuration comprises a total of eight devices, two of which are installed at each rocking interface. In both cases, the dissipators are treated as hysteretic devices and energy dissipation is achieved by yielding.



a) b)

Fig. 1. Rocking frame with ED devices in two different configurations: a) in the corners (OC), b) at the rocking interfaces (VI) (units: m).

2.2. Life Cycle Thinking in the proposed system

Life Cycle Thinking is a holistic approach that considers the environmental, economic and social impacts of a product or system throughout its life cycle, from raw material extraction to disposal or reuse. It encourages the development of solutions that minimize negative impacts at each stage, improving sustainability, resource efficiency and resilience. The proposed rocking system complies with LCT principles by emphasizing durability, ease of maintenance and earthquake resistance. During earthquakes, it keeps the superstructure within the elastic range by concentrating the displacement at the first floor level. This strategy reduces structural damage, limits resource consumption and emissions over time, and minimizes maintenance during the use phase. Damage is localized in sacrificial energy dissipators that can be quickly replaced without affecting the main structure, reducing material consumption and enabling rapid recovery. This contributes to reduced social impact as residents can safely return to their homes shortly after an event. Dry connections allow for quick, reversible assembly and disassembly and support the repair, upgrade and reuse of components. This promotes a circular approach and reduces demolition waste, while encouraging the conservation of resources. The system can also be used as a solution for seismic retrofitting of existing reinforced concrete buildings, in line with LCT principles as proposed by Marini et al. (2017) and Passoni et al. (2021). The combination of seismic and energy retrofitting in a single measure further reduces the overall impact of building refurbishment.

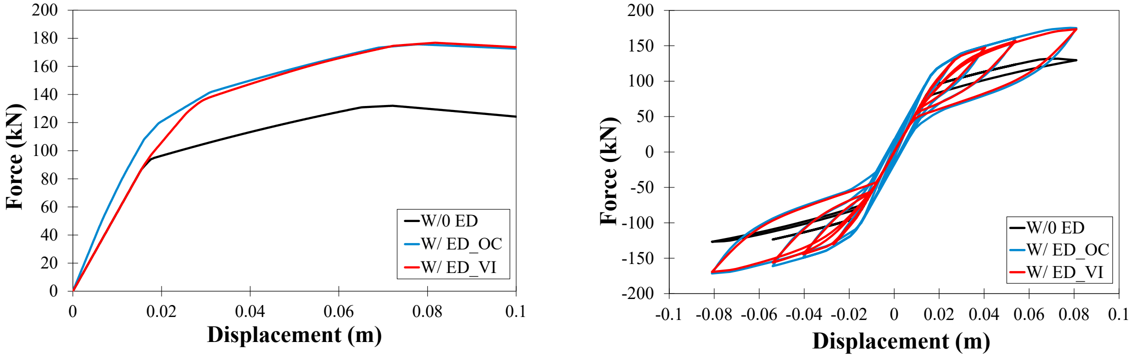
3. Preliminary assessment of the system with ED devices

3.1. Modelling strategy

The finite element model of a perimetral rocking frame was created using OpenSees software (McKenna and Fenves, 2013). Beams and columns were implemented as elastic beam elements, using a linear transformation for beams and a corotational transformation for columns. Prestressed rods were modelled as corotTruss elements with Steel01 material, connected to the beams via rigid connections and hinged to the ground. The prestressing was simulated using InitStrain material. The interface between beam and column was defined by rigid elements connected at both ends with vertical axial compression-only springs (stiffness $k=1.68\times10^9$ kN/m). The ED devices were modelled differently depending on the configuration. In the OC configuration, four truss elements with Steel02 material (D=20 mm, $f_y=235$ N/mm^2, E=420000 N/mm^2) were placed at the frame corners, connected to beams and columns at a distance of 0.5 m from their baricentric axes. These devices dissipate energy in both tension and compression. In the VI configuration, two dissipators (D=20 mm, L=400 mm) were positioned at each end of the rocking interfaces and modelled as zeroLength elements with Steel02 material ($F_y=73.87$ kN, k=164934 kN/m). These are activated by opening the gap during rocking and only act in tension, as the compressed side remains in contact and does not deform.

3.2. Nonlinear static and cyclic analyses

Non-linear static and cyclic analyses were performed to evaluate the performance of the system without ED devices and with ED devices in OC and VI configurations. Gravity loads were applied to the upper beam and the analyses were performed by controlling the displacement of the centre of the upper beam. The static pushover results (Figure 2a) show that the inclusion of energy dissipation devices increases the lateral resistance of the system. An increase in initial stiffness is only observed for the OC configuration. Figure 2b shows the results of the cyclic analyses and illustrates that the system without dissipators exhibits only limited energy dissipation as it relies solely on the yielding of the PT bars. With the introduction of ED devices, the system is able to effectively dissipate energy regardless of configuration while maintaining the ability to re-centre. Furthermore, the energy dissipation performance is comparable between the two configurations.



a) b)

Fig. 2. Pushover analyses results: (a) monotonic and (b) cyclic behaviour of the system with and without dissipators.

3.3. Time-history analyses

A sequence of ground motions was applied to the investigated system to evaluate its behaviour under different seismic intensity levels. The building was assumed to be located in L'Aquila (Italy), on a site with soil type C and topographic amplification factor T_1. The input was derived from a spectrum-compatible accelerogram according to NTC18 (2018). This dataset was scaled while maintaining its shape to obtain different levels of spectral horizontal acceleration Sa(T_1). A lumped mass was introduced at the centre of the upper beam and Rayleigh damping proportional to mass and stiffness was considered. Preliminary results, shown in Figure 3, indicate that the addition of energy dissipators reduces both the overall displacement of the system and the axial force in the PT rods while increasing the base shear. In the configuration without dissipators, the PT rods yield at Sa(T_1)=1.27g. However, when dissipators are installed, the PT rods are prevented from yielding and their ability to re-centre is maintained. This emphasises the effectiveness of the additional devices in improving seismic performance. As expected, the dissipators achieve their yielding force in both configurations and contribute to energy dissipation. However, the dissipators in the OC configuration are activated earlier than those in the VI configuration. This difference is due to the mechanism of gap opening: in the VI configuration, the dissipators only start to act when the rocking interface starts to open, while the devices in the OC configuration are already activated by the relative displacements at the corners.

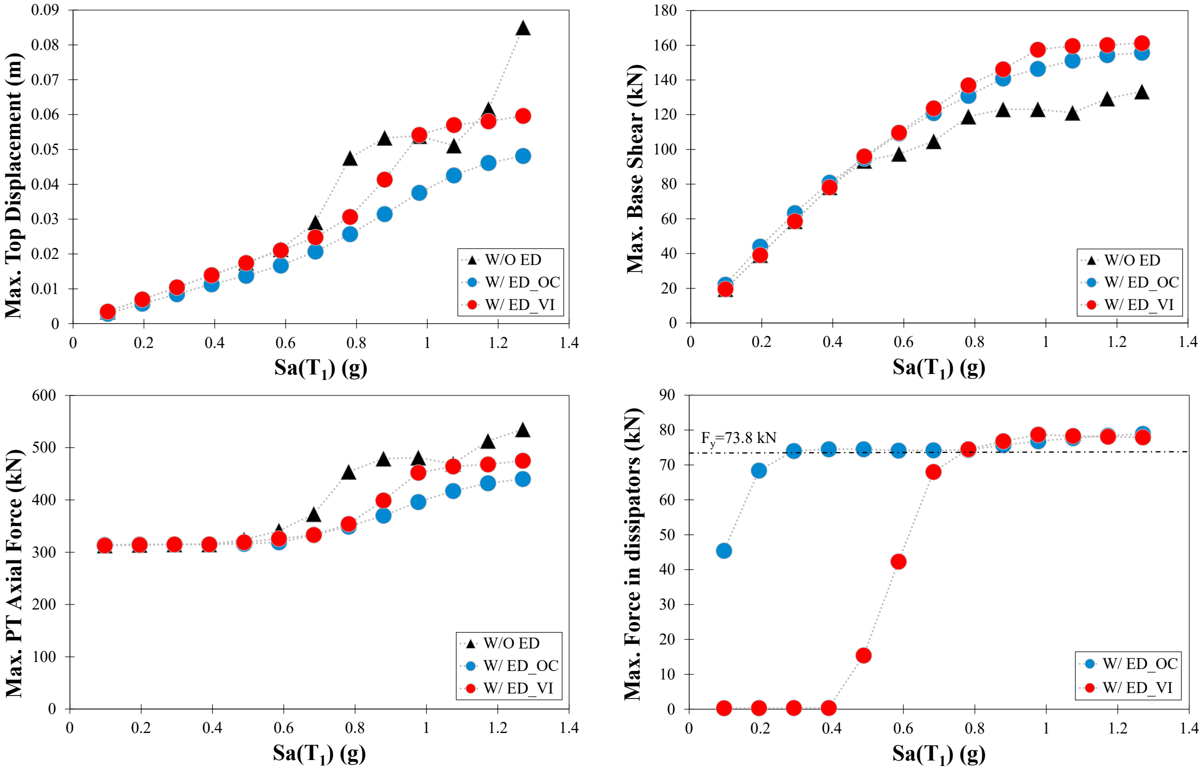


Fig. 3. Time history results (maximum) with and without dissipators: displacement at the top, base shear, axial force in the PT rods and axial force in dissipation devices.

The base shear–displacement curves, corresponding to three horizontal acceleration levels, are shown in Figure 4. These results not only confirm the reliable ability of the system to re-centre and effectively limit residual displacements, but also show that the inclusion of energy dissipation devices significantly increases the amount of dissipated energy. This improvement increases the overall seismic performance of the rocking frame, resulting in lower displacements and higher structural efficiency.

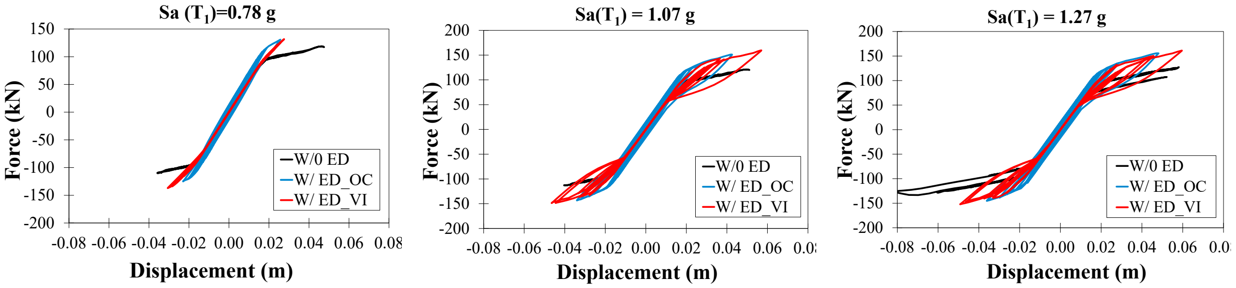


Fig. 4. Time history base shear-displacement results at three different Sa(T$_1$).

4. Conclusions

This study presented a preliminary proof of concept for an innovative, self-centring and self-balanced steel frame system with integrated energy dissipation devices, specifically designed for light steel buildings, but also suitable for seismic retrofitting of existing reinforced concrete structures. The proposed solution is based on the principles of Life Cycle Thinking and it is designed to minimise structural damage, improve functionality after an earthquake and support long-term sustainability through easy maintenance, disassembly and reuse. Two configurations of hysteretic dissipators were analysed: oblique at the corners (OC) and vertical at the vibration surfaces (VI). A finite element model was developed and nonlinear static and time-history analyses were performed to evaluate the performance of the system. The preliminary results have confirmed that the system is capable of concentrating damage in the dissipating elements and maintaining the ability to re-centre. The use of energy dissipation devices increased both the lateral strength and the energy dissipation capacity, while maintaining the restoring behaviour provided by the prestressed bars. In particular, the OC configuration showed an earlier engagement of the dissipators and a higher initial stiffness compared to the VI configuration. Overall, the proposed rocking LWS frame system represents a promising contribution to a resilient and sustainable seismic design where performance objectives are met in technical, environmental and social terms. As this study is an initial proof of concept, further research and development is required to define a design procedure and optimise the system components.

References

Bachmann J.A., Vassiliou M.F., Stojadinović B., 2017. Dynamics of rocking podium structures. Earthquake Engineering & Structural Dynamics 46, 2499-2517.

Belleri A., Labò S., Marini A., Biffi M.A., Vigani M., 2023. Preliminary considerations on the selective weakening of RC columns through rocking systems, XIX ANIDIS Conference, Seismic Engineering in Italy, Tourin, Italy.

Belleri A., Schoettler M.J., Restrepo J.I., Fleischman R.B., 2014. Dynamic Behavior of Rocking and Hybrid Cantilever Walls in a Precast Concrete Building. ACI Structural Journal 111(3), 661-671.

Belleri A., Torquati M., Riva P., 2013. Finite Element Modelling of "Rocking Walls", 4th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2013), Kos Island, Greece.

Casprini E., Belleri A., Marini A., Labò S., Passoni C., 2022. Pin-supported walls as seismic retrofit for existing RC frames: feasibility and preliminary design. Bulletin of Earthquake Engineering 20, 5349-5381.

Christopoulos C., Filiatrault A., Uang C.M., Folz B., 2002. Posttensioned Energy Dissipating Connections for Moment-Resisting Steel Frames. Journal of Structural Engineering 128(9), 1111-1120.

Elettore E., Freddi F., Latour M., Rizzano G., 2021. Design and analysis of a seismic resilient steel moment resisting frame equipped with damage-free self-centering column bases. Journal of Constructional Steel Research 179, 106543.

Freddi F., Dimopoulos C.A., Karavasilis T.L., 2017. Rocking damage-free steel column base with friction devices: design procedure and numerical evaluation. Earthquake Engineering and Structural Dynamics 46(14), 2281-2300.

Gualdi M., Belleri A., Marini A., Labò S., Rota L., 2025. Preliminary assessment of self-centering rocking steel systems for lightweight buildings, 10th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2025), Rhodes Island, Greece.

Labò S., Belleri A., Bianchessi M., Gualdi M., 2025. Preliminary performance assessment of rocking systems with viscous dampers, 10th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2025), Rhodes Island, Greece.

Marini A., Passoni C., Belleri A., Feroldi F., Preti M., Metelli G., Riva P., Giuriani E., Plizzari G., 2017. Combining seismic retrofit with energy refurbishment for the sustainable renovation of RC buildings: a proof of concept. European Journal of Environmental and Civil Engineering 26(7), 2475-2495.

McKenna F., Fenves G.L., 2013. OpenSees Manual. Available online: https://opensees.berkeley.edu/wiki/index.php/ Command_Manual.

Ministry of Infrastructure and Transport, 2018. Norme Tecniche per le Costruzioni (Ministerial Decree of January 17, 2018). Official Gazette of the Italian Republic, 42.

Mpampatsikos V., Bressanelli M.E., Belleri A., Nascimbene R., 2020. A non-dimensional parametric approach for the design of PT tendons and mild steel dissipaters in precast rocking walls. Engineering Structures 212, 110513.

Passoni C., Marini A., Belleri A., Menna C., 2021. Redefining the concept of sustainable renovation of buildings: State of the art and an LCT-based design framework. Sustainable Cities and Society 64.

Pollino M., 2015. Seismic design for enhanced building performance using rocking steel braced frames. Engineering Structures 83, 129-139.

Priestley M.J.N, Sritharan S., Conley J.R., Pampanin S., 1999. Preliminary Results and Conclusions from the PRESS Five-Story Precast Concrete Test Building. PCI Journal 44(6), 42-67.

Restrepo J.I., Rahman A., 2007. Seismic Performance of Self-Centering Structural Walls Incorporating Energy Dissipators. Journal of Structural Engineering 133(11), 1560-1570.

Ricles J.M., Sause R., Garlock M.M., Zhao C., 2001. Posttensioned Seismic-Resistant Connections for Steel Frames. Journal of Structural Engineering 172(2), 113-121.

Schoettler M.J., Belleri A., Zhang D., Restrepo J.I., Fleischman R.B., 2009. PCI Journal 54, 100-124.

Vassiliou M. F., Broccardo M., Cengiz C., Dietz M., Dihoru L., Gunay S., Mosalam K. M., Mylonakis G., Sextos A., Stojadinovic B., 2021. Shake table testing of a rocking podium: Results of a blind prediction contest. Earthquake Engineering & Structural Dynamics 50, 1043–1062.

Wiebe L., Christopoulos C., 2015. Performance-Based Seismic Design of Controlled Rocking Steel Braced Frames. I: Methodological Framework and Design of Base Rocking Joint. Journal of Structural Engineering 141(9), 04014226.

Zaki M., Zhong C., Christopoulos C., 2025. Analytical Study on the Predictability of Con-trolled Rocking Frame and Podium Systems. Earthquake Engineering & Structural Dynamics 0, 1-21.

Zhong C., Christopoulos C., Self-centering seismic resistant structures: Historical overview and state-of-the-art. Earthquake Spectra, 2021.