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PRELIMINARY PERFORMANCE ASSESSMENT OF ROCKING SYSTEMS WITH VISCOUS DAMPERS

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Abstract

In recent years, research has heavily focused on the decarbonization of the building sector, promoting a new design paradigm that takes into account eco-efficiency, resilience, safety, robustness, functionality and the impact on the life cycle of buildings. As the field is increasingly shifting towards multi-performance-based and lifecycle-oriented design approaches, rocking systems have proven to be a promising solution for overcoming the limitations of traditional design methods. For example, these systems enable controlled damage localization and improved repairability in the event of earthquakes.
In this context, the use of dissipative devices, such as viscous dampers, at the base of rocking systems is investigated. These devices localize damage in replaceable components that do not affect the system's ability to support gravity loads. The additional damping provided by these devices reduces displacements, accelerations and shear forces along the height of the building. This study investigates the effectiveness of completely replacing hysteretic devices at the wall-foundation interface with viscous dampers. Nonlinear dynamic analyses were performed using the finite element software OpenSees. The results are analyzed in terms of base moment and shear, comparing the response of the system before and after the integration of linear viscous dampers into the rocking wall.

Keywords: Rocking, viscous, controlled damage.

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1 INTRODUCTION

In recent years, the growing emphasis on the decarbonization of the building sector has driven significant advancements in sustainable and resilient structural solutions. The shift towards multi-performance-based and lifecycle-oriented design approaches has led to the exploration of innovative systems capable of enhancing the seismic performance of buildings while minimizing environmental impact. Among these, rocking systems have emerged as a promising alternative to traditional seismic design strategies, providing improved damage control and repairability [1-3] while ensuring high structural performances when implemented in new and existing buildings [4-6].

Rocking systems, consisting of a rocking wall and a post-tensioned (PT) cable that enables recentering, exhibit limited energy dissipation during seismic events due to their bilinear elastic behavior. Typically, these systems have a damping of 1-2%. External dissipative devices can be designed and added to rocking systems to increase the dissipated energy. Dissipative devices can be placed in different positions on the rocking wall, they allow for damage localization and, when damaged after an earthquake, they can be easily replaced. The behavior curve of the rocking wall changes to a flag shape when adding dissipative devices such as, for example, hysteretic [7-9], viscous [10-12] or frictional [13-15] systems.

This study assesses the feasibility of replacing hysteretic devices with viscous dampers as a proof of concept. Dynamic analyses were performed on a FEM model, validated against experimental results from the DSDM research program at the University of California, San Diego [7,8].

2 POTENTIAL BENEFITS OF REPLACING HYSTERETIC DEVICES WITH VISCOUS DAMPERS

2.1 Experimental campaign

A precast half scale reinforced concrete building with three floors, measuring 7 m in height and 17 m x 4.9 m in plan, was subjected to shaking table tests during the DSDM program. The building had an inter-story height of 1.98 m, and the masses of each floor slab were 42.36 t, 44.50 t, and 39.76 t, respectively. Two rocking walls, each 2.4 m width and 0.2 thick, were placed on the short side of structure and connected to transfer only horizontal loads. The walls were designed to serve as either rocking or hybrid walls, depending on the test setup, by grouting non-adherent steel bars at the wall-foundation interface for the latter configuration. In this study, only the hybrid configuration was considered.

The post-tensioned cables in the walls consist of two sets of prestressing steel strands. Each set comprises five strands with a diameter of 12.7 mm, anchored at the top of the wall and at the foundation. The yield strength of the cables is 1800 MPa, while the ultimate tensile strength is 1915 MPa; a post-tension of 321 kN (648.5 MPa) was applied.

Hysteretic dampers, made of typical corrugated steel bars with a diameter of 22 mm, a yield strength of 490 MPa and ultimate capacity of 673 MPa, were grouted at the wall-foundation interface to provide energy dissipation [8]. In the following only the results related to a particular ground motion, referred to as only SEA-4, were considered. Figure 4 plots the SEA-4 ground motion and the response spectra of the input ground motion. [7,8]. In the analysis, the ground motions were scaled by 1.855 to account for similitude law requirements (Figure 1c).

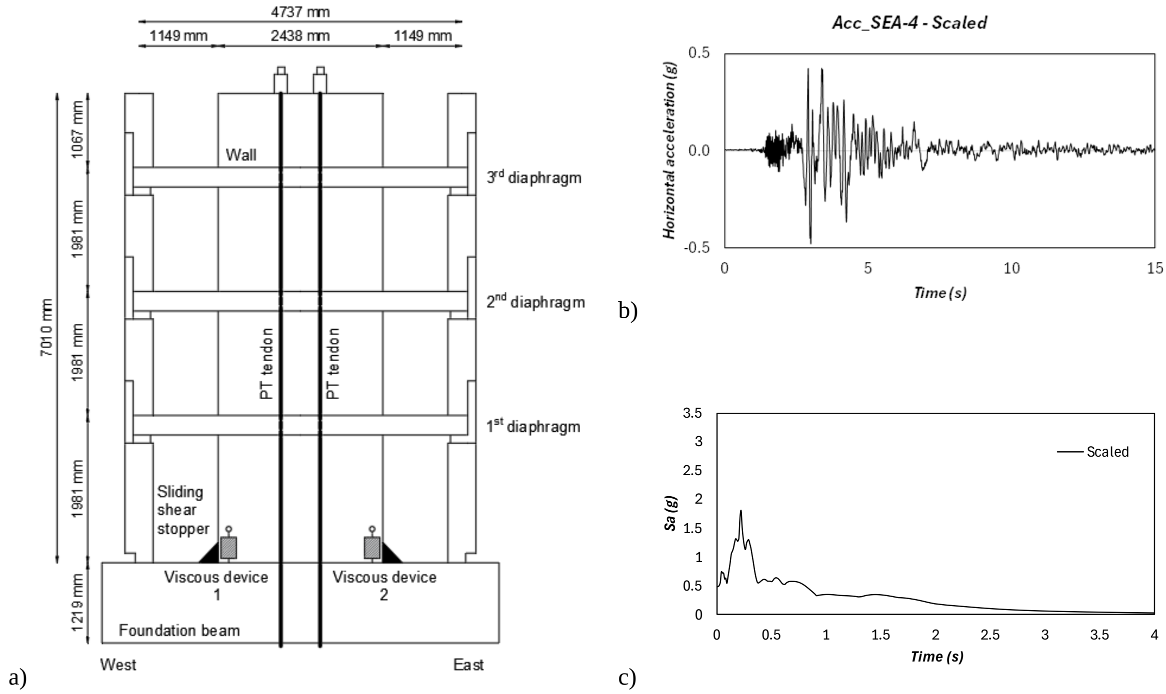


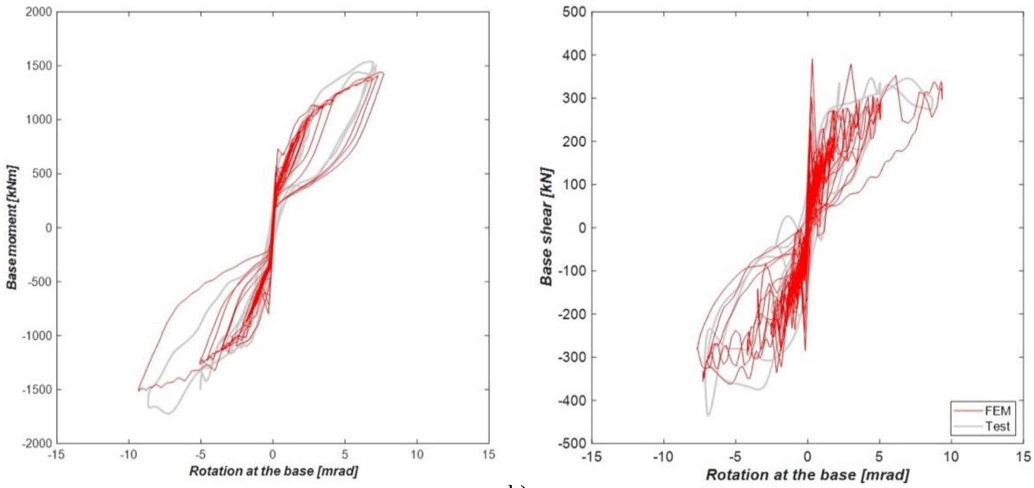
Figure 1: a) Geometry of the tested rocking wall; b) considered ground motion; c) response spectrum.

2.2 Modeling

The finite element model of the system was developed using the software OpenSees [16] considering the modeling choices described in [17]. Post-tensioned cables were implemented as truss elements and connected at the top to the rocking wall through rigid elements. A bilinear elastic behavior was used for the post-tensioned cables. The wall was modeled using beam elements based on the Bernoulli formulation, while the rocking interface and confined elements were modeled with dispBeamColumn elements. The 2.5 cm-wide rocking interface was modeled using a fiber approach with a uniaxialMaterial ENT-type relationship. The elastic modulus was set to 280 MPa to achieve an axial stiffness at the base comparable to that of an axial spring with a length equal to half the rocking wall width (2.4 m).

The confined reinforced concrete was also modeled using a fiber approach, with the uniaxialMaterial Concrete07 model based on Chang & Mander's [18] formulation, and a fiber width of 1 cm. Following Twigden et al. [19], the elastic modulus was reduced by 40 % to 22560 MPa. A compressive stress of 85.5 MPa was considered, corresponding to a strain of 0.0076, while the tensile stress was set to a negligible 4.6 MPa, with a corresponding strain of 0.121. The fiber sections were discretized in 120 elements in the longitudinal direction and 4 in the wall depth. Lumped masses were introduced at each floor. Rayleigh damping proportional to the masses with a damping factor value of 0.01 was considered [17].

Hysteretic devices were modeled with fiber elements, fixed at the foundation level, and rigidly connected to the rocking wall base. The length of the dissipators corresponds to their total unbonded length (38 mm). The dissipators were discretized by defining a circular fiber section divided into three rings, each composed of eighteen sub-elements. Uniaxial Material Dodd-Restrepo type were introduced [20]. The numerical results obtained were compared with the experimental ones in Figure 2.



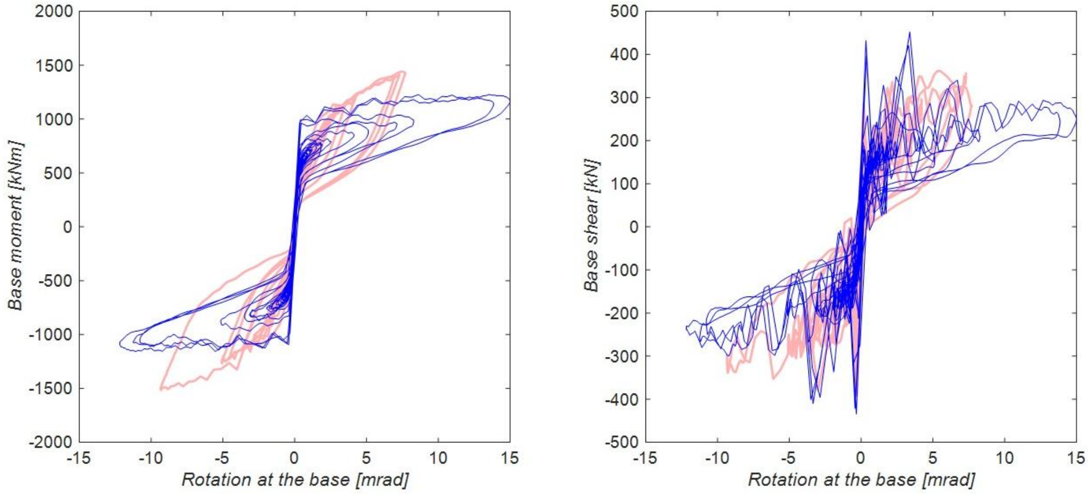
a) b)

Figure 2: Numerical model against the experimental results: a) base moment and b) base shear as a function of the base rotation.

2.3 Replacing hysteretic devices with viscous devices

Based on the model replicating the experimental test (Figure 2), the hysteretic devices were completely replaced by viscous devices with progressively increasing damping coefficient (*C*) to evaluate the effectiveness of using viscous devices as a substitute for hysteretic devices. Specifically, values of *C* equal to 400, 800, and 1200 kNs/m were considered. The viscous devices were modeled as two-node link elements and placed at the ends of the wall. They were assigned an uniaxialMaterial Viscous-type behavior. The results are shown in (Figure 3) in terms of base moment and base shear as a function of base rotation.

C=400 kNs/m



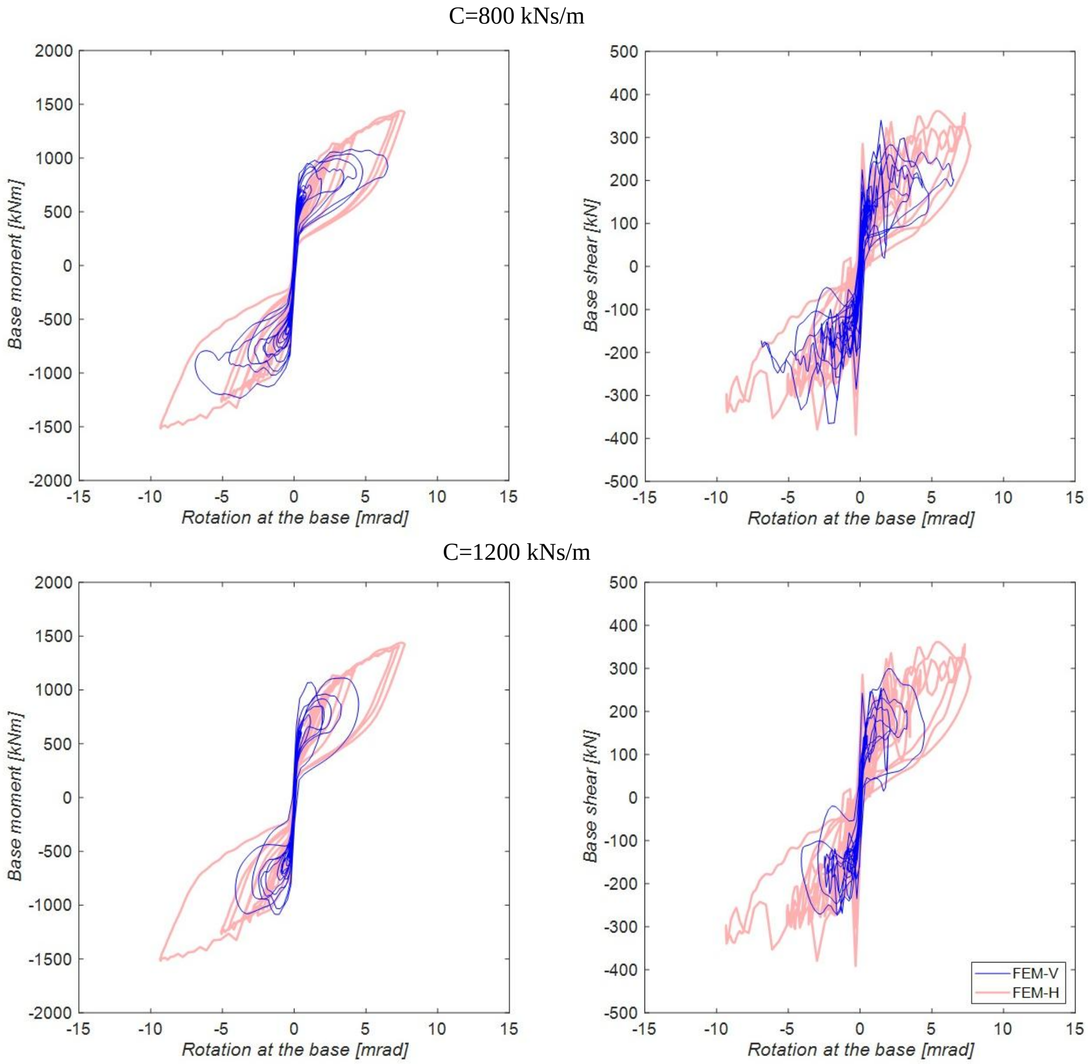


Figure 3: Comparison in moment-rotation and shear-rotation between and numerical results with mild steel rebars (red line) and numerical results with linear viscous dampers (blue line).

The diagrams in Figure 3 show that the maximum moment at the base remains approximately constant for all values of *C* and is around 1200 kNm. This value is lower than that observed for hysteretic devices, with a reduction of about 25 %. A similar trend is observed for the base shear, except for the case with *C*=400 kNs/m, where peak values equal to or higher than the case with hysteretic devices (+30%) are recorded. As *C* increases, the maximum displacement at the top of the wall decreases. For low values of *C* (*C*=400 kNs/m), the maximum displacement exceeds that observed with hysteretic dampers by +67% in terms of absolute maximum displacement. However, as *C* increases from 400 kNs/m to 1200 kNs/m, the maximum displacement becomes progressively lower than that observed with the hysteretic devices by 20% and 87%, respectively.

Figure 4 plots the behavior of the linear viscous devices in terms of force-displacement (Figure 4a) and force-velocity (Figure 4b). In each case, the maximum force in the devices remains almost constant while deformation and velocity reduce.

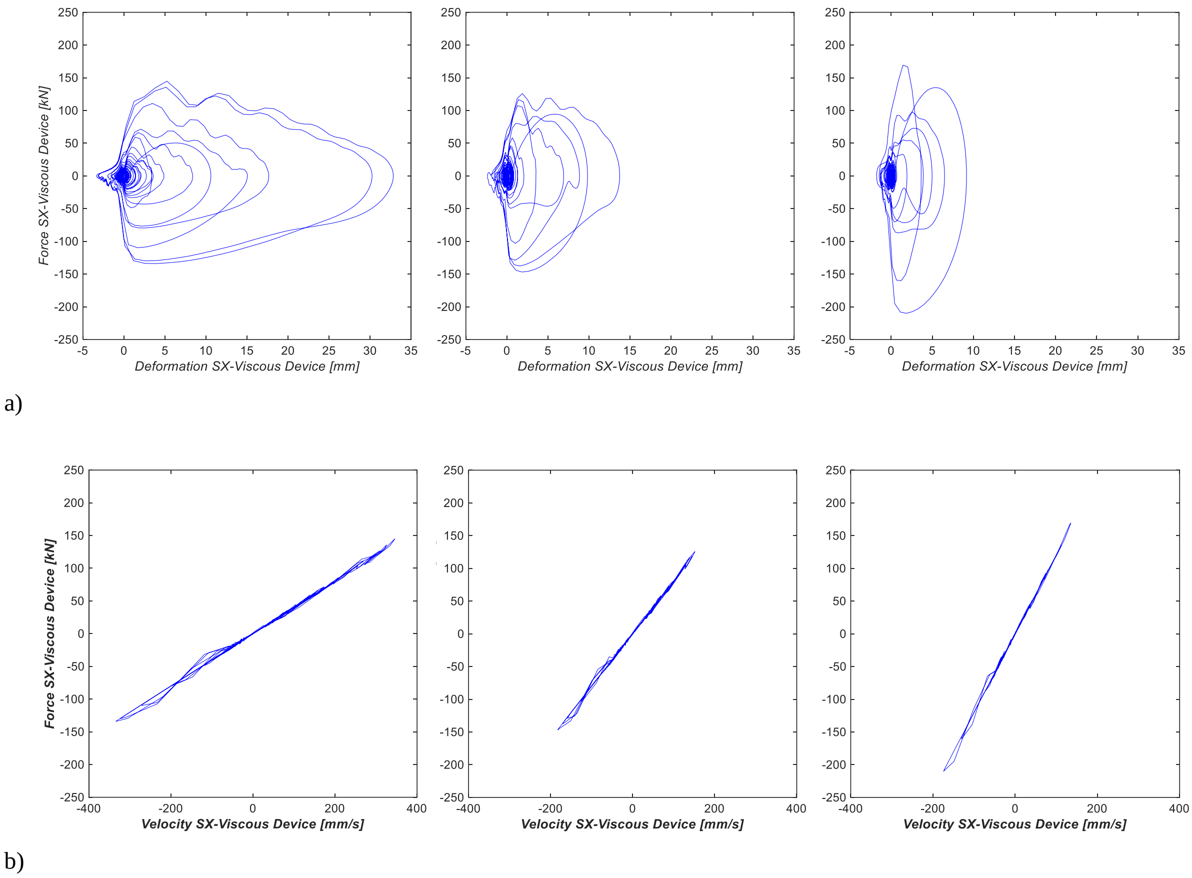


Figure 4: Results in terms of force displacement (a) and force-velocity (b) of linear viscous dampers.

3 CONCLUSIVE REMARKS

This study provides a proof of concept for the use of viscous devices in rocking wall systems and illustrates their potential as an alternative to hysteretic dampers. Viscous dampers in these systems offer advantages in terms of maintenance and repairability, as they can be easily replaced if damaged. This aspect is particularly important in the context of lifecycle-oriented design, where ease of repair and lifecycle performance are critical factors.

Numerical analyses were performed with a validated finite element model of a rocking wall originally equipped with hysteretic devices. These devices were replaced by linear viscous dampers characterized by different damping coefficients. As expected, the results show that the effectiveness of the viscous dampers depends on the choice of the damping coefficient C, which influences important response parameters such as base moment, base shear, and maximum displacement at the top of the wall. The analyses indicate that for sufficiently high damping coefficients (e.g. C=800 kNs/m), viscous devices can significantly reduce the maximum displacement of the rocking wall while keeping the base moment relatively constant.

Future research could focus on developing simplified design methods for implementing viscous dampers in rocking walls as well as exploring their application in seismic retrofitting of existing buildings.

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