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Design and experimental testing of a concrete rocking wall structural system

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Abstract

The seismic design for concrete structures typically relies on the ductility of elements like beams in frame structures, ensuring occupant safety but often causing irreparable damage to the building. This damage leads to prolonged recovery times and considerable social and economic consequences. To improve resilience, alternative systems like base isolation and viscous dampers have been developed to limit damage. However, some of these solutions may be impractical or too costly for certain building types, such as precast concrete structures. For these cases, researchers have suggested using post-tensioned concrete elements that rock at their base, paired with easily replaceable external dissipative devices. These systems aim to overcome the limitations of ductility-based design by providing self-centering capabilities and facilitating easy repairs. This paper presents preliminary experimental results on the cyclic behavior of a novel PreWEC (Precast Wall with End Columns) system, which includes post-tensioned rocking concrete walls, end-columns, and steel dissipative devices. The system features a concrete wall with post-tensioned cables, two end-columns connected by beams, and hysteretic dampers between the wall and columns. The columns support the beams while their uplift is limited during base rocking due to their small cross-section. The study examines the quasi-static cyclic behavior of this system. Findings show excellent energy dissipation and minimal damage.

Keywords: post tension ; concrete walls ; rocking walls ; hysteretic dampers ; low-damage design

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1. Introduction

Structural Reinforced Concrete (RC) walls are one of the most effective lateral load resisting systems thanks to their high stiffness and strength. The current seismic design approaches for structures mainly aim at obtaining a ductile behaviour through the definition of proper capacity design criteria and detailing rules (Paulay and Priestly, 1992). Ductility, and therefore damage, is exploited to dissipate part of the seismic energy, with the aim of achieving both life safety for the building occupants and collapse prevention. Strong ground-motions are likely to cause high damage in the plastic regions of structural elements. This is particularly relevant for RC walls, characterized by the formation of

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a single plastic hinge at their base. The subsequent repairing process, when possible, could take a very long time and have negative social and economic consequences (Katafygiotis and Lam, 2002). Furthermore, the costs associated with business interruption, damage to equipment and structural rehabilitation are, often, comparable to the entire building cost. For these reasons, researchers have proposed the so called "Low-damage systems" that combine good seismic performances with low damage and negligible residual displacements. Different effective technologies already exist to date, like base isolation or viscous dampers. However, their application might be unpractical for some types of buildings, such as low-rise precast concrete structures, mainly because of economic restraints. An alternative to these technologies is based on precast concrete elements free to rock at their base with unbonded post-tensioned cables. Unbonded cables provide self-centring capabilities, thus offering a resilient solution against structural damage caused by earthquakes. Furthermore, in many of these systems damage is concentrated in specific elements, which are easy to either replace or repair. The idea of using post-tensioned cables in lateral force resisting elements was introduced for the first time in the '90s, in the context of the PRESSS (PREcast Seismic Structural Systems) research project (Priestley (1991); Stone et al. (1995); Priestley et al. (1999); Nakaki et al. (1999)). These researches showed that the use of post-tensioned cables in lateral force resisting elements allowed achieving low damage levels in concrete elements compared equivalent RC frame. Further studies were carried out by Restrepo and Rahman (2007), who investigated the behaviour of unbonded precast panels able to dissipate seismic energy through the yielding of mild steel bars at the wall-foundation joint. This solution presented the benefit introduced by the use of unbonded cables and a bending capacity similar to a RC wall. However, the positioning of the mild steel bars inside the concrete grout made impossible their substitution. An alternative approach to jointed walls was obtained by reducing the dimensions of the panels at the ends, up to assume them as columns. They provided necessary support to slab thanks to the limited uplift due to small section dimensions. The study by Sritharan et al. (2015) was carried out in the same context. They designed and experimentally validated a resisting system, called PreWEC, that consisted in one precast unbonded concrete wall and two steel or concrete end-columns at both sides. In this system, O-shaped hysteretic dissipative devices were placed in wall-column joints.

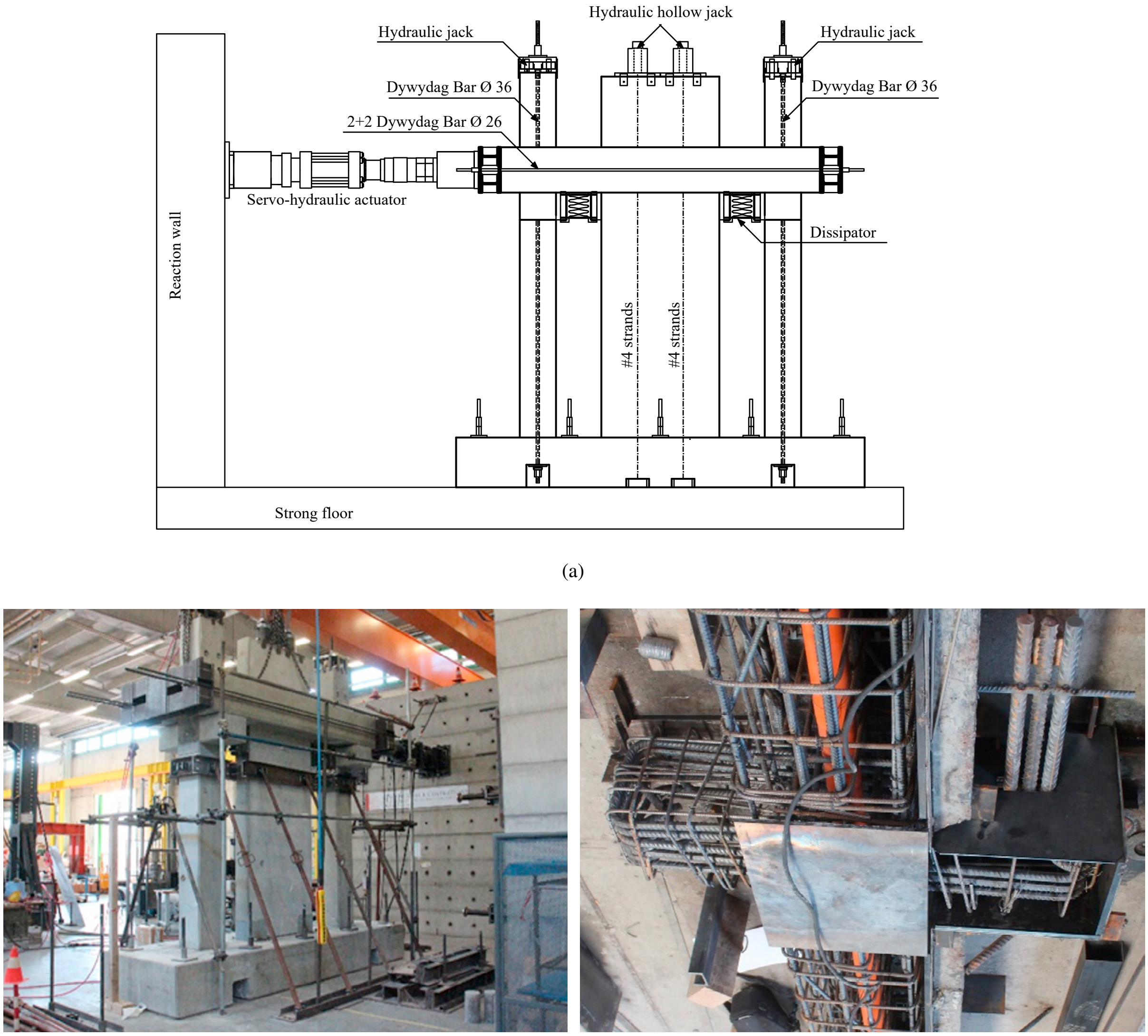
This paper presents and analyses the preliminary results of an experimental campaign aimed at investigating the behaviour of an original PreWEC system. The system is composed of a precast concrete wall with two bundles of post-tensioning cables and concrete end-columns connected to concrete beams. Beam-column connection is made with steel dowels, while the wall and the end-columns are connected through special steel hysteretic dampers. The wall of the resisting system is equipped with shear keys at its base. The paper analyses the quasi-static cyclic behaviour of the resisting system observed experimentally.

The structure of the paper is as follows. Section 2 provides a description of the PreWEC structural system, followed by a discussion of the steel dampers in Section 3. The experimental program and the corresponding results are presented in Sections 4 and 5, respectively. Finally, conclusions are presented in Section 6.

2. Description of the PreWEC structural system

The tested PreWEC system (Figure 1) consisted in a post-tensioned precast concrete wall with two bundles of unbonded tendons and two precast concrete columns with unbonded post-tensioned steel bars. The columns supported, through corbels, two concrete beams that in a real building would support slabs. As discussed in Sritharan et al. (2015), using columns to support beams has the positive effect of reducing their vertical movements during rocking, resulting in a mitigation of the possible damage to slabs. The whole system was positioned on a precast concrete foundation. Steel dampers connected the columns to the wall with the twofold purpose of transferring lateral loads from the columns to the wall and dissipating energy. The energy dissipation occurs thanks to the relative vertical movements between the wall and the columns during rocking. In particular, each damper was installed between each column and the wall by means of welded connections, in order to avoid gaps. Further details about the design of the dampers are discussed in section 3.

The wall measured 1300 mm in width, 250 mm in thickness, and 4000 mm in height. At the base, it was featured with steel toes and shear keys welded to the foundation. Prior to assembly, a 20 mm layer of high-strength mortar was cast to level the surface. Two 20 mm thick steel plates, serving as supports for the shear keys, were then positioned over the mortar and secured using four threaded bars anchored into the foundation. Once the wall was placed, cylindrical shear keys were inserted and welded to the plates to ensure proper contact. Finally, the pockets were filled with an



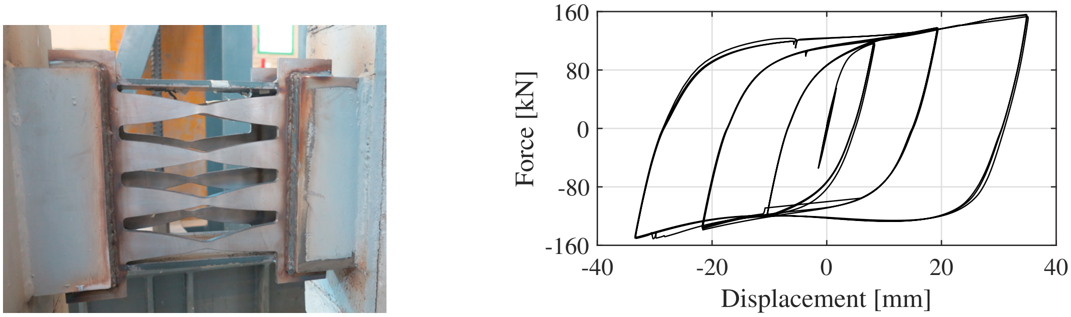
(a)

(b) (c)

Fig. 1. The PreWEC structural system: (a) a schematic view, (b) a picture of the system and (c) a picture of the corbel reinforcement.

additional 20 mm layer of high-strength mortar. At 2420 mm from the base, steel plates were installed on both sides to enable damper connections. The columns had a cross section of 400×400 mm and were 4000 mm tall, featuring corbels and steel plates for damper attachment at the same height (see Figure 1(c)). The beams measured 300×500 mm in cross section and 4000 mm in length. The foundation had a cross section of 1400×550 mm and a length of 4500 mm, and was anchored to the laboratory strong floor using eight Dywidag bars. Its top surface included three 40 mm deep recesses for the installation of the wall and columns.

Initial tension was set to 475 kN for the wall and 270 kN for each column. The wall included two bundles of four 15.7 mm diameter strands (600 mm² each), while each column used one 36 mm Dywidag bar. Tendons were anchored at both the top of the elements and within the foundation.



(a)

(b)

Fig. 2. (a) Picture of the steel dampers connected to the steel plates through welds and (b) force-displacement response of the steel damper.

3. Hysteretic dampers

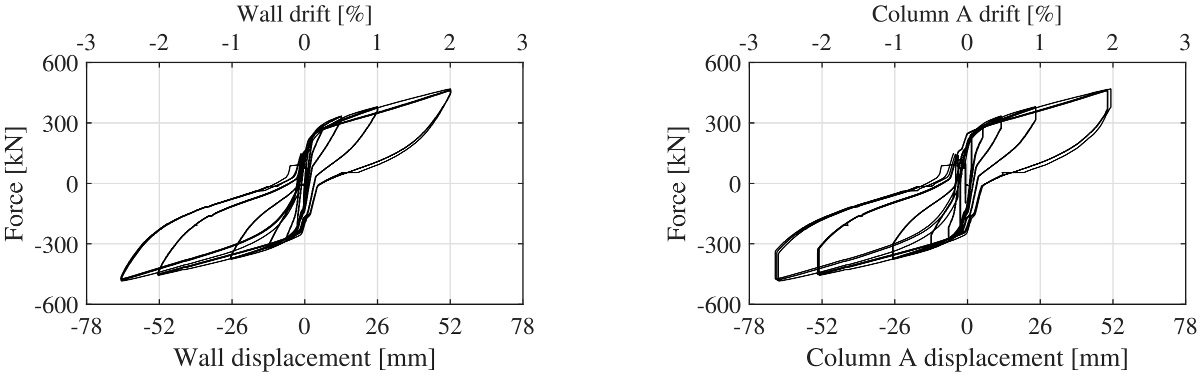
As previously introduced, steel dampers have the dual objective of transferring the lateral loads from the columns to the wall as well as of dissipating energy. A total of two steel dampers has been employed, each one connecting one column to the wall, as shown in Figure 2(a). Each steel damper consisted of four plates welted together to create a tubular element. The two main plates constituting the tubular element were designed to dissipate as much energy as possible and were placed in the vertical plane like the wall. The other two plates were placed in the horizontal plane at the extrados and the intrados of the main plates so as to create the tubular element. The two main plates presented slits that allow identifying four slats. The steel damper was connected to the wall and the column through the steel plates set in concrete as described in section 2. In particular, each main plate of the steel damper was welded to the steel plates embedded in concrete (see figure 2(a)). The welded connection between the damper and the concrete element allowed avoiding the deformability of bolted connections caused by the relative displacement between the bolt and the hole.

The tubular shape of the damper was necessary to avoid torsional deformation and, consequently, out-of-plane deformation of the slats. The two horizontal plates presented a thickness of 10 mm, were subjected mainly to axial forces and did not affect the slat stiffness in the vertical plane. The two main plates were 10 mm thick and contained the slats. To maximize the energy dissipation, the slat height was not constant but decreased toward the center of the slat. The optimal shape of the slats was designed so that the slat stress was uniform along its length and, consequently, all the slant reached the yield stress at once. This allowed maximizing the plasticized material as well as the energy dissipation. On the contrary, slants with constant height would have allowed for the plasticization of the endpoints only, without exploiting all the element ductility. Finally, it is worth noting that the all the corners of the slits were rounded to avoid local failures.

The so-designed dampers are characterized by a great dissipative capacity, as shown by the hysteresis cycles presented in figure 2(b). The force-displacement response shown in figure 2(b) was obtained from a laboratory experiment focused on the damper behaviour. The experiment was conducted by connecting the two dampers to local portions of three RC elements, representing the wall and the columns. A vertical displacement was applied to the central RC elements to impress a relative displacement to the ends of each damper. The force-displacements curve shown in figure 2(b) relates the shear in the damper to the relative vertical displacement. The experiment involving the dampers is not detailed here, being it out of the scope of the paper.

4. Experimental program

The experimental program described in the present paper was aimed at verifying the performance levels at the life-safety limit state of an original PreWEC system. According to Restrepo and Rahman (2007), these are: i) ensuring self-centring capability; ii) maintaining the post-tensioning elements in elastic conditions; iii) avoiding concrete spalling at the element toes during rocking. The self-centring capability is guaranteed by a proper calibration of the initial



(a) Wall

(b) Column A

Fig. 3. Force-displacement plots of (a) the wall and (b) column A (black). Red color: result of the analytical model.

post-tensioning force, by limiting the stress-loss due to permanent deformations in compression and by predicting the pre-stressing force increments during rocking. To this purpose, the analytical procedure developed by Aaleti and Sritharan (2009) was applied to define the initial post-tension value and to estimate the stress in the cables during the test.

All reinforced concrete elements were cast using the same concrete mix, with an average compressive strength of 80 MPa and an elastic modulus of 33,400 MPa, measured according to UNI EN standards. Reinforcing bars showed a yield strength of 545 MPa and tensile strength of 640 MPa. Steel plates had a yield strength of 295 MPa, while the high-strength strands and Dywidag bars exhibited yield strengths of 1670 MPa and 963 MPa, respectively.

Quasi-static cyclic tests were performed using a 1000 kN servo-hydraulic actuator with ±125 mm stroke, applying load at 2950 mm from the wall base to simulate seismic action. The loading protocol followed ACI ITG-5.1 guidelines and included two initial force-controlled cycles (50 and 100 kN), followed by displacement-controlled cycles up to 2.5% drift.

Displacements were recorded using a total of 21 LVDTs and 2 wire transducers installed at key locations on the wall, columns, beams, and foundation. Strain gauges (6 per damper) were applied to the steel dampers, while load cells and hollow hydraulic jacks monitored the actuator force and post-tensioning forces, respectively. This comprehensive instrumentation setup enabled accurate measurement of wall drift, uplift, sliding, and relative displacements.

5. Experimental results

The hysteretic response of a resisting system can be assessed based on the amount of self-centring force and its dissipative capacities. Rocking behaviour is characterized by the opening of a joint at the element base and it occurs when the external moment due to the imposed lateral force is larger than the system decompression moment. The base gap opening leads to a reduction of the stiffness which is restored when the unbonded cables bring the element back in its initial position. Energy dissipation is made possible by the steel dampers.

The PreWEC tested systems has shown an excellent cyclic behaviour for all drift levels. Wall and columns have rotated independently and a relative vertical sliding in wall-column joints was generated. This movement caused a yielding deformative state in the dampers that produced high energy dissipation. Thanks to the presence of the dissipative devices as well as to the concrete confinement, no cracks were observed in the concrete at the element base, which is regarded as an improvement compared to the traditional cracking pattern observed in RC elements.

The results below relate to the force-displacement behavior of both the wall and Column A, specifically the one positioned near the actuator.

The global behaviour of the resisting system tested is illustrated in the force-displacement plots of Figure 3. The force-displacement plot of the wall is presented in Figure 3(a), while that of column A in Figure 3(b). The wall displacement was computed as the average of the displacement measures obtained from the transducers placed at both sides of the wall. The shape of the observed hysteretic cycles is consistent with the typical flag-shape behaviour observed on similar systems tested in the literature. It is easy to notice that the tested systems satisfied the requirements discussed in section 2 in terms of energy dissipation and self-centring capability, showing a stable and symmetrical response and good self-centring capabilities.

6. Conclusions

This paper presented the design and experimental evaluation of a novel PreWEC system incorporating unbonded post-tensioned concrete walls, end-columns, and steel hysteretic dampers. The quasi-static cyclic tests demonstrated excellent seismic performance, combining significant energy dissipation with minimal structural damage. The steel dampers effectively transferred lateral loads and provided high dissipative capacity, while the unbonded post-tensioning ensured self-centering behavior without concrete cracking at the wall base.

Overall, the PreWEC system proves to be a promising solution for achieving low-damage seismic performance in precast concrete structures, combining resilience, reparability, and reliable design methodologies.

References

Aaleti, S., Sritharan, S., 2009. A simplified analysis method for characterizing unbonded post-tensioned precast wall systems. Engineering Structures 31, 2966–2975. doi:https://doi.org/10.1016/j.engstruct.2009.07.024.

Katafygiotis, L.S., Lam, H.F., 2002. Tangential-projection algorithm for manifold representation in unidentifiable model updating problems. Earthquake Engineering & Structural Dynamics 31, 791–812. doi:https://doi.org/10.1002/eqe.122.

Nakaki, S.D., Stanton, J.F., Sritharan, S.S., 1999. An overview of the presss five-story precast test building. PCI Journal 44, 26–39. doi:https://doi.org/10.15554/pcij.03011999.26.39.

Paulay, T., Priestly, M.J.N., 1992. Seismic Design of Reinforced Concrete and Masonry Buildings. John Wiley & Sons, Inc. doi:10.1002/9780470172841.

Priestley, M.J.N., 1991. Overview of presss research program. PCI Journal 36, 50–57. doi:https://doi.org/10.15554/pcij.07011991.50.57.

Priestley, M.J.N., Sritharan, S.S., Conley, J.R., Pampanin, S., 1999. Preliminary results and conclusions from the presss five-story precast concrete test building. PCI Journal 44, 42–67. doi:https://doi.org/10.15554/pcij.11011999.42.67.

Restrepo, J.I., Rahman, A., 2007. Seismic performance of self-centering structural walls incorporating energy dissipators. Journal of Structural Engineering 133. doi:https://doi.org/10.1061/(ASCE)0733-9445(2007)133:11(1560).

Sritharan, S., Aaleti, S., Henry, R.S., Liu, K.Y., Tsai, K.C., 2015. Precast concrete wall with end columns (prewec) for earthquake resistant design. Earthquake Engineering & Structural Dynamics 44, 2075–2092. doi:https://doi.org/10.1002/eqe.2576.

Stone, W., Cheek, G., Stanton, J., 1995. Performance of hybrid moment-resisting precast beam-column concrete connections subjected to cyclic loading. ACI Structural Journal 92. doi:10.14359/1145.