Cyclic behaviour of prestressed precast concrete walls

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SUMMARY
This study introduces a new patented system of prestressed precast reinforced concrete walls for the construction of dwelling houses. The precast concrete walls were made with a high strength concrete, with web reinforcement and prestressing wires. Six full-scale walls were tested under procedures of severe cyclic loads. The tests allowed us to evaluate the system capacity under cyclic loads, shear strength, ductility, energy dissipation, damping and crack appearance in the walls with the severe load increase. From the results is concluded that the prestressed precast concrete walls with web reinforcement and prestressing wires can be used for housing construction.

Keywords: Precast concrete walls; Prestressing wires; Cyclic test.

1. INTRODUCTION

The seismic activity in western and central America is classified as moderate and high. Since strong earthquakes may take place in this zone (for example, Haiti 2010, Chile 2011), high performance of the existing structural systems is required. In consequence, several experimental investigations have evaluated the seismic performance of hybrid construction systems based on reinforced concrete and prestressing cables [Priestley et al., 1999, 2002, 2007; Kurama, 1999; Rahman et al, 2000; Restrepo et al, 2001; Pérez et al, 2004, Kurama, 2004]. These kinds of hybrid systems improve the cost-effectiveness ratio and increase the seismic performance of concrete walls in comparison to structures without prestressing [Kurama, 2002; Sauce, et al., 2005; Panian, et al., 2007]. Preliminary cyclic tests have shown the benefits of this kind of structures and have elucidated the behaviour of the system when subjected to dynamic loads [Kurama, 1999, 2005; Sauce, et al., 2005]; furthermore, such experimental campaigns have fostered the creation of standards for earthquake resistant design and construction [Thomas et al., 2004; ACI, 2007, 2008, 2009].

Recently, the Colombian company PRECONCRETO S.A.S., has developed and patented a building system named *"Prestressed Precast Reinforced Concrete Walls"* (PPRCW) [PRECONCRETO, 2010]. This system, as its name indicates, comprises precast concrete walls which are assembled by fixing them to the foundation and ceiling beams, in order to produce a cost-effective structure for lateral resistance. Fig. 1.1 shows some dwelling houses built with the patented system.

In the present study, six full-scale PPRCW were tested under cyclic loading conditions; the results of the tests assessed the capacity of the system under dynamic loads, shear strength, ductility, energy dissipation, damping and crack appearance on the surface of the walls.

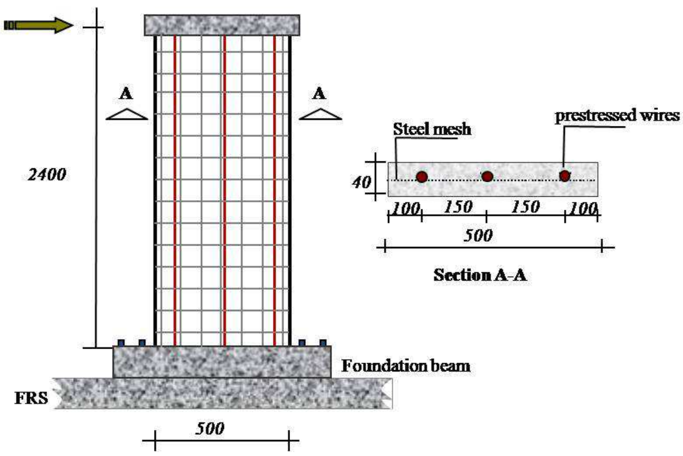
The plan of this article is as follows: Section 2 gives a brief description about the proposed system and the experimental setup. In Section 3 some structural parameters are computed from the data drawn from the cyclic test. Finally, Section 4 gives some conclusions from the experimental campaign.

Figure 1.1. Houses built with prestressed precast reinforced concrete walls

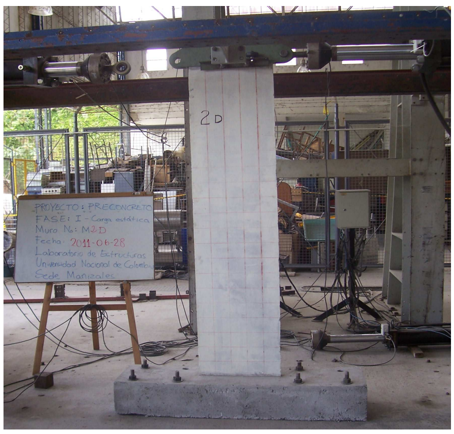
2. TEST SPECIMENS

The PPRCW were built with concrete and were reinforced with a wire mesh with square opening and prestressing wires. The concrete used in the construction of the walls achieved a compressive strength after 28 days of 31.7 MPa. The yield resistance of the reinforcing mesh was 485 MPa, and the yield strength of the prestressing wires was 1801 MPa.

The typical PPRCW used in this investigation had the following dimensions: 500 mm width, 2400 mm height and 40 mm thick. Six full-scale models were built and tested at the structures laboratory of the Universidad Nacional de Colombia at Manizales. The geometry of the specimens and reinforcement detail are shown in Fig. 2.1a; an overview of the test set up is shown in Fig 2.1b.



(a) Reinforcement detail and geometry



(b) Overview of test setup

Figure 2.1. Detail of test PPRCW

The walls were embedded in highly rigid foundation beams in order to provide lateral resistance. Thereafter, each "wall-foundation beam" system was anchored to a reaction floor with steel screws as shown in Fig. 2.1b. Lateral bracing was used in order to avoid lateral displacements of the wall.

2.1. Test setup and procedure

An axial load equivalent to 2% of the capacity of the walls was applied to the models; such capacity was computed based on the ultimate resistance of the concrete and the wall cross-section. The axial load was kept constant during the tests. A lateral load was applied with a calibrated actuator, which was fixed to a steel reaction frame. Fig. 2.2 shows the time history of the applied cyclic load, following the model proposed by Park (1989). The lateral displacements were recorded using LVDTs embodied in the actuator. Data were measured on the top of the walls and stored in a data acquisition system. In addition, photography and video equipment was used during the tests.

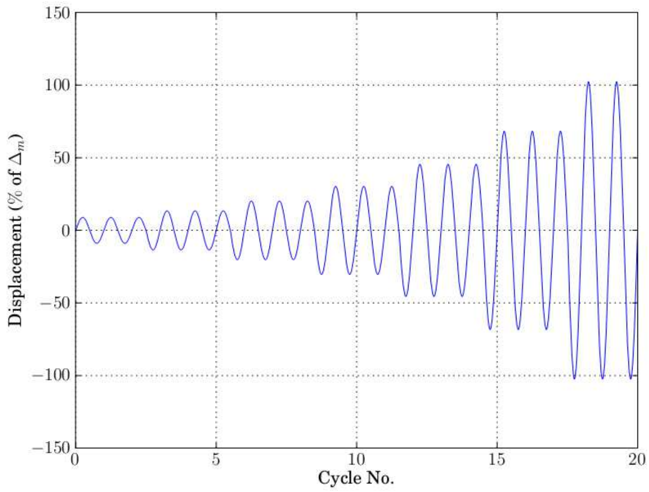


Figure 2.2. Time history of applied load on test structures

3. TEST RESULTS

3.1. Force-drift ratio response

Fig. 3.1 shows the resulting hysteresis curves of one of the tests with its respective envelopes. From the hysteresis it can be seen that the PPRCW exhibited pinching due to the early appearance of cracks in the base of the walls and the opening and closing of those cracks due to the cyclic load. The lateral capacity and other parameters of the system were drawn from the envelopes of the hysteresis curves.

Fig. 3.2a details the positive and negative envelopes of the hysteresis cycles from one of the tests; it can be seen that both envelopes are similar, so the average of these envelopes is used in order to compute structural parameters of the system. Fig. 3.2b shows the *Equivalent Energy Elastic-Plastic* (EEEP) curve computed from the average envelope [ASTM, 2011].

Table 3.1 summarizes the experimental values of the structural parameters deduced from the hysteresis loops. The maximum lateral load applied to the wall was 7.05 kN, and the estimated maximum lateral load was 6.20 kN, which means that the wall was able to support 14% more than the theoretical maximum capacity of the system; the theoretical maximum lateral load was calculated according to the procedure described in chapter 18 of [ACI 318, 2008].

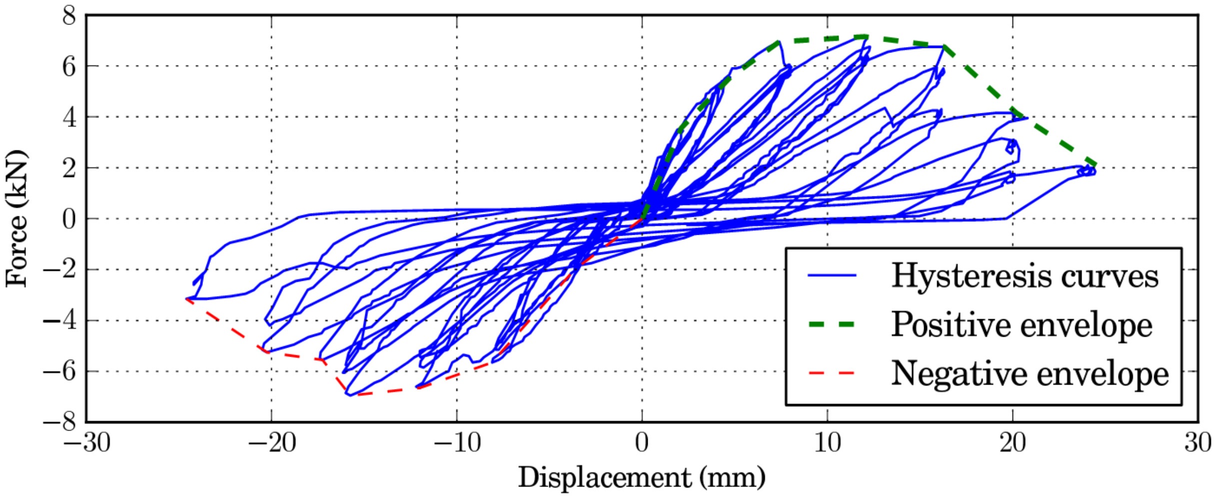
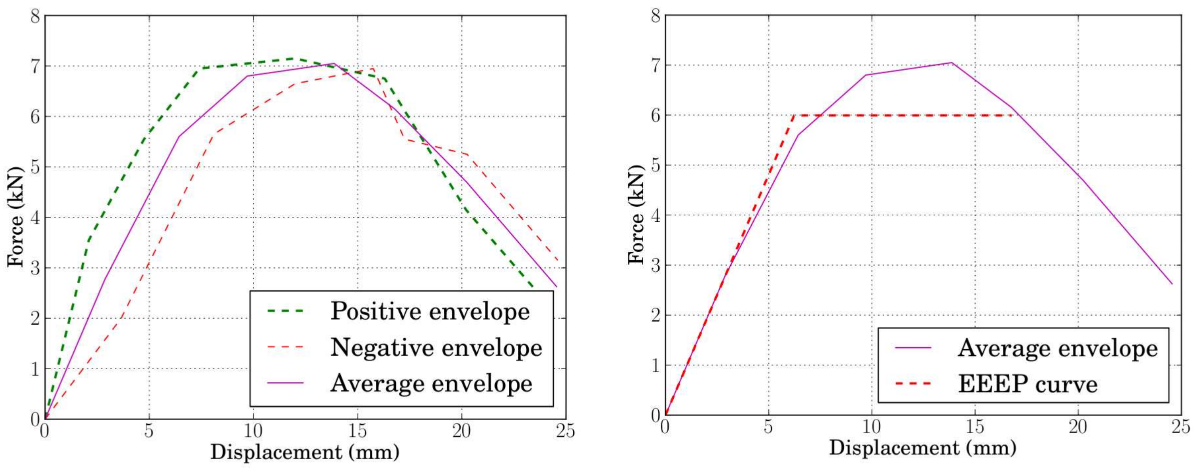


Figure 3.1. Hysteresis cycles and envelopes



(a) Envelopes of hysteresis

(b) Average envelope and EEEP curve

Figure 3.2. Envelopes and EEEP curve

Table 3.1. Parameters drawn from cyclic tests, calculated according to the ASTM E 2126-11

Elastic shear stiffness (K_e) (kN/mm)	Maximum absolute load (P_{peak}) (kN)	Ultimate displacement (Δ_u) (mm)	Yield displacement (Δ_{yield}) (mm)	Cyclic ductility ratio ($\mu = \Delta_u / \Delta_{yield}$)
1.32	7.05	16.78	6.23	2.69

With those quantities, it is possible to compute the shear strength (v_{peak}), the shear modulus of the specimen (G') and the yield load (P_{yield}). The resultant values are summarized in Table 3.2.

Table 3.2. Strength parameters obtained from cyclic tests, computed according to ASTM E 2126-11

Shear strength (v_{peak}) (kN/mm)	Shear modulus (G') (kN/mm)		Yield load (P_{yield}) (kN)
	$0.4P_{peak}$	P_{peak}	
0.0141	4.43	1.93	5.99

3.2. Energy dissipation and damping

Currently, structural designs are based on fragility analysis, which aims to dissipate the energy transmitted by external dynamical forces by means of the phenomenon of hysteresis, so the safety margin of structural elements is increased and the sudden failure of the material is avoided.

The damage is related to the capacity of the structural system to dissipate the energy when it is subjected to cyclic loads. The capacity of the material in terms of energy dissipation can be quantified by the so-called *equivalent viscous damping ratio* (ξ_{eq}) [Shaingchin, 2007; Priestley, 1996] of a structural element or system subjected to cyclic loading; this equivalent viscous damping ratio is given by the following expression:

$$(\xi_{eq})_i = E_i / 4\pi(E_e)_i, \tag{3.1}$$

where E_i is the energy dissipated by the structural element or system in the *i*-th loading cycle, and $(E_e)_i$ is the energy "stored" by an equivalent linear elastic system when the maximum displacement in the *i*-th cycle is reached in static conditions.

To compute the energy stored by the equivalent linear elastic system $(E_e)_i$, the hysteresis curves from the cyclic test were used. The energy stored by an equivalent linear system is given by the area under the load vs. displacement curve, which is a right triangle whose base equals the maximum positive displacement suffered by the model $(\Delta_{max})_i$ and whose height $(P_m)_i$ is the average peak load of the cycle analyzed, i.e.:

$$(P_m)_i = 0.5 \cdot (\,|\, (P_{max})_i \,|\, + \,|\, (P_{min})_i \,|\,); \tag{3.2}$$

here $(P_{max})_i$ and $(P_{min})_i$ stand for the maximum and minimum values that the load reaches in the *i*-th cycle. With these data, the energy $(E_e)_i$ can be computed as follows:

$$(E_e)_i = 0.5 \cdot (P_m)_i \cdot (\Delta_{max})_i. \tag{3.3}$$

The dissipated energy in the *i*-th cycle E_i can be computed from the readings measured in the laboratory. Table 3.3 shows the energy E_i and $(E_e)_i$, the drifts and the equivalent viscous damping computed for each drift level.

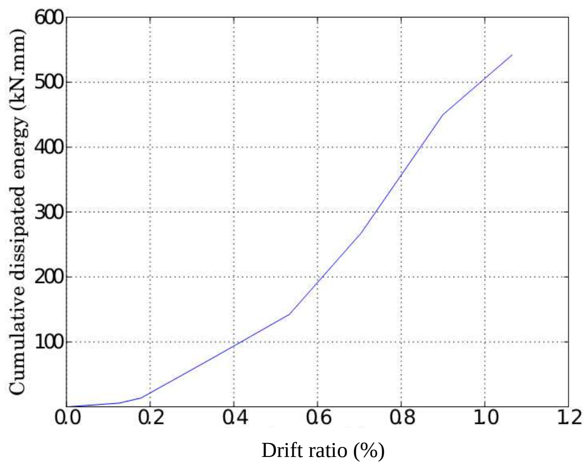
Table 3.3. Computation of equivalent viscous damping from energy

Cycle No. *i*	E_i (kN.mm)	$(E_e)_i$ (kN.mm)	Drift (%)	Equivalent viscous damping (ξ_{eq})
1	1.6587	1.2166	0.0674	0.1085
2	5.1362	10.0653	0.2065	0.0406
3	42.00	41.8038	0.5261	0.0800
4	50.6613	47.9251	0.6913	0.0841
5	56.9162	44.5159	0.8870	0.1017
6	52.50	30.4690	1.0630	0.1371

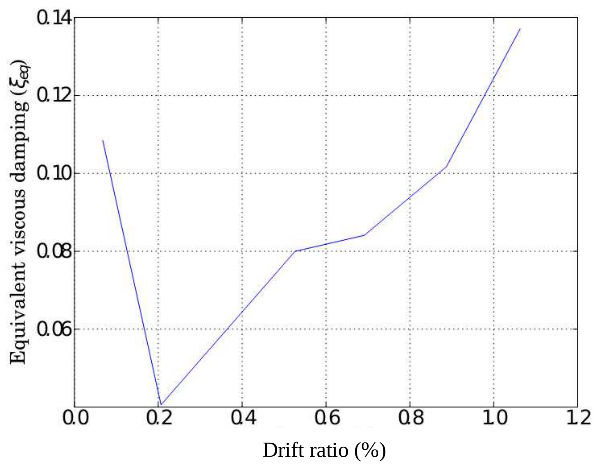
Fig 3.3 shows the accumulated dissipated energy and the equivalent viscous damping (ξ_{eq}) as a function of the drift. Typical values of damping for reinforced concrete-based structures range between 2% - 7% [Priestley, 1996]; the increased values for the equivalent viscous damping observed here may be attributed to the prestressing wires.

3.3. Observed damages and crack patterns

The walls were tested until failure. All walls failed with the same type of pattern, which was a single crack at the base of the wall; this crack crossed the wall from one side to the other, and it opened or closed according to the direction of the cyclic load; this fact explains the pinching which can be observed in the hysteresis curves (Fig. 3.1). It must be pointed out that the conventional reinforcing mesh and the prestressing reinforcement did not show any damage at all.

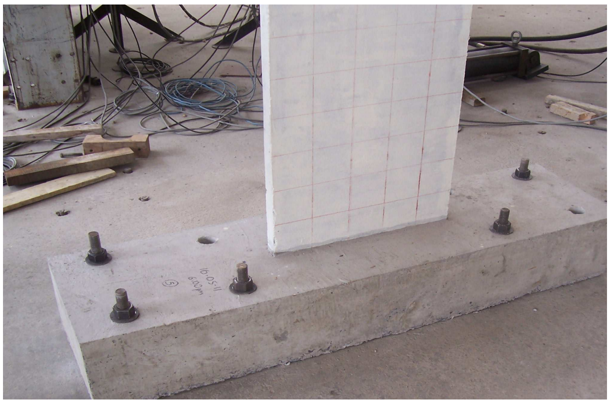


(a) Energy dissipation

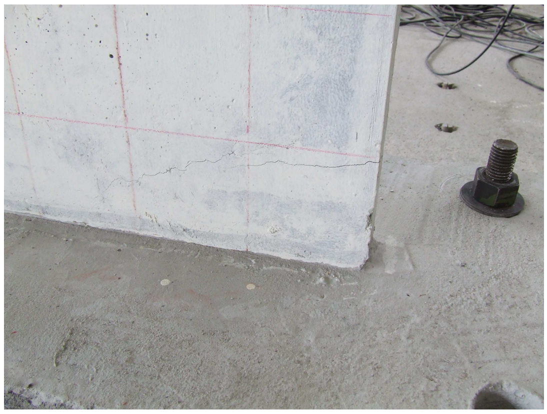


(b) Equivalent viscous damping ratio

Figure 3.3. Energy dissipation and damping



(a) Wall at 0.06% drift ratio

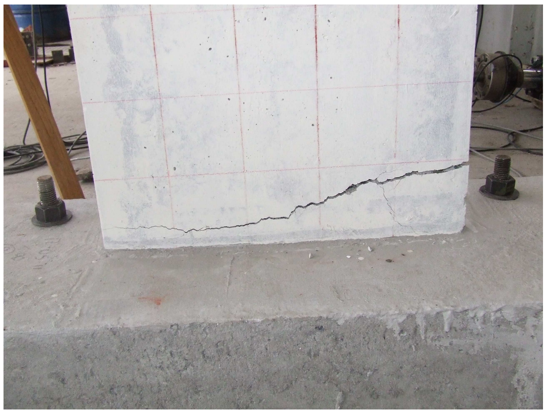


(b) Fracture at the edge of module (0.20% drift)

(c) Fracture at the base (0.55% drift ratio)

(d) Fracture at the base (0.69% drift ratio)

(e) Fracture at the base (0.85% drift ratio)



(f) Fracture at the base (1.00% drift ratio)

Figure 3.4. Crack patterns of wall at different drift levels

4. CONCLUSIONS

The PPRCW system exhibited good performance when it was subjected to cyclic loads, which makes the tested system an appropriate alternative for housing construction in zones with seismic activity.

It can be observed that the equivalent viscous damping ratio increases from 4% at 0.2% drift to 13% at 1% drift. These values are consistent with those computed by Holden et al. (2003) for precast concrete wall systems.

It was observed that the concrete failed at the end of the tests, but the system did not collapse because the reinforcing mesh and the prestressing wires remained undamaged during the application of the cyclic load.

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