Cyclic Behaviour of Precast Concrete Modules with Post-tensioned Unbounded Bars

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SUMMARY:
This study shows the cyclic behaviour of a patented system for the construction of dwelling houses in seismic zones. The system comprises precast reinforced concrete modules assembled using steel connectors; the modules are post-tensioned with unbounded bars. A single-story full-scale 3D model was built and tested under cyclic loading. The test revealed that the system has a satisfactory performance in terms of load-lateral deflection, shear strength, ductility, energy dissipation, damping, crack appearance and propagation with load increase. The constructive system response suggests that it could be used in zones with moderate and high seismic activity as an innovative system for the construction of dwelling houses.

Keywords: Cyclic test; Precast concrete modules; Post-tension unbounded bars.

1. INTRODUCTION

The seismic activity in Latin America affects directly the structures in the region. Recent earthquakes in the zone (Colombia 1999, Perú 2007, Haiti 2010, Chile 2011) have demonstrated the poor performance of some materials and building systems employed in the construction of dwelling houses. In order to tackle this problem, new building techniques, such as prestressed concrete-based systems, have been proposed by several authors. Those researches have carried out cyclic load test in order to determine and improve the seismic performance of prestressed concrete structural elements, mainly walls, which are the more affected elements when dynamic loads act on the structure [Priestley et al., 1999, 2002, 2007; Rahman et al, 2000; Restrepo et al, 2001; Perez et al, 2004, Kurama, 2002, 2004; Sauce, et al., 2005]. The characterization of structural elements under cyclic load has allowed a complete understanding of the material [Kurama, 2005], as well as the application and creation of standards for earthquake resistant design and construction [Thomas et al., 2004; ACI, 2007, 2008 2009]. Prestressed concrete-based systems have been the subject of research and innovation in modern buildings and dwelling houses.

Recently, the Colombian company FABRICASAS S.A. developed and patented a novel building system [FABRICASAS, 2002] known as *" Precast Reinforced Concrete (PRC) Modules"*, which is based on precast concrete walls assembled with steel connectors and vertically post-tensioned with unbounded bars. In this article, we will evaluate the seismic performance of this construction technique.

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 PRC modules proposed by FABRICASAS

2. DESCRIPTION OF THE TEST MODEL AND EXPERIMENTAL SETUP

2.1. Description of the materials

The PRC modules were built with concrete and reinforced using a mesh with square opening. The compressive strength of the concrete after 28 days was 24 MPa. The yield resistance of the reinforcing mesh and the prestressing bars was correspondingly 485 MPa and 1696 MPa.

2.2. Description of the PRC modules and the system

The concrete modules have a fixed height of 485 mm and variable thickness and width that depend on the architectural design of the building. Fig. 2,1 shows the PRC module used in this research. In order to build a house, the PRC modules are assembled with four steel connectors of 6 mm in diameter and 80 mm in length, located according to Fig. 2.1. Once the walls have been placed, the prestressing bars are introduced into the 20 mm-diameter holes, and then, they are post-tensioned according to the structural design.

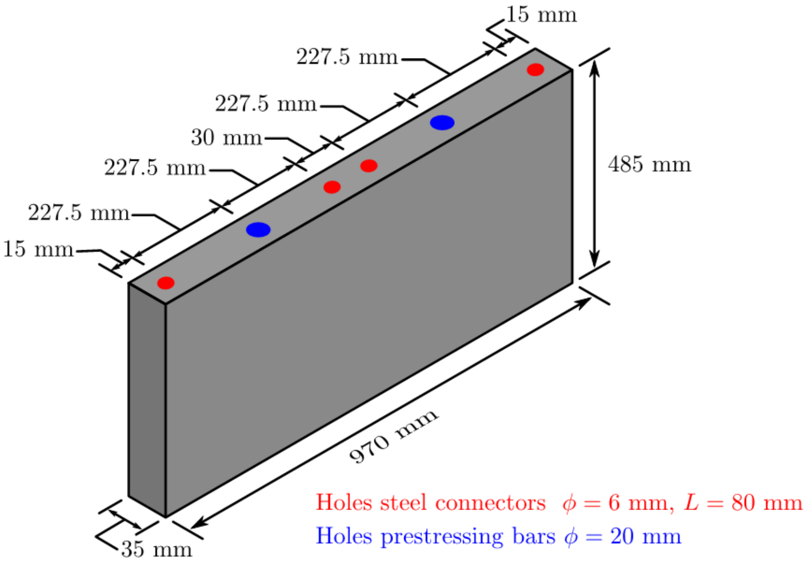
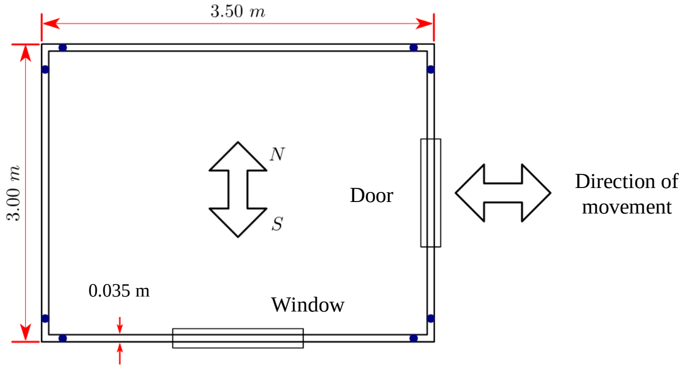


Figure 2.1. Precast reinforced concrete modules and holes for steel connectors and prestressing bars

2.3. Experimental setup

A one-story 3D specimen was built in full-size scale in the structures laboratory of the Universidad Tecnológica de Panamá. The model had 3.50 m width, 3.00 m long and 2.44 m height, as shown in Fig. 2.2. The total weight of the structure, including the ceiling, was 23 kN.



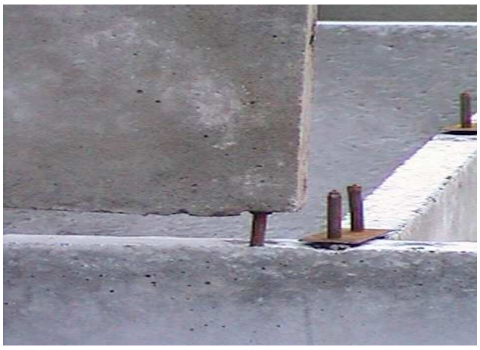
(a) Geometry of the specimen

(b) Test model

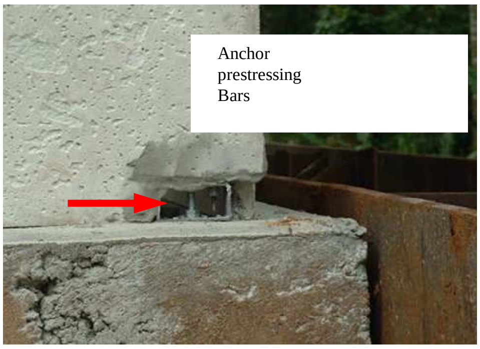
Figure 2.2. General view of the test structure

The model was anchored to highly rigid reinforced concrete beams. The first modules were fixed to a foundation with the 6 mm-diameter steel connectors (Fig. 2.3a), and the remaining modules were assembled according to the traditional construction process (Fig. 2.3b). The post-tensioned bars crossed the modules from the ceiling to the foundation of the structure, and they were anchored to the foundation beams with high resistance screws and metal sheets. The diaphragm of the ceiling was simulated with a set of steel beams bolted to the reinforced concrete modules as shown in Fig. 2.3d. Thereafter, the structure was loaded in order to simulate service conditions.

(a) Foundation



(b) Assembly between modules



(c) Anchorage of post-tensioned bars

(d) Diaphragm of the ceiling

Figure 2.3. Details of the construction of the model

2.4. Instrumentation

The lateral displacements were measured with LVDTs during the test as shown in Fig. 2.4. The data was captured using a data acquisition system. In addition, photography and video equipment was used during the test.

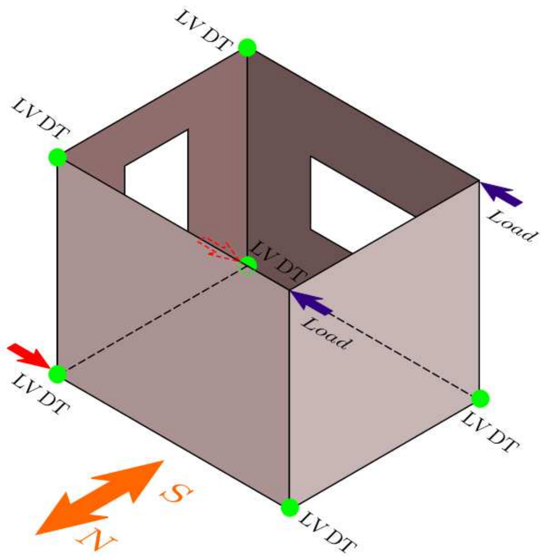


Figure 2.4. Instrumentation of the model

2.5. Applied load on test structures

In order to apply the load in the cyclic test, a hydraulic actuator was used. The actuator has 250 kN of capacity in compression and 160 kN in tension. Fig. 2.5 shows the time history of the applied load following the model proposed by Park (1989).

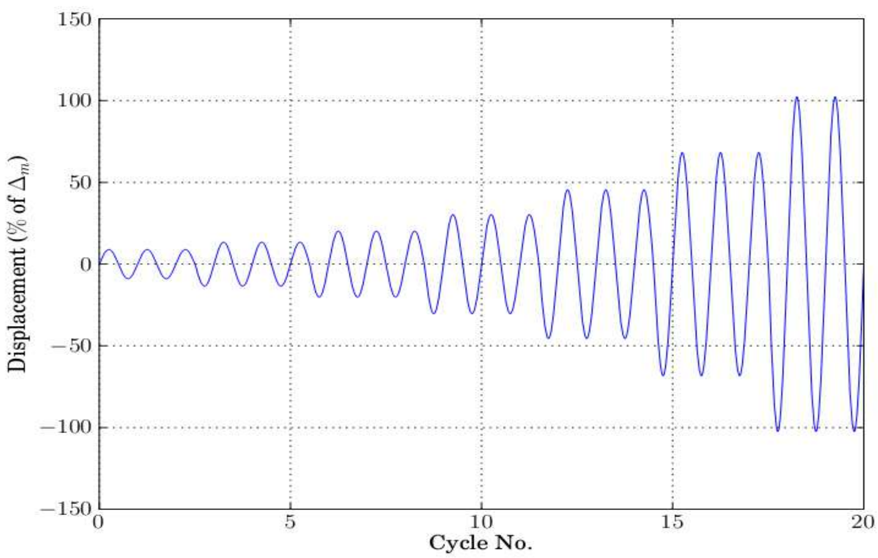


Figure 2.5. Time history of applied load on test structures

3. EXPERIMENTAL RESULTS

3.1. Force-drift ratio response

Fig. 3.1 shows the resulting hysteresis curves and their respective envelopes. The PRC modules with unbounded bars exhibited some pinching, probably caused by the slipping of the connectors. The lateral capacity and other characteristics of the system were obtained from the average envelope drawn from the hysteresis cycles (Fig. 3.1).

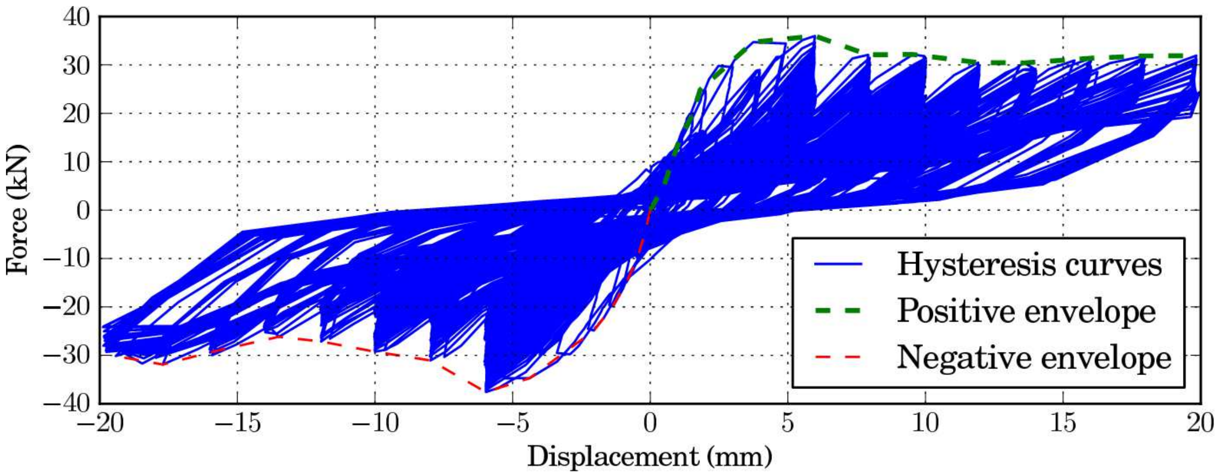
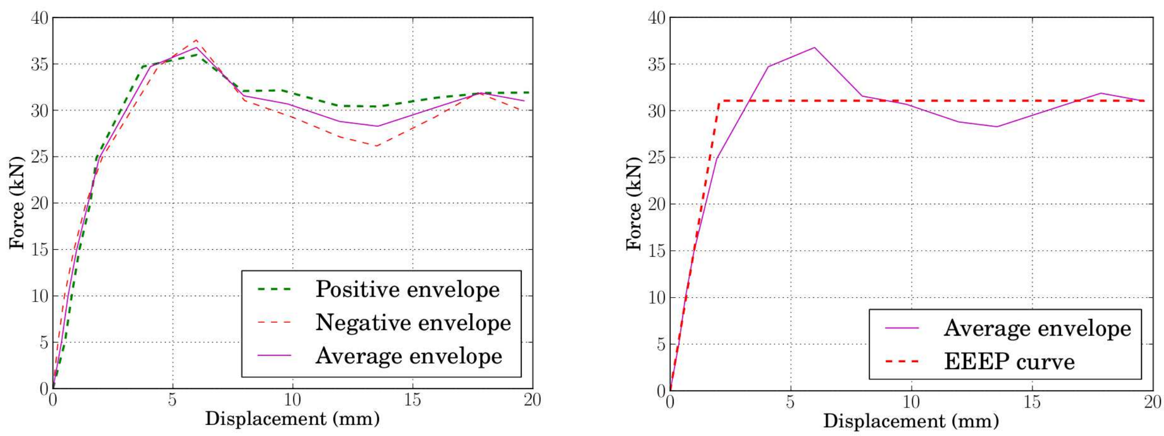


Figure 3.1. Hysteresis cycles

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



(a) Envelopes of hysteresis

(b) Average envelope and EEEP curve

Figure 3.2. Envelopes and EEEP curve

These envelopes can be used to compute the elastic shear stiffness (K_e), the maximum absolute load that the model can withstand (P_{peak}) and the ultimate displacement of the specimen (Δ_u). The ductility ratio (which is the relation between the ultimate displacement Δ_u and the yield displacement Δ_{yield}) was 9.62, which compared to other concrete-based traditional systems with mesh but without prestress, is larger [Pavese et al., 2011]. The obtained results are shown in Table 3.1.

Table 3.1. Parameters computed from cyclic tests 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 ($\mu = \Delta_u / \Delta_{yield}$)
15.22	36.77	19.63	2.04	9.62

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 resulting values are summarized in Table 3.2.

Table 3.2. Strength parameters obtained from cyclic tests, , calculated according to the 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}	
0.0105	10.61	1.31	31.07

3.2. Energy dissipation and damping

One of the requirements of seismic design is the control of damage of the structure during the occurrence of severe loads due to earthquakes. The damage is related to the capacity of the wall system to dissipate the energy when subject to cyclic loads. Currently, some structural designs are based on fragility analysis, which are methods that take into account the phenomenon of hysteresis in order to dissipate the energy; in this way, the safety of structural elements is increased and the sudden failure of the material is avoided.

Another way to evaluate the capacity of the material in terms of energy dissipation is by means of the so-called *equivalent viscous damping ratio* (ξ_{eq}) [Shaingchin, 2007; Priestley, 1996], which 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.:

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

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:

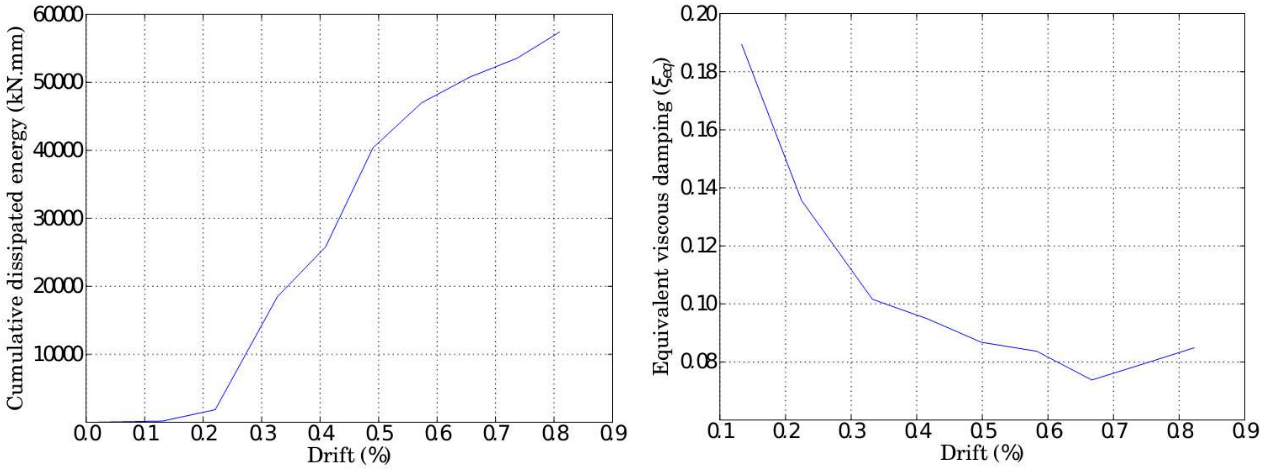
$$(E_e)_i = 0.5 \cdot (P_m)_i \cdot (\Delta_{max})_i. \tag{3.3}$$

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.

Fig 3.3a shows the accumulated dissipated energy and the equivalent viscous damping as a function of the drift. The system achieves higher energy dissipation with an increase in the displacements. Furthermore, the equivalent viscous damping is above the usual values for concrete-based systems.

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	98.8460	41.5361	0.1331	0.1894
2	125.9126	73.8543	0.2243	0.1357
3	158.8409	124.4107	0.3324	0.1016
4	180.8167	151.6091	0.4160	0.0949
5	186.2741	170.8234	0.4985	0.0868
6	199.7695	189.8793	0.5829	0.0837
7	225.7073	243.3079	0.6669	0.0738
8	279.1819	279.0823	0.7490	0.0796
9	315.0891	295.2192	0.8229	0.0849



(a) Energy dissipation (b) Equivalent viscous damping ratio

Figure 3.3. Equivalent viscous damping ratio

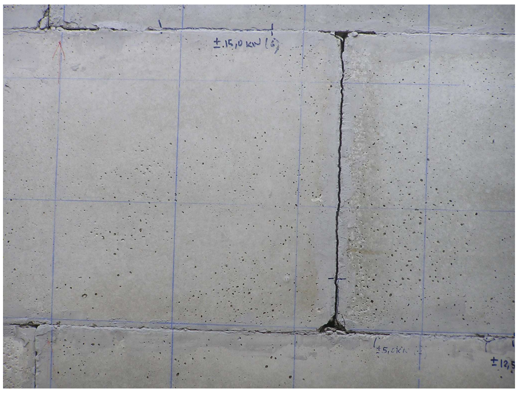
3.3. Observed damages and crack patterns

The walls of the tested model did not show severe damages or collapse. During the test execution, detachment of the sealing material between modules was observed (See Fig. 3.4a). Probably the detachment of sealing material was caused by a shear force that acted between the modules. Other kind of damage was relatively mild; in addition, the unbounded post-tensioned bars behaved satisfactorily.

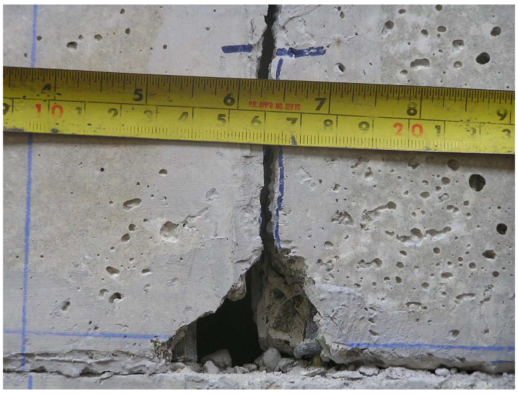
Fig. 3.4b shows the crumbling at the corners of the modules and separation of them; these were generated by the shear strain imposed by the cyclic load. Fig. 3.4c and 3.4d show a general view of the walls at the end of the test. None of the PRC modules failed. All the observed damages are easily reparable and the damages did not compromise the integrity and/or stability of the structure.

4. CONCLUSIONS

The housing system proposed by FABRICASAS is an innovative hybrid system between the precast reinforced concrete and the post-tensioned one. The PRC modules showed a good performance when subject to cyclic loads. The test showed that the PRC modules achieved high strength and high degree of energy dissipation with reduced damage level in the shear wall direction, and no significant strength loss in the frame direction. The performed test revealed that the system has satisfactory behaviour in terms of load-lateral deflection, shear strength, stiffness degradation, ductility, energy dissipation, damping and damage (crack appearance and propagation with load increase).

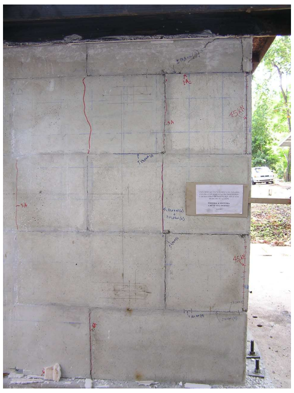


(a) Detachment of sealing material



(b) Crumbling of module at the corners

(c) Shear wall



(d) Edge of model after loading

Figure 3.4. Observed damages in the structure after cyclic test

ACKNOWLEDGMENTS

This research was developed under the project: " Evaluación y modelación sísmica de viviendas en módulos de hormigón ensamblados mediante conectores y tensores". The authors acknowledge to Universidad Nacional de Colombia at Manizales, the company FABRICASAS S.A., and the Structures Laboratory of Universidad Tecnológica de Panamá for their support during the execution of the project. Also the researches acknowledge to COLCIENCIAS for the support under the program: "Young Researches and Innovators - Virginia Gutiérrez de Pineda".

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