Behavior of precast ferrocement thin walls under cyclic loading: an experimental and analytical study

Comportamiento bajo y carga cíclica de muros prefabricados de pared delgada de ferrocemento: una investigación experimental y analítica

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ABSTRACT

Thin ferrocement walls are the structural elements that comprise the earthquake resistant system of housing built with this material. This article presents the results drawn from an experimental campaign carried out over full-scale precast ferrocement thin walls, which were assessed under cyclic loading conditions. The tests assessed the strength of the walls, their hysteretic behavior, ductility, energy dissipation, equivalent damping, their coefficient of energy dissipation and their characteristic failure mode when subjected to cyclic loading conditions. Finally, an analytical model that modeled the nonlinear dynamic behavior exhibited by ferrocement walls was implemented; its feasibility and potential use in earthquake resistant design of ferrocement walls was evaluated.

Keywords: Precast ferrocement walls, cyclic loading, ductility, Bouc-Wen-Baber-Noori model, earthquake resistant design.

RESUMEN

Los muros de ferrocemento de pared delgada son los elementos estructurales, que conforman el sistema sismo resistente de viviendas construidas con este material. En este artículo se presentan los resultados obtenidos de una campaña experimental; llevada a cabo sobre muros prefabricados de pared delgada a escala real, los cuales fueron evaluados bajo ensayos de carga cíclica. Los ensayos permitieron evaluar: la resistencia, el comportamiento histerético, la ductilidad, la disipación de energía, el amortiguamiento equivalente, el coeficiente de disipación de energía y los modos de falla característicos de los muros de ferrocemento bajo carga cíclica. Al final, se implementó un modelo analítico que captura el comportamiento no lineal, exhibido por los muros de ferrocemento bajo carga cíclica y se evalúo la factibilidad y su potencial uso en el diseño sismo resistente de muros realizados en dicho material.

Palabras clave: muros prefabricados de ferrocemento, carga cíclica, ductilidad, modelo de Bouc-Wen-Baber-Noori y diseño sismo-resistente.

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Introduction

Seismic demand determines the material and type of the structural systems used in housing construction. Earthquakes prompt the need for research of innovative systems with better cost-effectiveness and better seismic performance than current systems. Ferrocement-based structural systems have demonstrated high resistance (Naaman, 2000; Bedoya-Ruiz, 2005), low seismic fragility (Bedoya-Ruiz et al., 2005), and environmental sustainability (Bedoya-Ruiz, 2011). These systems usually are comprised of precast thin walls, which are assembled in different configurations according to the constructive system of the dwelling (Naaman, 2000; Castro, 1979; Gokhale, 1983; Olvera, 1998; Wainshtok-Rivas, 1994; Abdullah, 1995; Machado, 1998).

Typical dimensions of precast ferrocement walls range between 500 and 1000 mm in width, 2000 to 2400 mm in height and 10 to 50 mm in thickness. The strength of the walls is provided by a set of meshes and sometimes reinforced by bars embedded in a high-strength mortar. Homes built using precast ferrocement thin walls have been constructed in the Malay Archipelago, Sumatra Islands, Sri Lanka, New Guinea, Mexico, India, Thailand, Cuba, USA, Brazil and Colombia.

The first recorded applications date back to the early 1940s, when Nervi (1956) proposed the use of ferrocement for the construction of fishing boats. Later, Castro (1979) and Olvera (1998) built one and two-story houses with ferrocement walls in Mexico. In India, in 1983, Gokhale (1983), documented a system for housing construction called "Catone". In 1998, Wainshtok-Rivas (1994) described the first ferrocement constructions made in Cuba in

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1986. Naaman (2000) published the results of his investigations developed on ferrocement houses at the University of Michigan. He explored the advantages of ferrocement from an industrialized viewpoint, in order to enable the development and dissemination of the benefits of using this material. Bedoya-Ruiz (2005) published, on the experimental and analytical research carried out on walls and ferrocement houses.

There have been some methodologies for the earthquake resistant design of houses, based on precast ferrocement thin walls using static analysis. For example, Bedoya-Ruiz (2002) and Wainshtok-Rivas (2004) developed an approach to earthquake resistant design of ferrocement houses using the Method of Equivalent Horizontal Force (MEHF), in order to obtain seismic forces for areas of moderate to high seismic activity. Recently, Bedoya-Ruiz et al. (2010) proposed a nonlinear dynamical model to evaluate the vulnerability of ferrocement houses. This model was in accordance with the experimental behavior exhibited by the structures when subjected to cyclic loading conditions, while allowing several damage scenarios for zones with different seismic activity.

This article treats the seismic behavior of precast ferrocement thin walls subjected to cyclic loading conditions. A nonlinear dynamical model for earthquake resistant design of ferrocement homes built in areas of moderate to high seismic hazard is presented.

The plan of this study was as follows: first, laboratory tests on full-scale walls were carried out in order to evaluate the hysteretic behavior, strength, energy dissipation capacity, damping and failure modes of precast ferrocement thin walls when subjected to cyclic loading conditions. Then, a nonlinear dynamical model that is able to simulate the behavior exhibited by ferrocement walls under cyclic loading conditions was proposed. The Bouc-Wen-Baber-Noori (BWBN) model of hysteresis (Bouc, 1967; Baber and Wen, 1981) was used here. Finally, an evaluation of the performance of the walls when subjected to random external excitations using the proposed nonlinear dynamical model was performed.

Test specimens

Several ferrocement thin walls were built and tested as depicted below.

Description of the materials

Each wall was constructed using mortar, wire mesh and steel bars. The mortar was made with Portland cement type I (CEM I), sand screened with a No. 7 sieve (approx. 2mm), water and superplasticizer using the following proportions by weight: sand-cement ratio 1:2, water-cement ratio 0.40, superplasticizer 1% of cement weight. The superplasticizer was used in order to improve the workability and penetrability of the mortar through the meshes. The reinforcement distributed in the cementitious matrix consisted of six hexagonal mesh layers with an opening of 31.75 mm (this mesh was placed longitudinally); and two #2 bars at the ends of the wall. The specific surface of the reinforcement was 0.0314 mm^2/mm^3 and its volume fraction was 0.39%.

The compressive strength of the mortar (f'_{cm}) after 28 days was 33 MPa, and its Young modulus (E_c) was 11050 MPa; the yield resistance (σ_{ry}) of the hexagonal mesh was 282 MPa, and its Young modulus (E_r) was 81 GPa. Finally, the yield resistance of the #2 bars was 420 MPa.

Test setup and load history.

The geometry of each of the 12 specimens is sketched in Fig. 1; an overview of the test set up is also shown in Fig. 1.

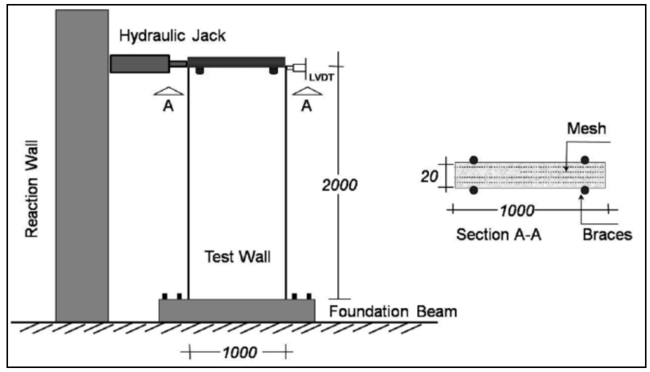

Figure 1. Test setup and dimensions (in mm)

The walls were anchored to very rigid foundation beams in order to provide lateral support. Then, each "wall-foundation beam" system was anchored to a reaction floor with steel screws as illustrated in Fig. 2. In order to constrain the walls to in-plane-displacements, lateral bracing was employed. The lateral displacement induced by the hydraulic actuator was measured using LVDTs placed at the top of the walls.

Figure 2. Actual configuration

Each precast ferrocement thin wall was subjected to the cyclic loading pattern shown in Fig. 3, where Δ_m is the ultimate displacement corresponding to the failure limit state.

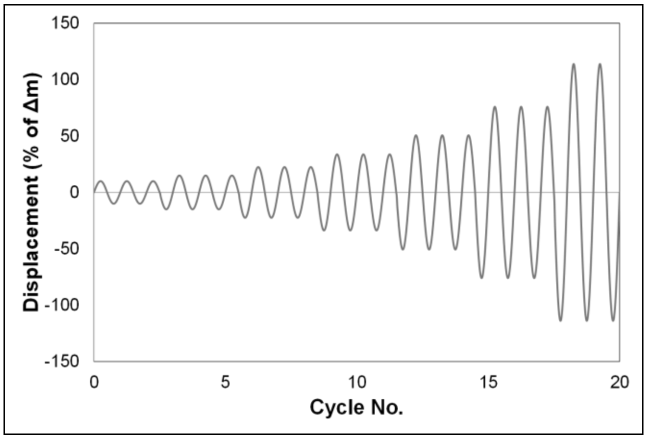

Figure 3. Time history of applied load

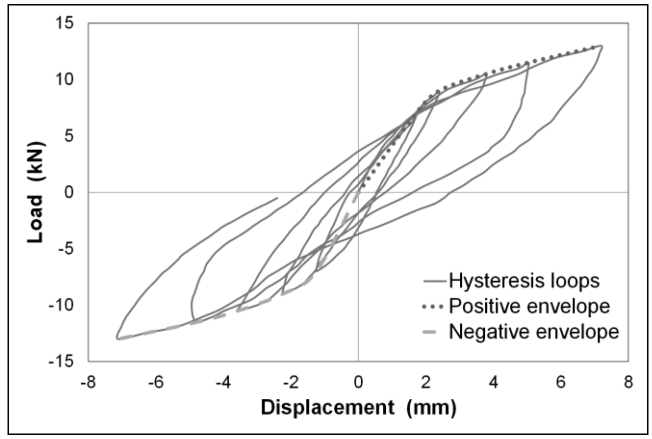

Figure 4. Hysteresis cycles

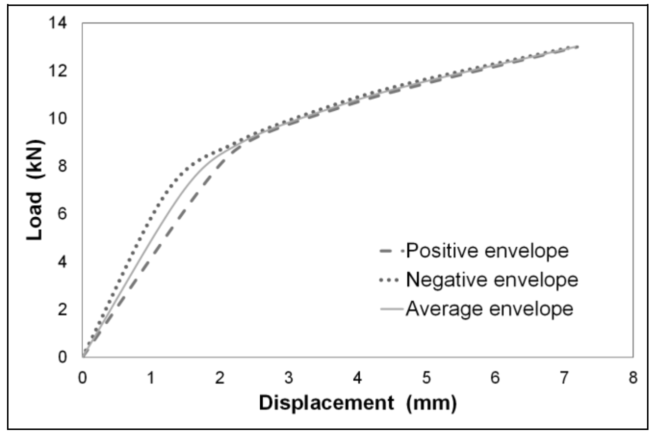

Figure 5. Positive, negative and average envelope

Test results

The results drawn from the tests are summarized in the following sections.

Hysteretic behavior and strength.

In order to compute the structural parameters of the precast ferrocement thin walls, the specimens were subjected to cyclic loads that simulate seismic action; the hysteresis response curves drawn from the tests were used to assess the ultimate strength and the ductility of the system.

Fig. 4 shows one of the hysteresis cycles drawn from the cyclic tests carried out on the precast ferrocement thin walls. Fig. 5 shows the envelope corresponding to the same hysteresis loops. The positive and negative envelopes are similar; therefore, the average is computed and used for subsequent calculations.

The envelopes drawn from the cyclic tests showed a maximum average lateral load capacity of 13 kN. Using the ASTM E2126-11 norm (ASTM, 2011), and the envelopes of the hysteresis loops, structural parameters of the ferrocement thin walls were computed as shown in Table 1.

Table 1. Parameters computed from the cyclic loading tests according to the ASTM E2126-11 norm

Elastic stiffness (K_i)	Elastic shear strength (v_{peak})	Yield load (P_{yield})	Maximum absolute load (P_{peak})	Ultimate displacement (Δ_u)	Yield displacement (Δ_{yield})	Ductility ($\mu = \Delta_u/\Delta_{yield}$)
kN/mm	kN/m	kN	kN	mm	mm	
6.27	13.00	11.06	13.00	7.16	2.33	3.07

Energy dissipation and damping.

Current structural designs are based on fragility analysis, which aims to dissipate the energy transmitted by external dynamical forces by means of the hysteretic response; in this way, the safety margin of the structural elements is increased and the sudden failure of the material is avoided. In order to achieve this control in ferrocement structures, the walls should have the capacity to dissipate the energy when subjected to cyclic loading conditions. One way to quantify the amount of dissipated energy when a structure is subjected to time-varying loads is by computing the area enclosed by the hysteresis loops (see Fig. 4).

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}), which is defined as (Priestley, 1996; Chopra, 2006):

$$\xi_{eq} = \frac{E_i}{4\pi(E_e)_i}100\% \qquad (1)$$

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

The dissipated energy in the i-th cycle E_i can be computed from the measured hysteresis loops. The elastic potential energy stored by an equivalent linear system $(E_e)_i$ is given by the area under the load vs. displacement curve obtained in the cyclic tests. It is given by the area under a right triangle whose base equals the maximum positive displacement measured in the model $(\Delta_{max})_i$ and whose height $(P_m)_i$ is the average peak load of the analyzed cycle, i.e.:

$$(P_m)_i = \frac{|(P_{max})_i| + |(P_{min})_i|}{2} \qquad (2)$$

where |.| represents the absolute value, $(P_{max})_i$ and $(P_{min})_i$ represent 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:

$$(E_e)_i = \frac{(P_m)_i(\Delta_{max})_i}{2} \qquad (3)$$

Table 2 shows the energy E_i and $(E_e)_i$, the drifts and the equivalent viscous damping computed for each drift level.

Table 2. Energy dissipation and equivalent viscous damping

Cycle	E_i (kN.mm)	E_e (kN.mm)	Drift (%)	ξ_{eq} (%)
1	**8.0129**	**5.9570**	**0.09**	**10.70**
2	**12.5463**	**10.7460**	**0.12**	**9.29**
3	**26.2902**	**19.8713**	**0.19**	**10.53**
4	**59.1484**	**28.9225**	**0.25**	**16.27**
5	**90.2374**	**46.7220**	**0.36**	**19.93**

Fig. 6 shows the accumulated dissipated energy as a function of the drift. Fig. 7 shows 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.

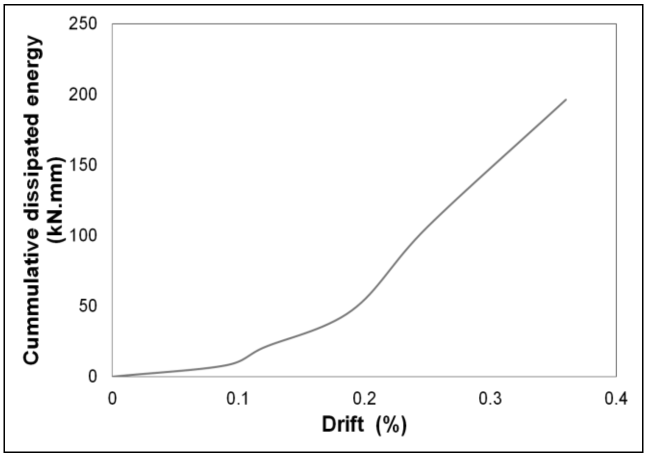

Figure 6. Cumulative dissipated energy

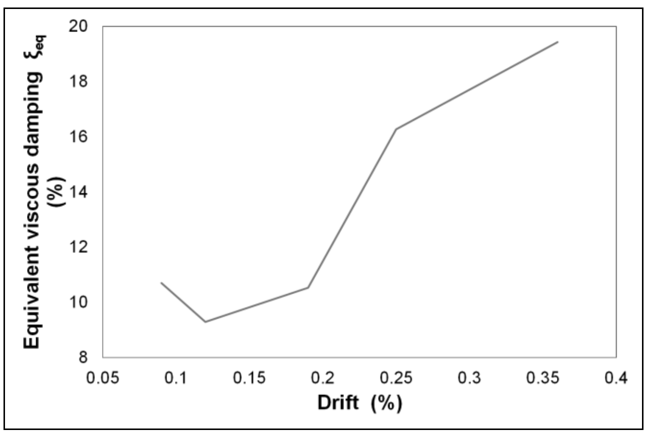

Figure 7. Equivalent viscous damping ratio

Similarly, and according to Priestley (2003), for wall systems, the damping ratio can be computed according to:

$$\xi_{eq} = 5 + 95\left(\frac{1 - \mu^{-0.5}}{\pi}\right)\% \quad (4)$$

where μ is the ductility ratio computed above. According to the ductility ratio shown in Table 1 and from the cyclic tests performed on the ferrocement walls, the equivalent viscous damping ratio is 17.98%, this value is within the behavior shown in Fig. 7.

All walls exhibited loss of energy. However, the rounded shape of the hysteresis curves and the area enclosed by those loops suggest that the system has good energy dissipation capacity, as this increases with the drift. The shape of the hysteresis loops effectively determines the ability of these walls to dissipate energy when they are subjected to loads beyond its linear range. On the other hand, a small degree of pinching can be observed in the center of the hysteresis loops due to opening and closing of cracks generated in the surface of the walls, which affects the ability of the system to dissipate energy. These effects will be considered in the nonlinear dynamical model that will be proposed below.

Coefficient of energy dissipation capacity.

The coefficient of energy dissipation capacity (R_μ) is a design-oriented concept, which aims to approximate the nonlinear behavior of structural systems when subjected to seismic loads. It is used in most of the earthquake resistant design codes, in order to reduce the magnitude of the loads assessed from an elastic viewpoint.

In order to determine R_μ, we used the model proposed by Takada et al. (1988), which is independent of the period of the structure:

$$R_\mu = \varepsilon\sqrt{2\mu - 1} \quad (5)$$

where ε is an adjustment factor, which represents the degree of deviation of the R_μ vs. μ relation from the equal energy expression $\sqrt{2\mu - 1}$. Results drawn from Monte-Carlo simulations indicate that the average value of ε is between 1.05 - 1.34 (see Miranda and Bertero, 1994 and Takada et al., 1988 for further details about the Monte-Carlo simulation). Taking $\varepsilon = 1.05$, we have that $R_\mu = 2.38$, and taking $\varepsilon = 1.34$, we have that $R_\mu = 3.04$; these values of R_μ are similar to those used by Wainshtok-Rivas (2004) for earthquake resistant design of dwellings based on precast ferrocement thin walls in Cuba.

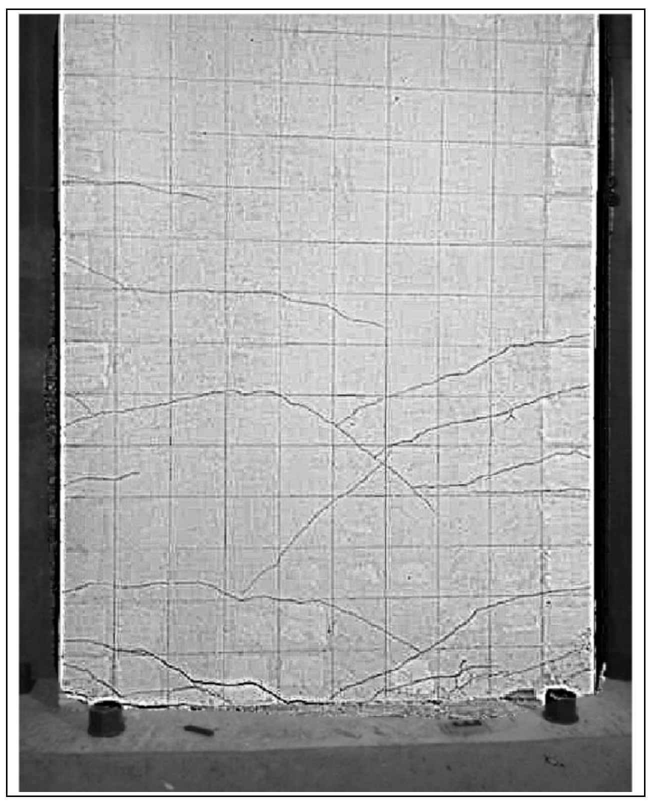

Figure 8. Failure modes of ferrocement walls subjected to cyclic loading conditions

Observed failure modes of the walls subjected to cyclic loading.

Fig. 8 shows the precast ferrocement thin walls after the tests. The main source of energy dissipation of the walls was due to yielding of the flexural reinforcement in areas where plastic hinges appeared. In general, these zones are located at the base of the wall. The observed crack pattern suggests a predominant failure due to sliding-shear. Initially, the overall behavior was flexural and most of the shear force at the base of the wall was transmitted by bending to the compressive zone. There were also cracks in the compressive area. Later, the increase in the cyclic action led to yielding of the meshes. Several cracks appeared on the surface of the walls and their width and length increased at the base of the wall. It must be pointed out that during the cyclic test, there were no fragile failure modes of the ferrocement walls.

Analytical model

The Bouc-Wen-Baber-Noori (BWBN) model of hysteresis (Baber and Wen, 1981; Baber and Noori, 1985) is very popular in the field of structural dynamics because it models not only degradation of the material, but also pinching effect. It has been used in an ample range of applications such as vibration of concrete structures (Kunnath et al., 1997), wood joints (Foliente, 1995; Ajavakom et al., 2008), among others.

Let us consider a single-degree-of-freedom (SDOF) system with hysteretic restoring force and viscous damping, described by the differential equation

$$\ddot{x}(t) + 2\xi\omega_0\dot{x}(t) + \alpha\omega_0^2 x(t) + (1-\alpha)\omega_0^2 z(t) = u(t) \quad (6)$$

with initial conditions $\dot{x}(0) = v_0$ and $\ddot{x}(0) = a_0$. Here, v_0 and a_0 represent the initial velocity and acceleration of the system, $x(t)$ denotes the displacement at time t, $\omega_0^2 := k_i/m$ is the squared pseudo-natural frequency of the non-linear system, m is the mass of the system, ξ is the viscous damping ratio, $u(t)$ is the external excitation (acceleration), $\alpha := k_f/k_i$ is the ratio of post-yield k_f to pre-yield (elastic) k_i stiffness. The hysteretic component is governed by the so-called *hysteretic displacement* z, which is given by the following equation

$$\dot{z}(t) = h(t)\,\frac{A(t)\dot{x}(t) - v(t)(\beta|\dot{x}(t)||z(t)|^{n-1}z(t) + \gamma\dot{x}(t)|z(t)|^n)}{\eta(t)} \quad (7)$$

with the initial condition $z(0) = 0$. The parameters β, γ and n control the shape of the hysteresis loops, and the parameters $v(t)$, $\eta(t)$ and $h(t)$ are associated respectively to the strength, stiffness and pinching degradation effects, and they are defined as functions of the absorbed hysteretic energy $\varepsilon(t)$

$$\begin{aligned} v(t) &:= v_0 + \delta_v\varepsilon(t) \\ \eta(t) &:= \eta_0 + \delta_\eta\varepsilon(t) \\ A(t) &:= A_0 - \delta_A\varepsilon(t) \end{aligned} \quad (8)$$

The pinching function $h(t)$ is governed by the following equation

$$h(t) := 1 - \varsigma_1(t)exp\left(-\frac{(z(t)sgn(\dot{x}(t)) - qz_u)^2}{(\varsigma_2(t))^2}\right) \quad (9)$$

where z_u is the ultimate value of z,

$$z(u) = \sqrt[n]{\frac{1}{v(t)(\beta+\gamma)}} \quad (10)$$

and,

$$\begin{aligned} \varsigma_1(t) &:= (1 - exp(-p\varepsilon(t)))\varsigma_0 \\ \varsigma_2(t) &= (\psi_0 + \delta_\psi\varepsilon(t))(\lambda + \varsigma_1(t)) \end{aligned} \quad (11)$$

The constants p, q, ς_0, ψ_0, δ_ψ and λ define the form of the pinching.

Identification of parameters of the BWBN model for the precast ferrocement thin walls.

We employed a novel methodology proposed by Ortiz et al. (2012), which uses multi-objective evolutionary algorithms in order to identify the parameters of the BWBN model of hysteresis. The set of parameters that must be identified is represented by vector $\boldsymbol{p}$:

$$\boldsymbol{p} = [\xi, \alpha, \beta, \gamma, n, v_0, \delta_v, A_0, \delta_A, \eta_0, \delta_\eta, p, \varsigma_0, \psi_0, \delta_\psi, \lambda, q]^T \quad (12)$$

Table 3 shows the results of the identification process. The first two parameters (m, k_i) were obtained from the experimental tests.

Table 3. Identified parameters of the BWBN model of hysteresis for the precast ferrocement thin walls

Parameter	Value	Unit
m	456	Kg
k_i	6.27	kN/mm
ξ	19.77	%
α	0.2183	
β	3.025	
γ	-1.3156	
n	1.5173	
v_0	0.4092	
δ_v	3.2397	
A_0	2.4929	
δ_A	0.8155	
η_0	3.4873	
δ_η	-0.8492	
p	9.7076	
ς_0	1.0962	
ψ_0	1.2478	
δ_ψ	-3.6339	
λ	-3.2035	
q	1.5662	

It can be seen that the value of ξ is slightly different from the one computed previously. It may be noted that there is a discrepancy of about 9% with respect to the one estimated before.

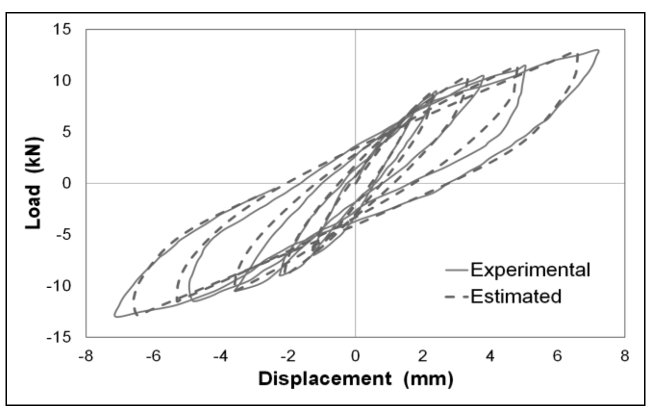

Figure 9. Experimental and estimated response of the system

Fig. 9 compares the experimental hysteresis with the fitted BWBN hysteresis model. It can be seen that the agreement is fairly good and the approximation with the estimated parameters is good enough for simulation purposes. The maximum experimental displacement was 7.19 mm, and the maximum estimated displacement is 6.60 mm, which represents a difference in displacement of 0.59 mm. It can also be seen that the degradation effects are successfully simulated by the proposed model.

Seismic evaluation of the prefabricated ferrocement thin walls.

In order to test the ability of the model to compute the displacements suffered by the structure when a random external excitation is applied, the equivalent SDOF system was subjected to the 1994 Northridge earthquake (CESMD, 2012); the parameters shown in Table 3 were used within the model. The simulated response of the ferrocement thin wall is shown in Fig. 10.

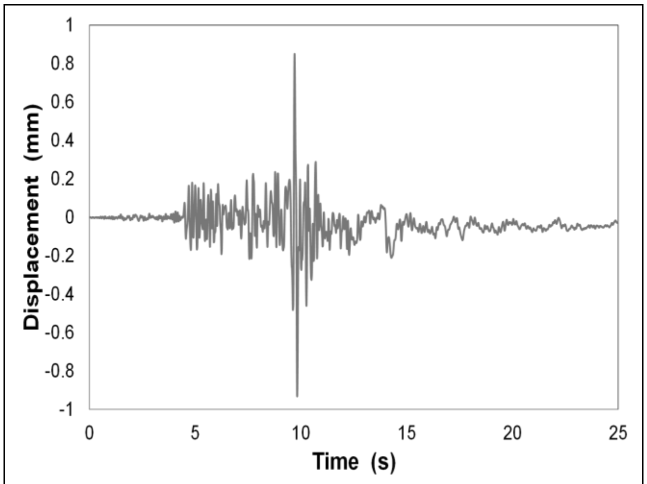

Figure 10. Estimated response of the precast ferrocement thin wall when subjected to the 1994 Northridge earthquake

The seismic design codes in many countries, aim to keep the damage of structures under control when subjected to earthquakes of different magnitudes. For each intensity level, different damage scenarios are predicted. In Colombia, for the precast structural systems for houses based on thin walls, the maximum drift interstory is less than 1/200, that is applicable to all kinds of damage scenarios or seismic zone activity (from 0.05g to 0.9g). In this case, the maximum allowed displacement for precast ferrocement thin walls used in this experimental research is 10 mm, and the maximum displacement computed using the 1994 Northridge earthquake (intensity 0.8g) was 1 mm, which is 90% less than the maximum displacement allowed by the Colombian design code. According to the failure modes observed in the experimental campaign, for displacements less than 1 mm, there are no fragile failure modes. This fact demonstrates the excellent performance of this material when subjected to random external excitations.

Conclusions

Based on the experimental results, the precast ferrocement thin walls exhibited high resistance and good performance when subjected to cyclic loading conditions. The proposed nonlinear dynamical model fits well with the experimental results and the material and it can be used for the earthquake resistant design of houses built with ferrocement in zones with moderate to high seismic activity.

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