# HYSTERETIC MODEL AND SEISMIC VULNERABILITY OF FERROCEMENT HOUSES

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ABSTRACT :

In developing countries the lack of adequate housing for low income population is a critical problem. The frequency of strong seismic motions in some of them renders the problem even more critical. As a common aftermath of a earthquakes is a large destruction of non-engineered houses. Ferrocement panel housing has been proposed as a building technique for coping with this problem as a low cost solution. In this paper the results of a experimental analysis on 3D models of ferrocement houses at a 1:1 scale is reported. The purpose of the research is two-fold: First, to analyze the overall behavior of this building type, its hysteretic response and to fit a Bouc-Wen-Baber-Noori model for it using system identification techniques. Second, to calculate vulnerability matrices for a certain seismic region of Colombia (having a design acceleration equal to 0.25 g), in order to promote the system as a economical as well as safe solution for low-income inhabitants. The results show that in spite of the stiffness and strength degradation exhibited by the lab model under strong lateral displacements, the vulnerability for the target region is rather low.

KEYWORDS: Ferrocement, hysteresis, system identification, cyclic behavior, vulnerability matrices

## 1. INTRODUCTION

In countries in continuous growth and low resources economic, where the demand of house of low cost is very high, the ferrocement has been used like an effective alternative that, on the one hand, offers durable houses and of good quality, and, on the other hand, it offers a constructive system with base in not described intensive manpower. This combination makes of the ferrocement an appropriate solution for developing societies that require of solutions of house of low cost and generation of use. The ferrocement widely has been used in different countries from the world for the construction of prefabricated houses. In the archipelago of Malaysia, in the islands of Sumatra, Sri Lanka and New Guinea, houses in ferrocement have been constructed. Countries like Mexico, India, Thailand, Cuba, the United States, Brazil and Colombia, are pioneering in the use of the ferrocement to construct houses of low cost [Bedoya-Ruiz, 2005]. Unfortunately, in these regions the seismic activity is high or moderate. The recent earthquakes, Colombia 1999 and Peru 2007, have shown to the poor performance of the majority of the systems and materials that are used in the region for the construction of dwelling. The low seismic behavior exhibited by these houses to taken to propose studies that allow of some way to quantify the vulnerability of the houses in these zones. The objective of this study is to implement a model that simulates the hysteretic behaviour of the ferrocement houses and to apply this model to investigate the seismic vulnerability.

## 2. STRUCTURAL MODEL

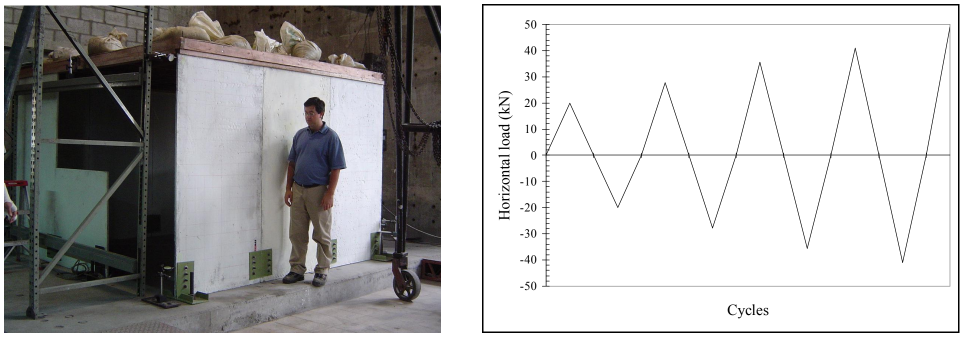
### *2.1 Experimental basis*

#### *2.1.1 materials*

Ferrocement is a material made out of a wire-mesh of low calibre embedded in a mortar matrix. The matrix is generally made of Portland cement, some filling, which usually is sand, water, and in some cases admixtures. In the particular case of ferrocement the reinforcement is in the form of wire-mesh of small diameters which is uniformly placed across the transverse section of the element, which facilitate the production of walls with thickness no greater than 50 mm.

#### *2.1.2 Test structure*

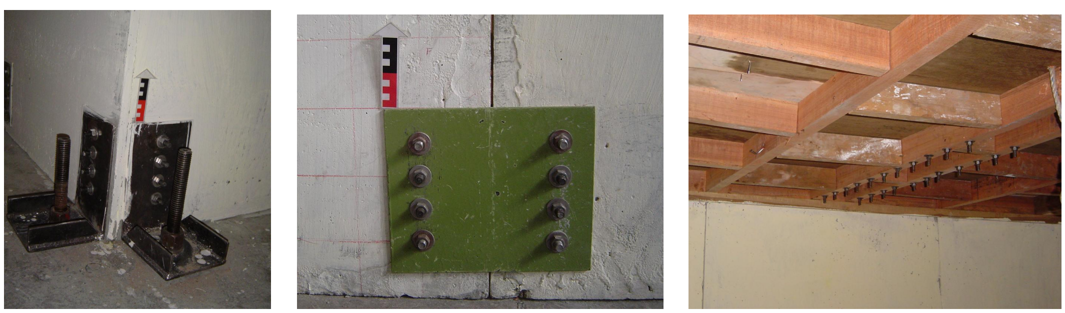
The panels were built with typical local materials customarily used for houses and low budget buildings. Nine 1:1 scale specimens were produced having 2.0 m of height, 1.0 m of length and 20 mm of the thickness, which can be considered as typical dimensions for panel members in pre-cast construction of dwellings with this type of material. Six hexagonal woven meshes were provided as reinforcement for the panels, Water-to-cement ratio equal to 0.4, sand-to-cement ratio equal to 2 and superplasticizing admixture of 1% of the cement weight were used to prepare the mortar [Bedoya-Ruiz, 1996]. The mortar strength $f'_{cm}$ is 33 MPa, the elasticity modulus $E_c$ of the composite material is 11050 MPa, the elasticity modulus of the reinforcement, $E_r$, is 81 GPa and its yield strength $\sigma_{ry}$ is 282 MPa. Figure 1a shows a dwelling of ferrocement. In this paper, we have chosen a module of 3.0 x 3.0 m (test structure), which is typically found in Colombia houses. The weight of the test structure was 10.60 kN. Lateral load was applied to the top of the test structure following the static cyclic protocol shown in Figure 1b.




(a) (b)

Figure 1. Experimental: (a) general view of test structure and (b) loading sequence

The panels were anchored to the laying of foundations with steel flanges in the four corners (Figure 2a); The panels do not have anchorages to each other, are free only exists contact by friction and steel flanges (Figure 2b). In the part superior a wood frame, conformed by beams in U was placed, the panel penetrates 25 mm the cover was constructed with wood and anchored with screw of steel to the beams in U (Figure 2c).



(a) (b) (c)

Figure 2. Details of integrity of the test structure: (a) support panels, (b) support between panels and (c) roof

## *2.2 System identification*

The model of hysteresis raised by BWBN, to evaluate the dynamic behaviour of structural systems, explicitly needs to be defined for a particular set of materials and configurations. This problem is known especially like a problem of estimation of parameters or generally like a problem of identification of systems. The identification of systems is defined as a process to construct to a mathematical description or model of a physical system, when the entrance of the system and the corresponding exit are known [Yao, 1985]. The general term identification of systems, has its origins in the theory of the control mechanics and electrical engineering, but it has been used in many branches of science and engineering. For applications in structural engineering, usually the entrance is a function of well-known force and the exit is displacement, speed or acceleration, like answer of the structure to this force. Thus, the obtained particular model of the identification process must produce an answer similar to the one of the exit system, since the entrance is the same [Yao, 1985]. For the identification of systems several techniques exist such as the method of squared minimums, the sequential regression analysis, the iterative algorithm of Newton, the method of Gaussian and the technique of Kalman filter and recently the genetic algorithms and the neuronal networks. These techniques have been used systematically to determine the parameters of the model of hysteresis of BWBN from the experimental data [Sues et al, 1988; Foliente, 1996b; Hornig, 2003]. The great advantage of these algorithms is the ability to model to the hysteresis and the precision of the nonlinear answer of the structure. Nevertheless, in other studies [Foliente, 1995; Jaramillo, 2000; Bedoya-Ruiz, et al, 2008] the majority of the parameters of the model of BWBN hysteresis, has been obtained from the experimental data. The model of final hysteresis is calculated and compared with the experimental hysteresis. That is to say, the procedure is repeated several times until the model reproduces all the characteristics (it forms basic of nonlinear the experimental hysteresis with loss of resistance, degradation of rigidity and strangling) observed experimentally satisfactorily.

Let us consider a single degree of freedom structure having a restoring force of model the Bouc-Wen. The equation of motion is:

$$m\ddot{u}(t) + c\,\dot{u}(t) + F_H\left[u(t),\ z(t); t\right] = F(t) \tag{1}$$

where $c$ is the coefficient linear of viscous damping, $F_H\left[u(t),\ z(t)\right]$ is the nonlinear restoring force composed by a linear term $f_R(u,t) = \alpha\,\omega^2\,u(t)$ and a hysteretic term . On the other hand, $F(t)$ is external load. The corresponding equation of motion is:

$$\ddot{u}(t) + 2\,\xi_0\,\omega\,\dot{u}(t) + \alpha\,\omega^2\,u(t) + (1-\alpha)\,\omega^2\,z(t) = f(t) \tag{2}$$

where $\alpha$ is the ratio between post- yielding stiffness to the pre-yielding stiffness, given by $k$, and $z$ is a nonlinear auxiliary variable (with displacement units), which is specified by a differential equation:

$$\dot{z}(t) = \frac{A\dot{u}(t) - \nu\left(\beta\left|\dot{u}(t)\right|\left|z(t)\right|^{n-1} z(t) + \gamma\,\dot{u}(t)\left|z(t)\right|^{n}\right)}{\eta(\varepsilon)} \tag{3}$$

in which $A, \beta, \gamma, n$ are parameters controlling the strength, the energy dissipation capacity and the transition from elastic to plastic behavior. Use was made of a generalization of this model proposed in (Baber and Noori 1985) to incorporate the strength ( $\nu$ ) and stiffness degradation ( $\eta$ ) parameters, which are functions of the dissipated energy $\varepsilon(t)$, given by

$$\varepsilon(t) = (1-\alpha)\,\omega^2 \int z(t)\,\dot{u}(t)\,dt \tag{4}$$

On the other hand, the stiffness degradation is governed by the denominator in Eq. (3), which is given by

$$\eta(\varepsilon) = 1.0 + \delta_\eta\,\varepsilon(t) \tag{5}$$

Here $\delta_\eta$ is a parameter controlling stiffness degradation. Use was made of a generalization of this model proposed in (Baber and Noori 1985). The parameters were fitted to the measured hysteresis loops using a methodology proposed recently in (Ikhouane et al. 2007). In the Figure 3 shown the experimental hysteresis (Fig. 3a.) and the fitted Bouc-Wen hysteresis model (Fig. 3b.).

The identified model has mass $m$=1060 kg, initial tangent stiffness $k_i$=5.73 kN/mm, Final tangent stiffness $k_f$= 5.73 kN/mm, Coefficient of damping $\xi_o$=5%, and the following hysteresis parameters: A=1.0, $\alpha$=0.197, $\beta$=0.85, $\gamma$ =−0.50, n=1.0, and $\delta\eta$=0.1.

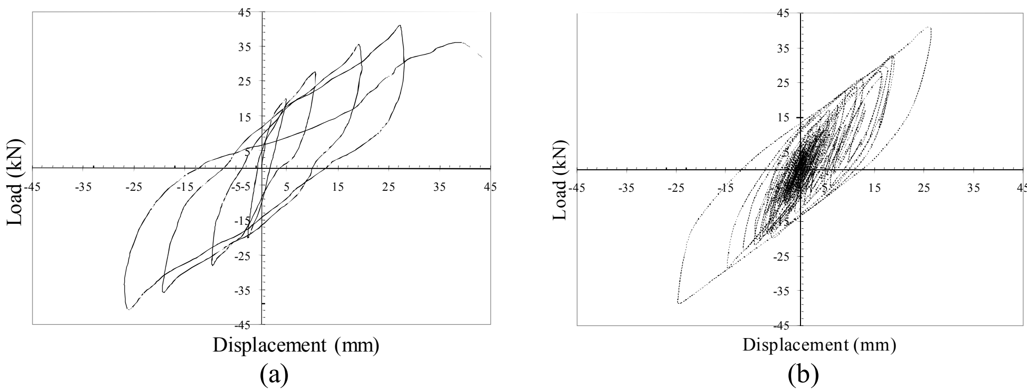



Figure 3. Experimental and fitted hysteresis loops for (a) Experimental test and (b) Model BWBN

It can be seen that in spite of the stiffness and strength degradation exhibited by the lab model under strong lateral displacements and the prefabricated houses of ferrocement showed an excellent seismic behavior under static cyclic. Also It can be seen that the agreement is fairly good.

### *2.2 Earthquake ground motions*

The stochastic model of the seismic action was used proposed by Hurtado (1999). The model was developed from the registered seismic information in the zone and as much considers the evolutionary nature of the earthquakes in amplitude as in frequency content, by means of functions of frequency and amplitude modulation respectively. The stochastic model facilitates the generation of accelerograms synthetic that additionally incorporates the characteristics of the registered previous earthquakes in the region and, cover different ranks from acceleration maximum and frequency content. The Monte Carlo analysis also requires the definition of random seismic acceleration signals given as input at the base of the structures. To this end use was made of an evolutionary spectral model proposed in (Yeh and Wen, 1990), consisting in a time-variant Kanai-Tajimi (1960) power spectral density function incorporating intensity and frequency evolution.

$$G(\omega) = \frac{\omega_g^4 + 4\nu_g^2\omega_g^2\omega^2}{\left(\omega_g^2 - \omega^2\right)^2 + 4\nu_g^2\omega_g^2\omega^2} G_0 \qquad (6)$$

Where $G_0$, $\omega_g$ and $\nu_g$ are parameters defining the ground motion intensity, the central frequency and the spread of the waves in the frequency domain, respectively. Additionally, it was chosen like random variable the duration of the strong phase of the movement of the ground $s_0$. The parameter, contains the randomness in the variable $\varepsilon$ obtained in the (7) equation and that controls the duration of the strong phase

$$\ln s_0 = -0.0102\,PGA + 3.1707 + \varepsilon \qquad (7)$$

$\varepsilon$ is a variable with mean 0.0 and standard deviation 0.2867. The parameters were fitted to the seismic conditions found in the central region of Colombia, where the design code acceleration is 0.25g. To give the ground motion history a nonstationary character, use was made of the Amin-Ang modulating function. The values $\omega_g$ and $\nu_g$ in Eq. (6) and $\varepsilon$ in Eq (7) were given a random character. In this case $\omega_g$ Distribution of the Weibull with mean=12.096 and standard deviation= 3.022 (rad/s); $\nu_g$ Distribution of the Lognormal with mean=0.154 and standard deviation= 0.062.

## 3. VULNERABILITY MATRICES

In order to derive the vulnerability matrices of the dwelling houses, Monte Carlo simulation should be applied to a nonlinear model. To this end the Bouc-Wen hysteretic model (Bouc 1967; Baber and Wen 1981) was selected due to its versatility and easy application. The model has been widely applied for seismic analyses, such as those of concrete piles [Lin, 2002], in special procedures for the seismic design [Clarke, 2005] and prefabricated houses [Bedoya, 2008]. The models for seismic action in the framework of a Monte Carlo simulation using 1000 artificial accelerograms for each value of the peak ground acceleration (PGA) varying in the range from 0.05g to 0.90g with increments of 0.05g. The damage states appearing were defined according to the observations made on the behavior of ferrocement dwelling houses after a strong earthquake occurred in January 25th, 1999, in the Quindio region of Colombia having a maximum acceleration of 0.58 g and the laboratory tests [Bedoya, 2005]. The results for the four damage states appear in Table 1.

Table 1. Damage states

| **Damage state** | **Main feature** | $u$ (mm) | $h$ (mm) | $\theta$ (mm/mm) |
|---|---|---|---|---|
| | No visible cracks | 0,90 | 2000 | 0,0005 |
| *Minor* | Cracks of width up to 0.90 mm | 2,42 | 2000 | 0,0012 |
| *Moderate* | First failure of wire reinforcements and mortar | 17,05 | 2000 | 0,0086 |
| *Severe* | Initiation of nonlinear behavior and pane buckling | 27,33 | 2000 | 0,0137 |
| *Collapse* | Crushing of panel corners and extensive panel buckling | 40.00 | 2000 | 0,0200 |

In table 2, the matrices of probability of damage for each one of the PGA appear selected. It is necessary to understand these results like resulting average values of the simulation.

The vulnerability matrices allow to construct damage scenarios. The vulnerability matrices showed that the majority of the ferrocement houses has a probability of minor damage superior to 90% and one smaller probability of 5% of a state of damage of collapse in zones of moderate and high seismicity.

Table 2. Matrices of probability of damage for each one of the PGA

| PGA (%g) | Values of damage probability | | | | |
|---|---|---|---|---|---|
| | Damage states | | | | |
| | *No damage* | *Minor* | *Moderate* | *Severe* | *Collapse* |
| 0,05 | 0,87 | 0,11 | 0,02 | 0,00 | 0,00 |
| 0,10 | 0,44 | 0,55 | 0,01 | 0,00 | 0,00 |
| 0,15 | 0,18 | 0,79 | 0,01 | 0,01 | 0,01 |
| 0,20 | 0,05 | 0,90 | 0,03 | 0,01 | 0,00 |
| 0,25 | 0,02 | 0,91 | 0,05 | 0,01 | 0,01 |
| 0,30 | 0,01 | 0,86 | 0,08 | 0,03 | 0,02 |
| 0,35 | 0,00 | 0,82 | 0,12 | 0,04 | 0,02 |
| 0,40 | 0,00 | 0,74 | 0,18 | 0,06 | 0,03 |
| 0,45 | 0,00 | 0,67 | 0,22 | 0,06 | 0,05 |
| 0,50 | 0,00 | 0,60 | 0,25 | 0,09 | 0,07 |
| 0,55 | 0,00 | 0,49 | 0,27 | 0,13 | 0,10 |
| 0,60 | 0,00 | 0,43 | 0,32 | 0,15 | 0,10 |
| 0,65 | 0,00 | 0,36 | 0,35 | 0,15 | 0,14 |
| 0,70 | 0,00 | 0,29 | 0,35 | 0,19 | 0,17 |
| 0,75 | 0,00 | 0,26 | 0,33 | 0,23 | 0,18 |
| 0,80 | 0,00 | 0,22 | 0,33 | 0,23 | 0,22 |
| 0,85 | 0,00 | 0,18 | 0,29 | 0,28 | 0,25 |
| 0,90 | 0,00 | 0,15 | 0,31 | 0,26 | 0,29 |

## 4. CONCLUSIONS

The prefabricated houses of ferrocement showed a good seismic behavior under static cyclic. The vulnerability analysis conducted up to a peak ground acceleration of 0.90g shows that it is an adequate system for strong earthquakes. The state of predominant damage is the minor state. from this point of view the houses prefabricated of ferrocement are a good alternative for the house of low cost in developing countries

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