International Journal of Civil and Structural Engineering
Volume 3 : Issue 3 [ISSN 2372-3971]
Publication Date : 30 December, 2016

Prefabricated ferrocement system for a low-cost resistant dwelling

H. Z. López Calvo, H. Gómez Barranco, V.M. Alonso Arguello and R.N. Sánchez Reyes.

Abstract— **In this paper the developed of an experimental building system using prefabricated elements for a low-cost resistant dwelling, is described. Prefabricated box-shaped ferrocement blocks, measuring 1000 x 500 x 12 mm and 500 x 500 x 12 mm, both with 25 mm of wall thickness were manufactured. The dimensions of the prefabricated blocks were kept as small as possible in order to allow one or two people handle them without need of special equipment. Connections between blocks were bolted in order to avoid the use of mortar and therefore produce a water-free system ideal for self-construction. In order to ensure the structural safety, the stresses distribution resulting from the application of axial and shear loads on walls sections, as well as loads on a roof section were evaluated through finite element models. The information gathered from the finite element analysis served to design loading tests carried out in real scale walls and roof sections. The results from the computer analysis indicated that the critical areas were the bolted connections, which were subjected to high concentration of stresses as it was corroborated during the experimental tests. Finally, the structural performance and economic feasibility was proven with the construction of a real scale prototype dwelling.**

Keywords— ***Ferrocement, prefabricated building system, low-cost dwelling.***

I. Introduction

Around the world, "ferrocement" has been extensively used successfully in a variety of applications; however, most of them requiring intensive labor processes. Attempts to implement industrialized methods to manufacture precast ferrocement elements for massive building production have been applied in many countries; nevertheless, most of them requiring sophisticated industrialized processes and only few of them have been exclusively designed for self-construction housing applications (Naaman and Hammoud, 1992; Wainshtok, 1996; Patent ferrocement system FC2, 1993; Desayi et al.1983). In a previous experimental program conducted by one of the authors, the developing of a prefabricated ferrocement system for the construction of a low-cost dwelling was reported (López-Calvo, 2005; López-Calvo et al. 2006).

∗ Herwing Zeth López Calvo

∗ Heidy Gómez Barranco

∗ Víctor Manuel Alonso Arguello

* Rafael Nicolás Sánchez Reyes

∗ Facultad de Arquitectura "5 de Mayo", Universidad Autónoma Benito Juárez de Oaxaca, México. Calle 5 de Mayo #100, Centro Histórico, Oaxaca, Oax. México.

Results obtained from this investigation have demonstrated the feasibility of application of the prefabricated system for self-construction housing production without the need of sophisticated equipment. In a similar experimental work, carried out in the National University of Singapore, a prefabricated system based in a ferrocement hollow sandwich, was developed and tested to evaluate its flexural moment capacity; as a result, parameters for structural design were determined (Bhattacharrya et al. 2001). Similarly, in Cuba, Wainshtok et al. (2004) evaluated a seismoresistant prototype of a two floor ferrocement house using prefabricated elements with bolted connections. Other researcher reported the seismic evaluation of a low-cost dwelling built with prefabricated ferrocement panels with bolted connections. Results indicated that the proposed system was appropriated for seismic areas in Mexico (Castro, 1979). In this same manner, other researchers in Oaxaca Mexico, have designed and built several structures such as small houses, public buildings, bridges and schools employing ferrocement as a main construction material; however, all of those structures were manufactured using in situ methods, which were labor intensive and time consuming; consequently, the proposed construction system for massive housing production was not appropriated (Fernandez et al. 1998; Fernandez and Montes 1998; Fernandez and Cano 1995).

In the present paper, the results of an experimental work undertake to develop a prefabricated ferrocement building system for a structurally safe and low-cost housing, is reported.

II. System Development

As shown in Fig. 1, two types of prefabricated blocks were manufactured, type 1 (T1) measuring 1000 x 500 x 120 mm and type 2 (T2) measuring 500 x 500 x 120 mm, both with 25 mm wall thickness. The ferrocement blocks were employed as the "cells" of construction for walls and roof sections. Those were designed to replace ordinary clay bricks or cement blocks system, commonly used in traditional masonry construction in Mexico.

Figure 1. Wall section assembled with prefabricated elements T1 and T2.

A highly fluid mortar with auto leveling properties was employed to manufacture the precast elements and the connections between elements were bolted in order to eliminate the use of mortar. The use of the self-consolidating mortar allowed producing thin sections without need of special equipment or high skilled labor. The reinforcement used was one layer of electro-welded mesh and one layer of chicken wire mesh with wire diameter of 0.8 mm. Mortar proportions and properties are shown in Table 1.

TABLE I. MORTAR´S PROPERTIES

Cement-sand proportion (by weight)	Water to cement ratio	Poisson ratio	Modulus of elasticity (MPa)	Flow diameter (mm)	28 days compressive strength (MPa)
1 : 2.5	0.50	0.2	2760	600 - 700	35.0

III. Structural Assessment

In order to evaluate the structural behavior and stresses distribution caused by service loads in the wall and roof sections, finite element models were employed. The tridimensional models of the roof and wall sections were modeled using standard “Shell” elements measuring 50 x 50 mm. Also, anchorages, bolted connections, restraints and service loads according to Mexican codes were simulated in the model. Finally, displacements and stresses caused by service loads are shown in the model, where dark areas represent zones in which the mortar is in compression and light areas represent tensional stresses (SAP2000 Manuals, 1997).

A. *Wall Section*

Three dimensional wall sections, measuring 1500 x 1500 mm, were modeled using box-shaped blocks of 1000 x 500 x 12 mm and 500 x 500 x 12 mm, both with 25 mm of wall thickness. For axial compression test, a distributed service load of 21.3 kN/m was applied along the wall section. For diagonal compression test a concentrate load of 100 kN was applied in a vertex of the wall section which was rotated in a 45 degrees angle (See Fig. 2 and 3).

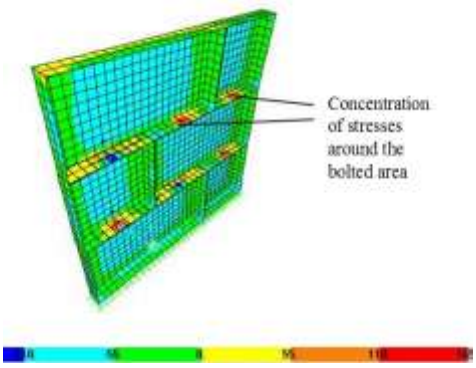

Figure 2. Distribution of stresses under distributed service load

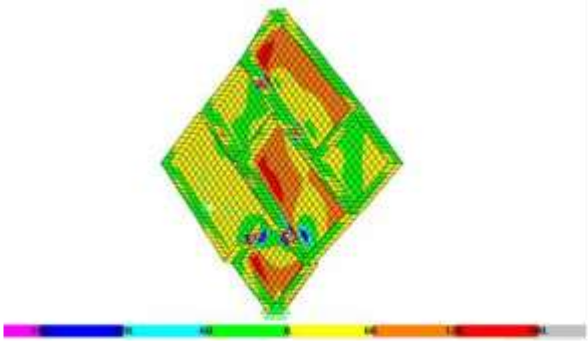

Figure 3. Distribution of stresses under diagonal compression test

In order to validate the data gathered from the computer program, real-scale wall sections were fabricated and tested under similar loading conditions as the virtual models. Before tested, the ferrocement blocks were cured in laboratory conditions for 28 days and then the wall sections were assembled. A distributed load of 32.0 kN and a concentrated load of 50.0 kN, were applied for axial and diagonal loading test, respectively. Fig. 4 and 5 show the setup used during the real-scale structural assessment.

Figure 4. Wall section for axial compression test

Figure 5. Wall section tested under diagonal compression

B. *Roof Section*

The structural assessment of the roof, a finite element model of the roof measuring 1000 mm wide and 3500 mm in length was employed. Bolted connections, restrains and supports were also simulated in the model. The roof section was tested in two point bending test with a total load of 5.0 kN/m^2. Results are presented in Fig. 6, where dark areas represent zones in compression and light areas are tension zones.

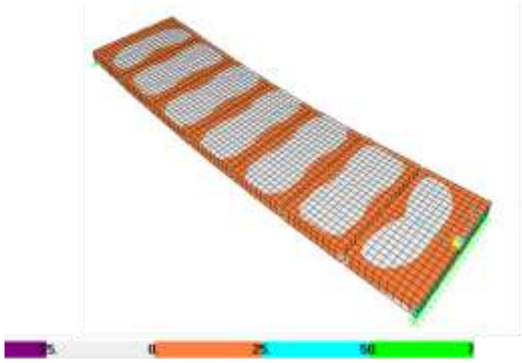

Figure 6. Roof section under simulated bending test

To corroborate information obtained from the finite element model of the roof, a real-scale section of the roof measuring 1200 mm wide and 3000 mm length was tested in bending test using a 5.0 kN/m^2 two point load. The setup of the structural evaluation of the slab is show in Fig. 7.

Figure 7. Roof section tested under two point bending test

C. *Architectural Design*

As illustrated in Fig. 8, a 30 m^{2}architectural plan was designed to apply the dwelling's prototype. Prefabricated ferrocement blocks were considered in the project for external and internal walls and the roof as well. A bedroom and a service area were proposed as a future enlargement in the right side of the house. In the design, windows and doors ways were modules of 1000 mm wide according to the block's size. Bathroom facilities were included into the house; however, it could be also located outside, since potable water and sewage infrastructure often may not be available in rural areas of México.

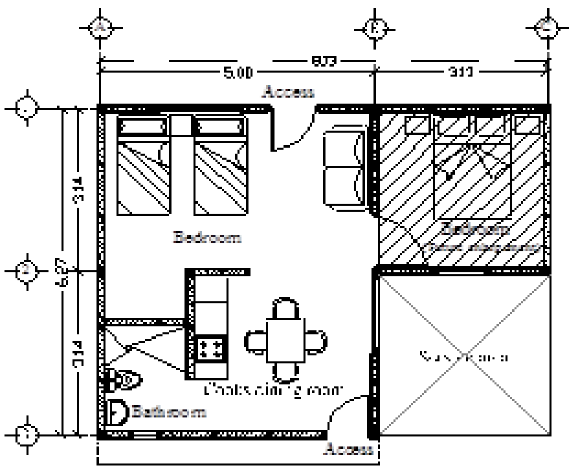

Figure 8 Dwelling's plan view

In order to provide stiffness to the walls, reinforced concrete frames of 120 x 120 mm were considered as confinement of the walls. Such reinforcement was used to improve the dwelling structure and thus increasing its safety against accidental loads, wind and earthquakes, as suggested by the local construction codes. The Fig. 9 illustrates the prototype cross section.

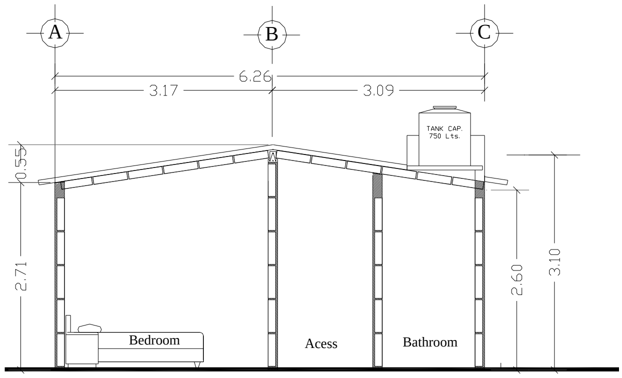

Figure 9. Prototype cross section

IV. Prototype's Construction

Due to their light weight, of about 90 Lb. for block type 1 and 63 Lb. for block type 2, prefabricated elements were assembled without need of special equipment and bolted in an alternated way as the traditional wall masonry construction. As can be seen in Fig. 10 and 11, housing partitions and the external walls were manufactured with precast ferrocement elements. Additionally, the openings for doors and windows during the construction process were left according to the architectural project.

Fig.ure 10. Placement and leveling of prefabricated elements

Since the weight of the prototype is only a fraction of conventional masonry construction, a reinforced concrete slab measuring 500 mm wide by 100 mm high was employed as foundation. Slabs were built with a 25 MPa compressive strength concrete and electro-welded mesh as reinforcement.

Figure 11. Ensemble of walls using prefabricated elements

The roof was build using prefabricated blocks of 1000 x 500 x 12 mm (Blocks type 1). During the construction process, ferrocement blocks were assembled on prefabricated concrete beams as illustrated in Fig. 12. Using such process, no wooden forms were needed because the precast beams served as support and formwork at the same time. Also, a concrete layer on the compression zone, as used in the traditional construction method, not was necessary because the slabs system was sufficient to support the service loads to which the roof was subjected. Fig.13 portrays the dwelling's prototype completely finished.

Figure 12. Roof´s construction using prefabricated beams

Figure 13. Dwelling's prototype

V. Results and Discussion

A. *Structural Evaluation*

The axial and diagonal compression test performed in the computer models revealed that there were compressive and tensional stresses, ranging from 5 MPa to 10 MPa, around the perimeter and internal ribs of the walls. Nevertheless, as can be seen in the Fig. 4 and 5, higher stress concentrations of about 18 MPa were found around the bolted area. Hence, it can be inferred that such areas could be highly susceptible to failure by punching.

Regarding the experimental tests carried out on the wall's sections, results revealed that the use of bolted connections, tended to increase the shear strength of the walls substantially. In Table 2, the shear strength calculated for bolted blocks is compared with other commonly used masonry systems.

TABLE II. SHEAR STRENGTH (V*) FOR WALLS MANUFACTURED WITH DIFFERENT MASONRY MATERIALS.

Type of material	Type of Joint	V* (MPa)
* Clay Brick	Mortar cement-lime	0.30
* Hollow clay brick	Mortar cement	0.20
* Heavy concrete block	Mortar cement	0.25
* Concrete block	Mortar cement	0.20
** Prefabricated ferrocement blocks	Bolted	0.61

* Values obtained from Mexican Standards
** Value calculated by the authors

Also, vertical and horizontal displacements of the walls were measured during the experimental test and compared with the displacements calculated in the computer model. Results measured in the experimental and computer assessment are compared and presented in Table III.

TABLE III. WALL'S DISPLACEMENTS MEASURED DURING THE LAB TEST AND COMPUTER MODEL

	Axial Compression test (32 kN)		Diagonal compression test (50 kN)	
Displacement (mm)	Lab test	Computer model	Lab test	Computer model
Vertical	0.75	0.54	1.60	0.90
Horizontal	1.65	0.90	3.20	2.00

According to the computer models, compression forces of 8 MPa and a maximum tensile stress of 75 MPa were observed in the roof secton during the two point bending test. The loading test was adjusted to a 5.0 kN/m^2 in the computer model as well as in the experimental test. The maximum displacement was determined to be 8.3 mm as required by the Mexican Standard NMX-C-405. Comparative of flexural displacements obtained in the

TABLE IV. COMPARISON BETWEEN COMPUTER MODEL AND EXPERIMENTAL TEST PERFORMED IN THE ROOF SECTION.

Structure	Service load (kN/m^2)	Total load (kN/m^2)	Displacements (mm)		
			Computer model	Experimental Test	NMX-C-405 L/360
Roof	2.45	5.00	4.20	5.00	8.30

* Value calculated according to Mexican Standard NMX-C-405.

B. *Cost Assessment*

A cost assessment was performed in order to compare the construction feasibility between the traditional housing building method used in Mexico (brick masonry and reinforced concrete) versus the precast ferrocement building system. The same architectural project was considered in either case in order to permit the comparison between methods. Construction time, labor, consumption of industrialized materials, costs, and CO_2 emissions due to cement and steel consumption, were considered in the analysis. In Table 4, results obtained from the cost assessment are presented. Results obtained in the cost assessment reported in Table 4, revealed that a reduction of almost 35% of overall construction cost is achieved using prefabricated ferrocement elements.

TABLE IV. COST ASSESSMENT

Concept	Precast ferrocement elements	Masonry and reinforced concrete	Savings
Labor (persons)	2	2	---
Construction time	2 weeks	8 weeks	6
Cement consumption	4.7 Ton.	7.39 Ton.	36 %
Steel consumption	0.255 Ton.	0.642 Ton.	60 %
Construction cost	280 USD/m^2	389.5 USD/m^2	28 %
CO_2 emissions*	5.13 Ton.	8.48 Ton.	3.35 Ton.

*CO2 emission due to the consumption of the main industrialized materials, cement and steel.

VI. Conclusions

Based on the results from this research, the following conclusions can be drawn:

- The precast elements were manufactured using a standardized process which allowed obtaining high quality in finishing, major labor safety, lower wasting of material and savings in construction time.
- Results obtained from the computer models provide a good understanding of the behavior of the walls and roof sections when compared with the results obtained from the laboratory tests.
- Based on the experience obtained during the prototype construction, it can be conclude that the prefabricated ferrocement system can be used in self-construction without the need of special equipment and not skilled labor due to the use of bolted connections and the lightness of the ferrocement blocks.
- The cost analysis revealed that the construction system is around 35% cheaper than the common housing building method used in urban areas of México.

Acknowledgment

The authors acknowledge the support of the Autonomous University Benito Juarez of Oaxaca, Mexico, the CIIDIR-IPN Unidad Oaxaca, and the financial support of the Harp Helú Foundation. The National Council of Sciences and Technology of México (CONACYT).

References

[1] A.E. Naaman and H. Hammoud. “Ferrocement Prefabricated Housing”: The next generation. Journal of Ferrocement, V. 22, No. 1, 1992, pp. 35- 47.*)*

[2] R. H. Wainshtok. “Ferrocement precast elements for housing. Journal of Ferrocement”, Vol. 26, No.4, 1996, pp. 303-306.

[3] Patent FERROCEMENT SYSTEM FC2. Elementos prefabricados para viviendas de 50 a 70 m2, en Córdova Argentina. Information, Journal of Ferrocement, Vol. 23 No. 3, 1993, pp. 10-15.

[4] P. Desayi, L.S. Viswanathan and G.K. Hubli. “Precast ferrocement roofing elements”. Journal of ferrocement, vol 26, No 1, 1983, pp.19-29.

[5] H.Z. López-Calvo. Desarrollo de un sistema constructivo modular de mortero armado para vivienda de interés social. Tesis de postgrado. Benemérita Universidad Autónoma de Puebla, México, 2005.

[6] H.Z.. López-Calvo,V. Jiménez-Quero, P.F. Cano-Barrita. “Comportamiento de un Muro Construido con Paneles Prefabricados de Mortero Armado Sometido a Compresión Simple y Diagonal”, Revista Naturaleza y Desarrollo, Instituto Politecnico Nacional de México, Vol. 4, No.1, 2006, pp.55-63.

[7] P. Bhattacharrya, K.H. Tan and M.A. Mansur. “Flexural moment capacity of ferrocement hollow sandwich panel system”. Proceeding of the Seventh International Symposium on Ferrocement and Thin Reinforced Cement Composites”, National University of Singapore, 2001, pp 55-62.

[8] R.H. Wainshtok, B.A. Ramos and B..E. Vega.. “Model of seismoresistant ferrocement house”. Journal of Ferrocement, Vol. 34, No.2, 2004, pp. 363-371.

[9] J. Castro. “Applications of ferrocement in low cost housing in Mexico”. ACI Publication Sp-61. Detroit 1979, pp. 143-146.

[10] A. Fernandez, L. Juarez, and F. Cano. “An Economical Earthquake/Hurricane Resistant Ferrocement School Building”, Journal of Ferrocement, V. 28, No. 4, 1998, pp. 351-357.

[11] A. Fernandez. and P. Montes. “A Monolithic Ferrocement Auditorium. Ferrocement”. 6: 6th International Symposium on Ferrocement, University of Michigan, Ann Arbor, 1998. pp. 173-186.

[12] A. Fernandez. and P.F. Cano. “Seismic Characteristics of Low Cost Ferrocement Integral Housing, Proceedings of the International Symposium on New Development in Concrete Science and Technology (DeCSAT’95), Southeast University, Nanjing, China, 1995, pp. 772-777.

[13] SAP2000 Manuals, 1997. “Integrated Finite Element Analysis and Design of Structures”, Computers and Structures, Inc. Berkeley, California, USA.

[14] NMX–C– 405 –1997-ONNCCE, (Organismo Nacional de Normalización y Certificación de la Construcción y Edificación, S.C.) Paneles para uso estructural en muros, techos y entrepisos. México, D.F., (November 2003).