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Ferrocement Structural Components Molded from Ordinary PVC Pipes: Tests for Low-Cost Housing Use

By

Vera Karla S. Caingles
Civil Engineering Department, University of Science and Technology of Southern Philippines
Email: vera.karla@ustp.edu.ph

Jose Lorenzo D. Bucton
Civil Engineering Department, University of Science and Technology of Southern Philippines

Nestor E. Ybanez
Civil Engineering Department, University of Science and Technology of Southern Philippines

Joel M. Jaos
Engineering Department, National Irrigation Administration

Abstract

The integration of ferrocement as structural element in a building is one of the breakthrough studies that promotes sustainability and environmental protection. Several studies have been conducted and applied globally yet has not been fully developed in the Philippines. This project intends to first, evaluate maximum compressive stress and maximum bending stress capacity; and second, evaluate cost-effectiveness of the material and manufacturing process for hollow-cored columns and beams made with ferrocement. A total of 4-set of 4m hollow-core ferrocement samples with varying cross-sections, and another 4-set of 0.3m were designed and prepared for the flexural and compressive strength tests, respectively. Commercially available 3-inc uPVC pipes were used as an inner form to support the wire mesh and mortar cement. The house is now designed with 36 single pipe cross-section of various heights and 23 double pipe cross-sections acting as columns. Most of the double pipe cross-section were installed as columns hidden in the firewall. This is to follow the National Building Code Provisions of having firewalls not less than 150mm in thickness for fire and heat resistivity. The total bill of materials for the designed house is calculated to be at 391,000.00 pesos. Under the current administration, the total cost of the unit would still fall below the new costing rules for the National Housing Administration. In essence, it can be concluded that a ferrocement house can be created using modular members which can carry the loads safely and is cost efficient. It recommended to seek for a different mold and manufacturing technique which can reduce the time to create the structural elements to further reduce total cost.

Index Terms: Cost Estimates, Quantitative Method, Structural Analysis, Structural Engineering

Introduction

Rapid urbanization, inadequate infrastructure, and basic services in large towns and cities have led to the proliferation of slums and informal settlements in the country. From a national average of 32%, slum population has been exponentially rising at an average rate of 3.4% [1]. Global Urbanization is fastest in developing countries and informal settlements are rapidly growing making affordable sustainable housing strategies crucial [2]. Providing low-cost housing specially to middle- and low-income group both in rural and urban areas is a serious national problem. As conventional construction materials are becoming excessively costly day by day, innovative and low-cost construction materials and techniques are of urgent need [3]. Although growth levels for the Philippines is currently at 1.72%, a total population of 100.57 million individuals, in 22.98 million family units [4] of which 44.8% is [5] will drive up the cost of land. With average monthly family income of Php22,000.00 [4], the government controls cost for socialized housing units by setting a price ceiling of Php450,000.00 [6] per house with lot. In accordance to maximum budget allocated for the total unit, the National Housing Authority is constrained to build standard houses at a total material and labor cost of Php150,000.00. This design takes the least concession to ergonomics. NHA units employ Galvanized Iron Roofs without ceiling boards. G.I. sheets used as roofs is a cost-effective way to rainproof human habitats. However, it does not provide adequate heat insulation. Ceiling systems made of plywood and wood frames with appropriate air vents shields the house interior from solar heat however, it entails additional cost.

Philippines is among the countries that is most vulnerable to global warming. As recorded by the National Oceanic and Atmospheric Administration (NOAA), 2017 is the 3rd warmest year in the country without an El Niño present in the tropical Pacific Ocean. It is therefore imperative to conduct studies on new designs using materials and systems which will alleviate problems inherent in these systems. The increase in Solar Heat Gain coupled with current materials adopted translates to houses which are definitely affordable but uncomfortable at the very least to unhabitable at its worst. It is therefore imperative to conduct studies on new designs using materials and systems which will alleviate problems inherent in these systems.

Ferrocement is a type of thin wall reinforced concrete commonly constructed of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small size wire mesh. The mesh may be made of metallic or other suitable materials [7]. The uniform distribution and dispersion of reinforcement in the ferrocement composite provide better cracking characteristics, higher tensile strength, ductility and impact resistance [8] It has been used to construct boats, ships and buildings in the past but being labor intensive, it has not gained much attention in the construction industry.

Green Roofs are building roofs that are partially or completely propagated with plants. The roofs are structurally designed to carry the weight of the vegetation and the substrate. Employing green roofs would help ambient temperature variations, reduced energy consumption for cooling, decreases run-off and increased property value and roof lifetime [9].

The rapid increase in the urban population produces an enormous demand for shelter and tenure security [10]. With the increasing demand of affordable housing, the utmost challenge is to create and design quality and inexpensive materials for these houses. The integration of ferrocement as green roof is one of the breakthrough studies that promotes sustainability and environmental protection. Several studies have been conducted and applied globally yet has not been fully developed in the Philippines. This study purports to establish low-cost structural elements in ferrocement as substitute for expensive conventional materials in the development of an inexpensive house that incorporate green roof as insulation. Furthermore, it proposes to appraise the capability of hollow-cored ferrocement structural elements to carry normal loads and additional loads brought on by green roof systems. Thus, it intends to first, evaluate maximum compressive stress and maximum bending stress capacity; and second, evaluate cost-effectiveness of the material and manufacturing process for hollow-cored columns and beams made with ferrocement.

Methodology

Selection of Sample Dimensions and Mold diameter

Houses created by the National Housing Authority and other construction entities in the market typically have walls that are around 100 mm – 150 mm thick. This is due to the use of Concrete Hollow Blocks as primary materials for wall construction. The empty blocks are then filled with plaster (concrete mix of cement and sand without gravel) to lend sturdiness to an otherwise weak CHB. To hide unsightly corners on columns, single storey houses usually have column cross-sections of 150 mm by 200 mm. These dimensions are ideal for "hiding" the columns when the walls are plastered. Beams to support the roof have the same dimensions as the columns for the same reason.

In this study, combination of 3" diameter uPVC orange pipes and ½" diameter uPVC blue pipes were used for internal molds. The pipes have inherent circumferential compressive strength due to its geometry and material. This design was safe to carry the pressure applied during production. A preplanned devised technique for placement was carried out and tested for workability.

Cross-sections of the proposed columns and beams of the hollow core ferrocement samples

Tables 1 and 2 showed the cross sections and number of materials used for the flexural and compressive strength samples, respectively. The proposed internal placement of 3" uPVC orange and ½" uPVC blue pipes of the four variants for both flexural and compressive strength samples were laid out as shown in Fig. 1. The 3D layout of the hollow core ferrocement samples for flexural and compressive tests was drafted in Fig. 2.

Table 1: *Cross-sections and number of samples for flexural test*

Flexural Samples	Number of Samples	Dimension		
		Width(mm)	Height (mm)	Length (mm)
Flexural Set 1	6	100	100	4000
Flexural Set 2	6	100	180	4000
Flexural Set 3	6	100	260	4000
Flexural Set 4	6	180	180	4000

Table 2: *Cross-sections and number of samples for compression test*

Compression Samples	Number of Samples	Dimension		
		Width(mm)	Height(mm)	Length(mm)
Compression Set 1	6	100	100	300
Compression Set 2	6	100	180	300
Compression Set 3	6	100	260	300
Compression Set 4	6	180	180	300

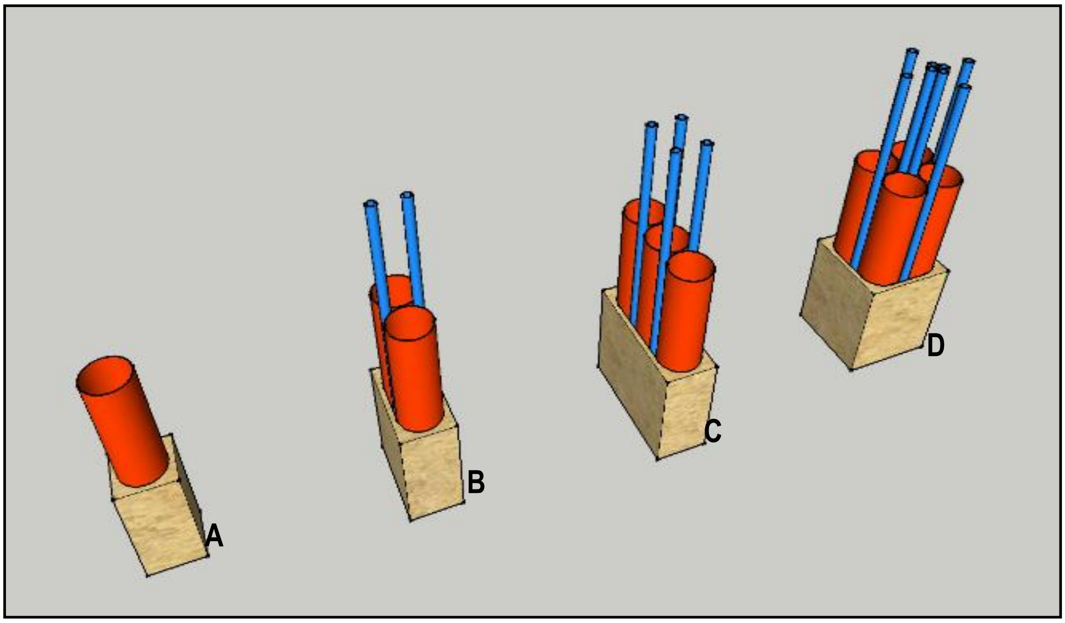

Fig. 1: *Internal arrangement of pipes for (A) 100mm x 100mm sample; (B) 100mm x 180mm sample; (C) 100mm x 260mm sample; and (D) 180mm x 180mm sample*

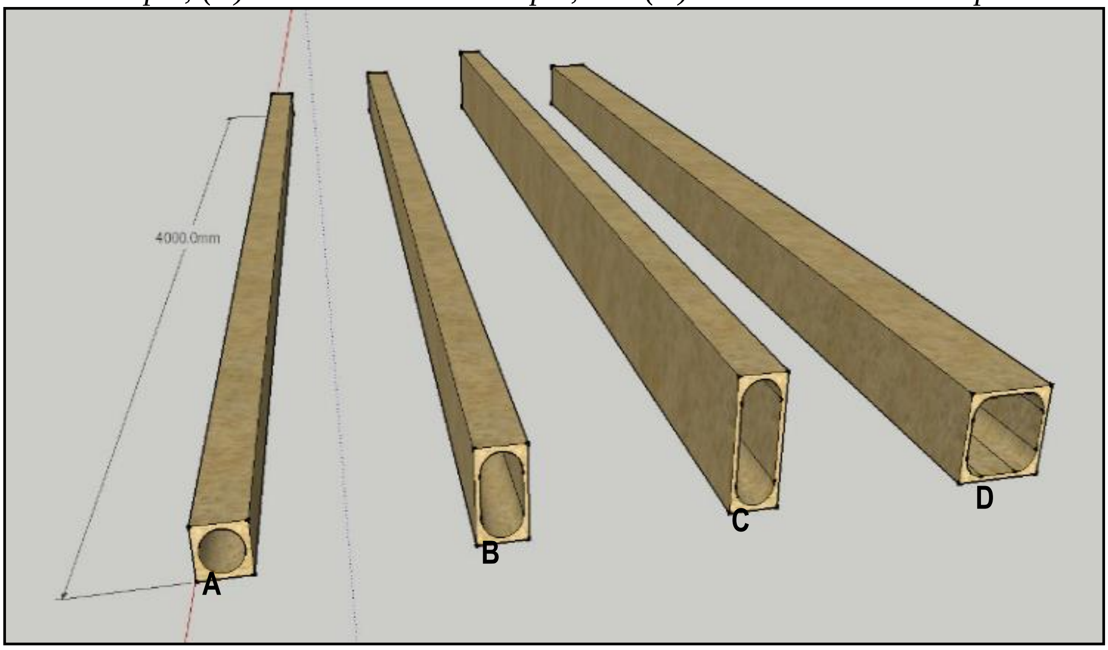

Fig. 2: *3D layout of the (A) 100mm x 100mm sample; (B) 100mm x 180mm sample; (C) 100mm x 260mm sample flexural; and (D) 180mm x 180mm sample*

Steps in creating hollow core ferrocement columns and beams

Fig. 3 presents the chronological steps involved to manufacture hollow core ferrocement columns and beams. The preliminary part covers the determination of the optimum length of the column and beam based on the structural plans. The length of the column and beam specimen differ because of the its purpose and function. The second step is the wire mesh installation. The materials include 3" uPVC orange pipe, ½ x ½ gauge no.21 wire mesh, gage no.16 tie wire, and ½ uPVC blue pipes. The third part is the reinforcing bars installation which uses 8mm diameter reinforcement bars as shown in Fig. 4. The arrangement of the bars is based on the types of structure. The fourth part details the casting of the ferrocement column and beam. Similar procedures in plastering and setting of mortar cement employed for both structures followed by curing of specimen for 28 days as shown in Fig. 5.

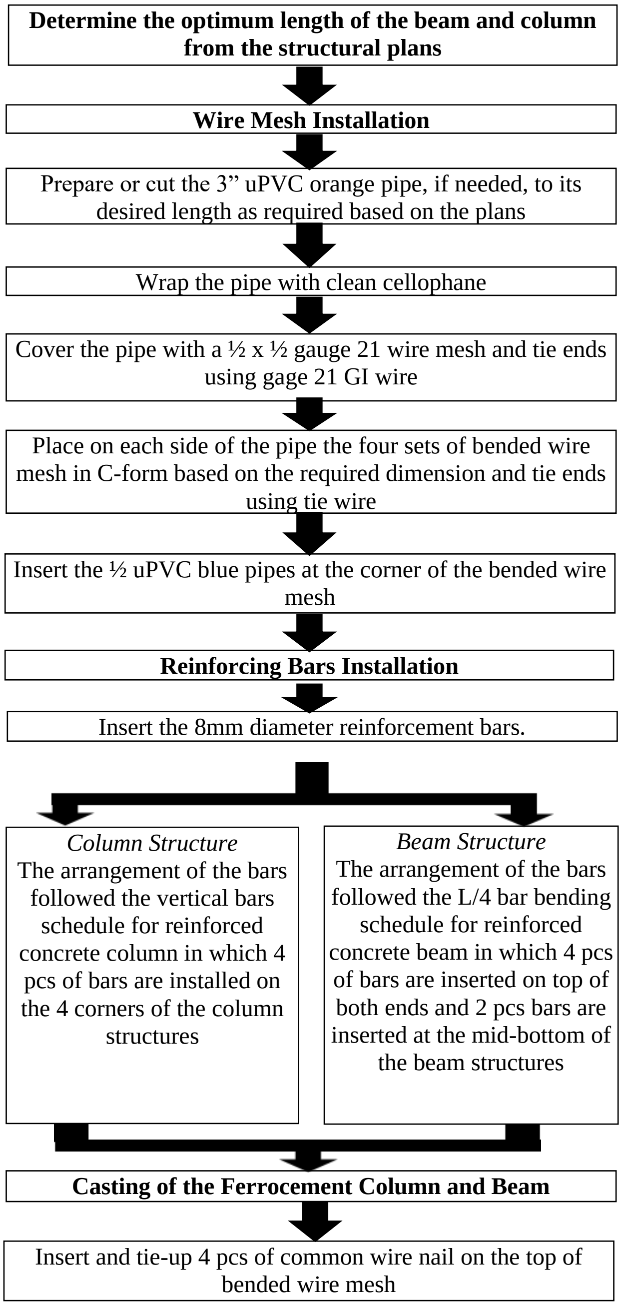

Fig. 3: *Steps in making the hollow core ferrocement beam and column*

Fig. 4: *Orientation of ½" uPVC blue pipes and 8mm Ø bars*

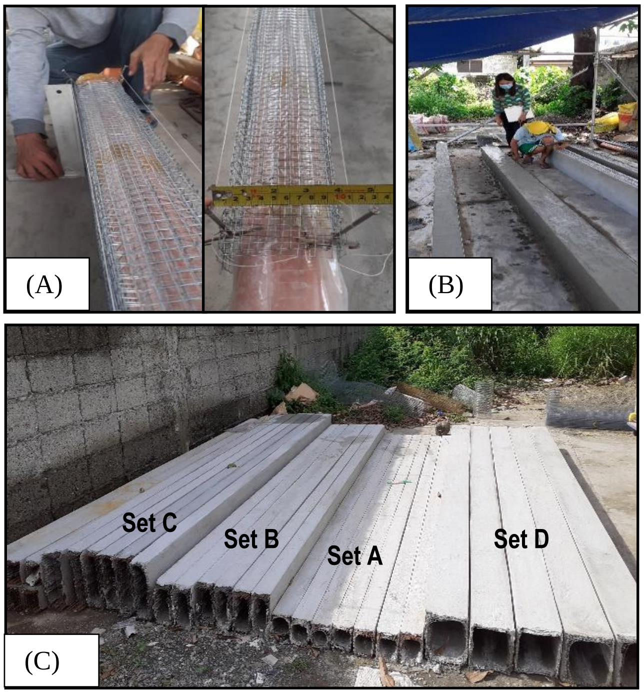

Fig. 5: *(A) Checking of dimension (B) Casting of samples (C) Curing of samples*

Structural analysis

A Structural Model of the house design is created using SAP2000 as shown in Figure 6. Using the current material properties and standard assumptions the structure is mathematically able to carry the loads assigned to it with the usual generous margin of safety.

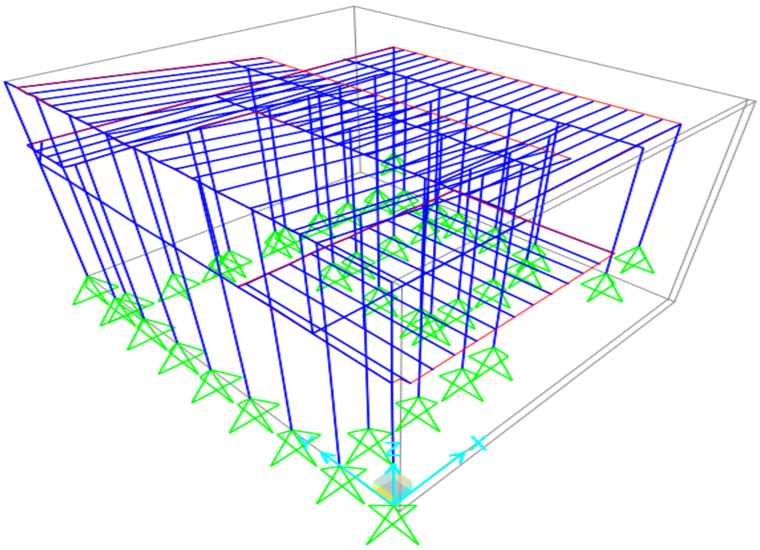

Fig. 6: *A finite element model of the house structure carrying designed loads*

Table 3: *Compression test data on mortar cube*

Cube Sample	1	2	3
Age in days	28	28	28
Compressive strength (MPa)	21.1	21.9	20.1
Average (MPa)		21.03	

Compressive and flexural tests results

The compressive and flexural values of the columns and beams specimen based on the laboratory tests conducted are summarized in Tables 4 and 5. The tables show the average strength values, and these values were used in the computation of compressive and flexural stresses.

Table 4: *Compressive strength values*

Specimen name	Compressive strength (kN)						Average (kN)
	1	2	3	4	5	6	
Single Tube	27.8	42.8	51.1	42.3	54.9	56.5	45.9
Double Tube	93.6	104	74.5	121.3	91.3	116.2	100.2
Triple Tube	115.6	98.9	111.1	101.9	107.1	112.9	107.9
Quadruple Tube	164.8	129.3	113.7	136.2	92.7	124.8	126.9

Table 5: *Flexural strength values*

Specimen name	Flexural strength (kN)						Average (kN)
	1	2	3	4	5	6	
Single Tube	12.2	11.4	8.0	9.4	10.0	9.5	10.1
Double Tube	25.1	20.8	17.8	23.3	25.0	17.6	21.6
Triple Tube	19.8	19.7	11.4	22.1	13.3	15.4	16.9
Quadruple Tube	21.7	21.8	17.7	15.4	n/a	n/a	19.14

Compressive strength

Compressive strength involves testing and calculating how well a given specimen, product or material can withstand a compressive stress. Unlike tension, which expands or pulls, compression means a specimen, product or material is shortened or pressed down. Compressive strength of a material is the point at which the material fails. Calculating compressive strength involves testing to find this failure point. To calculate the compressive strength of a specimen, Equation 1 is used:

$$f = \frac{P}{A} \qquad (1)$$

Where:
f = compressive strength
P = total maximum load
A = area of loaded surface

Transverse load

Transverse load is the load applied perpendicularly to longitudinal axis of a member. Transverse loading causes the member to bend and deflect from its original position, with internal tensile and compressive accompanying change in curvature. The cracking moment, *M*, is computed using Equation 2:

$$M = \frac{PL}{4} + \frac{W_{sw}L^2}{8} \qquad (2)$$

Expected nominal moment

The nominal or ultimate flexural moment for reinforced concrete beam represents the ultimate moment that beam can carry. Moments generated by service load shall be less than the nominal moment of the beam (Equation 3). At this stage, reinforcing steel assumed to yield. Concrete mortar stress will not vary linearly from the neutral axis. Compressive stress will be similar to that shown in Fig. 7.

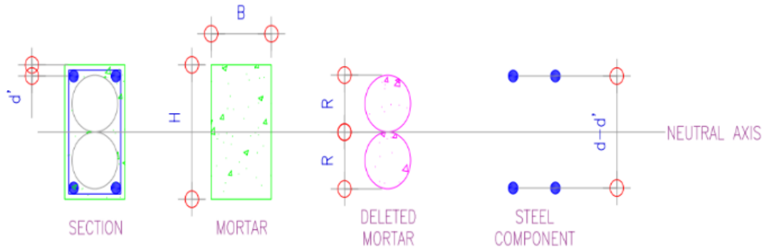

Fig. 7: Section component breakdown

For simplification, the following assumptions are made:

1. Concrete compressive stress transferred into the various shapes with a constant stress of 0.45fc' as defined in the provisions of the ACI Code ACI 549 1R-93 (Fig. 8).
2. Steel reinforcement is assumed to yield.

Solving for the moment, using Equation 3, of each component in the composite section yields:

$$m_1 = m_{mortar} = \frac{0.45}{4} f'cBH^2$$
$$m_2 = m_{deleted\ mortar} = \frac{11}{14} R^3 (0.45f'c) \qquad (3)$$
$$m_3 = m_{steel} = Asfy(d - d')$$

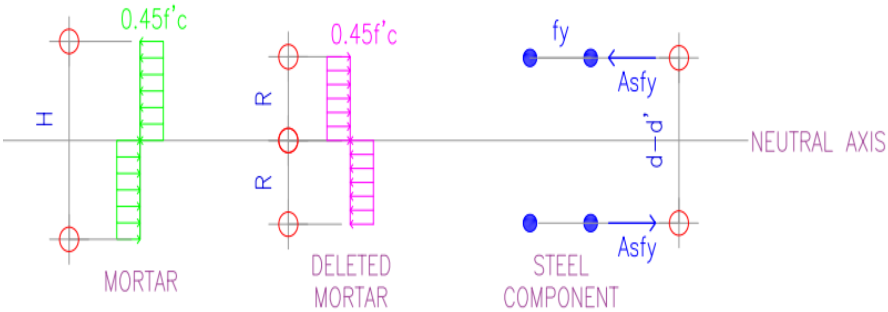

Fig. 8: *Stress diagram*

Thus, calculating the equilibrium of the entire system the nominal flexural capacity of the beam is shown in Equation 4:

$$m_u = m_1 - m_2 + m_3$$
$$m_u = \frac{0.45}{4} f'cBH^2 - \frac{11}{14} R^3 (0.45f'c) + Asfy(d - d') \qquad (4)$$

Extending this concept further to triple and quadruple pipe cases yields the following expressions in Equations 5 and 6, respectively.

$$m_u = 0.45f'c\left[\frac{1}{4}BH^2 - \frac{73}{42}R^3\right] + Asfy(d - d') \qquad (5)$$
$$m_u = 0.9f'c\left[\frac{1}{4}BH^2 - \frac{11}{14}R^3\right] + 2Asfy(d - d') \qquad (6)$$

Analysis for double pipe case

Table 6 shows the input parameters used in the computation for the expected nominal moment. In this study, the value for yield strength of steel used is 276 MPa which is for Grade 40 steel. The compressive strength of concrete value used is 8.411MPa which is from the compression test results. Using Equation 7, the computed expected moment for double pipe case is 5.3452 kN.m.

Table 6: *Parameters for nominal moment*

Parameter	Value	Unit
B	0.1	m
H	0.18	m
R	0.076	m
t	0.0006	m
h	0.1762	m
b	0.0762	m
d	0.1524	m
d'	0.0238	m
As	0.000101	mm^2

$$m_{expected} = 0.45f'c\left[\frac{1}{4}BH^2 - \frac{11}{14}R^3\right] + Asfy(d - d') \quad (7)$$

On the other hand, the actual nominal moment is computed using the following criteria: (a) actual length of the specimen is 3.990m, (b) selfweight of the beam is 0.18816 kN/m, (c) actual moment of beam is 5.0 kN.m. Using Equations 8 and 9, the actual selfweight and moment for the double pipe case are 0.3725 kN.m and 5. 3725kN.m, respectively.

For self-weight:

$$\frac{W_{sw}L^2}{8} = \frac{\left(0.18816\frac{kN}{m}\right)(3.980m)^2}{8}$$

$$\frac{W_{sw}L^2}{8} = 0.3725kN.m \quad (8)$$

For actual moment:

$$m_{actual} = m_{recorded} + \frac{W_{sw}L^2}{8} \quad (9)$$

$$m_{actual} = 5.00kN.m + 0.3725kN.m$$

$$m_{actual} = 5.3725kN.m$$

Thus, solving for the percentage error, using Equation 10, between the expected and actual moment gave a value of 0.5081% which implies that the constructed hollow core ferrocement structure can carry the designed load.

$$m_{expected} = 5.3452\ kN.m$$

$$m_{actual} = 5.3725kN.m$$

$$PERCENTAGE\ ERROR = \left|\frac{m_{actual} - m_{expected}}{m_{actual}}\right| \quad (10)$$

Table 7: *Parameters for nominal moment*

Parameter	Value	Unit
B	0.1	m
H	0.26	m
R	0.0762	m
t	0.0006	m
h	0.1762	m
b	0.0843	m
d	0.1605	m
d'	0.0157	m
As	0.000101	mm^2

Analysis for triple pipe case

Table 7 shows the input parameters used in the computation for the expected nominal moment. In this study, the value for yield strength of steel used is 276 MPa which is for Grade 40 steel. The compressive strength of concrete value used is 8.411 MPa which is from the compression tests results. Using Equation 7-10, the computed expected moment, selfweight moment, actual moment and percentage error, respectively, for triple pipe case. Results revealed values of 7. 1075kN.m, 0. 5171kN.m for selfweight moment, 5. 5171kN.m for actual moment, and 28.83% for the percentage error.

Analysis for quadruple pipe case

Table 8 shows the input parameters used in the computation for the expected nominal moment. In this study, the value for yield strength of steel used is 276 MPa which is for Grade 40 steel. The compressive strength of concrete value used is 8.411 MPa which is from the compression tests results. Using Equation 7-10, the computed expected moment, selfweight, actual moment and percentage error, respectively, for quadruple pipe case. Results revealed values of 10. 6904kN.m, 0. 7451kN.m for selfweight moment, 10. 7451kN.m for actual moment, and 50.91% for the percentage error.

Selection of Best Cross-section

Flexural Strength capacity determines maximum moment loads that a beam could carry while Axial Strength is dependent on material strength. The best material that can be used in any structure would be that which exhibits the capacity to carry both loading conditions. Material cost on the other hand would limit the choice to the material which would can bear loading conditions plus a reasonable margin of safety. As such, it would be deemed wise to prefer a cross-section or a combination of cross-sections which would give the optimal “value for money” conditions.

The Quadruple Pipe Cross-section

These as expected generated the biggest compressive strength capacity. However, its moment load capacity did not follow predictions. This cross-section returned moment load capacity smaller than that expected. Further, the material cost of manufacturing samples with this cross-section is greater than the other three. Therefore, the quadruple pipe cross-section was not deemed good enough for the house design.

The Triple Pipe Cross-section

This cross-section was deemed to be the most ideal among the four choices due to the depth of section. The calculated moment of inertia for flexural stress capacity is for this section at the optimum. The test samples however returned a breaking point capacity less than that expected. In addition to this undesirable property, it was observed during the actual procedures of sample handling that this cross-section is difficult to transport and install manually due to its weight. Safe installation procedures in actual construction would necessitate the use of mechanical lifters which would increase construction cost.

The Double Pipe Cross-section

The material cost of producing this sample is almost twice that of the single pipe-construction (see appendix on detailed unit price analysis). Breaking point strength in both flexure and axial capacity is also double that of the single pipe-construction. At a mass of around 75 kgs, this cross-section can easily be manhandled by a team of two persons.

Single Pipe Cross-section

The process of producing all cross-sections is similar in nature. Although the single pipe internal form is easier to manipulate than the previous three, the cutting, folding and installation of the wire screen use the same process. This results to an average of two samples at 4.0m length produced within a day regardless of the number of pipes acting as internal forms. Nonetheless material needed to produce this sample is around one-half less than that needed for the double pipe cross-section. This makes the single pipe cross-section cost competitive.

The flexural stress capacity in a 4.0m beam is not ideal. The material at this configuration results to a very ductile sample which readily bends before its elastic limit is breached. These makes the cross-section less desirable for use as beams. A compressive strength capacity of 45.9 kN or 4600 kgs is impressive.

Combined Cross-section

The test results on sample are enough to conclude that the ideal combination of cross-section to use would be that of the single-pipe and double-pipe cross-section. The single-pipes would act to hold the double-pipe cross-sections. In effect, the double-pipe sections would serve as joists that would hold the roof loads and the single-pipe sections would act as hidden columns to support the beam and the house walls at the same time.

House Design

The house is now designed with 36 single pipe cross-section of various heights and 23 double pipe cross-sections acting as columns. Most of the double pipe cross-section were installed as columns hidden in the firewall. This is to follow the National Building Code Provisions of having firewalls not less than 150mm in thickness for fire and heat resistivity.

63 pieces of double pipe cross-section of various lengths were used as beams for joists to support the roof loads. As the roof load would consist of the grasses, growing media, and other additional live loads, the joists are designed to carry 2.40 kN/m^2 or 245 kg/m^2. These necessitates a tributary width or distance between joists of 300 mm.

Cost of Structure

Due to the increase of material prices the original target of 150,000.00 pesos per housing unit cannot be achieved. The total bill of materials for the designed house is calculated to be at 390,965.67 pesos per unit as shown on the Table 9. Under the current administration, the total cost of the unit would still fall below the new costing rules for the National Housing Administration. For a 30 sq.m. house, the cost is currently pegged by NHA at 400,000.00.

Table 9: *Estimated Bill of Quantities per unit house*

Item No	Description	Unit	Quantity	Unit Cost
1	Structural Excavation	cu.m.	5.26	333.18
2	Gravel Bedding	cu.m.	0.75	1,974.25
3	Structural Concrete for Footings	cu.m.	0.71	12,079.28
4	Ferrocement Single Core	pcs	29.00	1,612.22
5	Ferrocement Double Core Columns	pcs	23.00	2,362.12
6	Ferrocement Double Core Beams	pcs	63.00	2,301.14
7	Ferrocement Wall Works	sq.m.	43.42	464.57
8	Ferrocement Slab Works	sq.m.	30.00	369.33
9	Painting Works (Masonry Painting)	sq.m.	169.94	79.66
10	Finishing Hardware	sq.m.	17.00	1,368.20
11	Green Roofing Works	sq.m.	62.00	385.66
12	Plumbing Fixtures	Lump Sum	1.00	31,717.81
13	Conduit Works, Boxes, Fittings	Lump Sum	1.00	9,395.25
	Housing Construction Cost			390,965.67

Conclusion

The study is a real time measurement and observation of full-sized structural elements that can be used in a building structure. The structural members were manufactured in real field conditions and their capacity were measured in real conditions. As such, any designed structure that uses the components recommended in this paper should behave in the manner tested. The study presents the manner in which the elements were manufactured; the tests done and the results of such tests; a computer aided mathematical model of an NHA house than can be created using such material; and the total costs for such house. In essence, it can be concluded that a ferrocement house can be created using modular members which can carry the loads safely and is cost efficient.

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