FINITE ELEMENT BASED ANALYSIS AND DESIGN OF A HYBRID FERROCEMENT RESIDENTIAL STRUCTURE

N. ANWAR [(1)] AND O. WALDSCHLAGEL [(2)]

(1) Asian Center for Engineering Computations and Software (ACECOMS), Asian Institute of Technology (AIT), Thailand

(2) Intact Structures, Inc., New York, USA

Abstract ID Number (given by the scientific editors/organizers): …………..

Author contacts

Authors	E-Mail	Fax	Postal address
N. Anwar	nanwar@ait.ac.th	(662)-524-6059	ACECOMS, SET, AIT P.O. Box 4, KlongLuang Pathumthani 12120, Thailand
O. Waldschlagel	info@intactstructures.com	01-718-273-3674	Intact Structures, Inc., 78 Corson Avenue, Staten Island, New York, 10301, USA

Contact person for the paper: N. Anwar

Presenter of the paper during the Conference: N. Anwar

Total number of pages of the paper (this page and the license to publish excluded): 10

Revised Edition: 2006-05-01

FINITE ELEMENT BASED MODELING ANALYSIS AND DESIGN OF FERRO CEMENT AND SANDWICH SHELL STRUCTURES

N. ANWAR [(1)] , A. TUNGTONG(2), O. WALDSCHLAGEL [(3)]

(1) Associate Director, Asian Center for Engineering Computations and Software (ACECOMS), Asian Institute of Technology (AIT), Thailand

(2) Intact Structures, Inc., New York, USA

Abstract

Ferrocement structures are categorized typically by its thin wall, which is much thinner and lighter than reinforced concrete structures and have much greater tensile strength and flexibility than ordinary concrete. The response of ferrocement structure can be determined reliably through full shell models. This paper describes the modeling, analysis and design of residential structure system utilizing the ferrocement shell partly supported by conventional framing. The form of the structure is defined in such a way as to reduce out of plane bending components and most of the forces are carried through inplane stresses. The shell structures has several openings, stiffening ribs, and is analyzed for hurricane level wind forces as well as very high intensity earthquake to enable its construction as regular houses as well as shelters from adverse environmental forces.

Keywords: Ferrocement, Shell model, Stiffness ribs, Inplane stress.

1. INTRODUCTION

Ferrocement has been used for various purposes ranging from marine applications, agricultural applications, water and sanitation applications, industrial applications, rural energy applications, and as low cost housing [1]. Ferrocement is a highly versatile form of composite material made of cement mortar and layer of wire mesh closely bound together to create a stiff structural form. Ferrocement material exhibits a behavior different from conventional concrete in its performance and strength. Ferrocement is an excellent material for the use in house construction because of its lower cost, durability and weather resistance. The Intact Structures Inc., USA currently focuses on the ferrocement construction, such as housing projects and retaining walls [2].

The Intact Structures Inc. focuses on creating low cost mass ferrocement housing. The ferrocement degreed–ellipse residential housing discussed in this paper is one of such house design and constructed by Intact Structures Inc. The house has been modeled and analyzed under all applicable load combinations with appropriate support conditions. The analysis is based purely on the maximum design loads specified by codes.

2. OVERVIEW OF INTACT HOUSE

Two ferrocement degreed–ellipse houses were analyzed and designed: the first structure is a hybrid and second model is pure shell. The main difference between these two structures is that the hybrid structure has eight RC columns, while these columns had been removed in pure shell and some additional ribs has been added to connect the roof as shown in Figure 1 and Figure 2. The modified features are as follows: (i) removal of the reinforced concrete columns and the corresponding reinforced concrete beams connected to the respective columns, (ii) addition of a new hollow beam to connect the degreed–ellipse roofs, (iii) extension of the wall ribs attached to door up to the upper roof structure. The thickness of ferrocement components provided for both structures is 75mm (3”) for beam and main ribs and 50mm (2”) for rest of members. The RC column is of diameter 200 mm (8”) and beam of section 200mm x 200mm (8” x 8”). Both houses have maximum transverse and longitudinal dimensions of 6 m and 9 m, respectively. The maximum height of both houses is 4 m above ground level.

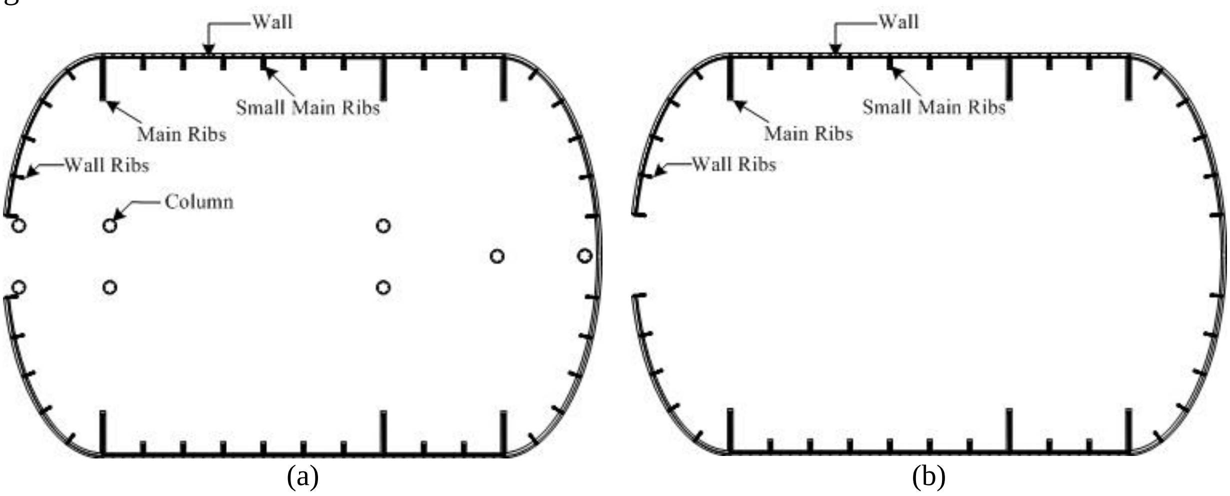


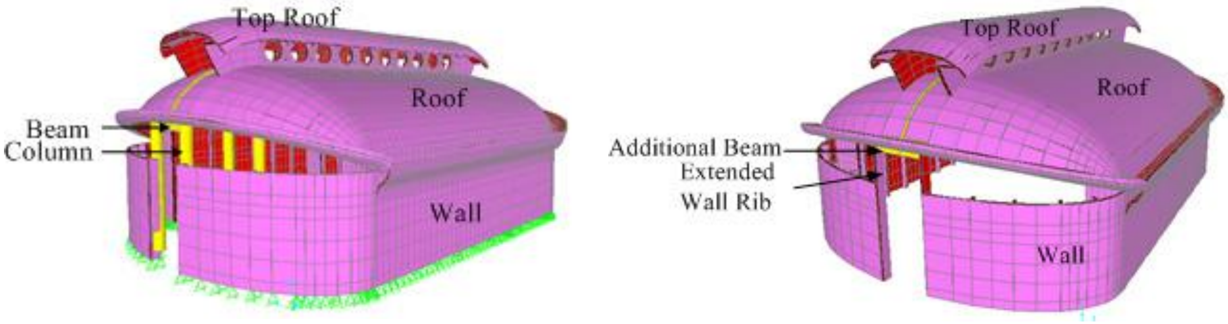
Figure 1: Plan view of Ferrocement Intact Structure (a) Hybrid (b) Pure Shell

3. FINITE ELEMENT MODELING

A full three-dimensional finite element (3D–FE) model of the structural system was created using SAP2000 [3]. Two models (hybrid structure and pure shell structure) were developed with varying levels of complexity. The model and its component terminology for both original and modified structures are shown in Figure 2. All models have been based on the gross cross-sectional dimensions of the members.

3.1 Modeling of Ferrocement Components

In both structures, most of the ferrocement components (top roof, main roof, beam, wall, and all ribs) were modeled as shell elements. Both the degreed–ellipse shape and the hole in every beam are modeled carefully so that the model represents the actual structures as closed as possible. The window opening in the front view is also of special consideration due to its dimensions.



(a) (b)

Figure 2: FE model of Ferrocement Intact Structure (a) Hybrid (b) Pure Shell

3.2 Modeling of Reinforced Concrete Members

The reinforced concrete (RC) members as RC beams and RC columns were modeled as frame element. The connections are modeled as fully rigid.

3.3 Modeling of Foundation

The foundation type used in the housing structures was slab on ground. The connections between the slab on ground and the RC column were modeled as hinge appropriately. This was also applied to the slab on ground–wall connections as well as the slab on ground–rib connections. The hinge supports were chosen since there was no moment transfer from the slab on ground to the soil.

4. ANALYSIS CASES AND LOAD APPLICATIONS

A complete linear, static analysis and response spectrum analysis was carried out for different load cases. The structure has been subjected to a number of static loads. This section describes the external loads applied to the structure and used in the analysis. Three load cases were used for the analysis and design which are: Dead load (D), Wind load (W), Earthquake load (QUAKE). Dead load was applied as self weight of the structure.

4.1 Wind Load

Wind load is automatically calculated by SAP2000 [3]. The effective area exposure was taken equal to the area exposure of wall objects. The wind coefficients (windward/leeward) to the walls have been applied using following parameters:

- Design Code: UBC97
- Wind Speed: 120 mile/hour (193 kmph)
- Importance Factor: 1.0
- Exposure Type: C
- Windward Coefficient: 0.8
- Leeward Coefficient: 0.5
- Effective Area: Area objects

4.2 Earthquake Load

Earthquake load is automatically calculated by SAP2000 [3]. The seismic coefficients were applied to both structures using following parameters:

- Design Code: IBC2003
- Site Class: D
- Response Accelerations: Ss = 1.5, S1 = 0.5
- Response Modification: R = 2

4.3 Load Combination

Total five load combinations had been considered in the analysis for ferrocement design for strength design according to IFS10-01 Model Code [4] as shown in Table 2. These load combinations are the expected load situations under various conditions.

Table 1: Load Combination

Notation	Load Combination
LC1	2 D
LC2	0.75 (2D + 1.7W)
LC3	0.9 D + 1.3 W
LC4	0.75 (2D + 1.7 EQ)
LC5	0.9 D + 1.4 EQ

5. MATERIAL SPECIFICATION

Two types of material were used in the structure. The first one is ferrocement (FERRO) and other is concrete (CONC). The ferrocement material has been used for top roof, main roof, beam, arc beam, wall, and rib. The modulus of elasticity for ferrocement material was calculated based on modulus of elasticity and volume fraction of matrix and reinforcement as shown in equation 1 [1].

$(E_c)_u = E_m \text{ x } V_m + E_r V_{rL}$ (1)

where,

$(E_c)_u$ = Modulus of elasticity of ferrocement composites

E_m = Modulus of elasticity of matrix = 3000 ksi = 20 GPa

E_r = Modulus of elasticity of reinforcement = 30,000 ksi = 200 GPa

V_m = Volume fraction of matrix

V_r = Volume fraction of reinforcement

Modulus of elasticity of composite $(E_c)_u = E_w \text{ x } V_m + E_r V_{rL}$ = 35,90000 psi = 24 GPa

5.1 Wire mesh details

Two types of wire mesh were used for two different thicknesses of members as shown in Figure 3. The wire mesh type 1 was used in entire wall, main roof, top roof, small main ribs, and wall ribs. The thickness of section is two inches with two layers of fine mesh, one coarse mesh and skeletal reinforcement. The detail of wire mesh type 1 is as descried below:

- Skeletal reinforcement of diameter 3/8”
- Coarse wire mesh of diameter 1/8” @ 6” x 6” spacing towards exterior wall
- Finer mesh of diameter 1/16” @ ½” x ½” spacing at outer face towards exterior wall
- Inside rolled wire of tight gauge expanded metal mesh

The wire mesh type 2 was used in big main rib and beams. The thickness of section is three inches with four layers of fine mesh, one coarse mesh and skeletal reinforcement. The detail of wire mesh type 2 is as descried below:

- Skeletal reinforcement of diameter 3/8”
- Coarse wire mesh of diameter 1/8” @ 6” x 6” spacing towards exterior wall
- Two layers of finer mesh of diameter 1/16” @ ½” x ½” spacing towards exterior wall
- Two layers of finer mesh of diameter 1/16” @ ½” x ½” towards interior wall

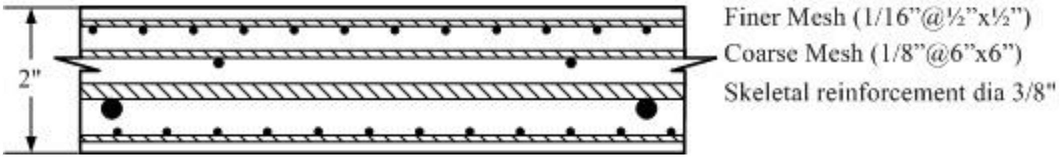


Figure 3a: Wire mesh Type 1

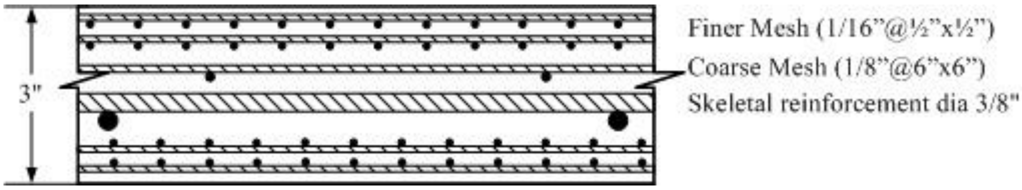


Figure 3b: Wire mesh Type 2

6. RESULTS AND DISCUSSIONS

The tensile and bending design checks were performed in detail for each component for both structures. The time period and maximum deformation in both structures is as below:

	Time Period (t), sec	Maximum Deformation (mm) U1	U2	U3
Hybrid Structure	0.0634	0.38	0.17	1.17
Pure Shell Structure	0.0646	1.02	1.68	1.166

6.1 Demand to Capacity Ratio

Demand to capacity ratio is an index that gives an overall relationship between effects of load and ability of the member to resist those effects. The tension and bending capacity ratio was checked for every member. From results showed that all the components were within margin of safety for extreme loading conditions. In original structure, some of the elements in big ribs, wall ribs and beam exceeds D/C ratio of 1.0 for tensile capacity and bending capacity. Similarly in modified structure, some of the elements in main ribs, wall ribs and main roof exceeds D/C ratio of 1.0 for tensile capacity and bending capacity respectively.

6.1.1 Tension Capacity

The tensile loads leading to first cracking in the matrix occurs when the stress in the matrix reaches its ultimate strength ($\sigma_m = \sigma_{mu}$) [1] and is given by equation 2.

$N_{cr} = \sigma_{mu} (A_m + nA_r)$ (Equation 2)

$= 350 (27.52) = 9632$ lbs = 43 KN

Similarly, the yielding and ultimate failure of the reinforcement along the cracked section are given by,

$N_y = \sigma_{ry} A_r = 60{,}000 \times (0.391) = 23460$ lbs = 104 KN

$N_u = \sigma_{ru} A_r = 80{,}000 \times (0.391) = 31280$ lbs = 139 KN

The tension capacity of every component was checked for both original and modified structure for each load combination. In original structure the tension force in every component was found to be much below the critical tensile capacity of the section except for some elements of main ribs and beams as shown in Table 2 and 3. The maximum force develop in main ribs is 144 KN. The most critical location of big ribs for the most extreme loading condition is shown in Figure 4.

Table 2: Tensile capacity ratio range (for X-X direction) for hybrid structure

Capacity Ratio	**Wall**	**Main Ribs**	**Small Ribs**	**Wall Ribs**	**Main Roof**	**Top Roof**	**Beams**
Ratio < 0.50	994	462	256	140	1587	920	652
0.50 < Ratio < 0.75	0	12	0	0	17	0	33
0.75 < Ratio < 0.90	0	0	0	0	0	0	3
0.90 < Ratio < 1.00	0	0	0	0	0	0	0
1.00 < Ratio	0	**6**	0	0	0	0	0
Total Number of Elements	994	480	256	140	1604	920	688

Table 3: Tensile capacity ratio range (for Y-Y direction) for hybrid structure

Capacity Ratio	**Wall**	**Main Ribs**	**Small Ribs**	**Wall Ribs**	**Main Roof**	**Top Roof**	**Beams**
Ratio < 0.50	968	378	230	136	1604	920	649
0.50 < Ratio < 0.75	26	57	26	4	0	0	33
0.75 < Ratio < 0.90	0	15	0	0	0	0	3
0.90 < Ratio < 1.00	0	24	0	0	0	0	1
1.00 < Ratio	0	**6**	0	0	0	0	**2**
Total Number of Elements	994	480	256	140	1604	920	688

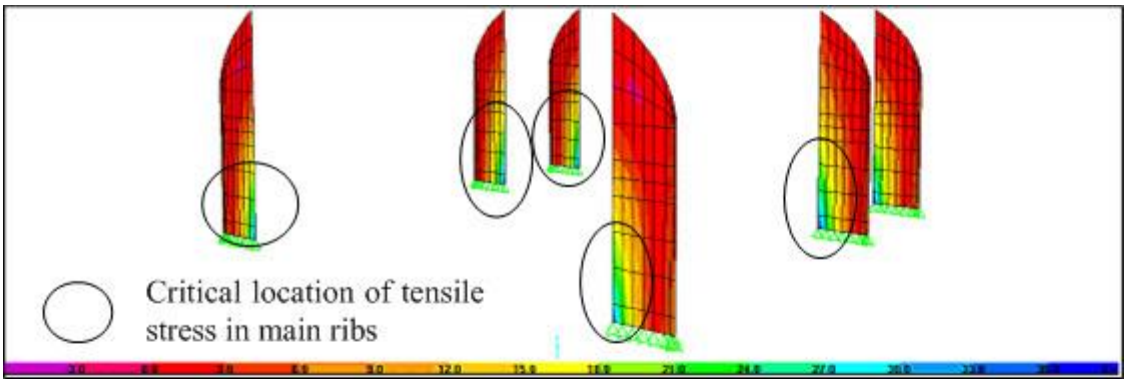


Figure 4: Location of critical tensile force in Y-Y direction in big main ribs in hybrid structure (for load combination LC5)

Similarly, in modified structure the tension force in every component of was also below the critical tensile capacity of the section except for some elements of main ribs, roof and wall ribs as shown in Table 4 and 5. The maximum forces develop in main ribs and a wall rib is 149 KN. The location of critical member in the most extreme loading condition is shown in Figure 5.

Table 4: Tensile capacity ratio range (for X-X direction) for pure shell structure

Capacity Ratio	Wall	Main Ribs	Small Ribs	Wall Ribs	Main Roof	Top Roof	Roof Beam	Beams
Ratio < 0.50	944	450	256	144	1534	917	400	657
0.50 < Ratio < 0.75	0	20	0	4	58	3	0	29
0.75 < Ratio < 0.90	0	6	0	0	16	0	0	2
0.90 < Ratio < 1.00	0	0	0	0	3	0	0	0
1.00 < Ratio	0	**4**	0	0	**1**	0	0	0
Total Number of Elements	944	480	256	148	1612	920	400	688

Table 5: Tensile capacity ratio range (for Y-Y direction) for pure shell structure

Capacity Ratio	Wall	Main Ribs	Small Ribs	Wall Ribs	Main Roof	Top Roof	Roof Beam	Beams
Ratio < 0.50	915	303	236	120	1599	920	400	658
0.50 < Ratio < 0.75	67	166	20	24	24	0	0	26
0.75 < Ratio < 0.90	4	5	0	0	0	0	0	4
0.90 < Ratio < 1.00	8	2	0	2	2	0	0	0
1.00 < Ratio	0	**4**	0	**2**	**2**	0	0	0
Total Number of Elements	994	480	256	148	1612	920	400	688

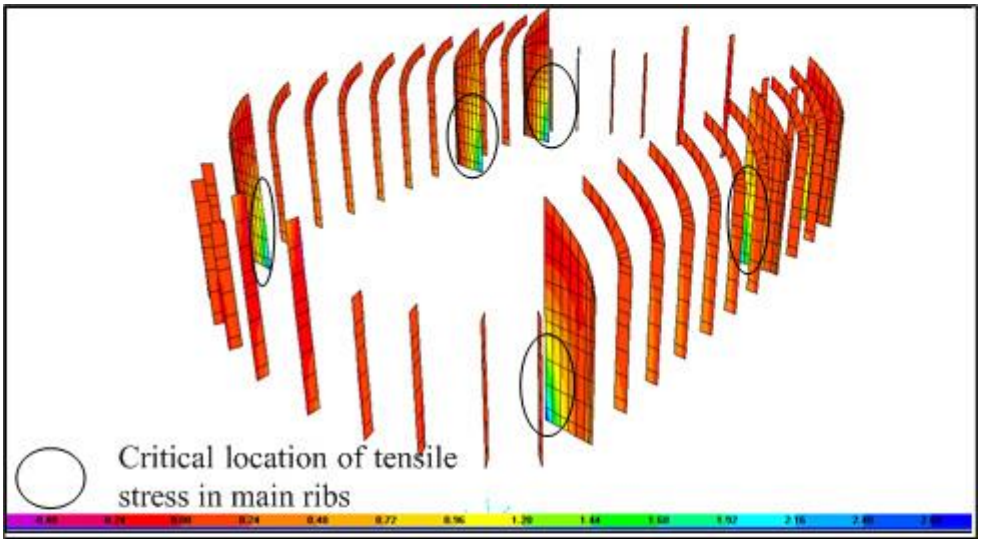


Figure 5: Location of critical tensile force in Y-Y direction in big main ribs in pure shell structure (for load combination LC5)

6.1.2 Bending Capacity

The bending moment of every component was checked for both original and modified structure. In original structure the bending moment in every component was much below the critical bending capacity of the section except for some elements of wall ribs. The maximum moment develop in wall ribs 7600 N-m and in beam is 12300 N-m. The location of critical elements in the most extreme loading condition is shown in Figure 6.

Table 6: Bending capacity ratio range (for X-X direction) for hybrid structure

Capacity Ratio	**Wall**	**Main Ribs**	**Small Ribs**	**Wall Ribs**	**Main Roof**	**Top Roof**	**Beams**
Ratio < 0.50	988	480	256	138	1600	920	680
0.50 < Ratio < 0.75	6	0	0	0	4	0	8
0.75 < Ratio < 0.90	0	0	0	0	0	0	0
0.90 < Ratio < 1.00	0	0	0	0	0	0	0
1.00 < Ratio	0	0	0	**2**	0	0	0
Total Number of Elements formed	994	480	256	140	1604	920	680

Table 7: Bending capacity ratio range (for Y-Y direction) for hybrid structure

Capacity Ratio	**Wall**	**Main Ribs**	**Small Ribs**	**Wall Ribs**	**Main Roof**	**Top Roof**	**Beams**
Ratio < 0.50	994	480	256	140	1600	920	668
0.50 < Ratio < 0.75	0	0	0	0	4	0	4
0.75 < Ratio < 0.90	0	0	0	0	0	0	2
0.90 < Ratio < 1.00	0	0	0	0	0	0	6
1.00 < Ratio	0	0	0	0	0	0	**8**
Total Number of Elements	994	480	256	140	1604	920	688

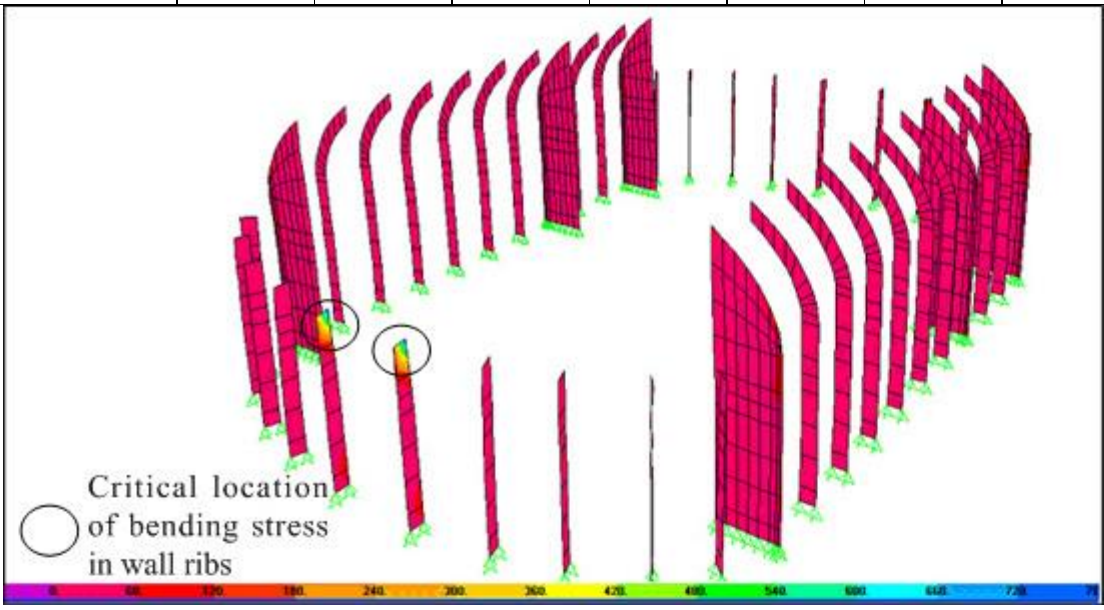


Figure 6: Location of critical bending element along X-X direction in wall ribs in hybrid structure (for load combination LC5)

Similarly in modifies structure the bending moment in every component was much below the critical bending capacity of the section except for some elements of wall ribs. The maximum moment develop in wall ribs 5065 N-m. The location of critical elements in the most extreme loading condition is shown in Figure 7.

Table 8: Bending capacity ratio range (for X-X direction) for pure shell structure

Capacity Ratio	**Wall**	**Main Ribs**	**Small Ribs**	**Wall Ribs**	**Main Roof**	**Top Roof**	**Roof Beam**	**Beams**
Ratio < 0.50	986	480	256	148	1588	920	400	688
0.50 < Ratio < 0.75	4	0	0	0	24	0	0	0
0.75 < Ratio < 0.90	0	0	0	0	0	0	0	0
0.90 < Ratio < 1.00	4	0	0	0	0	0	0	0
1.00 < Ratio	0	0	0	0	0	0	0	0
Total Number of Elements	994	480	256	148	1612	920	400	688

Table 9: Bending capacity ratio range (for Y-Y direction) for pure shell structure

Capacity Ratio	**Wall**	**Main Ribs**	**Small Ribs**	**Wall Ribs**	**Main Roof**	**Top Roof**	**Roof Beams**	**Beams**
Ratio < 0.50	994	480	256	126	1606	920	420	688
0.50 < Ratio < 0.75	0	0	0	10	6	0	0	0
0.75 < Ratio < 0.90	0	0	0	5	0	0	0	0
0.90 < Ratio < 1.00	0	0	0	3	0	0	0	0
1.00 < Ratio	0	0	0	**4**	0	0	0	0
Total Number of Elements	994	480	256	148	1612	920	400	688

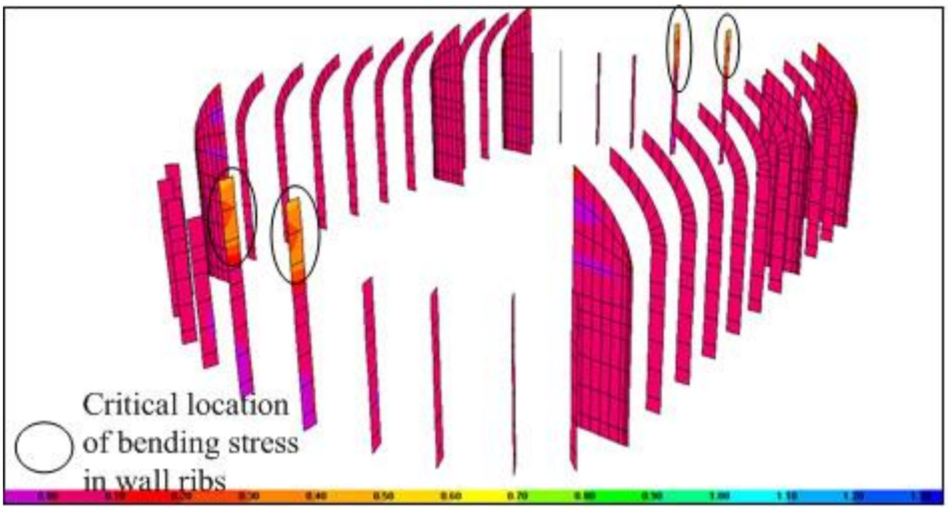


Figure 7: Location of critical bending element along Y-Y direction in wall ribs in pure shell structure (for load combination LC5)

6.2 Material Quantity

Cost is one of the most important factors in a civil engineering project. However, it is specific to geographic location, time, and other constraints. Thus, it is difficult to wisely judge whether a building system is more or less economic than another. It is more useful to estimate the quantity of materials rather than the final cost under particular circumstances.

The original ferrocement house consists of about 9.2 m^3 of ferrocement and 0.852 m^3 of concrete, respectively. On the other hand, the modified ferrocement house will consist of about 9.5 m^3 of ferrocement and 0.075 m^3 of concrete, respectively. Hence the pure shell structure is more economic as the concrete used is only 9% of hybrid structure.

7. DISCUSSION

The full 3D finite element model for both original and modified structures were created and the computed results were analyzed to check design safety and stability condition for every component. The analysis results shows that the proposed wire mesh has sufficient tensile and bending capacity against worst loading condition for both wind load case and earthquake load case. The D/C ratios of most of elements in each component are less than 0.5. However, there is some stress concentration in some elements of big main ribs, wall ribs, beams and main roof for load combination LC5. The stress concentration is mostly near connections and corners, which can be minimize by careful detailing at every connections and joints.

Some member has D/C ratio of one or slightly higher however it does not mean the failure of a member. D/C ratio more than 1 means that the design capacity of the member has been fully utilized at the factored load. The mesh should be increased in locations to keep D/C ratio<1. Since the D/C ratio of these elements were found to be less than 1.5 and such extreme loading condition is very rare to occur, we can say that the proposed ferrocement design is adequate to withstand most worst loading condition if supplemented by careful detailing at joints and connections.

8. CONCLUSION

Ferrocement is an excellent material for house construction due to its relatively low cost, durability and weather resistance. Both the hybrid and pure shell structure as discusses in this paper can withstand extreme loading conditions. The forces develop in the component in both structure is nearly same however the construction cost of pure shell structure is less than hybrid structure due to less requirement of concrete. Hence pure shell structure is more economic and preferable than hybrid structure.

REFERENCES

[1] Naaman, A. E., Ferrocement and Laminated Cementitious Composites, Techno Press, USA (2000)
[2] www.intactstructures.com
[3] Computers and Structures, Inc., CSI Analysis Reference Manual for SAP2000, ETABS, SAFE, Berkley, California, USA (October 2005)
[4] International Ferrocement Society, Ferrocement Model Code-Building Code Recommendations for Ferrocement (IFS 10-01), Asian Institute of Technology, IFIC, Thailand (January 2001).