

Finite Element Analysis and Experimental Study on Seismic Performance of Ferrocement-Composite Shell in a Full-Scale Building

Robabeh Jazaei*, Robabeh Jazaei^a, Manuchehr Behruiyan^b Samad Gharehdaghi^c

Fatemeh Azari^d

*University of Nevada, Las Vegas
1480 Lorilyn Ave, Las Vegas, NV, 89119
Robabeh.jazaei@unlv.edu

^a Civil Engineering Department, University of Nevada, Las Vegas

^b Civil Engineering Department, Azad University, Tehran, Iran

^{c,d} Mechanical Engineering Department, University of Nevada, Las Vegas

Abstract

Design of reinforced-concrete shell is most challenging for structures in seismic zones. Ferrocement-masonry buildings require seismic evaluation. However, a seismic code has not yet developed for ferrocement building. The complexity of structures' geometry substantially contributes to structural performance when an earthquake occurs [1]; the more complex the geometry is, the more likely building elements are to not move together. Ferrocement composite in low-rise buildings is a cost-effective solution in developing countries because it requires minimal skilled labor. Woven square mesh reinforcement decreases crack propagation and ferrocement enhances homogeneity of the concrete matrices [3]. Additionally, ferrocement is used for rehabilitation of existing reinforced-concrete (RC) structures. Some studies result indicated ferrocement higher in-plain shear and moment capacity compared to fiber reinforced polymer (FRP) [2]. In this research, the behavior of ferrocement masonry building incorporating steel-fiber reinforcement was assessed under dynamic load. Steel fiber and ferrocement increased stress capacity and reduced shrinkage, crack propagation, early fatigue mechanism, and failure under cyclic load.

The main objective of this research is to simulate ferrocement shell in a high seismic zone and assess it with finite-element method (FEM). Structural damage zones, failure mechanism under static and seismic loads were designed by Sap 2000 software (Version 11.07). Numerical FEM analysis was based on fabricating steel-square meshes and ferrocement matrices as homogenized and isotropic laminates. The experimental result of this research in a full-scale building indicated 70% reduction in construction costs compared to conventional masonry building.

Keywords: Ferrocement; Seismic behavior; Finite element method; Masonry; Building; Shear wall; Cyclic loading; FRP; Design, concrete

1. Introduction

Ferrocement composite materials include cement, fly ash, sand, wire mesh, skeletal steel [4, 20-22, 24]. Steel bar is considered a costly material for reinforcing concrete. Additionally, crack propagation along rebar is a crucial issue [6-7, 9]. However, ferrocement provides less expensive composite, reduces the number of rebars, develop fewer cracks on and within the concrete due to wire mesh and steel fibers [14, 8, 24, 26]. Ferrocement research begun by Lambot and offered a various residential and commercial applications for reinforced concrete in 1850. However, in almost hundred years, ferrocement research had little improvement until Nervi introduced thin-wall by using ferrocement in 1940 [11]. Ferrocement

became popular because it was not only a cost-effective solution, but also provides better physical and mechanical properties for thin-wall, boat, and prefabricate-building panel [30-32]. In 1988, American Concrete Institute (ACI) Committee 549 report, “State-of-the-Art Report on Fiber Reinforced Concrete”, developed physical and mechanical, performance, applications, and research for ferrocement structures [13]. In 1989, ACI Committee provided a manual for ferrocement rehabilitation of existing constructions [23]. There is no standard developed for ferrocement buildings, but researchers modified ACI code and suggested ferrocement for low-rise building and limited its application to a two-story residential building [17].

2. Schematic View of Experimental Full-Scale Building

An experimental full-scale building designed and constructed on the campus of Azad University, Damghan campus (Figure 1). This building designed for students’ coffee shop with 150 square meters (1614 ft²). The building architectural perspective is shown in figure 1. Reinforced concrete design in hazardous seismic zone is more challenging in complex and modern architectural forms. However, ferrocement offers various designed-shape in reinforced concrete structure and allows architectural imagination happens.



Figure 1. Architectural plan and perspective view of the designed building, Azad University, Damghan campus

3. Numerical analysis

One story building with a circular-thin-wall shell designed in compliance with Iran Building Code of Practice for Seismic Resistential Design of Building, Standard No. 2800, 3rd edition [26]. However, the load transfer mechanism from top roof to the foundation in such a structure is different than conventional reinforced concrete (RC) structures [12], [15], and [19].

As roof slab is braced with the consistent connection of continues rebars, it is considered confined structure under gravity and lateral load [10], and [29].

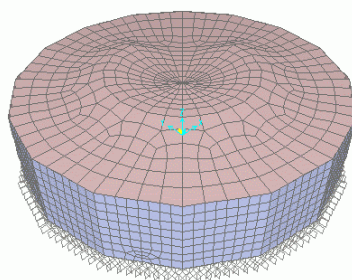


Figure 2. Ferrocement Shell model

The ferrocement system allows the thin wall and roof slab provide a mechanism to resist lateral load effectively and limits the lateral deformations of structure [27]. In this research, it was assumed the ferrocement lamina are completely bonded and the roof slope equals or greater than 20 % in finite element method (FEM) analysis. Live load does not require extra coefficient. The base acceleration ratio is varying in the different part of Iran. This building is located in a very high level of relative seismic hazardous, so the base acceleration assumed 0.35 /g. P-Delta effects of the structure due to applied loads and other imposed displacement calculated [26].

Building response (B) to ground motion in the earthquake was calculated 0.14 and is shown in the graph 1. The circular-ferrocement structure simulated as an ordinary-reinforced-concrete-shear walls in a hazardous seismic zone.



Graph 1. Building response verses fundamental structure period of vibration in ferrocement reinforced concrete shear wall

Average Shear wave velocity in each layer of soil (d_i) soil thickness and V_{si} shear wave velocity in each soil layer calculated from equation 1.

$$V_s = \frac{\sum d_i}{\sum \frac{d_i}{V_{si}}} \quad (1)$$

Shear wave velocity in soil with medium compaction, layer of sand and gravel with the medium intragranular bond; and clay with intermediate compaction is $175 < V_s < 375$. Building behavior factor (R) indicates the type of lateral-force resistance. In this design, the building behavior factor was 6 for intermediate reinforced concrete shear walls [26]. Occupancy category is III based on Iran seismic Code because students congregate in one area. Therefore, the important factor (I) which is related to occupancy category is considered one for this type of structure [26]

3.1. Governing Equation in Ferrocement Anisotropic Laminated shell

Numerical FEM analysis was based on fabricating steel mech square and ferrocement as homogenized and isotropic laminates (Figure 3). In accordance with lamination theory for thin Shell, it was assumed the displacement field of each layer was equal. However, the thickness is varies due to nonuniformly ferrocement material properties [5], [16].

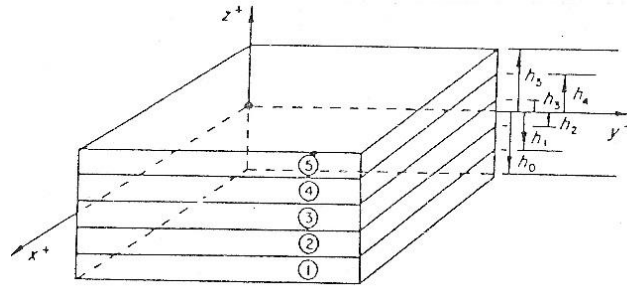


Figure 3. Schematic each ply of laminate [28]

Stress and moment resultant can be defined as following equation (2) and (3):

$$(N_x, N_y, N_{xy})^n = \int_{-h/2}^{h/2} (\sigma_x^{(k)}, \sigma_y^{(k)}, \sigma_{xy}^{(k)}) dz \quad (2)$$

$$(M_x, M_y, M_{zxy})^n = \int_{-h/2}^{h/2} (\sigma_x^{(k)}, \sigma_y^{(k)}, \sigma_{xy}^{(k)}) z dz \quad (3)$$

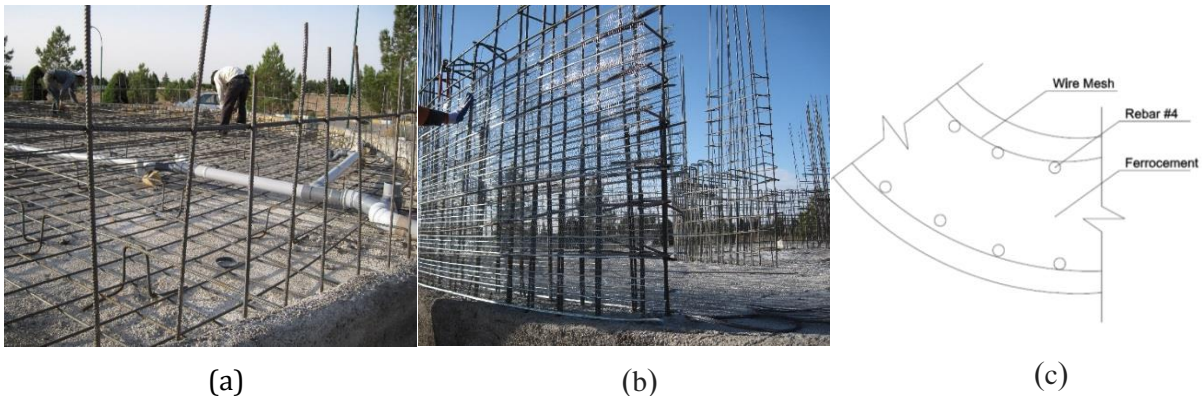


Figure 4. Experimental full-scale ferrocement building (a) skeleton rebar implement (b) fabricating wire mesh on thin wall (c) schematic detail of thin ferrocement wall

4. Results and conclusion

Steel Fiber Reinforced High-Strength Concrete behavior under dynamic load and fatigue was assessed. Steel fiber and ferrocement increased stress capacity and reduce shrinkage, crack propagation, early fatigue mechanism, and failure under cyclic load (Figure 5-7).

Concrete precast and molds expenses for concrete shells are an obstacle. However, fabricating wire mesh on thin wall is a cost-effective strategie to address this challenge and provide flexible and complex shape. In this experiment, the full-scale ferrocement building cost reduced by 70% compared to conventional masonry building because related expenses for casting and molding was deducted as steel-square meshes were replaced to conventional precast products for complex architectural thin shell. Shotcrete method provided a finished surface.

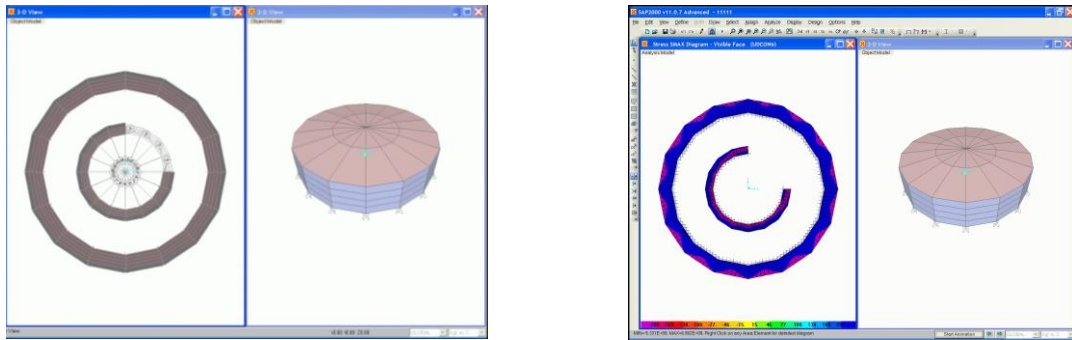


Figure 5. Finite element model of ferrocement-reinforced-concrete shell structure.

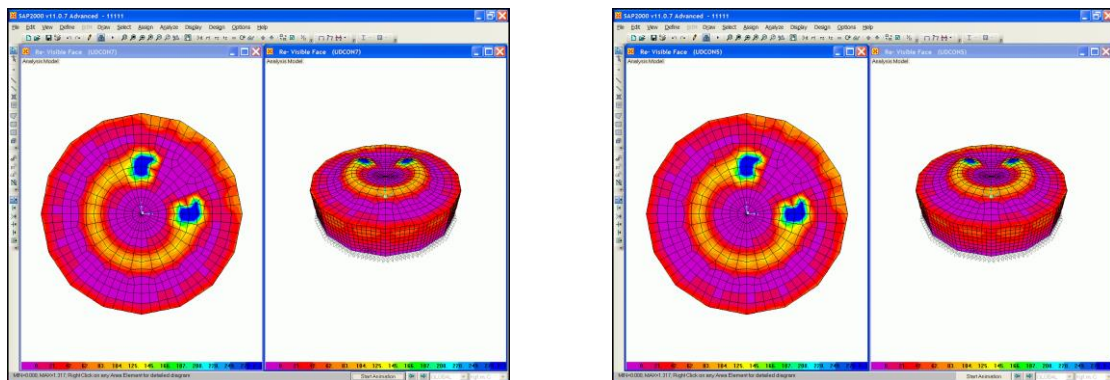


Figure 6. Geometry of the structure, finite element mesh and failure location at ultimate load in numerical simulation.

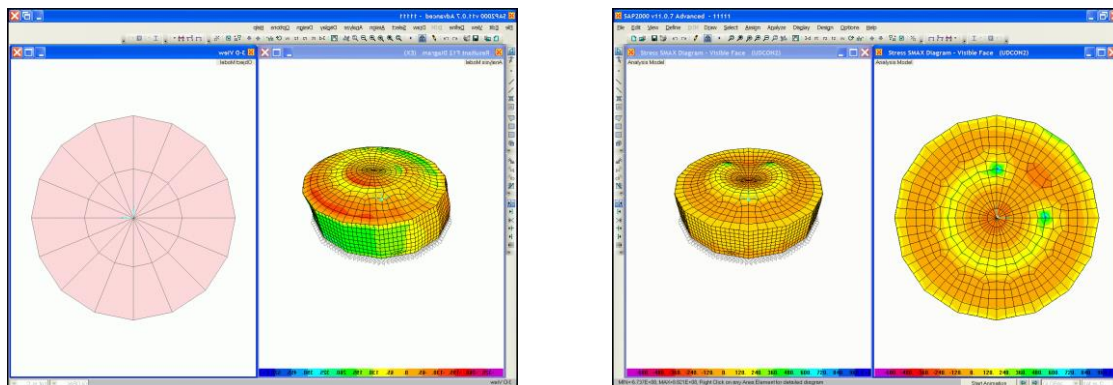


Figure 7. Displacement of ferrocement-reinforced-concrete shell structure a) horizontal displacement b) vertical displacement.

Acknowledgements

Authors are thankful to the faculty and staff of the Department of Civil Engineering at Azad University, Central Tehran Branch, especially Professor Shahriar Tavousi; The presidents of the Azad University, Damghan campus, Dr. Mosaieb Abbaci, and Dr. Mohammad Bigdeli to motivate, support, and fund this Project; Rohollah Khalilnejad the architecture designer of this project, and my colleagues at the Technical Design Office of Azad University, Damghan campus, Dr. Mohammadreza Hashemi.

References

- [1] Mackerle, J. (1999). "Finite-element analysis and simulation of machining": A bibliography (1976–1996) doi:[https://doi-org.ezproxy.library.unlv.edu/10.1016/S0924-0136\(98\)00227-1](https://doi-org.ezproxy.library.unlv.edu/10.1016/S0924-0136(98)00227-1)

- [2] Kaish, A. B. M. A., Jamil, M., Raman, S. N., Zain, M. F. M., & Nahar, L. (2018). "Ferrocement composites for strengthening of concrete columns: A review." *Construction and Building Materials*, 160, 326-340. doi:<https://doi-org.ezproxy.library.unlv.edu/10.1016/j.conbuildmat.2017.11.054>
- [3] Sasmal, S., & Nath, D. (2017). Seismic performance of non-invasive single brace made of steel and shape memory alloy for retrofit of gravity load designed sub-assemblages doi:<https://doi-org.ezproxy.library.unlv.edu/10.1016/j.engstruct.2017.04.024>
- [4]. Bellido de Luna, J.A. "Admixtures for ferrocement construction in Cuba." *Journal of ferrocement*, vol.21, No .1, pp.15-23 .1991
<https://doi.org/10.1007/BF00045647> .”431 :Nonlinear Dyn (1992) 3“ .A.H ,Nayfeh & .P.F ,Pai [5]
- [6] Alexander, S., "Cracks in Concrete-Which Ones Matter?" *Concrete*, Oct.1986, pp.33.
- [7] ACI Committee 224, "Control of Cracking in Concrete Structures", *ACI Journal ,Proceedings* V.69,No.12,Dec.1972,pp.717-753
- [8] Chowdhury, S.M. M.I., and Nimityongskul, P., "Some Aspects on Corrosion of Galvanized wire mesh in ferrocement Under Simulated Adverse Environments", *Proc. Second Int. Symp. on ferrocement Bangkok, Jan1985*, pp687-700.
- [9]. Chen, X.B and Zhao, G.F., "The Calculation of Crack Width in ferrocement Under Axial Tension", *Proc, 3rd Int. Symposium on ferrocement, Roorkee,1988*, pp12-20.
- [10] Sun Wei,Gao Jianming, "Flexural and fatigue of steel fiber reinforced concrete for use in pavement", *Journal of the Southeast University*,Vol.88,No.1,pp41-48.1991.
- [11] P.J. Nedwell and R.N. Swamy, *Ferrocement*, 1994 pama,R.P ,”Research on ferrocement – global of ferrocement” ,vol.20,No.4,pp.385-410,1990
- [12] Kaboyashi, Y.; Tanaka. Y, and Ono, M. “flexural impact damage of ferrocement.” Vol.22, No.3, pp249-263,1992
- [13] ACI Committee 549, “State-of-the-Art Report on Ferrocement.” Reported by ACI Committee 549, 1988
- [14] Walraven, J.C and Spiernbuge, S.E.J "Behavior of ferrocement with chicken wire mesh reinforcement ", *Journal of ferrocement*, Vol.15, No.1, January 1985, pp.1-15
- [15] Clarke, R.P., Sharma,A.K. “The Experimental Behavior of Ferrocement Flat Plate Under Biaxial Flexure.” *Journal of ferrocement*, Vol.21, No.2, pp.127-136
- [16]. Ashton,J.E. Whitney,J.M. “Theory of Laminated Plates, Westport Connecticut” : Thehnicic Publishing Co.1970.
- [17]. Bhandari, N.M., Trikha, D.N, and Syam Prakash,V. “study of a two-story precast ferrocement model building” . *Journal of ferrocement*.22 (1):49-59.1992
- [19]. Byung Hwan Oh, “Cumulative damage theory of concrete under variable-amplitude fatigue loadings”, *Materials Journal*, Vol.88, No.1, pp41-48.1991
- [20] Sun Wei, Yan Yun, “Mechanical behavior and interfacial performance of steel fiber reinforced silica fume high strength concrete”, *Dcience in China (Series A)* Vol.35, No.5, pp 607-617.1992.
- [21] Swamy, R.N., and Hussin, M.W., “Flexural behavior of thin fiber reinforced and ferrocement sheet, Thin-Section Fiber Reinforced Concrete and Ferrocement”, *ACI Publ.SP-124*,1990.
- [22] Swamy, R.N. and Falhih, F.M., “Development of a small aggregate concrete for structural similitude of slab-column connections, *Design of Concrete Structures: The Use of Model Analysis*”, Elsevier Applied Science Publishers, 1985

- [23] ACI Committee 549, "Guide for Design, Construction and Repair of Ferrocement ACI 549 IR-881989, 1989"
- [24] M.A. Al-Kubaisy, M.Z. Jumaat, "Flexural behavior of reinforced concrete slabs with ferrocement tension zone cover", *J. Construct. Build. Mater.*, 14 (2000), pp. 245-252
- [25] Chithambaram, S. J., & Kumar, S. (2017). "Flexural behavior of bamboo based ferrocement slab panels with flyash" doi:<https://doi-org.ezproxy.library.unlv.edu/10.1016/j.conbuildmat.2016.12.205>
- [26] Shaaban, I. G., & Seoud, O. A. (2018). "Experimental behavior of full-scale exterior beam-column space joints retrofitted by ferrocement layers under cyclic loading" doi:<https://doi-org.ezproxy.library.unlv.edu/10.1016/j.cscm.2017.11.002>
- [26] IRANIAN CODE OF PRACTICE FOR SEISMIC RESISTANT DESIGN OF BUILDINGS (Standard No. 2800) 3rd Edition
http://iisee.kenken.go.jp/worldlist/26_Iran/Iran%20National%20Seismic%20Code_2007_3rd%20Version_English.pdf
- [27] El-Diasity, M., Okail, H., Kamal, O., & Said, M. (2015). "Structural performance of confined masonry walls retrofitted using ferrocement and GFRP under in-plane cyclic loading" doi:<https://doi-org.ezproxy.library.unlv.edu/10.1016/j.engstruct.2015.03.035>
<https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19950009349.pdf> [28]
- [29]. Balaguru, P.N., Naaman, A.E. and Shah, S.P., "Fatigue Behavior and Design of ferrocement Beams", *Journal of Structural Division, ASCE*, 105(ST7), 1979, PP.1333-1345.
- [30] Ip, M.F.L., "Fatigue of ferrocement in a Corrosive Environment", Ph.D. thesis, University of Leeds, 1989.
- [31] Ahmad, S.H. and Shah, S.P. (1982a) "Stress-Strain of concrete confined by spiral reinforcement" *Journal of ACI*, 9(6), 484-490
- [32] Balagure, P.N. "Use of ferrocement for confinement of concrete." *Proc. 3rd Int. Symp. on ferrocement*, New Dehli, India, 52-58. 1988.

Design of reinforced-concrete shell is most challenging for structures in seismic zones. Ferrocement-masonry buildings require seismic evaluation. However, a seismic code has not yet developed for ferrocement building. In this research, the behavior of ferrocement masonry building incorporating steel-fiber reinforcement was assessed in a high seismic zone. Steel fiber and ferrocement increased stress capacity and reduced shrinkage, crack propagation, early fatigue mechanism, and failure under cyclic load. Numerical FEM analysis was based on fabricating steel-square meshes and ferrocement matrices as homogenized and isotropic laminates. The experimental result of this research in a full-scale building indicated 70% % reduction in construction costs compared to conventional masonry buildin