IASS 2018 BOSTON, JULY 16-20
CREATIVITY IN STRUCTURAL DESIGN

Proceedings of the IASS Symposium 2018
Creativity in Structural Design
July 16-20, 2018, MIT, Boston, USA
Caitlin Mueller, Sigrid Adriaenssens (eds.)

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

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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 Inistitute (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 ft^2). The building architectural perspective is shown in figure1. Reinforced concrete design inhazardous 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 Resistantial 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].

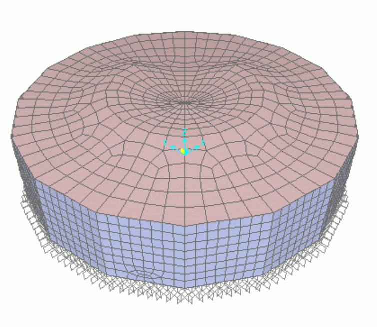
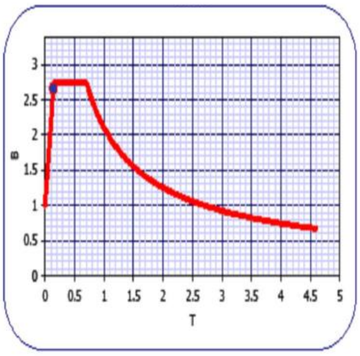


Figure 2. Ferrocement Shell model

The ferrocement system allows the thin wall and roof slab provide a mechanism to resists 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.

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

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 hemogenized and isotropic laminates (Figure 3). In accordance with lamination theory for thin Shell, it was assumed the displacementfield of each layer was equal. However, the thickness is varies due to nonuniformly ferrocement materil properties [5], [16].

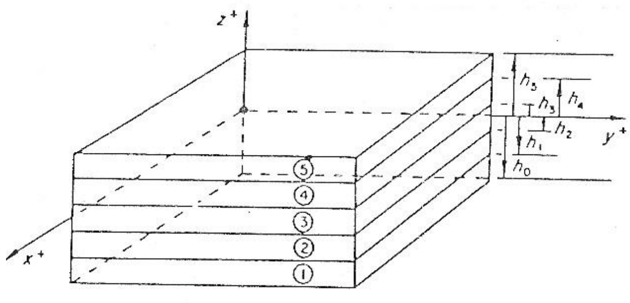


Figure 3. Schematic each ply of laminate [28]

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

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

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

(a) (b) (c)

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.

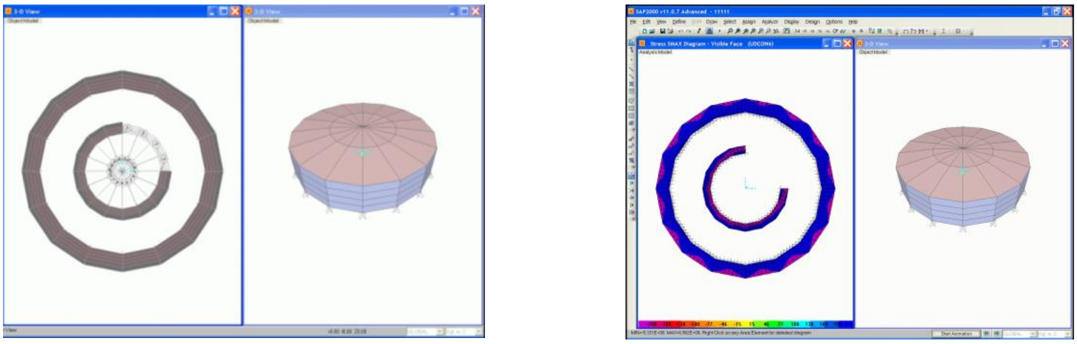


Figure 5. Finite element model of ferrocement-reinforced-concrete shell structure.

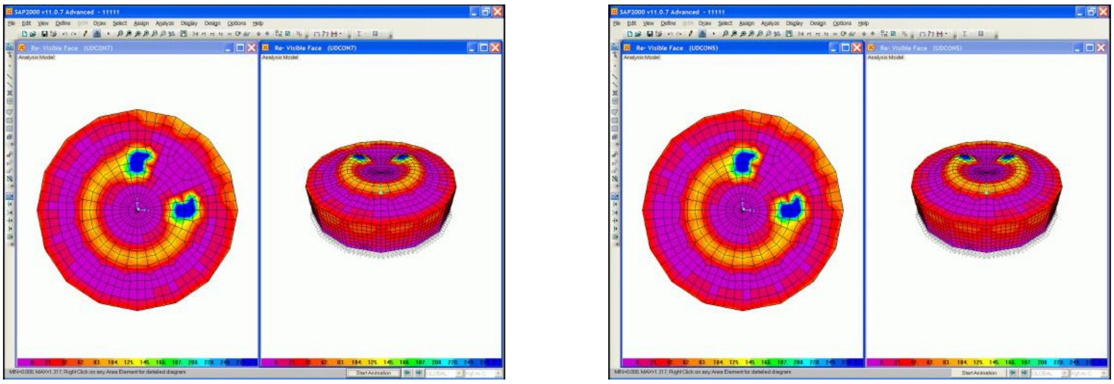


Figure 6. Geometry of the structure, finite element mesh and failure location at ultimate load in numerical simulation.

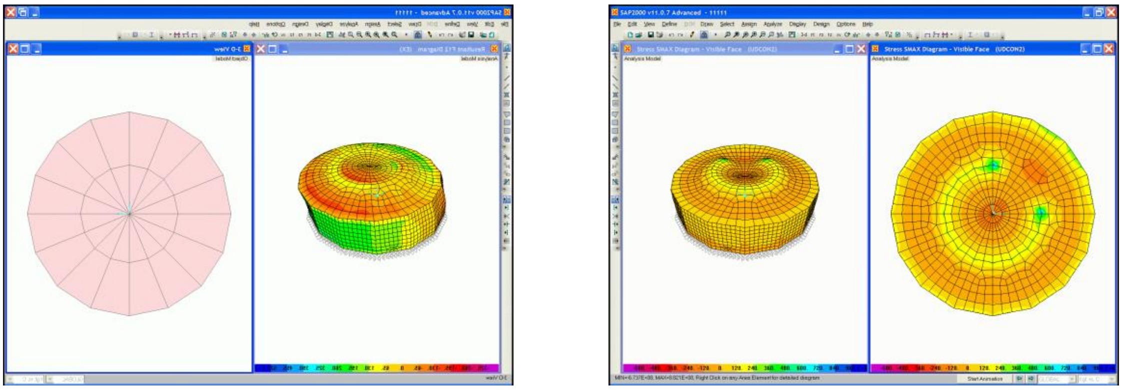


Figure 7. Displacement of ferrocement-reinforced-concrete shell structure a) horizontal displacement b) vertical displacement.

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.

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