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Investigation of ferrocement channels using experimental and finite element analysis

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ABSTRACT

It is necessary to design and calculate tensile reinforcement for ferrocement channels with various spans used in different structures such as rural houses and mosques. However, such analysis is challenging due to the application of different types of wire meshes, dissimilar tensile and compressive reinforcement, and mechanical properties of the mortar. The present study provided an experimental sample to assess deflection in a standard ferrocement channel (span: 4.5 m; width: 70 cm). The Abaqus Unified finite element analysis (FEA) has been also used to model the ferrocement channel by various system supports and beam spans. The obtained results indicated the acceptable accuracy of FE simulations in the estimation of experimental values. Such models can thus be used as quick, simple, and inexpensive methods to calculate the optimal deflection of ferrocement channels for various spans and sizes of tensile reinforcement.

1. Introduction

Ferrocement, also called reinforced concrete, is obtained by mixing cement with sand mortar and applying the mixture over some layers of woven [1] or welded [2] steel mesh with small-diameter holes [3]. It is widely used in shipbuilding [4–7], water and food storage tanks [8,9], water transport tubing [10], silos [11], roofs [12–15], urban and rural houses [16], and structure repair [17–19]. Ferrocement is especially popular because its raw materials are available, it is easy to prepare and shape, and it is fire resistant [20,21]. It is also known to promote the seismic resistance of masonry structures [22]. Research has indicated the use of additives such as fibers [23–25], silica [26–28], fly ash [29], and resin [30] to increase the strength of mortar in ferrocement. Other experimental studies have also suggested the applicability of polymer fibers instead of meshes in ferrocement. Moreover, ferrocement slabs are used as secondary roof structures to insulate against heat [31], in the manufacture of beams [32–36], and in building components such as doors [37] and drywalls [38]. The mechanical behavior of ferrocement elements such as beams, slabs, and columns has been examined under applied loads up to failure by experimental models such as Hago et al. [12] and Ibrahim [39] who studied experimentally the ultimate capacity of simply supported slab panels and ferrocement slabs.

Although the need for experimental research to provide the basis for design equations continues but by applying the FEM, can reduce the time and cost of otherwise expensive experimental tests, and may better simulate the loading and support conditions of the actual structure. So to this end the FEM is used by Nassif and Najm [40] to investigate the behavior of ferrocement composite beams under a two-point loading system. They used a smeared crack model, which can be applied the constitutive equations independently at each integration point of the model to determine failure in concrete and as a result they found that the ferrocement composite beams have better ductility, cracking strength, and ultimate capacity compared to reinforced concrete beams. Likewise Qasim Mohammad [41] studied the FEM to analyze the ferrocement slabs. Modeling of concrete compression and tensile cracking has been done by a plasticity model and smeared cracking approach respectively. Moreover, to study the composite action between the ferrocement slabs and steel sheeting, Aboul-Anen et al. [42] applied ANSYS software with Eight-node solid isoparametric elements. This finite element software was also used by Shaheen et al. [8] to find the modal parameters of the healthy and damage tank.

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In the current research, a finite element simulation was implemented using Abaqus Unified FEA (Dassault Systèmes, France) [43] to evaluate the experimental work. This software consists of variable procedures that allows for the implementation of specific material models (ferrocement/concrete and steel), boundary conditions, bond behavior and the interaction between the reinforcing steel and concrete. The software has an extensive library of elements that can be used to model concrete and reinforcement and in this numerical analysis in order to achieve more compatible experimental and analytical results, a three-dimensional brick element and a beam element, both in linear geometry were considered for modeling the ferrocement mortar and reinforcement respectively. These models were also developed to determine the optimal span of ferrocement channel under various uses (e.g. roof and floor) with different maximum (ultimate) loads. In addition, two types of support channels were investigated to obtain the optimal tensile reinforcement for channel in direction of the Y axis.

2. Channel design based on ferrocement

The design strength of all sections of ferrocement structures and structural members should be at least equal to the required strengths for the factored load and load combinations stipulated in the American Concrete Institute's Building Code Requirements for Structural Concrete (ACI) 318 [44]. Design strength provided by a member or a cross-section is expressed in terms of axial load, bending moment, shear force, or stress. The values shall be taken as the nominal strength, calculated based on the requirements and assumptions of the ACI 318, multiplied by the strength reduction factor Ø. The aim would be to satisfy the general relationship U ≤ Ø N; where U is the factored load (equal to the minimum required design strength), N is the nominal resistance, and Ø is the strength reduction. Design strength for the mesh reinforcement should be based on the yield strength (fy) of the reinforcement but should not exceed 690 MPa [11].

The values of parameters used in calculations are presented in Table 1.

2.1. Volume fraction of reinforcement (V_f)

V_f is the total volume of reinforcement divided by the volume of composite (reinforcement and matrix) and can be obtained from the following equation:

$$V_f = \frac{N\pi d_b^2}{4h}\left(\frac{1}{D_l}+\frac{1}{D_t}\right) = 0.637\% \tag{1}$$

2.2. Effective area of reinforcement (A_{si})

The area of reinforcement per layer of mesh is considered effective to resist tensile stresses in a cracked ferrocement section. A_{si} can be determined as:

$$A_{si} = \eta V_{fi}\ A_c = 4.78 \times 10^{-5}\left(m^2\right) \tag{2}$$

When multiplied by the volume fraction of reinforcement, the global efficiency factor η gives the equivalent volume fraction (or equivalent reinforcement ratio) in the loading direction considered.

2.3. Nominal tensile strength (N_n)

The nominal resistance of cracked ferrocement elements subjected to pure tensile loading can be approximated by the load-carrying capacity of the mesh reinforcement alone in the direction of loading. The following procedure may be used:

$$N_n = A_s f_y = 82(KN) \tag{3}$$

2.4. Nominal moment strength (M_n)

If vibrating the compressive strength of ferrocement is considered 2 MPa; then M_n can be obtained through the following equation:

$$M_n = \sum_{i=1}^{n} C_{si} or T_{si}\left(d_i - \frac{\beta_1 c}{2}\right) = 2.9(KN.m) \tag{4}$$

where:

M_n = nominal moment strength;
C_{si} = the internal compressive force provided by the longitudinal reinforcing layer i;
T_{si} = the internal tensile force provided by the longitudinal reinforcing layer i;
di = distance from the extreme compression fiber to the centroid of reinforcing layer i;
β_1 = the factor defining the depth of the rectangular stress block; and
c = distance from the extreme compression fiber to the neutral axis.

3. Materials and methods

3.1. Materials and mixing proportions

Type II ordinary portland cement (OPC) was provided by Torbat and Sabzevar Cement Factories (Iran). The ferrocement mortar was

Table 1
Parameters used in ferrocement channel design.

Parameter	Definition	Value
B	Width of the ferrocement section	1 (m)
H	Thickness of the ferrocement section	0.05 (m)
N	Number of mesh layers (nominal resistance)	2
F_y	yield strength of mesh reinforcement or reinforcing bars	2400 (kg/cm^2)
W_m	Unit weight of mesh	0.5 (kg/m^2)
γ_m	Density of steel	7850 (kg/m^3)
d_b	Diameter of mesh wire	0.8×10^{-3} (m)
D_l	Center-to-center spacing of wires aligned longitudinally in the reinforcing mesh	0.06 (m)
D_t	Center-to-center spacing of wires aligned transversely in the reinforcing mesh	0.06 (m)
A_s	Total effective cross-sectional area of bonded reinforcement	352×10^{-6} (m^2)
η	Global efficiency factor of embedded reinforcement in resisting tension or tensile-bending loads	0.3
A_c	Cross-sectional area of the ferrocement composite	0.05 (m^2)