ANALYSIS OF FERROCEMENT ROOF STRUCTURES: New Construction and Utilization in Repair Procedures

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ABSTRACT

In recent years, a great deal of interest has been created regarding the use of ferrocement in constructing roofs for new buildings and utilizing this material in the repair of existing structures. In order to get the benefits of ferrocement (e.g. low cost), accurate methods of analysis and design have to be used. Finite strip method appears to have great potential in predicting the static response of the composite (multilayered) structural elements. Application of a high precision finite strip modeling in the analysis of ferrocement shell roof structures is investigated in this paper. Comparison with experimental results from other publications is included.

INTRODUCTION

The rapid increase in the cost of construction has forced engineers to look for economical materials to be used in building or repairing structures. Ferrocement is a form of reinforced concrete using closely spaced multiple layers of mesh and/or small diameter rods completely encapsulated in mortar. The use of ferrocement as a construction and rehabilitation material is a comparatively new approach, which can be potentially successful due to the inheret properties of this material (i.e. ferrocement is light weight, easy to manufacture, requires no formworks and economical (1)).

Ferrocement possesses a degree of toughness, ductility, durability, strength and crack resistance that is considerably greater than that found in other forms of concrete construction. All these properties are achieved within a thickness of about 25 mm. Combining this flexibility with the fact that steel stresses of 550 MPa and larger can be tolerated without excessive cracking, indicates a material which is tough, and ductile and hence ideally suitable for rehabilitation and/or new construction (2).

The most common type of ferrocement reinforcement is steel mesh (3). Multilayered type construction of ferrocement is ideally suited for the use as light weight prefabricated roof structures owing to its high-strength-to-weight and stiffness-to-weight ratios. Iorns (4) reported that the lamination process eleminates voids, allows more reinforcement to be incorporated without mortar penetration problems, allows mortar composition and density to be varied and generally reduce labor costs.

One of the main characteristics of multilayered structural elements is its heterogeneous and anisotropic nature which requires accurate analysis techniques in order to incorporate the coupling between bending and membrane forces which usually exists in such systems (5).

Finite strip approach was first published by Cheung (6) for the analysis of isotropic and orthotropic structures. It was later adapted by the authors (5) to deal with laminated anisotropic structures. This technique appears to have a great potential in predicting the static response of the laminated ferrocement roof structures since the computer storage requirements for the finite strip modeling are relatively small .

The objectives of this paper are firstly to review state of the art experience in ferrocement and secondly to apply the finite strip approach to shell roof structures made or repaired with ferrocement. This includes simulation of the mesh/mortar matrix as a laminated composite system and analysis this system using a finite strip model. The suitability of the model in predicting the structural response of ferrocement roof structures is examined. Comparison with experimental results from other publications is included in order to evaluate the numerical results.

BACKGROUND TO THE LAMINATED FERROCEMENT TECHNOLOGY

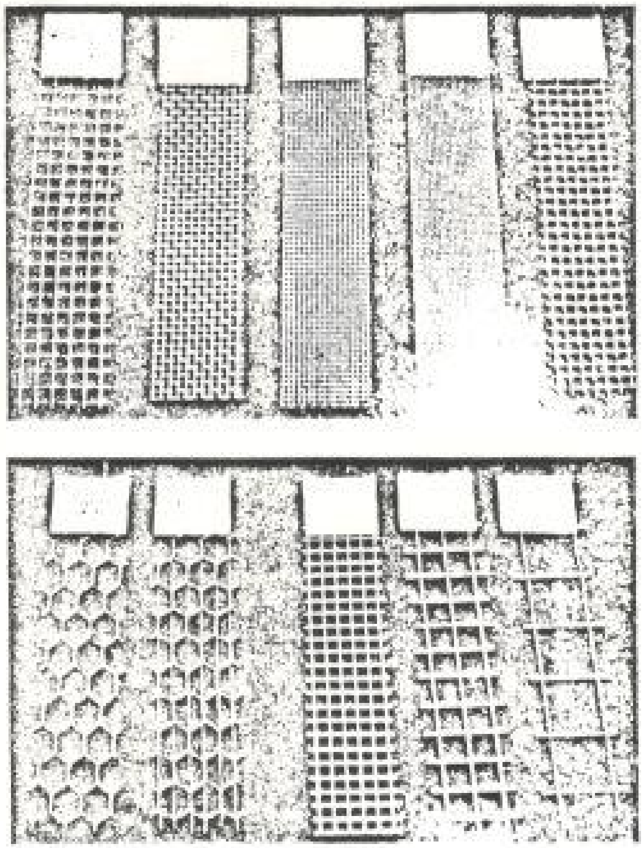
Laminated Ferrocement System

The two main items comprises the ferrocement system are the mortar matrix and the reinforcement steel mesh .

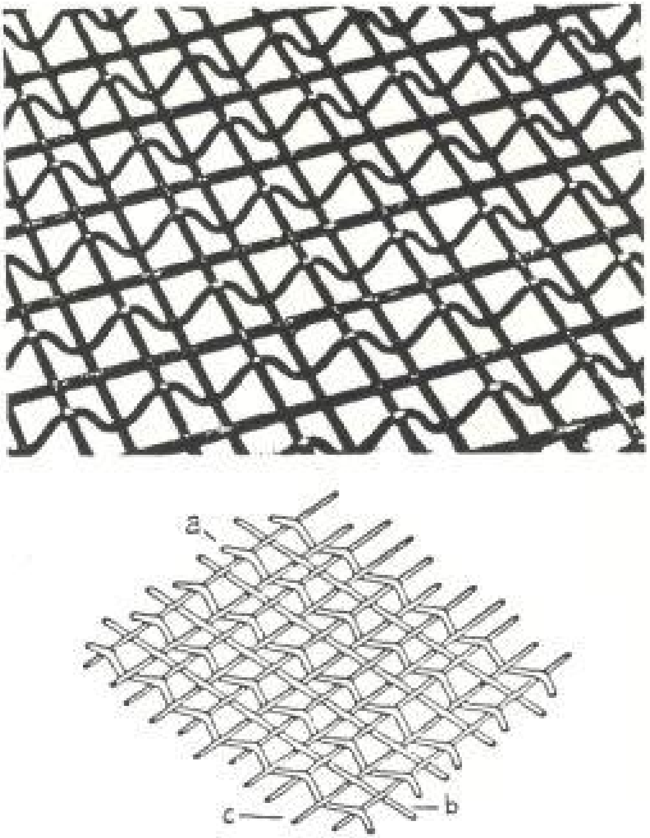
The mortar matrix
The mortar matrix usually comprises more than 95% of the ferrocement volume and has a great influence on the behaviour of the final product (3). Moreover the mortar matrix protects the steel mesh from corrosion. Therefore, great care should be exercised in choosing the constituent materials, namely cement, mineral admixtures, and fine aggregates, and in mixing and placing the mortar. The chemical composition of the cement, the aggregate-cement ratio, and the water-cement ratio are the major parameters governing the properties of the mortar. The influence of these parameters on the mortar characteristics is discussed in detail in (7).

Steel mesh reinforcement
Wire mesh with closely spaced wires is the most commonly used reinforcement in ferrocement. Common wire meshes have hexagonal or square openings (Figure 1.1). Meshes with hexagonal openings are not structurally as efficient as meshes with square openings because the wires are not always oriented in the directions of principal stresses (see Figure 1.1). However, they are flexible and can be used in doubly curved elements. Meshes with square openings are available in welded or woven form. Welded-wire mesh is made out of straight wires in both the longitudinal and transverse directions. Thus, welded-mesh thickness is equal to two wire diameters. Woven mesh is made of longitudinal wires bent around straight transverse wires. Welded-wire meshes have a higher modulus and hence higher stiffness than woven meshes.

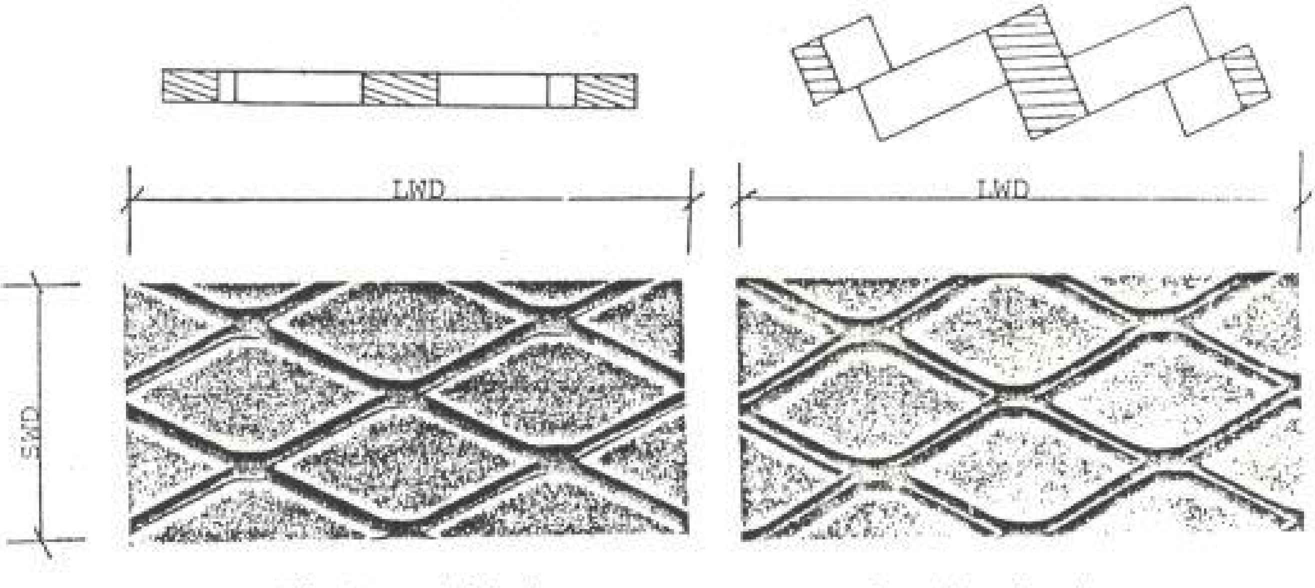
A three-dimensional mesh is also available (Figure 1.2). A Crimped keeper wire frictionally locks together three alternating layers of straight wires, thus forming a mesh with total thickness of five wire diameters. Other type of meshes formed by slitting thin-guage steel sheets and expanding them in a direction perpendicular to the slits is the expanded mesh reinforcement (see Figure 1.3). Expanded mesh is suitable for hulls and tanks if proper construction procedures are used.



1—Types of wire mesh reinforcement used in ferrocement



2—Schematic of three-dimensional mesh



3—Typical expanded metal mesh; LWD = longitudinal or long-way diamond, SWD = transverse or short-way diamond

Figure 1 Types of steel mesh Reinforcement (3).

Collen (8), Byrne and Wright (9) and Irons (4) reported that expanded mesh reinforcement and welded-wire mesh offer approximately equal strength in their normal orientation. Moreover, expanded mesh reinforcement provides excellent impact resistance and excellent crack control.

Construction Techniques

A number of procedures for the production of ferrocement were discussed in (3) and will be summarized herein.

Armature system

The armature system is a framework of tied reinforcing bars to which layers of reinforcing mesh are attached on each side. Mortar is then applied from one side and forced through the mesh layers towards the other side as shown in (Figure 2.1). The advantages of this system is that it allows the repair from both sides, and areas requiring touchup are visible. However, application of mortar from one side may be difficult for thick or dense mesh systems, resulting in internal voids. The armature system is a traditional system for repair damaged structures.

Closed-Mold system

The mortar is applied from one side through several layers of mesh (Figure 2.2). The mold may remain as a permanent part of the finished ferrocement structure. The use of that system tends to eleminate the use of rods or bars, thus permitting an essentially all-mesh reinforcement and requires plastering from one side. The advantage of this system is the use of molds to reinforce the structure. However, large and costly molds are uneconomical for one time application. This system is ideal for factory production .

Integral-Mold system

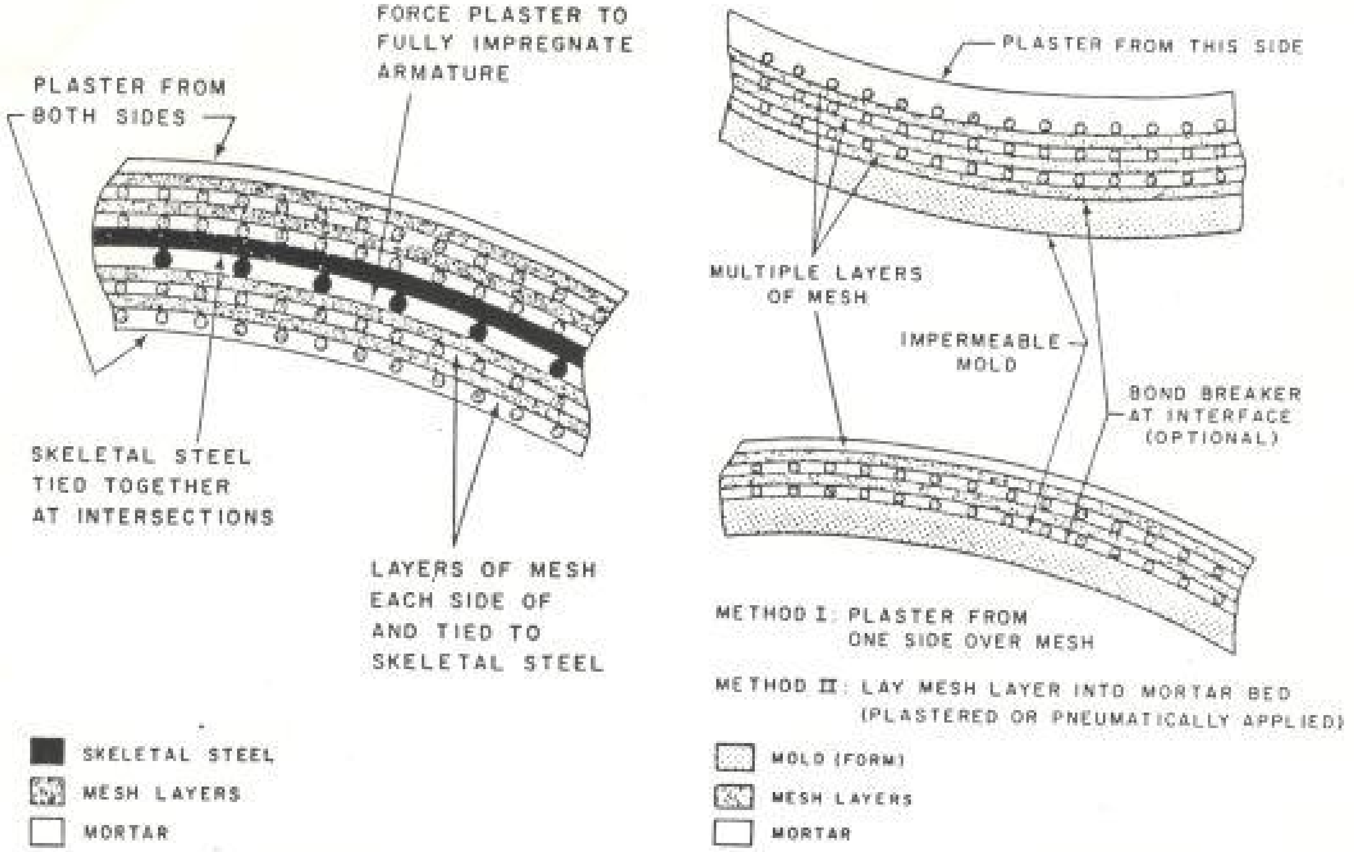
An integral mold is first constructed by application of mortar from one or two sides onto a semi-rigid framework made with a minimum number of mesh layers. This forms, after setting of mortar, a rigid but low-quality ferrocement mold. Further application of reinforcing mesh and mortar on both of the ferrocement mold results in this system of construction (Figure 2.3). This system allows excellent rigidity and insulating properties when insulating core is used. However, it requires special details for shear connection between rigid ferrocement layers, especially across insulating cores. This method is ideal for field applications.

Open-Mold system

In this system, mortar is applied from one side through layers of mesh or mesh and rods attached to an open mold made of lattice of wood stirups (Figure 2.4). The form is coated with a release agent to facilitate mold removal and permit repair and observation during the mortar application process. The system is similar to the closed-mold system in which the mortar is applied from one side but with far better control of the quality of the resulting ferrocement product. However, it requires constructing an extensive mold and shoring system that may not be usable. Irons (4) suggested this system for better repair of boats .

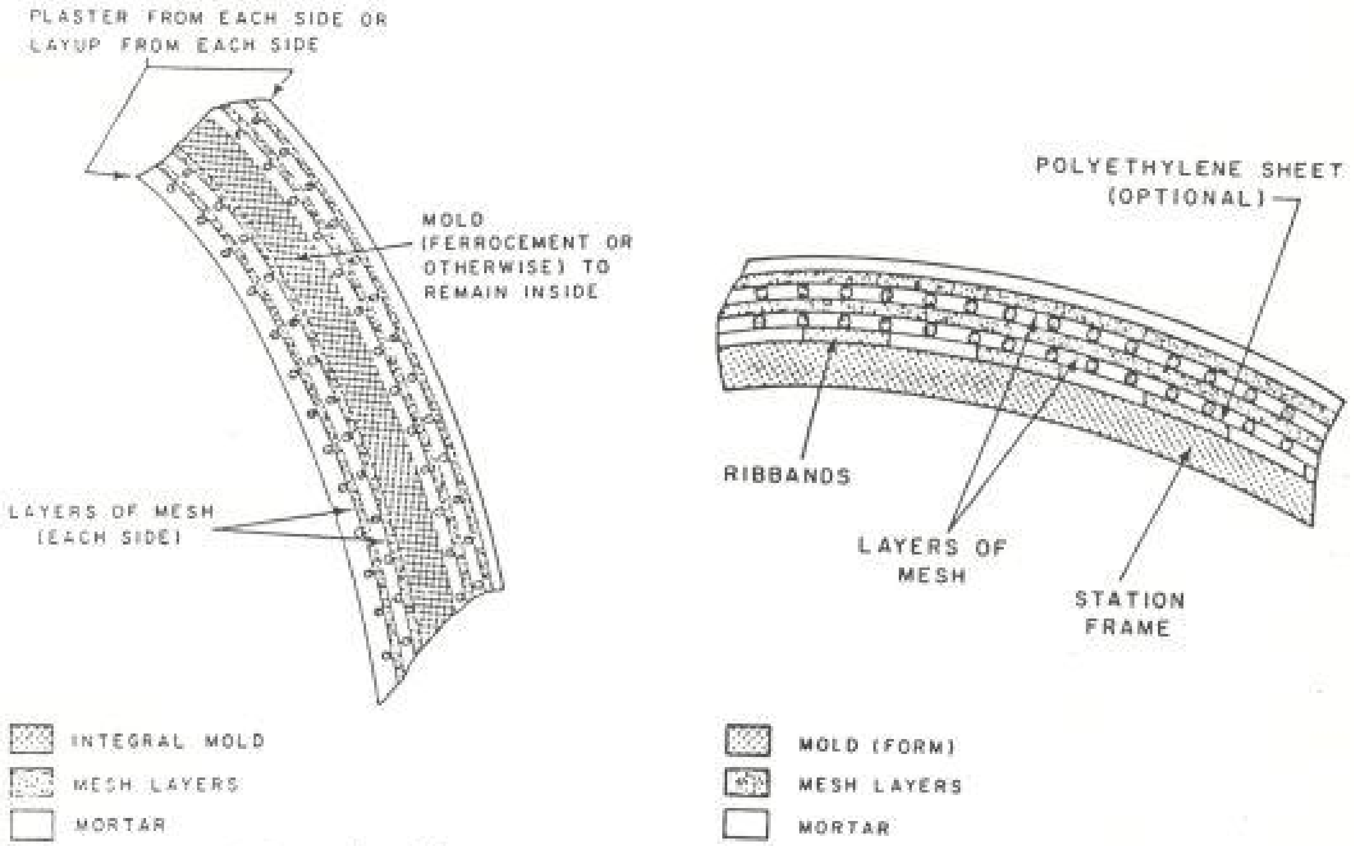
ANALYTICAL MODELLING

A finite strip model was developed and the FOLDSHL computer program was written (5) for the analysis of laminated composite roof structures. Full description of the finite strip model and the



1 - Armature system

2 - Closed-mold system



3 - Integral-mold system

4 - Open-mold system

Figure 2 Laminated ferrocement systems for construction (3).

computer program are reported elsewhere (5 and 10). Figure 3(a) shows a shell finite strip with 14 degrees of freedom.

To utilize the FOLDSHL program in the present investigation, the mortar layers and steel wire meshes of the Ferrocement Concrete are presented in the shell strip model as a number of "I" perfectly bonded layers of transverse isotropic material. The layers and "I+1" surfaces (interlayers surfaces and lower/upper laminate surface) are numbered from bottom to top of the laminate (see Figure 3(b)). The properties of each layer are given to the computer program as input data .

MATERIAL MODELLING

The analysis of a ferrocement cross section subjected to in-plane and/or transverse loads is similar to the analysis of a reinforced concrete element having several layers of steel (3). Therefore the strain and stress distribution in laminated ferrocement section is shown in Figure 4 .

Mortar Properties

The mortar in ferrocement systems acts as concrete in traditional reinforcement concrete structures. The parameters used in this investigation to describe the mortar in laminated ferrocement are :

A_c = cross-sectional area of ferrocement composite.
C = distance from extreme compression fiber to neutral axis (see Figure 4).
E_c = elastic modulus of mortar matrix.
h_i = distance from extreme compression fiber to centroid of reinforcing layer i.
f_c' = specified compression strength of mortar.
E_{cr} = elastic modulus of cracked ferrocement in tension (slope of the stress-strain curve in the cracked elastic state).

Wire Mesh Parameters

The four parameters used in characterizing the reinforcement in ferrocement applications are the volume fraction, the specific surface of reinforcement and effective modulus of the reinforcement and the effective area of reinforcement (3).

Volume fraction of reinforcement

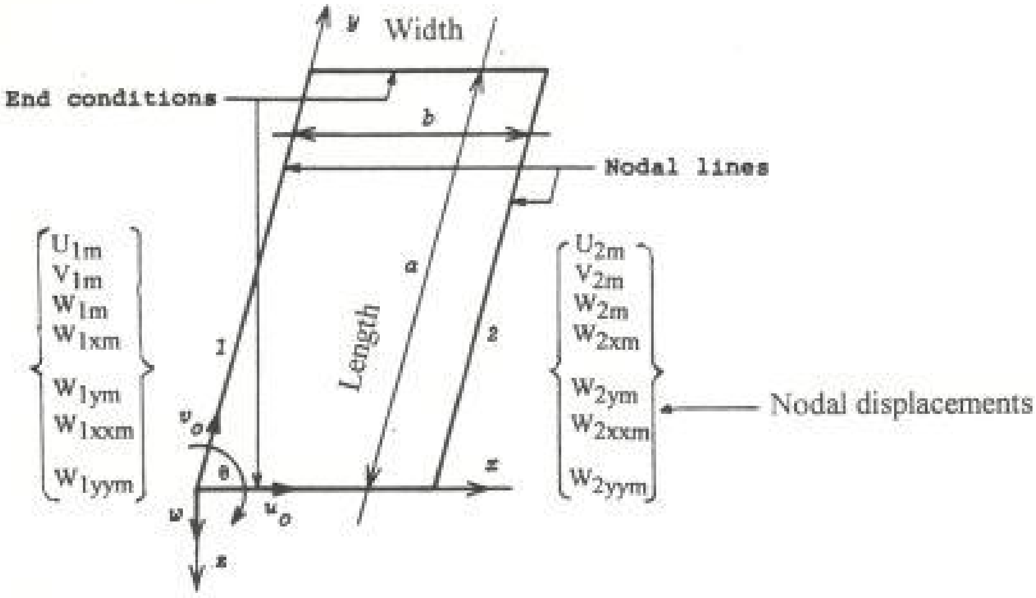
V_f is the total volume of reinforcement divided by the volume of composite section (reinforcement and mortar matrix) .

Specific surface of reinforcement

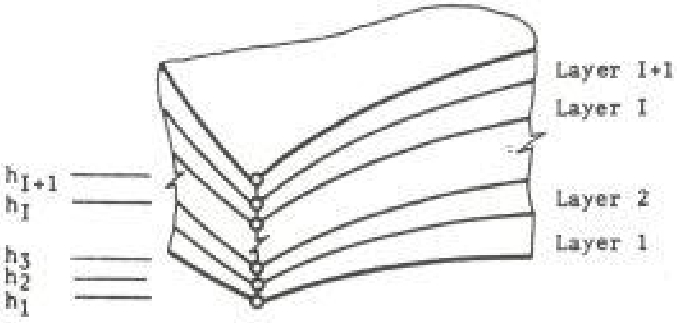
S_r is the total bonded area of reinforcement, or in other words, area of the steel that comes in contact with the mortar matrix divided by the volume of composite. For a ferrocement plate of width "b" and depth "h", the specific surface of reinforcement can be computed from

$$S_r = \frac{\Sigma s}{b\,h} \tag{1}$$

where; Σs = the total surface area on bonded reinforcement per unit length .

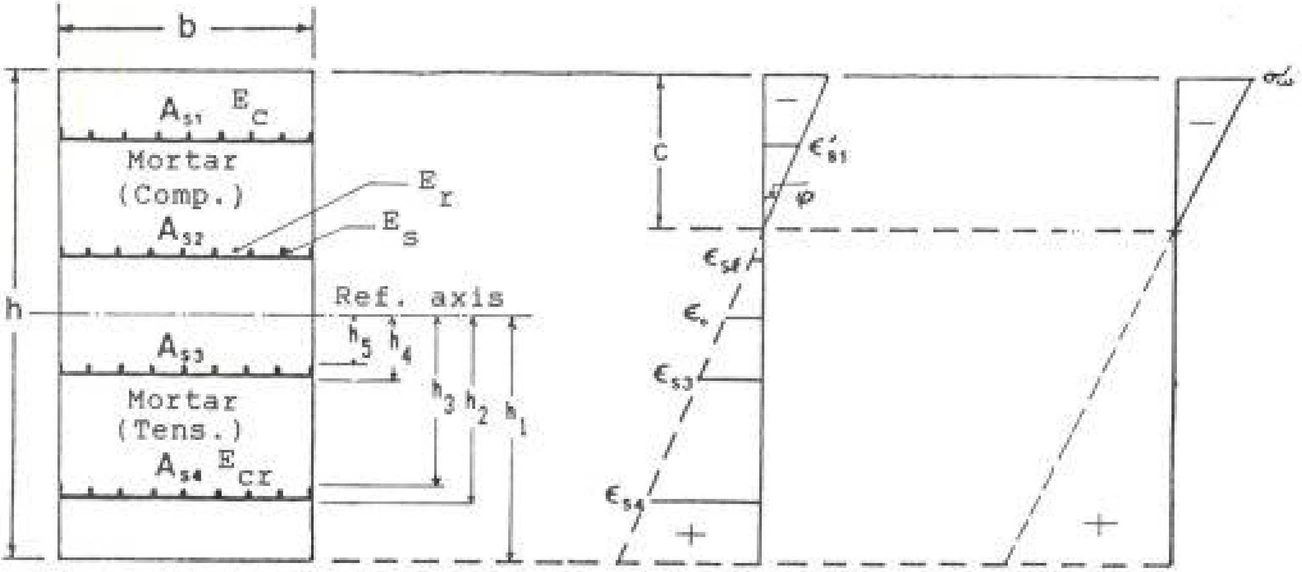


(a) A finite strip with 14 degrees of freedom



(b) Layer numbering system

Figure 3 Finite strip for multilayered composite structures.



E_C = Elastic modulus of mortar matrix.

E_{cr} = Elastic modulus of cracked ferrocement in tension.

E_r = Effective modulus of reinforcing system.

Es = Elastic modulus of steel reinforcement.

ϕ = The curvature of the cross section.

Figure 4 Strain and stress distribution in a laminated composite ferrocement section.

The relation between S_r and V_f for square-grid wire meshes are given by

$$S_r = \frac{4\ Vf}{d_b} \tag{2}$$

where; d_b = the diameter of the wire.

Effective modulus of the reinforcement

The definitions of most ferrocement properties are the same as for reinforced concrete. However, the effective modulus of the reinforcing system "E_r" may be different. This is because the elastic modulus depends on the type of mesh reinforcement. For welded steel mesh, "E_r" may be taken equal to the elastic modulus of the steel wires. For other meshes, "E_r" is determined from tensile tests on the ferrocement composites (3).

Effective area of reinforcement

The area of reinforcement per layer of mesh considered effective to resist tensile stresses in a cracked ferrocement section can be determined as follows :

$$A_{si} = \eta\ V_{fi}\ A_c \tag{3}$$

where ; A_{si} = effective area of reinforcement for mesh layer "i".
η = global efficiency factor of mesh reinforcement in the loading direction considered.
V_{fi} = volume fraction of reinforcement for mesh layer "i".
A_c = gross cross sectional area of mortar section.

The volume of η depends on the direction of loading and the type of steel mesh and is given in tables (11 and 12).

Assumptions

For investigation of stresses at service loads, analysis of ferrocement elements should be based on the following assumptions to satisfy equilibrium and compatibility of strains :

(a) Strains vary linearly with the distance from the neutral axis.
(b) Stress-strain relationships of mortar and wire meshes are linear for stresses less than or equal to stresses generated by permissible service loads.
(c) Mortar resists no tension.
(d) Perfect bond exist between steel and mortar.

The above assumptions are valid for the classical lamination theory (5).

NUMERICAL APPLICATIONS

The geometry, material properties and loading are the required input. The stresses, moments and deflection at the nodal lines of the finite strips are the output of the program.

Two numerical examples are analysed. These examples include a laminated ferrocement cylindrical shell and a composite single barell shell of reinforced concrete repaired by laminated ferrocement.

(1) A Bus Shelter Cylinderical Shell Roof Model

In order to evaluate the numerical results, a cylinderical butterfly shell tested previously by Lee et al (13), was modeled using 12 strips as shown in Figure 5(a) and (b).
The geometry and material properties used in the analysis are as follows :

Shell properties (geometry)
Shell thickness = 15 mm
Length of strip (Length of the shell) = 3.0 m
Width of the shell = 3.0 m
Uniform load applied per horizontal projection = 1.29 KN/m^2

Mortar parameters
Ec = 2.2×10^7 KN/m^2
G = 1.1×10^7 KN/m^2
υ = 0.0

Welded square mesh parameters
Er = 2.0×10^8 KN/m^2
G = 9.86×10^7 KN/m^2
υ = 0.014

where ; Ec and Er where previously defined.
G = Shear modulus of the material.
υ = Poisson's ratio.

To satisfy the design criterion discussed above, three wire mesh layers were chosen as shown in Figure 6.

Table 1 shows the longitudinal stresses and deflection at midspan of the shell. The maximum deflection and principle tensile stresses were found to be 7.5 mm and 2.1 MPa. These values were in close agreement with the experimental results obtained by Lee et al (13) which were 7 mm and 1.9 MPa respectively.

(2) A Composite Single Barrel Shell

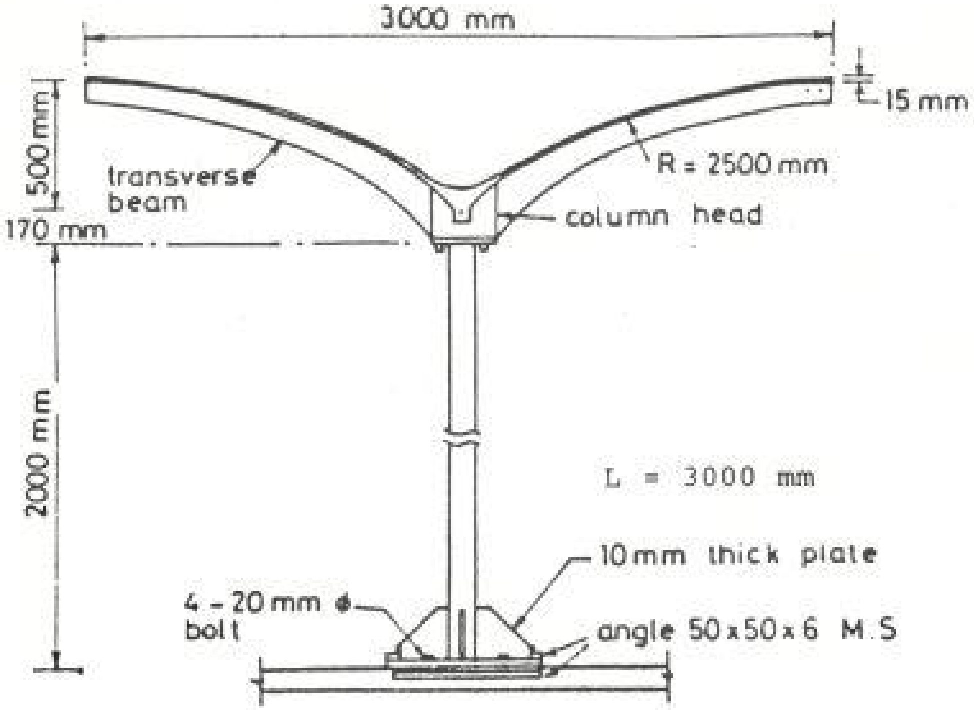
A cracked reinforced concrete single barrel shell was previously analysed by Billington (14). Loading and shell dimensions are shown in Figure 7. In order to repair this shell, the cracked and loose concrete is removed and replaced by laminated ferrocement. Thus, the structure will be a composite section consisting of reinforced concrete and ferrocement. The suitable construction system for this setup would be the closed mold system (see Figure 2).

The elastic properties of reinforced concrete are

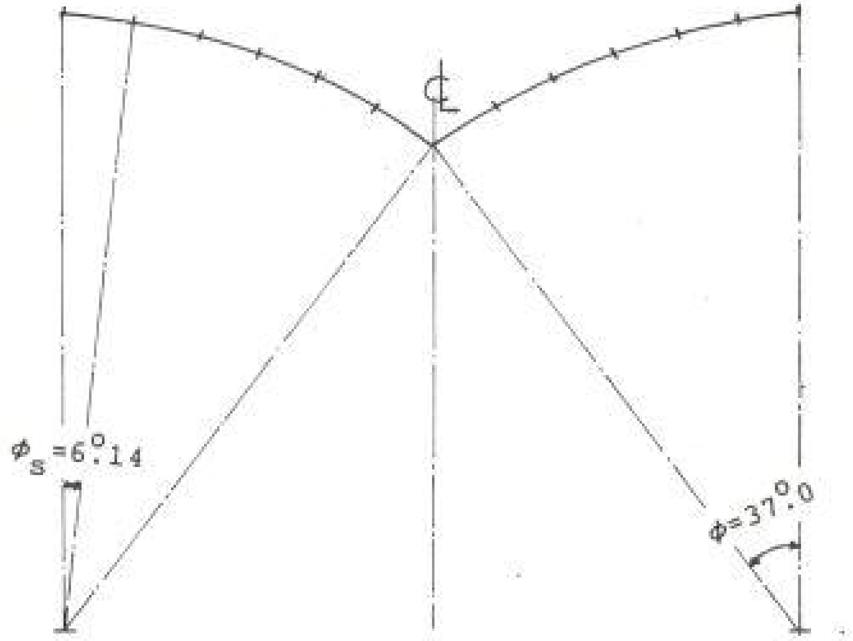
E = 1.38×10^7 KN/m^2 ; G = 5.31×10^6 KN/m^2 and υ = 0.30

where ; E = modulus of elasticity of cracked concrete.
G = Shear modulus.
υ = Poisson's ratio.

The elastic properties of laminated ferrocement are as in the previous example. According to the material modelling described previously, a laminated ferrocement of 12.7mm (0.5") thickness including 4 layers of welded square mesh reinforcement of 1mm wire diameter and 1.5 mm clear cover is used.



(a) Cylinderical shell sectional dimensions



(b) Finite strip simulations, 12 strips

Figure 5 Example (1) A bus shelter cylinderical shell model.

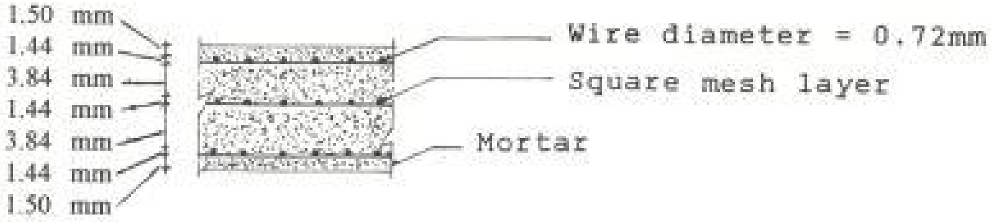


Figure 6 Cross section of laminated ferrocement roof of example (1).

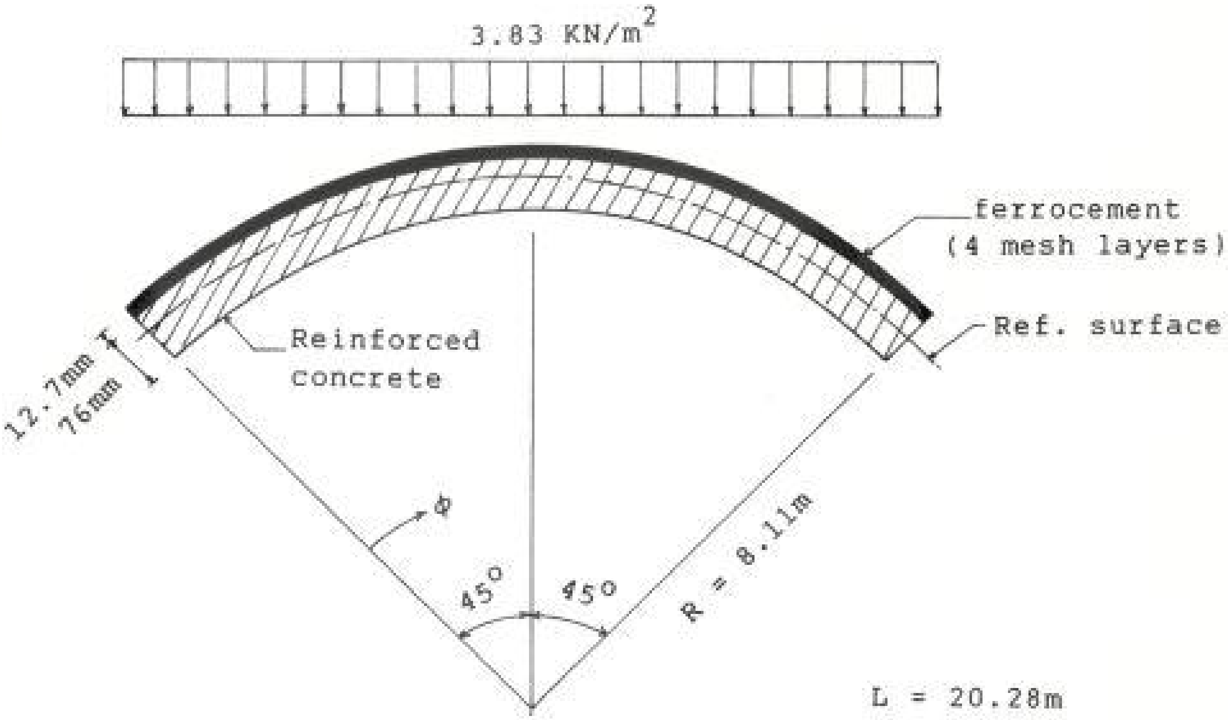


Figure 7 Dimensions and loading of example (2).

TABLE 1 Midspan Longitudinal stresses, σ_x , and deflection , w.

ϕ , deg. (from free edge)	0	6.14	12.28	18.43	24.58	36.72	36.87
σ_x , Mpa	2.1	-0.02	-0.65	-0.5	-0.08	0.26	0.39
w , mm.	-7.5	-5.25	-3.0	-1.0	0.22	0.88	1.05

TABLE 2 Transverse Moment, M_ϕ and shear stresses $\sigma_{x\phi}$ for cylindrical shell.

ϕ , deg.	Before	repair	After	repair
(from edge)	$\sigma_{x\phi}$ Mpa at support	M_ϕ (KN.m/m) at midspan	$\sigma_{x\phi}$ MPa at support	M_ϕ (KN.m/m) at midspan
0	0.0	0.0	0.0	0.0
10	-1.79	-0.67	-1.6	-0.39
20	-1.18	-5.2	-1.0	-4.0
30	-0.34	-9.34	-0.28	-8.2
40	-0.02	-11.43	-0.015	-9.7
45	0.0	-11.65	0.0	-9.9

For analysis, one-half of the shell was modeled using 5 strips taking symmetry conditions into consideration. Results of the longitudinal stresses (σ_x) and circumferential stresses (σ_ϕ) at midspan are plotted against ϕ (from edge to crown) in Figure 8. Table 2 comprises the results of transverse moments, M_ϕ at midspan and shear stresses ($\sigma_{x\phi}$) at supports before and after repair.

It can be seen from Figure 8 and Table 2 that the stresses and moments were reduced to varying degrees (depending on the location of the point in question) as a result of strengthening the concrete section with laminated ferrocement. For example, the maximum reduction of longitudinal stresses, σ_x , at midspan was 30% at $\phi = 0^o$ while that of circumferential stresses, σ_ϕ , was 45% at $\phi = 10^o$.

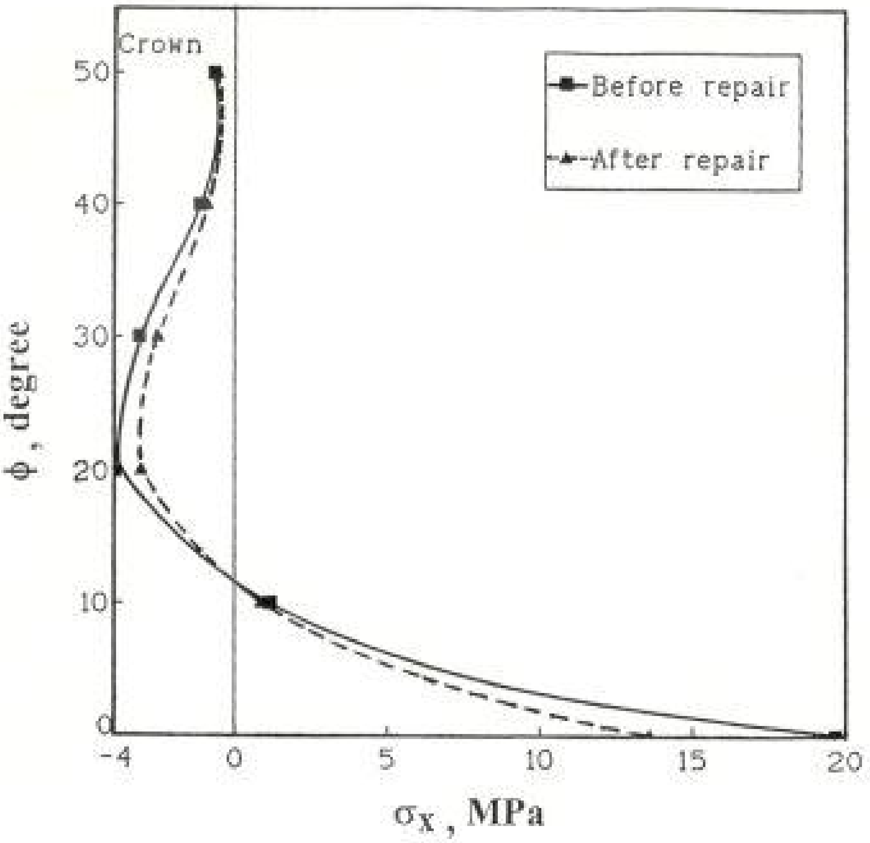
It was also found that the reduction of σ_x and M_ϕ due to repair decreases with the increase of angle ϕ while that of shear stresses increases with the increase of angle ϕ towards crown of the shell.

CONCLUSIONS

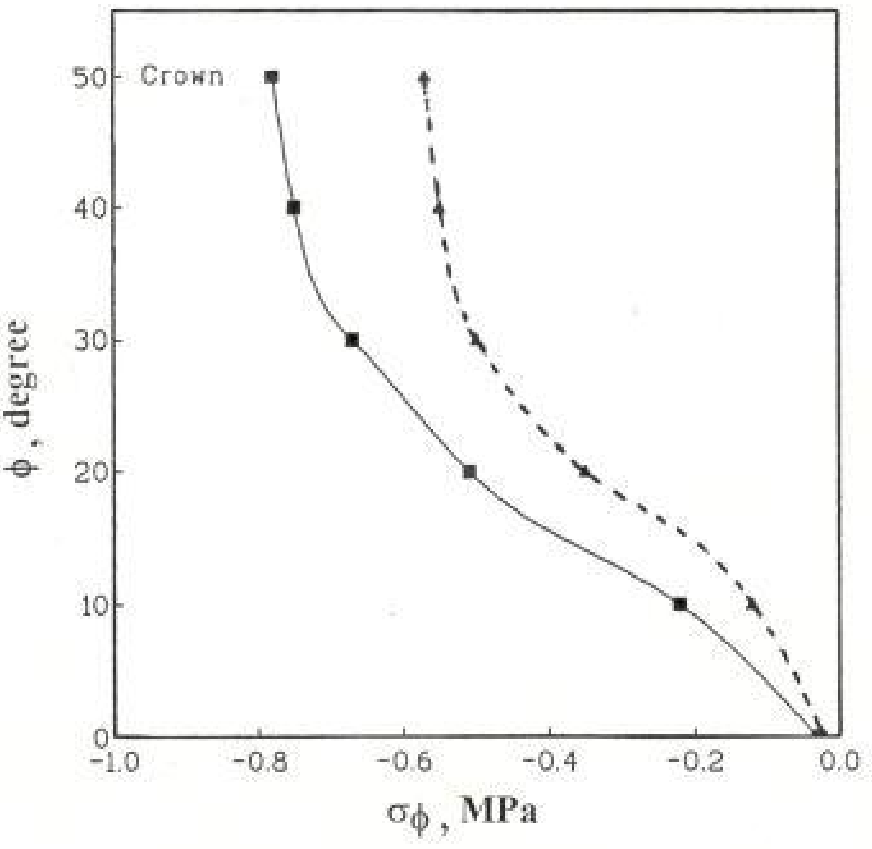
The state of the art review reported in this paper showed that ferrocement can be utilized in new construction or repair in various situations. However, to realize the full potential of this technology an accurate and reliable method of analysis is needed.

Finite strip method adapted by the authers (5) can be applied for the analysis of laminated ferrocement systems with some material and analytical modelling.

Two examples were studied. One for new construction whilest the other for repair. Results of both examples were successful.



(a) Longitudinal stresses, σ_X , at midsapn.



(b) Circumferential stresses, σ_ϕ , at midsapn.

Figure 8 Effect of repair using laminated ferrocement on longitudinal and

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