Guide for the Design, Construction, and Repair of Ferrocement

Reported by ACI Committee 549

Gordon B. Batson*
Chairman

Ronald F. Zollo*
Secretary

Perumalsamy N. Balaguru*

Colin D. Johnston

Narayan Swamy

Jose O. Castro

Antoine E. Naaman (former Chairman) *

Ben L. Tilsen

Antonio J. Guerra

James P. Romualdi

Robert B. Williamson

Martin E. Iorns*

Surendra P. Shah

Rogerio C. Zubieta

* Principal authors

The following associate members of Committee 549 contributed to the preparation of this report: Shuaib H. Ahmad, Douglas Alexander, Antonio Nanni, Ricardo P. Pama, P. Paramasivam, Sherwood P. Prawel, and Andrei M. Reinhorn.

Members of the Committee voting on the 1993 revisions:

P.N. Balaguru
Chairman

Parviz Soroushian
Secretary

M. Arockiasamy

Martin E. Iorns

Surendra P. Shah

Nemkumar Banthia

Colin D. Johnston

Narayan Swamy

Gordon B. Batson

Mohammad Mansur

Ben L. Tilsen

Jose O. Castro

John L. Mulder

Methi Wecharatana

James I. Daniel

Antoine E. Naaman

Robert B. Williamson

David M. Gale

Antonio Nanni

Robert C. Zellers

Antonio J. Guerra

D.V. Reddy

Ronald F. Zollo

Lloyd Hackman

James P. Romualdi

Rogerio C. Zubieta

This guide supplements two earlier publications (ACI 549R, State-of-the-Art Report of Ferrocement, and SP-61, Ferrocement-Materials and Applications). It provides technical information on materials and material selection, design criteria and approaches, construction methods, maintenance and repair procedures, and testing. The objectives are to promote the more effective use of ferrocement in terrestrial structures, provide architects and engineers with the necessary tools to specify, and use ferrocement, and provide owners or their representatives with a reference document to check the acceptability of ferrocement alternative in a given application.

Keywords: admixtures; cements; composite materials; construction; construction materials; ferrocement; fibers; flexural strength, maintenance; metals; modulus of elasticity; reinforced concrete; reinforcing materials; repairs; structural design; tension tests; welded wire fabric.

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ACI Committee Reports, Guides, Standard Practices, and Commentaries are intended for guidance in designing, planning, executing, or inspecting construction and in preparing specifications. References to these documents shall not be made in the Project Documents. If items found in these documents are desired to be a part of the Project Documents, they should be phrased in mandatory language and incorporated into the Project Documents.
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CHAPTER I-GENERAL

1.1-Scope

This guide is based on technical information assembled by ACI Committee 549, Ferrocement, from current practice, developments, and advances in the field of ferrocement around the world. It represents a practical supplement to the state-of-the-art report (ACI 549R) published earlier by the committee. The guide covers materials for ferrocement, materials selection, and standards; design criteria and approaches; construction methods; maintenance and repair procedures; and testing.

The objectives of this guide are to promote the effective use of ferrocement in terrestrial structures, provide architects and engineers with the necessary tools to specify and use ferrocement, and provide owners or their representatives with a reference document to check the acceptability of a ferrocement alternative in a given application. This guide is consistent with ACI Building Code Requirements for Reinforced Concrete (ACI 318) except for the special characteristics of ferrocement, such as reinforcement cover and limits on deflection.

Ferrocement is a form of reinforced concrete using closely spaced multiple layers of mesh and/or small-diameter rods completely infiltrated with, or encapsulated, in mortar. The most common type of reinforcement is steel mesh. Other materials such as selected organic, natural, or synthetic fibers may be combined with metallic mesh. This guide addresses only the use of steel reinforcement in a hydraulic cement mortar matrix.

Applications of ferrocement are numerous, especially in structures or structural components where self-help or low levels of skills are required. Besides boats and marine structures, ferrocement is used for housing units, water tanks, grain silos, flat or corrugated roofing sheets, irrigation channels, and the like (see ACI 549R).

1.2-Approval for use in design and construction

Use of ferrocement and the procedures covered in this guide may require approval by the authority or governmental agency having jurisdiction over the project.

CHAPTER 2-TERMINOLOGY

2.1-Reinforcing parameters

Three parameters are commonly used in characterizing the reinforcement in ferrocement applications: the volume fraction, the specific surface of reinforcement, and the effective modulus of the reinforcement.

2.1.1 Volume fraction of reinforcement $V_f$ is the total volume of reinforcement divided by the volume of composite (reinforcement and matrix). For a composite reinforced with meshes with square openings, $V_f$ is equally divided into $V_{fl}$ and $V_{ft}$ for the longitudinal and transverse directions, respectively. For other types of reinforcement, such as expanded metal, $V_{fl}$ and $V_{ft}$ may be unequal. Examples of computation of $V_f$ are shown in Appendix A.

2.1.2 Specific surface of reinforcement $S_r$ is the total bonded area of reinforcement (interface area or area of the steel that comes in contact with the mortar) divided by the volume of composite. $S_r$ is not to be confused with the surface area of reinforcement divided by the volume of reinforcement. For a composite using square meshes, $S_r$ is divided equally into $S_{rl}$ and $S_{rt}$ in the longitudinal and transverse directions, respectively.

For a ferrocement plate of width $b$ and depth $h$, the specific surface of reinforcement can be computed from:

$$ S_r = \frac{\Sigma_0}{bh} \tag{2-1} $$

in which $\Sigma_0$ is the total surface area of bonded reinforcement per unit length.

2.1.3 Relation between $S_r$ and $V_f$—The relation between $S_r$ and $V_f$ when square-grid wire meshes are used is

$$ S_r = \frac{4V_f}{d} \tag{2-2} $$
where $d_r$ is the diameter of the wire. For other types of reinforcement, such as expanded metal, $S_{rl}$ and $S_{rt}$ may be unequal.

2.1.3 Effective modulus of the reinforcement—Although the definitions of most ferrocement properties are the same as for reinforced concrete, one property that may be different is the effective modulus of the reinforcing system $E_r$. This is because the elastic modulus of a mesh (steel or other) is not necessarily the same as the elastic modulus of the filament (wire or other) from which it is made. In a woven steel mesh, weaving imparts an undulating profile to the wires. When tested in tension, the woven mesh made from these wires stretches more than a similar welded mesh made from identical straight wires. Hence, the woven mesh behaves as if it has a lower elastic modulus than that of the steel wires from which it is made.

In addition, when a woven mesh is embedded in a mortar matrix and tends to straighten under tension, the matrix resists the straightening, leading to a form of tension stiffening. A similar behavior occurs with expanded metal mesh (lath) and hexagonal mesh. To account for the above effects, the term “effective modulus of the reinforcing system” $E_r$ is used. For welded steel meshes, $E_r$ may be taken equal to the elastic modulus of the steel wires; for other meshes, $E_r$ may be determined from tensile tests on the ferrocement composite as explained in Chapter 7. Design values for common meshes used in ferrocement are recommended in Chapter 4.

2.2-Notation

$A_c$ = cross-sectional area of ferrocement composite

$A_S$ = total effective cross-sectional area of reinforcement in the direction considered

$$A_s = \sum_{i=1}^{n} A_{si}$$

$A_{si}$ = effective cross-sectional area of reinforcement of mesh layer $i$ in the direction considered

$b$ = width of ferrocement section

$c$ = distance from extreme compression fiber to neutral axis

$d''$ = clear cover of mortar over first layer of mesh

$d_b$ = diameter or equivalent diameter of reinforcement used

$d_i$ = distance from extreme compression fiber to centroid of reinforcing layer $i$

$E_c$ = elastic modulus of mortar matrix

$E_{cr}$ = elastic modulus of cracked ferrocement in tension (slope of the stress-strain curve in the cracked elastic state)

$E_r$ = effective modulus of the reinforcing system

$E_{r'}$ = elastic modulus of steel reinforcement

$f_c'$ = specified compressive strength of mortar

$f_{si}$ = stress in reinforcing layer $i$

$f_y$ = yield strength of mesh reinforcement or reinforcing bars

$h$ = thickness of ferrocement section

$M_{nl}$ = nominal moment strength

$N_{rl}$ = nominal tensile strength

$N'$ = number of layers of mesh; nominal resistance

$N_r$ = modular ratio of reinforcement

$s$ = mesh opening or size

$S_{rl}$ = specific surface of reinforcement in the longitudinal direction

$S_{rt}$ = specific surface of reinforcement in the transverse direction

$V_{fr}$ = volume fraction of reinforcement

$V_{fr}$ = volume fraction of reinforcement for mesh layer $i$

$V_{fi}$ = volume fraction of reinforcement in the longitudinal direction

$V_{ft}$ = volume fraction of reinforcement in the transverse direction

$\beta_1$ = factor defining depth of rectangular stress block (ACI 318, Section 10.2.7.3)

$\eta$ = global efficiency factor of embedded reinforcement in resisting tension or tensile-bending loads

$\eta_l$ = value of $\eta$ when the load or stress is applied along the longitudinal direction of the mesh system or rod reinforcement

$\eta_t$ = value of $\eta$ when the load or stress is applied along the transverse direction of the mesh reinforcement system or rod reinforcement

$\eta_{th}$ = value of $\eta$ when the load or stress is applied along a direction forming an angle $\Theta$ with the longitudinal direction

$\epsilon_{wu}$ = ultimate compressive strain of mortar (generally assumed to be 0.003)

$\epsilon_{ci}$ = strain of mesh reinforcement at layer $i$

$\epsilon_y$ = nominal yield strain of mesh reinforcement = $f_y/E$

$\Sigma_o$ = total surface area of bonded reinforcement per unit length

$\sigma_{cy}$ = stress in ferrocement composite at yielding of the reinforcement

$\sigma_{cu}$ = stress in ferrocement composite at ultimate strength in tension

2.3-Definitions

The following terms are defined because they do not appear in ACI 116R, Cement and Concrete Terminology, or have another meaning as applied to ferrocement.

Armature—The total reinforcement system or skeletal reinforcement and mesh for a ferrocement boat.

Longitudinal direction—The roll direction (longer direction) of the mesh as produced in plant (see Fig. 2.1).

Skeletal reinforcement—A planar framework of widely spaced tied steel bars that provides shape and support for layers of mesh or fabric attached to either side.
**Spritzing**—Spraying or squirting a mortar onto a surface.

**Transverse direction**—Direction of mesh normal to its longitudinal direction; also width direction of mesh as produced in plant (see Fig. 2.1).

**CHAPTER 3-MATERIALS REQUIREMENTS**

**3.1-Matrix**

The matrix used in ferrocement primarily consists of mortar made with portland cement, water, and aggregate. A mineral admixture may be blended with the cement for special applications. Normally, the aggregate consists of well-graded fine aggregate (sand) that passes an ASTM No. 8 (2.36 mm) sieve. If permitted by the size of the mesh openings and the distance between layers of mesh, small-size coarse aggregate may be added to the sand.

The mortar matrix usually comprises more than 95 percent of the ferrocement volume and has a great influence on the behavior of the final product. Hence, 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 nature of the aggregate, the aggregate-cement ratio, and the water-cement ratio are the major parameters governing the properties of the mortar. The importance of these parameters is discussed in detail in ACI 549R and in References 1 through 4. The following sections give a brief summary of the material requirements.

**3.1.1 Cement**—The cement should comply with ASTM C 150, ASTM C 595, or an equivalent standard. The cement should be fresh, of uniform consistency, and free of lumps and foreign matter. It should be stored under dry conditions for as short a duration as possible.

Detailed information regarding the types of cements, chemical and mineral admixtures, sampling, testing, and corrosion can be found in ACI 225R and in Reference 2. The most commonly used cement type is designated as Type I in ASTM C 150. Type II cement generates less heat during hydration and is also moderately resistant to sulfates. Type III is a rapid-hardening cement which acquires early strength more rapidly than Type I cement. Type IV is a low-heat cement used for mass concrete and is seldom considered for ferrocement. Type V is a sulfate-resisting cement used in structures exposed to sulfate.

The choice of a particular cement should depend on the service conditions. Service conditions can be classified as electrochemically passive or active. Land-based structures such as ferrocement silos, bins, and water tanks can be considered as passive structures, except when in contact with sulfate-bearing soils, in which case the use of sulfate-resistant cement, such as ASTM Type II or Type V, may be necessary.

For structures in electrochemically active environments such as boats and barges, it may be necessary to specify sulfate-resistant cement because of the sulfates present in sea water. ACI 357R reports that Type II cement was found adequate for sulfate resistance in a sea environment and better for resisting corrosion than Type V. If sulfate-resistant cement or a mineral admixture that improves sulfate resistance is not available, a rich mortar mix with normal cement (Type I) can be used with a protective surface coating (see Section 6.3).

Blended hydraulic cement conforming to ASTM C 595 Type I (PM), IS, I (SM), IS-A, IP, or IP-A can also be used.

Cement factors are normally higher in ferrocement than in reinforced concrete. Mineral admixtures, such as fly ash, silica fumes, or blast furnace slag, may be used to maintain a high volume fraction of fine filler material. When used, mineral admixtures should comply with ASTM C 618 and C 989. In addition to their possible improvement of flowability, these materials also benefit long-term strength gain, lower mortar permeability, and in some cases improved resistance to sulfates and chlorides.5
3.1.2 Aggregates—Normal-weight fine aggregate (sand) is the most common aggregate used in ferrocement. It should comply with ASTM C 33 requirements (for fine aggregate) or an equivalent standard. It should be clean, inert, free of organic matter and deleterious substances, and relatively free of silt and clay. Hard, strong, and sharp silica aggregates achieve the best strength results. Sharp sand may, however, cause pumping problems that may outweigh the slight gain in strength over rounded grains.

The grading of fine aggregate should be in accordance with the guidelines of Table 3.1, which are adapted from ASTM C 33; however, the maximum particle size should be controlled by construction constraints such as mesh size and distance between layers. It is generally agreed that a maximum particle size passing sieve No. 16 (1.18 mm) is appropriate in most applications. Uniform grading is desirable to achieve a workable high-density mortar mix, but trial-tested gap-graded mortars can also be used.6,7

Aggregates that react with the alkalis in cement should be avoided. When aggregates may be reactive, they should be tested in accordance with ASTM C 227. If proven reactive, the use of a pozzolan to suppress the reactivity should be considered and evaluated in accordance with ASTM C 441.

Lightweight fine aggregates can also be used for ferrocement. They should comply with the requirements for fine aggregate given in ASTM C 330. Volcanic ash, blast furnace slag, expanded shale fines, perlite, pumice, vermiculite, and inert alkali-resistant plastics may be suitable as lightweight aggregates. The use of lightweight aggregates instead of normal weight aggregates leads to a reduction in the strength of the mortar. Hence corresponding adjustments may be needed in the structural design.

3.13 Water—The mixing water should be fresh, clean, and potable. The water should be relatively free from organic matter, silt, oil, sugar, chloride, and acidic material. It should have a pH $\geq 7$ to minimize the reduction in the pH of the mortar slurry. Salt water is not acceptable, but chlorinated drinking water can be used.

3.1.4 Admixtures—Chemical admixtures used in ferrocement serve one of the following four purposes: water reduction, which increases strength and reduces permeability; improvement in impermeability; air entrainment, which increases resistance to freezing and thawing; and suppression of reaction between galvanized reinforcement and cement.1

Conventional and high-range water-reducing admixtures (superplasticizers) should conform to ASTM C 494. The use of water-reducing admixtures permits an increase in sand content for the same design strength or a decrease in water content for the same workability. Decreases in water content result in lower shrinkage and less surface crazing. Retarders are used in large time-consuming plastering projects, especially in hot weather conditions.

If watertightness is important, such as in water- or liquid-retaining structures, special precautions must be taken. To achieve watertightness, the water-cement ratio should preferably be kept below 0.4, crack widths limited (see Chapter 4) and, if necessary, waterproofing coatings applied1 (see Section 6.3.3).

Mineral admixtures such as fly ash (ASTM C 618) can be added to the cement to increase workability and durability. Normally, 15 percent of the cement can be replaced with mineral admixtures without appreciably reducing the strength. Unlike conventional cement mortars, the pozzolanic admixtures are not added to reduce cement but to replace part of the fine aggregates to improve plasticity. The tendency for some natural pozzolans to absorb water and thus adversely affect hydration of the cement phase should be checked by measuring the water of absorption. Adding silica fume is reported to reduce porosity and improve strength, permeability, and durability;5 however, little experience exists so far in using silica fumes in ferrocement. Plastering may be hindered by an excessive amount of silica fume, which may render the mix stickier.

Air-entraining admixtures conforming to ASTM C 260 can be used to increase resistance to freezing and thawing. To insure good resistance to freezing and thawing, the air content should be consistent with the requirements of ACI 201.2R.

A quality matrix can be obtained without using any admixtures if experience has shown its applicability. In special exposure situations, admixtures (Section 6.5.2) or coatings (Section 6.3.3) should be used to improve serviceability.

Other admixtures not covered in ASTM standards are not recommended.

3.1.5 Mix proportioning—The ranges of mix proportions recommended for common ferrocement applications are: sand-cement ratio by weight, 1.5 to 2.5, and water-cement ratio by weight, 0.35 to 0.5. The higher the sand content, the higher the required water content to maintain the same workability. Fineness modulus of the sand, water-cement ratio, and sand-cement ratio should be determined from trial batches to insure a mix that can infiltrate (encapsulate) the mesh and develop a strong and dense matrix. Shrinkage is not a problem in ferrocement because of the high reinforcement content. Instead, in ferrocement mortars it is most important to maintain plasticity as a design criterion.

### Table 3.1—Guidelines for grading of sand

<table>
<thead>
<tr>
<th>Sieve size, U.S. standard square mesh</th>
<th>Percent passing by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 8 (2.36 mm)</td>
<td>80-100</td>
</tr>
<tr>
<td>No. 16 (1.18 mm)</td>
<td>50-85</td>
</tr>
<tr>
<td>No. 30 (0.60 mm)</td>
<td>25-60</td>
</tr>
<tr>
<td>No. 50 (0.30 mm)</td>
<td>10-30</td>
</tr>
<tr>
<td>No. 100 (0.15 mm)</td>
<td>2-10</td>
</tr>
</tbody>
</table>

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The moisture content of the aggregate should be considered in the calculation of required water. Quantities of materials should preferably be determined by weight. The mix should be as stiff as possible, provided it does not prevent full penetration of the mesh. Normally the slump of fresh mortar should not exceed 2 in. (50 mm). For most applications, the 28-day compressive strength of 3 by 6-m. (75 by 150-mm) moist-cured cylinders should not be less than 5000 psi (35 MPa).

### 3.2-Reinforcement

The reinforcement should be clean and free from deleterious materials such as dust, loose rust, coating of paint, oil, or similar substances.

Wire mesh with closely spaced wires is the most commonly used reinforcement in ferrocement. Expanded metal, welded-wire fabric, wires or rods, prestressing tendons and discontinuous fibers are also being used in special applications or for reasons of performance or economy.

#### 3.2.1 Wire mesh

Common wire meshes have hexagonal or square openings (Fig. 3.1). Meshes with hexagonal openings are sometimes referred to as chicken wire mesh or aviary mesh. They are not structurally as efficient as meshes with square openings because the wires are not always oriented in the directions of the principal (maximum) stresses. However, they are very 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 woven around straight transverse wires. Depending on the tightness of the weave, woven-mesh thickness may be up to three wire diameters. Welded-wire meshes have a higher modulus and hence higher stiffness than woven meshes; they lead to smaller crack widths in the initial portion of the load-deformation curve. Woven-wire meshes are more flexible and easier to work with than welded meshes. However, welding anneals the wire and reduces its tensile strength.\(^9\)

A three-dimensional mesh is also available (Fig. 3.2). A crimped keeper wire frictionally locks together three alternating layers of straight wire, thus forming a mesh with a total thickness of five wire diameters. The mesh is sufficiently thick so that, in some applications, only one layer is required. The frictional locking of the alternating layers of wire causes little springback and enables the mesh to be easily formed into a desired shape.

Wire meshes are also available in galvanized form. Galvanizing, like welding, reduces the tensile strength. Galvanized meshes used with regular reinforcing bars may react to produce hydrogen gas. Atomic hydrogen may embrittle the steel reinforcement. Hydrogen gas bubbles permeate freely through the hardened concrete.

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**Fig. 3.1-Types of wire mesh reinforcement used in ferrocement**

**Fig. 3.2-Schematic of three-dimensional mesh**
and may have an adverse effect on the matrix strength and permeability particularly at the interface of the reinforcement. As suggested in Reference 10, this reaction can be passivated by adding chromium trioxide to the mixing water in proportion of about 300 parts per million by weight of mortar. However, a substantially smaller proportion may be sufficient to prevent hydrogen evolution. 1 Epoxy-coated mesh may be substituted for galvanized mesh.

Reinforcing meshes for use in ferrocement should be evaluated for their susceptibility to take and hold shape as well as for their strength performance in the composite system. Common types and sizes of steel meshes used in ferrocement are described in Table 3.2. Standards for the mechanical properties of steel meshes commonly used in ferrocement are not available. Some design information on yield strengths and elastic modulus of meshes available in the United States can be found in Chapter 4. Suggested tests and test procedures to derive relevant mechanical properties of ferrocement and ferrocement meshes are given in Chapter 7.

### Table 3.2—Common types and sizes of steel meshes used in ferrocement

<table>
<thead>
<tr>
<th>Type</th>
<th>Shape</th>
<th>Fabrication</th>
<th>Designation, gage*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wire spacing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>in.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>in.</td>
</tr>
<tr>
<td>Wire mesh</td>
<td>Square</td>
<td>Woven or welded</td>
<td>3/4 x 3/4 No. 16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2 x 2 No. 19</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3 x 3 No. 22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4 x 4 No. 23</td>
</tr>
<tr>
<td></td>
<td>Welded</td>
<td></td>
<td>1 x 1 No. 14</td>
</tr>
<tr>
<td></td>
<td>Rectangular</td>
<td>Welded</td>
<td>2 x 1 No. 14</td>
</tr>
<tr>
<td></td>
<td>Hexagonal</td>
<td>Twisted</td>
<td>1 No. 18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 No. 20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1/2 No. 22</td>
</tr>
<tr>
<td></td>
<td>Expanded metal mesh</td>
<td>Diamond</td>
<td>Slit and drawn</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gage No. 18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gage No. 20</td>
</tr>
</tbody>
</table>

* American wire gage

and Collen in 1960. 9 Further research findings were reported by Byrne and Wright 11 Johnston and Mowat, 12 and Iorns. 13 The general conclusions were: 12, 13

— Expanded mesh reinforcement and welded-wire mesh offer approximately equal strength in their normal orientation.

— Expanded mesh reinforcement in its normal (LWD direction shown in Fig. 3.3) orientation results in a stiffer composite when compared with welded mesh. This tends to minimize crack widths in the early stages of loading.

— Expanded mesh reinforcement provides excellent impact resistance and excellent crack control.

Despite the aforementioned advantages, expanded metal meshes are not suitable for some applications. Lacking flexibility except in lighter gages, they are difficult to use in construction involving sharp curves except in cut strips. However, expanded metal is cost effective compared to wire reinforcement and should be considered as an alternative.

The most cost effective type of expanded metal is plaster lath expanded from a 9-in. (229-mm) strip of 24 gauge [0.023-in. (0.58-mm)] cold-rolled steel to a width of 27 in. (0.68 m) and cut into 8-ft (2.43-m) lengths for the building trades. This lath weighs 3.4 lb/yd² (1.84 kg/m²). A lighter gauge lath weighing 2.5 lb/yd² (1.35 kg/m²) is also widely available. Other expanded metals are specialty items manufactured in a variety of different gauges, dimensions, and mesh openings, which are used for such purposes as machinery guards, grills, and gradings.

In structural applications, it must be noted that expanded metals are much weaker in the direction in which the expansion took place. The orientation of each layer in the ferrocement composite must be considered, as is done with plywood. The global efficiency factors recommended in Chapter 4 can be used in design.

### 3.2.4 Bars, wires, and prestressing strands—Reinforcing bars and prestressing wires or strands are sometimes used in combination with wire meshes in relatively thick ferrocement.
cement elements or in the ribs of ribbed or T-shaped elements.

Reinforcing bars should conform to ASTM A 615, A 616, or A 617. Usually reinforcing bars are Grade 60 steel with a minimum yield strength of 60,000 psi (414 MPa) and a tensile strength of about 90,000 psi (621 MPa). Prestressing wires and strands, whether prestressed or not, should conform to ASTM A 421 and A 416, respectively.

3.2.5 Discontinuous fibers and nonmetallic reinforcement
- Addition of fibers to ferrocement may enhance the properties of the matrix considerably. The addition of fibers retards crack growth and also permits the use of much heavier gauge wire mesh. The various types of steel fibers and their specific use are discussed in ACI 544.3R and in ASTM A 820.

Another type of fiber reinforcement consists of irregularly arranged continuous filaments of synthetic or natural organic fibers such as jute and bamboo. If organic materials are used, care should be taken to conduct appropriate investigations to insure the strength and durability of the finished ferrocement product.

CHAPTER 4-DESIGN CRITERIA

4.1-Design methods
The analysis of a ferrocement cross section subjected to either bending, or bending and axial load, whether based on strength or working stresses, is similar to the analysis of a reinforced concrete beam or column having several layers of steel (Fig. 4.1). The following guidelines are normally used for the design of ferrocement structures. When special provisions are not cited, the ACI Building Code Requirements for Reinforced Concrete (ACI 318) should govern.

In design of ferrocement structures, members should be proportioned for adequate strength in accordance with provisions of this guide using load factors and strength-reduction factors specified in ACI 318.

Alternatively, ferrocement members may be designed using service loads and permissible service-load stresses in accordance with the provisions of Section 4.3 of this chapter.

All members should also be designed to satisfy serviceability criteria in accordance with provisions of Section 4.4 of this chapter.

The width and spacing of cracks in ferrocement will be less than for conventional reinforced concrete at service loads because of the high specific surface and close spacing of the layers of mesh reinforcement.

4.2-Strength requirements
Ferrocement structures and structural members should have a design strength at all sections at least equal to the required strengths for the factored load and load combinations stipulated in ACI 318.

Required strength \( U \) to resist dead load \( D \) and live load \( L \) should be determined using ACI 318, Section 9.2, “Required Strength.”

Design strength provided by a member or cross section in terms of axial load, bending moment, shear force, or stress shall be taken as the nominal strength calculated in accordance with requirements and assumptions of ACI 318, multiplied by the strength reduction factor \( \phi \) to satisfy the general relationship

\[
U \leq \phi N
\]  

(4-1)
where $U$ is the factored load (equal to the minimum required design strength), $N$ is the nominal resistance, and $\phi$ is a strength-reduction factor defined in Section 9.3 of ACI 318, “Design Strength.”

Design strength for the mesh reinforcement should be based on the yield strength $f_y$ of the reinforcement but should not exceed 100,000 psi (690 MPa). Such a high limit on yield strength is justifiable for ferrocement because of its high reinforcement content, ductility, and very small crack widths that results from the high specific surface Sr close spacing of the reinforcement. Recommended design yield strengths of various mesh reinforcement representative of meshes available in the U.S. are given in Table 4.1.20 These could be used for design in lieu of test data. When tests for determination of yield strength are needed, they should be conducted in accordance with Sections 7.1.3 and 7.1.4 of this guide.

4.2.1.1 Assumptions-Strength design of ferrocement members for flexure and axial loads should be based on the following assumptions and on satisfaction of equilibrium and compatibility of strains.

a. Strain in reinforcement and mortar (concrete) should be assumed directly proportional to the distance from the neutral axis.

b. Maximum strain at extreme mortar (concrete) compression fiber should be assumed equal to 0.003.

c. Stress in reinforcement below specified yield strength $f_y$ should be taken as $E_r$ times steel strain where $E_r$ is defined in Table 4.1 and Section 2.1.3. $E_r$ could also be determined from tests such as those described in Sections 7.1.3 and 7.1.4 of this guide. For strains greater than that corresponding to $f_y$, stress in reinforcement shall be considered independent of strain and equal $f_y$.

d. Tensile strength of mortar (concrete) shall be neglected in flexural strength calculations.

e. Relationship between mortar (concrete) compressive stress distribution and mortar (concrete) strain may be considered satisfied by the use of the equivalent rectangular concrete stress distribution defined in Section 10.2 of ACI 318.

4.2.1.2 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 follows20

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

where:

- $A_{si}$ = effective area of reinforcement for mesh layer $i$
- $\eta$ = 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 (concrete) section

Table 4.1-Minimum values of yield strength and effective modulus for steel meshes and bars recommended for design

<table>
<thead>
<tr>
<th>Yield strength $f_y$ (ksi)</th>
<th>Effective modulus $E_r$ (ksi)</th>
<th>Effective modulus $E_{r,\text{long}}$ (ksi)</th>
<th>Effective modulus $E_{r,\text{max}}$ (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woven square mesh</td>
<td>65 (450)</td>
<td>20 (138)</td>
<td>24 (165)</td>
</tr>
<tr>
<td>Welded square mesh</td>
<td>65 (450)</td>
<td>29 (200)</td>
<td>29 (200)</td>
</tr>
<tr>
<td>Hexagonal mesh</td>
<td>45 (310)</td>
<td>15 (104)</td>
<td>10 (69)</td>
</tr>
<tr>
<td>Expanded metal mesh</td>
<td>45 (310)</td>
<td>20 (138)</td>
<td>10 (69)</td>
</tr>
<tr>
<td>Longitudinal bars</td>
<td>60 (414)</td>
<td>29 (200)</td>
<td>-</td>
</tr>
</tbody>
</table>

$A_{si} = \eta V_{fi} A_c$ (4-2)
Table 4.2—Recommended design values of the global efficiency factor $\eta$ of reinforcement for a member in uniaxial tension or bending

<table>
<thead>
<tr>
<th></th>
<th>Woven square mesh</th>
<th>Welded square mesh</th>
<th>Hexagonal mesh</th>
<th>Expanded metal mesh</th>
<th>Longitudinal bars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global efficiency factor $\eta_L$</td>
<td>0.50</td>
<td>0.50</td>
<td>0.65</td>
<td>0.65</td>
<td>1.00</td>
</tr>
<tr>
<td>Transverse $\eta_T$</td>
<td>0.50</td>
<td>0.50</td>
<td>0.30</td>
<td>0.20</td>
<td>0.00</td>
</tr>
<tr>
<td>At 45 deg. $\eta_T$</td>
<td>0.35</td>
<td>0.35</td>
<td>0.30</td>
<td>0.30</td>
<td>0.70</td>
</tr>
</tbody>
</table>

The global efficiency factor $\eta$, when multiplied by the volume fraction of reinforcement, gives the equivalent volume fraction (or equivalent reinforcement ratio) in the loading direction considered. In effect, it leads to an equivalent (effective) area of reinforcement per layer of mesh in that loading direction. For square meshes, $\eta$ is equal to 0.5 when loading is applied in one of the principal directions. For a reinforcing bar loaded along its axis, $\eta = 1$.

Some information on the derivations of $\eta$ and on other concepts concerning efficiency factors can be found in References 12, 24, and 25. In lieu of the values derived from tests for a particular mesh system, the values of $\eta$ given in Table 4.2 are for common types of reinforcement and loading directions can be used. The global efficiency factor applies whether the reinforcement is in the tension or the compression zones of the member. Definitions of reinforcement directions are illustrated in Fig. 2.1

Note that the value of $\eta_L = 0.2$ for expanded metal mesh (Table 4.2) may not always be conservative, particularly in thicker sections in flexure with the mesh oriented in the SWD (short way diamond). The values in Table 4.2 should be used for sections 2 in. (50 mm) or less in thickness, and tests conducted for global efficiency values for sections of 2 in. (50 mm) in thickness.

4.2.2 Tension 27-29. 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

$$N_n = A_s f_y$$  \hspace{1cm} (4-3)

where

- $N_n =$ nominal tensile load resistance in direction considered
- $A_s =$ effective cross-sectional area of reinforcement in direction considered
- $f_y =$ yield stress of mesh reinforcement

The value of $A_s$ is given by

$$A_s = \frac{\sum A_i}{\sum N_i}$$  \hspace{1cm} (4-4)

where

- $N =$ number of mesh layers
- $A_{si} =$ effective area of reinforcement for mesh layer $i$ (Eq. 4-2)

4.2.3 Compression—As a first approximation, the nominal resistance of ferrocement sections subjected to uniaxial compression can be derived from the load-carrying capacity of the unreinforced mortar (concrete) matrix assuming a uniform stress distribution of 0.85 $f'_c$, where $f'_c$ is the design compressive strength of the mortar matrix. However, the transverse component of the reinforcement can contribute additional strength when square or rectangular wire meshes are used, while expanded mesh contributes virtually no strengthening beyond that achieved by the mortar alone. 12 Slenderness effects of thin sections, which can reduce the load-carrying capacity below that based on the design compressive strength, should be considered.

4.2.4 Shear—No test data are available on the shear capacity of ferrocement slabs or beams in flexure.

4.3-Service load design

4.3.1 Flexure—for investigation of stresses at service loads, straight-line theory (for flexure) shall be used with the following assumptions.

a. Strains vary linearly with the distance from the neutral axis.

b. Stress-strain relationships of mortar (concrete) and reinforcement are linear for stresses less than or equal to permissible service load stresses.

c. Mortar (concrete) resists no tension.

d. Perfect bond exists between steel and mortar (concrete).

To compute stresses and strains for a given loading, the cracked transformed section can be used. The effective area of each layer of mesh reinforcement should be determined from Eq. (4-2). The same value of modular ratio, $n_r = E_r/E_c$, is commonly used for both tensile and compressive reinforcement. Recommended design values of $E_r$ are given in Table 4.1. Once that neutral axis is determined, the analysis proceeds as for reinforced concrete beams or columns having several layers of steel and subjected to pure bending.

4.3.1.1 Allowable tensile stress—The allowable tensile stress in the mesh reinforcement under service conditions may generally be taken as 0.60 $f_y$, where $f_y$ is the yield strength. Values of $f_y$ given in Table 4.1 are representative of steel meshes available in the United States and may be used for design. Tests to determine $f_y$ for a particular mesh system are described in Chapter 7. For liquid retaining and sanitary structures (refer to ACI 350R), it is preferable to limit the allowable tensile stress to 30 ksi (207 MPa). Consideration can be given to increasing the allowable tensile stresses if crack-width measurements on a model test indicate that a higher stress will not impair performance.
4.3.1.2 Allowable compressive stress—The allowable compressive stress in either the mortar (concrete) or the ferrocement composite may be taken as 0.45 $f'_c$, where $f'_c$ is the specified compressive strength of the mortar. Measurements of the mortar compressive strength may be obtained from tests on 3 x 6-in. (76 x 152-mm) cylinders.

4.4-Serviceability

Ferrocement members and structures should as a minimum meet the intent of the serviceability requirements of ACI 318 except for the concrete cover.

4.4.1 Crack-width limitations—It is recommended that the maximum value of crack width under service load conditions be less than 0.004 in. (0.10 mm) for noncorrosive environments and 0.002 in. (0.05 mm) for corrosive environments and/or water-retaining structures. It should be noted that the recommended crack widths are smaller for ferrocement than values suggested by ACI 318. Crack widths may be measured from model tests or their values may be estimated using acceptable prediction equations such as those recommended in ACI 549R or Reference 31.

4.4.2 Fatigue stress range—For ferrocement structures to sustain a minimum fatigue life of two million cycles, the stress range in the reinforcement must be limited to 30 ksi (207 MPa). A stress range of 36 ksi (348 MPa) may be used for one million cycles. Higher values may be considered if justified by tests.

4.4.3 Corrosion durability—Particular care should be taken to insure a durable mortar matrix and optimize the parameters that reduce the risk of corrosion (see also Section 3.1.4 of this report).

4.4.4 Deflection limitation—Because ferrocement in thin sections is very flexible and its design is very likely to be controlled by criteria other than deflection, no particular deflection limitation is recommended.

4.5-Particular design parameters

a. The cover of the reinforcement should be about twice the diameter of the mesh wire or thickness of other reinforcement used. However, a smaller cover is acceptable provided the reinforcement is not susceptible to rapid corrosion, the surface is protected by an appropriate coating, and the crack width is limited to 0.002 in. (0.05 mm). For ferrocement elements of thickness less than one in. (25 mm), a cover of the order of 0.08 in. (2 mm) has given satisfactory results.

b. For a given ferrocement cross section of total thickness $h$, the recommended mesh openings should not be larger than $h$.

c. For nonprestressed water-retaining structures the total volume fraction of reinforcement should not be less than about 3.5 percent and the total specific surface of reinforcement should not be less than 4 in. $^2$/in. $^3$ (0.16 mm$^2$/mm$^3$).

d. In computing the specific surface of the reinforcement, the contribution of fibers added to the matrix may be considered while the fiber contribution may be ignored in computing the volume fraction of reinforcement.

e. If skeletal reinforcement (see definition in Section 5.2.1) is used, it is recommended that the skeletal reinforcement not occupy more than 50 percent of the thickness of the ferrocement composite.

f. For a given volume fraction of reinforcement, better performance—not in terms of strength, but in terms of crack widths, water-tightness, and ductility—can be achieved by uniformly distributing the reinforcement throughout the thickness and increasing its specific surface. While for certain applications, a minimum of two layers of mesh would be acceptable, the advantages of ferrocement are mostly realized when more than two layers are used.

4.6-Examples

Typical examples for the analysis and design of ferrocement flexural elements in accordance with the procedures described in this chapter are provided in Appendix B.

4.7-Design aids

The computation of the nominal moment strength of ferrocement sections (as illustrated in Appendix B) can be time-consuming unless a computer is used. Following an extensive computerized parametric evaluation, Naaman and Homrich derived the following nondimensional equation to predict the nominal moment strength of ferrocement beams subjected to pure bending

$$\frac{M_n}{f'_c bh^2 \eta} = 0.005 + 0.422 \frac{V}{f'_c I'} - 0.0772 (\frac{V}{f'_c I'})^2$$

(4-5)

A design graph representing Eq. (4-5) is given in Fig. 4.2. In developing these design aids the net mortar cover to the first layer of mesh was assumed equal to 0.06 in. (1.5 mm), a minimum of two mesh layers was considered throughout, and when more than two layers of mesh were used they were assumed equally spaced. The application of Eq. (4-5) and Fig. 4.2 to the examples of Appendix B is illustrated in Appendix C.

CHAPTER 5-FABRICATION

5.1-General requirements

The materials used in ferrocement production and their selection have already been discussed in Chapter 3 of this report. This chapter discusses the mixing, placing, and handling of materials used in ferrocement construction.

5.1.1 Planning—It is generally believed that for any fabrication method with ferrocement, plastering has to be continuous through the completion of the job. This may require a large number of workers involved in plastering
Fig. 4.2-Chart for strength design of ferrocement in bending

and in maintaining a constant supply of materials during work, most often in confined work spaces. Adequate bond at cold joints may be achieved through surface roughness or treatment with bonding agents. Retarders may be useful in large time-consuming plastering projects, especially in hot weather conditions.

5.1.2 Mixing-Mixing of the mortar-like materials for ferrocement may be accomplished in a plaster (mortar) mixer with a spiral blade or paddles inside a stationary drum or in a pan-type mixer. To provide uniform mixes, the use of rotating drum mixers with fins affixed to the sides is discouraged. Any method, including hand mixing, which assures a homogeneous mixture of ingredients should be satisfactory. Mix ingredients should be carefully batched by weight, including the water, and added or charged in the mixer so that there is no caking. Mix water should be accurately weighed so that the water-cement ratio is controlled. The water-cement ratio should be as low as possible but the sand-cement ratio should be adjusted to provide a fluid mix for initial penetration of the armature followed by a stiffer, more heavily sanded mix at the finish. Mortar should be mixed in batches so that mortar is plastered within an hour after mixing. Retempering of the mortar should be prohibited. Batching will reduce the waste of mortar due to partial setting.

In designing the mortar mix, a recommended procedure used with plaster-type mixers is to put the water in first, then the cement and pozzolan, if used, to form a slurry. Then enough aggregate is added to obtain the desired mix consistency. Rotating-drum mixers used for conventional concrete depend on coarse aggregates for efficient mixing and are not, therefore, well-suited for ferrocement mortars. They may be used if care is taken to assure complete mixing by adding the dry ingredients gradually. The final desired consistency will vary somewhat with the construction method selected (see Section 5.2).

5.1.3 Mortar placement-Mortar is generally placed by hand plastering. In this process, the mortar is forced through the mesh. Alternately the mortar may be shot through a spray-gun device. Construction methods are discussed in greater detail in Section 5.2.

5.1.4 Finishing-Surfaces must be finished to assure the proper cover to the last mesh layer. The surface finish should be slightly roughened if a surface coating is to be bonded later. A steel trowel is generally not recommended for finishing boat hulls.

Surfaces that are too smooth may be mechanically abraded by sandblasting or other means of mechanical abrasion. Alternatively, such surfaces may be etched with phosphoric acid. The use of muriatic acid can cause corrosion of reinforcement which lies close to the surface. Phosphoric acid is preferable in this regard but may leave a residue which is insoluble in water and therefore cannot be readily washed away. Thus phosphoric acid is recommended if such residue will not interfere with specified finishes and mild solutions of muriatic acid may be applied with proper attention to corrosion potential. ACI 201.2R, however, reports that the reaction of phosphoric acid with concrete produces a non-water-soluble product that cannot be washed away as easily as that due to muriatic acid. Hence a mild solution of muriatic acid may be preferable in some cases. Additional care must be taken when plastering around openings.

5.1.5 Curing-Moist or wet curing is essential for ferrocement concrete construction. The low water-cement ratio and high cement factors create a demand for large quantities of free water in the hydration process, and the amount permitted to evaporate into the air should be kept to an absolute minimum. The use of fogging devices under a moisture-retaining enclosure is desirable. A double layer of soaked burlap covered with polyethylene or a soaker hose are also good procedures. Continuous wetting of the surface or of wet burlap or the like requires constant attention to avoid dry spots. Latex used in the surface mortar holds in moisture in and assists the curing process. Curing should start within a reasonable time after application of the finishing layer.

5.2-Construction methods
There are several means of producing ferrocement. All methods require high-level quality-control criteria to achieve the complete encapsulation of several layers of reinforcing mesh by a well-compacted mortar or concrete matrix with a minimum of entrapped air. The most appropriate fabrication technique depends on the nature of the particular ferrocement application; the availability of mixing, handling, and placing machinery; and the skill and cost of available labor. However, field and factory experience has shown that only a modest amount of training, production standardization, and preparation is required to produce ferrocement of consistent quality.

A number of procedures for the production of ferrocement are discussed here and represent the current state of the art. The procedure used on a particular project should be based on the experience and the ingenuity of the builders and the judgment of the engineer.
The objective of all construction methods is to thoroughly encapsulate a layered mesh system with a plastic portland cement matrix. This is satisfied to varying degrees, depending on the particular application, by the use of four principal application procedures: the armature system, closed-mold system, integral-mold system, and open-mold system. Within these four generic ferrocement molding systems, mortar may be applied by a variety of production techniques, including direct plastering and shotcreting. Variations of these basic systems may be engineered to incorporate factory production techniques, such as flat-bed vibrocasting and vacuum extraction.

Of the possible machine-assisted procedures, the use of dry-mix shotcrete is not recommended due to the difficulty of achieving a uniform matrix impregnation when rebound materials and mesh layers are present. Wet-mix shotcrete, with air added to the mix only at the nozzle to create the spray, is the preferred shotcrete method. This system is suitable for all types of ferrocement where mortar volumes justify the setup of needed machinery.

Each of the generic fabrication systems listed above are discussed separately. Some of the cautions and recommendations applicable to a particular system may also apply to the others, depending of the particular application. All systems have been successfully used in the construction of ferrocement structures, the vast majority in marine applications, i.e., boats, barges, bulkheads, piers, and docks.

In most ferrocement fabrication, the mesh sheets should be staggered or the ends lap-spliced at least two mesh openings to insure continuity of the steel. Alternating the direction of the principal axis of successive mesh layers by 90 deg to achieve continuity and isotropy may be desirable.

5.2.1 Armature system—The armature system is a framework of tied reinforcing bars (skeletal steel) 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 Fig. 5.1.

The skeletal steel can assume any shape. Diameter of the steel bars depends on the size of the structure. Skeletal steel is cut to specified lengths, bent to the proper profile, and tied in proper sequence. Sufficient embedment lengths should be provided to ensure continuity. For bar sizes commonly used in ferrocement (#2 or less), lap lengths from 9 to 12 in. (230 to 300 mm) are usually sufficient. The required number of layers of mesh are tied to each side of the skeletal steel frame.

A list of advantages and disadvantages in using this system is summarized below. For a particular application even one advantage may outweigh all listed disadvantages.

5.2.1.1 Advantages
a. Good mesh infiltration if mortar is pushed through the mesh.
b. No form material is required other than that needed to support the armature.
c. Repairs may proceed from both sides, and areas requiring touchup are visible.

5.2.1.2 Disadvantages
a. Reduced performance associated with embedment of reinforcement (see Section 5.2.1.3).
b. Added weight associated with use of bars or rods.
c. Possible galvanic corrosion between galvanized mesh and steel framework.
d. Time-consuming tying and bracing are required to stabilize framework and mesh layers under the pressures of plastering and the weight of mortar.
e. Two or more layers of mesh may be required on each side of the rod framework.
f. Application of mortar from one side may be difficult for thick or dense mesh systems, resulting in internal voids.

5.2.1.3 Discussion—Performance may be adversely affected by three primary factors: (1) the use of relatively large-diameter, rigid bars in a thin section; (2) the matrix in the space formed by the armature system contributing to weight but not to flexural strength; and (3) air voids trapped within the ferrocement during the plastering process. U.S. Naval Laboratory tests have demonstrated a remarkable increase in strength-to-weight ratio where only mesh is used.35-37

A certain amount of inefficiency is associated with the
armature system since a high percentage of the total steel used is located at or near the midsection of the bending cross section. Thus, weight is added to the structure without significant increase in strength. Further, the overall thickness of ferrocement sections produced in the fully plastered procedure is increased due to the use of armature bars in the form of a grid and tied together. If too few bars or rods are used and are not tied at a sufficient number of intersections, bulging may occur due to plastering pressures or simply the weight of the mortar. Often the weight of the framework and wet mortar can cause enough local and general distortion from the desired geometry that substantial shoring is required to prevent bulging. Bulging may result in thick, under-reinforced mesh sections that may later crack and spall.

5.2.2 Closed-mold system-Themortar is applied from one side through several layers of mesh or mesh and rod combinations that have been stapled or otherwise held in position against the surface of a closed mold, i.e., a male mold or a female mold. The mold may remain as a permanent part of the finished ferrocement structure. If removed, treatment with release agents may be needed.

The use of the closed-mold system represented in Fig. 5.2 tends to eliminate the use of rods or bars, thus permitting an essentially all-mesh reinforcement; it requires that plastering be done from one side.

5.2.2.1 Advantages

a. Molds are reusable.
b. The molds reinforce the structure sufficiently to allow moving it or reorienting it for curing.
c. The system is especially well suited for the patented layup method of mortar application, whereby mesh is placed in the mortar rather than the mortar placed in the mesh.32,33

5.2.2.2 Disadvantages

a. Large and costly molds are uneconomical for one-time applications.
b. Depending on the mold material, it may be difficult to keep the mesh together and close to the mold.
c. In plastering onto and through mesh reinforcement, internal voids and incomplete penetration of the mesh cannot be detected.

5.2.2.3 Discussion-The patented method of laying successive mesh layers in a bed of fresh mortar is facilitated by spray application of mortar layers and provides excellent mesh encapsulation. To assure that mesh layers do not pop out against the closed mold, a thin mortar cover layer is placed and allowed to set, but not dry out, prior to application of a second mortar layer and the first mesh layer. This first mortar layer is generally about 1/8 in. (3 mm) thick. The closed mold system is ideal for factory production.

Rolling in layers of mesh is aided by using an inexpensive and simply fabricated tool which is similar to a four-bladed disk harrow.33,34

5.23 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 mortar setting, a rigid but low-quality ferrocement mold onto which further application of reinforcing mesh and mortar are applied on both sides. Alternately, the integral mold may be formed using rigid insulation materials, such as polystyrene or polyurethane, as the core. A schematic description of this system is shown in Fig. 5.3.

The integral-mold system, as described herein, refers to any mold system which is left inside the ferrocement, or in which the mold is left permanently in contact with the ferrocement, such as to obtain an interior wood finish, or to core-type construction systems in which ferrocement layers are applied to each side of a core material. The core may be rigid foam insulation or, in the case of closed molds, it may consist of either a ferrocement or near-ferrocement material. The term “near” refers to precast products having a minimum number of layers of reinforcement, perhaps only two, and using lightweight or low-quality mortar to produce a rigid core.

5.2.3.1 Advantages

a. Excellent rigidity and insulating properties when insulating core is used.
b. A rigid mold can be formed using precast elements. No wood or other mold materials would then be required.
c. The layup method may be applied to both sides of the integral mold.
d. The layup method may be used against a closed mold, covered by the core materials, which are in turn laid up with another ferrocement layer.

e. If rods must be used to form or reinforce the precast core, their thickness can be filled with lightweight concrete mortar.

f. The precast core generally requires much less tying than, for example, the armature system.

5.2.3.2 Disadvantages

a. May require special details for shear connection between rigid ferrocement layers, especially across insulating cores.

5.2.3.3 Discussion-This method is ideal for field operations. The possible variations are unlimited, provided adequate attention is paid to structural detailing requirements that assure the completed system will function as a composite.

5.2.4 Open-mold system-In the open-mold system, mortar is applied from one side through layers of mesh or mesh and rods attached to an open mold made of a lattice of wood strips (ribbands) and station frames common to boat building. The form, shown in Fig. 5.4, is coated with a release agent or entirely covered with polyethylene sheeting (thereby forming a closed but nonrigid and transparent mold) to facilitate mold removal and permit repair and observation during the mortar application process.

This system is similar to the closed-mold system in which the mortar is applied from one side, at least until the mold can be removed. It enables at least part of the underside of the mold to be viewed and repaired, where necessary, to assure complete and thorough impregnation of the mesh.

5.2.4.1 Advantages

a. Similar to those of the closed-mold system but with far better control of the quality of the resulting ferrocement product.


5.2.4.2 Disadvantages

a. Requires finishing both sides, i.e., including the mold side, after removal of open-mold elements.

b. Requires construction of an extensive mold and shoring system which may or may not be reusable.

CHAPTER 6—MAINTENANCE AND REPAIR

6.1-Introduction

Terrestrial structures are susceptible to deterioration from pollutants in ground water and those that precipitate from the air (acid rain). Marine structures are attacked by sulfates and chlorides in seawater. Environmental temperature and humidity variations also affect ferrocement durability and maintenance procedures.

Maintenance primarily involves detecting and filling voids, replacing spalled cover, providing protective coatings, and cosmetic treatment of surface blemishes. Not all of the usual methods to treat conventional concrete surfaces can be applied to ferrocement. For example, due to the thin cover in ferrocement, muriatic acid (hydrochloric...
acid) should be used with extreme caution. Phosphoric acid and other nonchloride cleaners should be the specified alternative (see Section 5.1.4).

Repairs seldom involve large quantities of materials and are usually accomplished by hand. Emphasis should be placed on ability of the repair material to penetrate the mesh cage, to fully coat the reinforcing to inhibit corrosion, and to bond to the substrate. Rapid set and strength gain may be overriding considerations for emergency repairs. Protective coatings must bond well and be alkali tolerant, thermally compatible, and resistant to environmental pollutants and ultraviolet radiation, if exposed.

Some useful information can be derived from literature on bridge deck repair in the Guide for Repair of Concrete Bridge Superstructures by ACI Committee 546. Terrestrial ferrocement structures are seldom exposed to the severe conditions encountered by bridge decks, but the recommendations and procedures reported by Tut-hill and other references listed in Reference on restoration of deteriorated concrete provide a basis for understanding many repair methods that are applicable to ferrocement.

Available literature that details the methods for repair of ferrocement is generally non-technical and written for repair of boat hulls. The most complete repository of information on ferrocement maintenance is located at the International Ferrocement Information Center (IFIC), Asian Institute of Technology, in Bangkok, Thailand. IFIC publishes the Journal of Ferrocement, which is devoted to research and applications of ferrocement.

This chapter is intended to provide information on the most common generic compounds that are used in proprietary patching materials. Proprietary materials should be reviewed before using them to patch ferrocement. Many materials have been tested by government agencies, and over 300 are listed in the “Patching Materials” section of SPHEL, Special Product Evaluation List.

6.2-Blemish and stain removal

6.2.1 General—Because ferrocement is usually less porous than conventional concrete, stains do not penetrate very deeply in the mortar matrix. The thin cover of mortar over ferrocement reinforcement also means that greater care must be taken when preparing the surface. Reference 40 discusses stain removal for concrete. Bulletins on the subject are based on the results of a cooperative investigation by the U.S. Bureau of Standards and the National Association of Marble Dealers.

All sources agree that even weak acids, such as oxalic, carbonic, and acetic, may etch concrete if they are left for extended lengths of time and not neutralized or completely flushed off.

6.2.2 Construction blemishes—Construction blemishes are often caused by improper selection or use of materials, faulty workmanship, uneven evaporation, and uneven curing. Other causes include:

1. Cement from different mills will cause color variation, although most of the color in mortar is due to the sand component. Where appearance is critical, care should be taken to obtain sand from a single source and have it thoroughly washed.

2. Mottling results from the use of calcium chloride or high-alkali cement combined with uneven curing.

3. The use of polyethylene sheet material to cover surfaces promotes uneven curing.

4. The water-cement ratio affects tone and surface appearance. Low water-cement ratios will result in a darker appearance.

5. Hard steel troweling densifies the surface, causing more rapid drying and also leaving a darkened surface.

6.2.3 Stain removal—Treatment of stains should be done promptly after the discoloration appears. Thorough flushing and brushing with a stiff bristle brush and detergent is the first approach. If this is ineffective, a dilute (about three percent) solution of phosphoric or acetic acid can be applied. Another chemical treatment considered safe and effective is a 20 to 30 solution of diammonium citrate, a mild acid which attacks calcium carbonates and calcium hydroxide. This treatment makes the surface more porous and promotes hydration.

When a stain has penetrated too deeply to be removed by surface chemical application and scrubbing, a poultice or a bandage may be needed. A poultice is intended to dissolve the stain and absorb it into the poultice. The poultice is made by mixing one or more chemicals such as a solution of phosphoric acid with a fine inert powder such as talc, whiting, hydrated lime, or diatomaceous earth to form a paste. The paste is spread in a thick layer over the stain and allowed to dry. A bandage may consist of a few layers of cloth or paper toweling soaked in a chemical solution. More than one application of a poultice or bandage may be needed for stubborn stains.

Caution: Most of the chemicals used to remove stains are toxic and require safeguards against skin contact and inhalation. Whenever acids are used, surfaces should first be saturated with water or the dissolved stain material may migrate deeper into the concrete and reappear at a later date as efflorescence.

6.2.4 Efflorescence—When water-bearing salts migrate to exposed surfaces of concrete, evaporation will result in the deposit of salts on the surface. This process is termed efflorescence. It occurs most readily in porous concrete so it should not be a problem for ferrocement made with a water-cement ratio of not more than 0.4 and is well compacted to be free of voids. Voids, if present, may fill with water (in certain applications) and efflorescence will appear on surfaces around the place where water gained entrance to the void.

Treatment consists of breaking into the void, as with a hammer, and replastering, or drilling into the void with a masonry bit and injecting a nonshrinking cement grout.

6.3-Protective surface treatments

6.3.1 General—Good-quality mortar has excellent re-
sistance to weathering. General construction usually does not require any protective surface treatment. However, the application of protective surface treatments can improve the performance of ferrocement and extend its useful service life. Surface treatments can be used to improve appearance, harden the surface, and reduce permeability, thus guarding against the corrosive action of acids, alkaline salts, and organic substances.

Appendix D of this report, and ACI Committee 515’s report, *A Guide to the Use of Waterproofing, Dampproofing, Protective, and Decorative Barrier Systems for Concrete*, provide an extensive list of substances that may come in contact with ferrocement and recommend preventive measures for those which may be deleterious.

**6.3.2 Hardeners**—The most commonly available hardener often recommended is sodium silicate, also called water glass. It is quite viscous and must be diluted with water to achieve penetration. The amount of dilution depends on the quality of the silicate and the permeability of the concrete. Silicate of about 42.5 degree Baume gravity diluted in the proportion of 1 gal. (3.78 l) of silicate with 4 gal. (15.12 l) of water usually makes a good solution for the first application. A stronger solution can be used for succeeding coats. Each coat must be completely dry before the next coat is applied.

Other hardeners which seal and prepare the surface for application of oil-base paints are magnesium flusilicate and zinc flusilicate. The treatment consists of two or more applications. A solution containing about 1 lb. (0.45 kg) of flusilicate crystals per gal. of water should be used for the first application; and a solution containing 2 lb/gal. (0.24 kg/l) should be used for subsequent applications. After the last application has dried, the surface should be brushed and washed with water to remove any crystals that may have formed.

**6.3.3 Coatings**—Epoxy and polyurethane compounds are the most widely mentioned protective coatings for concrete. They have excellent adhesion to ferrocement mortar and are alkali resistant. Some compounds degrade under exposure to ultraviolet (UV) rays, become brittle with age, and have a much higher coefficient of expansion than concrete. They have not performed well on surfaces exposed to sunlight or subjected to wide thermal variation. A thick epoxy coating is stronger than the cement substrate and very likely will shear below the bondline of surfaces exposed to wide temperature changes such as boat decks. As the sealing and bond characteristics of epoxies are desirable, a satisfactory deck finish can consist of one or two thin coats of epoxy, followed by one or more coats of polyurethane containing a UV inhibitor.

Polyurethanes, especially those furnished in two-part mixtures, are considered to offer the best resistance to abrasion among the commonly available coatings, while those formulated from acrylics provide the best resistance to sunlight and weathering. An example can be found in Reference 44. Acrylic latex house paints are widely used on ferrocement and have the advantage of being water-based so they can be applied to damp surfaces.

For any surface opposite a surface sealed with an impermeable coating, an acrylic coating (or silicone and silane coating) formulated to allow the escape of water vapor should be specified.

**6.3.4 Sheathing**—Fiberglass laminates often have been used on boat hulls to seal the surface against leakage and improve impact resistance; however, the polyester resins used in the fiberglass boat building industry have poor adhesion to ferrocement, so epoxy resins are preferred.

Not all applications of epoxy-based fiberglass laminates have been successful. Several factors, such as ambient temperature during sheathing, soiled mortar surface, or thermal incompatibility of the materials, may contribute to failure of the sheathing.

**6.4 Damage repair**

**6.4.1 General**—Repairs have received little attention in ferrocement literature beyond instructions to remove loose mortar, push the armature back into shape, and replaster.

Hagenbach reports on several cases and tells how repairs were made, including one repair made under water. Donovan and Baugh cover several case studies on the grouting and repair of ferrocement hulls. Bowen reports on the reconstruction of a boat thought to be beyond repair. Watkins describes extensive damage and repair to a 53 ft (16.15 m) fishing vessel.

Biggs points out that damage must be repaired quickly because, while ferrocement has good resistance to a single impact, repeated impacts at load levels well below the initial impact will pulverize the mortar. A similar danger exists when major cracks are allowed to expand under cyclic loading.

**6.4.2 Common types of damage**

**6.4.2.1 Delaminations**—Delaminations occur when ferrocement splits between layers which may be in laminated construction. This may be due to springing back or bridging of the mesh during construction. Delamination sometimes occurs at or near the neutral axis under impact or flexure when there are many voids in the interior layers. Such areas give off a hollow sound when tapped with a hammer or stroked with a steel bar.

Pressure from expansive corrosion products may also cause delamination. The *Guide for Repair of Concrete Bridge Superstructures*, by ACI Committee 546 recommends tests to determine whether corrosion of the reinforcement is active, but as a practical matter, most ferrocement can be opened up for visual inspection.

**6.4.2.2 Spalls**—A spall is defined in ACI 116R as a depression resulting when a fragment is detached from a larger mass by a blow, by the action of weather, by pressure, or by expansion within the mass. Spalls are referred to as large when their size exceeds approximately $\frac{3}{4}$ in. (19 mm) in depth or 6 in. (152 mm) in any dimension. Spalls are usually caused by corrosion of steel, which causes an expansive pressure within the ferrocement. Chlorides in the concrete greatly increase the potential
for corrosion of the steel. Under such conditions, con-
tinued spalling is likely and the repair of local spall areas
may even promote the deterioration of the concrete be-
cause of the presence of dissimilar materials.

An area of steel corrosion and chloride-contaminated
concrete may be considerably larger than the area of
spalled concrete, and if only the spall area is repaired, a
continuing repair program will probably be required.

6.4.2.3 Scaling—Scaling is defined as local flaking or
peeling away of material near the surface of the mortar.
It is caused by the generation of internal pressures during
freezing of water trapped in saturated voids.

6.4.2.4 Fire damage—No definitive study of fire re-
 sistance has yet been published, although some work has
been done under the direction of Williamson. It has
been hypothesized that ferrocement might be more sus-
cceptible to fire damage than conventional concrete
because of the thin cover, but preliminary findings
indicate otherwise.

It is possible that the mortar protects the ferrocement
reinforcing, which in turn distributes and dissipates the
heat evenly with little damage to the composite. Also
contributing to fire resistance may be the fact that the
typical ferrocement mortar is relatively nonporous and
contains little water to generate steam pressure on
heating. The absence of large aggregate having varying
thermal characteristics may also contribute to increasing
fire resistance.

If the fire were intense enough to release the amount
of chemically bound water in the cement, destroy the
bond between the cement and the aggregate, or oxidize
the reinforcement, the surface would be charred and
spalled so that the damage could be easily identified.
Full-scale removal and repair is then required. Benford* and Iorns† have reported instances where ferrocement
boats survived fires which would have destroyed steel
boats.

6.4.2.5 Cracks and local fractures—Hairline cracks
and crazing due to temperature changes or drying shrink-
age in the cover coat do not require repair. Continuous
wet curing will cause autogenous healing, and a flexible
coating will conceal the crack from view. If cracks are
caused by continuing overloads or are due to structural
settlement and the cause cannot be removed, replace-
ment or a structural overlay will be required. Cracks due
to occasional impact or overload are repairable.

Local fractures are cracks in which displacement of
the section has occurred as a result of impact.

6.4.3 Evaluation and testing—Evaluation of damage
must take into consideration its extent, cause, and
likelihood of the cause still being active. The method of
repair will be dictated by the type of damage, the
availability of special equipment and repair materials,
and the level of skill of the workers employed.

Economic factors may influence the decision as to
whether the repair should be extensive and permanent,
or limited in scope in response to an immediate problem.
A leak in a tank or boat hull may be stopped with a sur-
face sealant, but the presence of the leak indicates that
the interior reinforcement has been exposed to moisture,
oxigen, and possibly other corrosive agents. It may also
indicate poor workmanship during fabrication, and the
strong possibility that other voids are present that need
to be located and repaired.

Repair materials should bond to the original structure;
resist pollutants in the surrounding soil, water or air; and
respond in the same way to changes in temperature,
moisture, and loads. Removal of deteriorated or chlor-
ide-contaminated mortar trapped within the reinforcing
mesh requires a large amount of hand labor, so it may be
economical (and better for long-term durability) to re-
construct or replace an entire area using the original
structure as a form which can be left in place or removed
after the overlaid structure has cured. Complete recon-
struction is advisable when chloride contamination, mesh
corrosion, and deterioration of the mortar are extensive.

Testing ferrocement is usually done by tapping with a
hammer to break into any voids under the surface, or by
drawing a metal bar over the surface and listening for
sounds indicating voids or the presence of deteriorated
crete. A high-quality ferrocement should produce a
bell-like sound and resist moderately severe hammer
blows without damage.

6.4.4 Surface preparation

6.4.4.1 General—The primary objective is to remove
any deteriorated mortar or mortar contaminated with
corrosive agents and to provide a surface to which the
repair materials can be bonded properly. The rougher the
surface, the greater the area available for bonding.

6.4.4.2 Removal of deteriorated concrete—The first
step in any repair is to remove all disintegrated, unsound,
and contaminated mortar. Saws and chipping hammers
used for conventional concrete are unsuitable for fer-
cement unless large sections are to be completely
removed.

Small areas are quickly prepared by hand hammering
just hard enough to pulverize deteriorated or cracked
mortar, but not to the point of damaging the reinforcing
mesh.

Scott and Greenius§ found that a pneumatic needle
gun is very effective for cleaning out broken ferrocement,
opening out cracks, and roughening the surface. This
device is similar to airpowered chipping and scaling tools,
but uses a bundle of small-diameter steel rods.

Particles of sound mortar embedded in the mesh need
not be removed if they are small enough not to interfere
with the penetration of new mortar or project from the
finished surface.

6.4.4.3 Reinforcement—Any loose, scaly corrosion
revealed on cleaning out the mortar must be removed by
sandblasting, water jet, airblasting, or vacuum methods.

An alternate method for removing rust is to brush
naval jelly or spray dilute phosphoric acid over the repair

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* Benford, J., personal communication to M.E. Iorns about a fire at the Peter-
son Boatyard, Tacoma, Washington.
area and flush thoroughly.

Where the mesh cage has been displaced but is still intact, it is pushed or jacked back in place and supported securely to withstand the pressure of applying the repair material. Where the reinforcing has been torn, the old mesh may need to be laced back to close the opening.

The rods supporting the mesh cage are often badly distorted by impact but seldom sheared off. If rods must be spliced, a 15-diameter overlap of the partner rod is usually sufficient; otherwise hooks can be used.

6.4.4.4 Cleaning—Loose particles and dust residue from hammering or sandblasting should be air jetted or vacuum cleaned if epoxy or methymethacrylate (MMA) is the repair material. Water jetting is an option if the repair is to be made with hydraulic cement or latex modified mortar.

If an air jet is used, the compressor should be equipped with an oil trap to prevent contamination of the surface. Surface oil or dirt can be removed by trisodium phosphate or other strong detergents.

6.4.4.5 Cracks—Cleaning cracks presents a special problem since ferrocement is seldom used for horizontal flat surfaces which can be filled by gravity flow. It is usually simpler to hammer out the mortar on each side of the crack and replaster with latex mortar.

If opening the crack is not feasible, epoxy or MMA injection systems may be attempted in accordance with the product directions. Generally the crack is first cleaned with oil-free compressed air, and small [about \(\frac{3}{8}\) in. (2 to 3 mm)] drill holes are made at the highest and lowest points in the crack. The surface between the holes is sealed with strong coatings or a pressure pad. Catalyzed epoxy or MMA is injected at the lower hole until it comes out at the upper hole.

If a latex-cement grout is to be used, the interior of the crack must be thoroughly saturated with water and allowed to drain.

6.5—Repair materials

6.5.1 Portland cement—Portland cement (see ACI 225R) is usually the most readily available and least expensive repair material. Its characteristics are well known and compatible with the ferrocement in terms of thermal and moisture variations. Some recommendations on cement selection can be found in Section 3.1.1 of this guide.

Sand matching that used in the original construction is suitable unless the need for the repair arose because of reactive or contaminated sand.

Neat portland or blended cement paste is used to fill small cracks, and a mortar with fine sand is used to fill larger cracks or voids. Both are used in combination with latex for thin patches and overlays. The chief disadvantage of paste is that it shrinks as it dries. Shrinkage disturbs the bond and necessitates repeated applications to achieve the original level. Otherwise, the patch must be overfilled and ground down.

The higher the sand content and the lower the water content of mortar, the less shrinkage. Larger cracks should be coated with a neat cement slurry, then dry-packed with a very low water-cement ratio mortar.

Of the synthetic latexes which have been promoted for use in portland cement mortars, polyvinyl acetate and polyvinylidene are unsuitable for wet environments.

The leading latexes are now styrene-butadiene, which is widely used in bridge deck overlays and for which U.S. standards have been established, and acrylics, which offer better protection from ultraviolet degradation and have been successfully used for over 15 years in the production and repair of ferrocement boats and pontoons. Acrylics can be used as admixtures to improve bonding and as curing compounds.

The addition of latex to portland cement mortar markedly improves bond to the substrate and the tensile strength of the patch. Further, the resin deposited as the water is removed from the latex emulsion fills the pores and blocks subsequent penetration of corrosive agents. The latex forms a skin over the surface through evaporation and keeps the interior water available for hydration of the cement. The patch or overlay thus becomes self-curing.

Acrylic latex in concentrated form contains slightly less than 50 percent solids. It is usually diluted to a range of between 10 and 20 percent solids and is then used as the mixing water for the mortar. Latex mortars can be applied to a damp surface, but the patch must be allowed to dry thoroughly before being immersed in water.

6.5.2 Polymer mortars—Nonlatex polymer mortars require the use of surface-dried and, preferably, oven-dried sand. The monomers have very low viscosity and so must be mixed with thickening agents to be placed in any area which cannot be sealed tightly. There are prepackaged proprietary MMA systems available that can be handled like conventional mortar. Epoxy resins are available in numerous formulations varying in viscosity and temperature requirements. Some are moisture tolerant and can be made to bond to damp surfaces.

Many polymers or the promoters and hardeners used with them are toxic, so great care must be used in their application.

6.5.3 Admixtures—Time is a critical element in many repairs, so accelerators are frequently employed where cement alone is the repair material. Because chloride compounds may promote corrosion, nonchloride accelerators are preferred for all ferrocement but particularly for ferrocement in marine service. Despite this, emergency repairs of small areas are often made below the waterline with neat cement moistened to a putty consistency with a concentrated solution of calcium chloride. This mixture soon becomes noticeably warm, so is referred to as a “hot plug.” It is carried in the hand or in a plastic bag to the site of the leak, pressed into the hole, and held a few minutes until set. Permanent repair should be accomplished as soon as possible, using materials without chlorides.
6.6-Repairs procedure

6.6.1 Mixing-Ferrocement repairs seldom involve large quantities of materials, so hand mixing on a flat surface or in a tray is customary and quality is good if premixed dry ingredients are used. For larger quantities, a plaster or pan mixer is preferable to a rotating drum-type mixer.

The best mixing sequence is to put the water first; then the cement, to form a slurry; then the pozzolan, if used; and finally, enough sand to bring the mortar to the desired degree of workability.

The consistency of the mortar will vary according to the nature of the repair. A slurry of cream consistency will be used first to paint the moistened edges of the repair area, fill cracks or small voids, and thoroughly coat all the interior mesh and rods. After this, more sand is added until the mortar is stiff enough to hold its shape when brought out flush with the finished surface.

To avoid excessive amounts of entrained air, mortars containing acrylics or epoxies should not be mixed longer than two minutes. Their application time is also limited to about thirty minutes.

6.6.2 Full-depth repair-The forming required for full-depth repairs in conventional concrete is not needed for ferrocement. At most, a backing board for simply curved surfaces, or an inflated plastic bag for doubly curved surfaces may be needed.

When both faces are accessible, a fluid mortar is pushed through the mesh cage from one side until an excess appears on the opposite face. This excess is then pushed back and finished flush. Pencil-type vibrators are seldom needed and may create slump voids if used indiscriminately. A vibrating float or trowel can help to place and finish a very stiff mortar.

6.6.3 Partial depth patches-The area to be patched is first saturated with water, then air blown or blotted free of standing water until only surface-moist. A cement slurry of not more than 0.4 water-cement ratio and of paint-like consistency is brushed over the whole area and into any openings in the mesh. This is immediately followed by a heavily sanded mortar of the same water-cement ratio, which can be vibrated or tamped into the patch and finished flush.

Scott and Greenius showed experimentally that Portland cement patches could achieve 80 percent of original strength, whereas epoxy patches approached 100 percent.

6.6.4 Overlays-It is very difficult to bond a thin overlay to old mortar by hand-troweling. Velocity placement, by pushing through the mesh cage from one side until an excess appears on the opposite face. This excess is then pushed back and finished flush. Pencil-type vibrators are seldom needed and may create slump voids if used indiscriminately. A vibrating float or trowel can help to place and finish a very stiff mortar.

If the overlay is exposed to much thermal variation, it will tend to delaminate unless the old surface has been thoroughly cleaned or scarified by mechanical means and the repair materials match the thermal characteristics of the substrate.

Chemical etching, unless followed by mechanical abrasion, may leave a thin layer of weakened cement mortar even after thorough flushing, unless the flushing is done with high-pressure water-jet equipment.

The substrate should be prepared in the same manner as described in Section 6.6.3 for patches.

6.6.5 Shotcrete-Shotcrete is seldom used in ferrocement repair unless a large area is involved. Small, low-cost portable plaster pumps operating on the Moyno progressive-cavity principle with a rotor inside a stator tube are adequate for both original ferrocement construction and repair.

Shotcrete or plastering equipment is valuable for large overlays incorporating additional layers of reinforcing mesh by laminating techniques. Existing surfaces should be scarified or sandblasted, then saturated with water and allowed to damp dry just before the shotcrete or mortar spray is applied. An initial application of cement slurry is not needed with shotcrete but a latex or wet-to-dry epoxy bonding compound may be used to advantage with repairs made with plastering equipment.

6.6.6 Curing-Curing is particularly important on Portland cement patches and overlays unless latex compounds are used to seal the surface and furnish water for hydration.

Thin patches and overlays dry so quickly that curing must be instituted immediately. There are several curing methods and proprietary curing compounds that can be used. Several layers of paper or cloth soaked in water and covered with a plastic sheet that is well secured at the edges work well on patches. A full plastic film covering overlays is effective but may produce discoloration where it contacts the surface.

CHAPTER 7-TESTING

7.1-Test methods

Tests and observations that are commonly made during the design, construction, and subsequent service life of concrete structures are also applicable to ferrocement structures. They include: (1) tests on the physical, chemical, and mechanical properties of the component materials prior to their acceptance (water purity, sieve analysis, strength of mesh, etc.); (2) tests to control the properties of the fresh mortar mix (slump, air content, etc.); (3) tests on the mechanical properties of the hardened composite (bending strength, cracking, fatigue permeability, etc.); and (4) design feedback tests and in-service condition assessment (potential for corrosion, cracking, durability of coating, etc.).

Five types of tests are recommended to predict the mechanical properties of ferrocement: compressive strength of mortar, static modulus of elasticity of mortar, flexural strength of ferrocement beams, tensile strength of the mesh reinforcement, and tensile load-elongation response of ferrocement elements. This last test provides information on the yield strength of the mesh system, its effective modulus, and its reinforcing efficiency when encapsulated by a mortar mix.

7.1.1 Compressive strength and static modulus of elasti-
7.1.3 Tensile properties of the mesh reinforcement—Square or rectangular meshes can be tested directly in tension; however, hexagonal meshes and expanded metal meshes cannot be tested without being encapsulated in mortar. In the latter case it is preferable to run a tensile test on the ferrocement material as described in Section 7.1.4.

For square and rectangular meshes, the yield strength, elastic modulus, and ultimate tensile strength can be obtained from direct tensile tests on samples of wires or flat coupons cut from the mesh. Testing has shown that meshes exhibit substantially different stress-strain response in different loading directions. The test should be in accordance with the following guidelines (see also Fig. 7.1).

1. The test specimen is prepared by embedding both ends of a rectangular coupon of mesh in mortar over a length at least equal to the width of the sample. The mortar-embedded ends serve as pads for gripping. The free (not embedded) portion of the mesh represents the test sample.

2. The width of the test sample should be not less than six times the mesh opening or wire spacing measured normally to the loading direction.

3. The length of the test sample should be not less than three times its width or 6 in. (150 mm), whichever is larger.

4. Measurements of elongations (from which strains are computed) should be recorded over half the length of the mesh sample. Fig. 7.2 illustrates a typical fixture arrangement for such measurements.

5. Yield strain of mesh reinforcement is taken as the strain at the intersection of the best straight line fit of the initial portion of the stress-strain curve and the best straight line fit of the yielded portion of the stress-strain curve, as in Fig. 7.1. The yield stress is then taken as the stress point on the original stress-strain curve at the yield strain found above. This procedure is demonstrated in Fig. 7.1.

References , , , and describe similar procedures to determine the stress-strain properties of mesh reinforcement. Typical examples of stress-strain curves for three steel meshes are shown in Fig. 7.3. Note that “half” and “quarter” refer to the spacing of wires, in inches, in either direction.

7.1.4 Tensile test of ferrocement—Direct tensile tests of ferrocement elements can be made using rectangular specimens satisfying the same minimum size requirements as those set in Section 7.1.3 for the mesh reinforcement. The test specimens should preferably be additionally reinforced at their ends for gripping. The middle half of the nongripped (free) portion of the test specimen should be instrumented to record elongations. A plot of the load-elongation curve up to failure (Fig. 7.4) may be used to estimate the effective modulus of the mesh system as well as its yield strength, ultimate strength, and efficiency factor [see Eq. (4-2)]. The yield strain and corresponding span direction.
stress should be determined according to the procedure described in Section 7.1.3 and illustrated in Fig. 7.1 and 7.4. Fig. 7.5 shows some typical values obtained for expanded metal mesh embedded in mortar.

**CHAPTER 8-REFERENCES**

### 8.1-Recommended references

Documents of the various standards-producing organizations referred to in this document are listed below with their serial designation.

- **American Concrete Institute**
  - 116 Cement and Concrete Terminology
  - 201.2R Guide to Durable Concrete
  - 225R Guide to the Selection and Use of Hydraulic Cements
  - 318 Building Code Requirements for Reinforced Concrete
  - 357R Guide for Design and Construction of Fixed Offshore Concrete Structures
  - 515.1R Guide to the Use of Waterproofing, Dampproofing, Protective and Decorative Barrier Systems for Concrete
  - 544.1R State-of-the-Art Report on Fiber Reinforced Concrete
  - 544.3R Guide for Specifying, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete
  - 546.1R Guide for Repair of Concrete Bridge Superstructures
  - 549R State-of-the-Art Report on Ferrocement

- **ASTM**
  - A 82 Standard Specification for Steel Wire, Plain, for Concrete Reinforcement
  - A 185 Standard Specification for Steel Welded Wire Fabric, Plain, for Concrete Reinforcement
These publications are available from the following organizations:

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094

ASTM
1916 Race Street
Philadelphia, PA 19103

8.2-Cited references


5. Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete, SP-79, American Concrete Institute, Detroit, 1983, 1196 pp.


ings, V. 78, No. 1, Jan.-Feb., 1981, pp. 69-78.
44. “Sculpture Protected Against Acid Rain,” Concrete Construction, Jan. 1983, p. 50.
48. Watkins, A.J., “Damage and Repair of Pearl Fish-
APPENDIX A-CALCULATION OF VOLUME FRACTION OF REINFORCEMENT

The volume fraction of mesh in a ferrocement section may be readily calculated if the density of mesh material and the weight of mesh per unit area are known.

**Example**—Determine the volume fraction represented by two layers of expanded metal mesh given the following information:

- Number of mesh layers: \( N = 2 \)
- Thickness of ferrocement: \( h = 0.80 \text{ in.} = 0.8/12 \text{ ft} \)
- Unit weight of mesh: \( W_m = 3.4 \text{ lb/yd}^2 = 3.4/9 \text{ lbs/ft}^2 \)
- Density of steel: \( \gamma_m = 490 \text{ lb/ft}^3 \)

\[
V_f = \frac{V_m}{V_c} \times \text{area}
\]

where

\[
V_c = \gamma_m h \times \text{area}
\]

\[
V_m = N W_m \times \text{area}
\]

Thus

\[
V_f = \frac{3.4 \text{ lb/yd}^2 \left( \frac{2 \text{ layers}}{490 \text{ lb}} \right) \left( \frac{1 \text{ yd}^2}{9 \text{ ft}^2} \right) \left( \frac{12 \text{ in.}}{1 \text{ ft}} \right)}{0.80 \text{ in.}} \times 100\% = 2.31\%
\]

Alternatively, for ferrocement reinforced with square or rectangular mesh, the volume fraction of mesh reinforcement may be calculated from the following relation

\[
V_f = \frac{N \pi d_b^2}{4h} \left( \frac{1}{D_t} + \frac{1}{D_t} \right)
\]

where

- \( d_b \) = diameter of mesh wire
- \( h \) = thickness of ferrocement
- \( D_t \) = center-to-center spacing of wires aligned longitudinally in reinforcing mesh
- \( D_t \) = center-to-center spacing of wires aligned transversely in reinforcing mesh

**Example**—Determine the volume fraction of mesh for ferrocement plate with two layers of 0.5-in. welded square wire mesh given the following

\[
N = 2\text{ layers}
\]

\[
d_b = 0.042 \text{ in.}
\]

\[
h = 0.75 \text{ in.}
\]

\[
D_t = 0.5 \text{ in.}
\]

\[
V_f = \frac{(2 \text{ layers}) \pi (0.042 \text{ in.})^2}{4 (0.75 \text{ in.})} \left( \frac{1}{0.5 \text{ in.}} + \frac{1}{0.5 \text{ in.}} \right) 100\% = 1.48\%
\]

APPENDIX B-FLEXURAL STRENGTH ANALYSIS OF FERROCEMENT SECTIONS

The flexural strength of a ferrocement section may be calculated by an approach similar to that followed for a reinforced concrete column using the ACI 318 procedure for strength analysis and the design recommendations on mesh efficiency factors, elastic moduli, and yield strengths recommended by ACI 549 (Tables 4.1 and 4.2). This is illustrated in the following examples, which are consistent with ACI notation.

**Example 1**—Determine the nominal moment capacity of a 5 x \( \frac{3}{4} \) in. ferrocement section with six equally spaced layers of \( \frac{3}{8} \) in. welded square mesh reinforcement given the following

\[
N = 6\text{ layers}
\]

\[
V_f = 4.32\text{ percent}
\]

\[
f'_c = 5000 \text{ psi}
\]

\[
b = 5 \text{ in.}
\]

\[
h = 0.75 \text{ in.}
\]

\[
d_b = 0.042 \text{ in.}
\]

\[
d_t = 1.5 \text{ mm} (0.059 \text{ in.})
\]

1. Choose standard recommended values of \( f_r, E_r, \) and \( \eta \) (Tables 4.1 and 4.2).

\[
f_r = 65 \text{ ksi}
\]

\[
E_r = 29000 \text{ ksi}
\]

\[
\eta = 0.50
\]

2. Calculate \( \beta_f, V_{fi}, \) and \( A_{si} \).

\[
\beta_f = 0.85 - 0.05 (5000 - 4000) \text{ psi}/1000 \text{ psi} = 0.80 \geq 0.65
\]

\[
V_{fi} = V_f/N = 4.32\%/6 \text{ layers} = 0.72\% \text{ per layer of mesh}
\]

\[
A_{si} = \eta V_{fi} A = 0.50(0.72/100)(5 \text{ in.})(0.75 \text{ in.}) = 0.0135 \text{ in.}^2
\]
3. Calculate the depth to each reinforcing layer.

Since the layers of mesh are equally spaced with clear cover \((d'' = 0.059\ \text{in.)}, the center-to-center spacing of the reinforcing mesh may be obtained from the following formula

\[
s = \left[ h - (2d'' + d_b) \right] / (6 - 1)
\]

\[
s = \left[ 0.75 \ \text{in.} - (2 \times 0.059 \ \text{in.} + 0.042 \ \text{in.}) \right] / (6 - 1)
\]

\[
= 0.118 \ \text{in.}
\]

4. Determine the distance from the extreme compression fiber to the neutral axis \(c\) by trial and error.

Begin by assuming a value for \(c\). If this estimated distance from the extreme compression fiber to the neutral axis is correct, then the summation of all compressive force should equal the summation of all tensile forces. This is a check on the accuracy of the assumed distance. If this condition is not met, another assumption must be made for the correct distance, the internal forces recalculated, and the accuracy rechecked.

After a number of trials the following value of \(c\) for which equilibrium is satisfied is selected: \(c = 0.179\ \text{in.}\)

Then \(\epsilon_{sl} = \left( \frac{d-c}{c} \right) \epsilon_{cu}\) and \(f_{sl} = E_r \epsilon_{sl}\) if \(\epsilon_{sl} > \epsilon_y\)

\[
\epsilon_{cu} = 0.003
\]

\[
\epsilon_{sl} = \left( \frac{0.080 \ \text{in.} - 0.179 \ \text{in.}}{0.179 \ \text{in.}} \right) \times 0.003 = -0.00166
\]

\[
f_{sl} = 29,000 \ \text{ksi} \times 0.00166 = 48.1 \ \text{ksi compression}
\]

\[
\epsilon_{s2} = \left( \frac{0.198 \ \text{in.} - 0.179 \ \text{in.}}{0.179 \ \text{in.}} \right) \times 0.003 = 0.00318
\]

\[
f_{s2} = 29,000 \ \text{ksi} \times 0.00318 = 9.2 \ \text{ksi tension}
\]

\[
\epsilon_{s3} = \left( \frac{0.316 \ \text{in.} - 0.179 \ \text{in.}}{0.179 \ \text{in.}} \right) \times 0.003 = 0.002296 > \epsilon_y
\]

\[
\Rightarrow f_{s3} = f_y = 65 \ \text{ksi T}
\]

\[
\epsilon_{s4} = \left( \frac{0.434 \ \text{in.} - 0.179 \ \text{in.}}{0.179 \ \text{in.}} \right) \times 0.003 > \epsilon_y - f_{s4}
\]

\[
= f_y = 65 \ \text{ksi T}
\]

\[
\epsilon_{s5} = \left( \frac{0.552 \ \text{in.} - 0.179 \ \text{in.}}{0.179 \ \text{in.}} \right) \times 0.003 > \epsilon_y - f_{s5}
\]

\[
= f_y = 65 \ \text{ksi T}
\]

\[\epsilon_{s6} = \left( \frac{0.670 \ \text{in.} - 0.179 \ \text{in.}}{0.179 \ \text{in.}} \right) \times 0.003 > \epsilon_y - f_{s6}
\]

\[
f_f = 65 \ \text{ksi T}
\]

\[C_c = 0.85 f_y b \beta_1 c = 0.85 \ (5000 \ \text{psi}) (5 \ \text{in.}) \]

\[(0.80) (0.179) = 3043 \ \text{lbs}
\]

\[c_{sl} = (f_{sl} - 0.85 f_y) A_{s1} = (48.1 \ \text{ksi} - 0.85 \times 5 \ \text{ksi})
\]

\[(0.0135 \ \text{in.}^2) \times 10^3 = 592 \ \text{lbf}
\]

\[T_{s2} = f_{s2} A_{s2} = 9.2 \ \text{ksi} \times (0.0135 \ \text{in.}^2) \times 10^3 = 124 \ \text{lbf}
\]

\[T_{s3} = f_{s3} A_{s3} = 65 \ \text{ksi} \times (0.0135 \ \text{in.}^2) \times 10^3 = 877.5 \ \text{lbf}
\]

\[T_{s4} = f_{s4} A_{s4} = 65 \ \text{ksi} \times (0.0135 \ \text{in.}^2) \times 10^3 = 877.5 \ \text{lbf}
\]

\[T_{s5} = f_{s5} A_{s5} = 65 \ \text{ksi} \times (0.0135 \ \text{in.}^2) \times 10^3 = 877.5 \ \text{lbf}
\]

\[T_{s6} = f_{s6} A_{s6} = 65 \ \text{ksi} \times (0.0135 \ \text{in.}^2) \times 10^3 = 877.5 \ \text{lbf}
\]

\[\Sigma T = \Sigma C = 0?
\]

\[4 \times 877.5 \ \text{lb} + 124 \ \text{lbf} - 592 \ \text{lbf} - 3043 \ \text{lbf}
\]

\[= -1 \ \text{lbf} \neq 0
\]

Therefore \(c = 0.179\ \text{in.}\)

5. Calculate nominal moment capacity \(M_n\).

\[M_n = \sum_{i=1}^{n} C_{si} \ \text{or} \ T_{si} \left( d_i - \frac{\beta_1 c}{2} \right)
\]

\[M_n = 592 \ \text{lb} \ (0.080 \ \text{in.} - 0.0716 \ \text{in.}) + 124 \ \text{lbf} \ (0.198 \ \text{in.} - 0.0716 \ \text{in.}) + 877.5 \ \text{lb} \ (0.316 \ \text{in.} - 0.0716 \ \text{in.}) + 877.5 \ \text{lb} \ (0.434 \ \text{in.} - 0.0716 \ \text{in.}) + 877.5 \ \text{lb} \ (0.552 \ \text{in.} - 0.0716 \ \text{in.}) + 877.5 \ \text{lb} \ (0.670 \ \text{in.} - 0.0716 \ \text{in.}) = 1500 \ \text{lb-in.}
\]

**Example 2A**—Determine the nominal moment capacity of a 5 x 1-in. ferrocement section with eight equally spaced layers of transversely aligned hexagonal steel given the following:

\[N = 8 \ \text{layers}
\]

\[f_y = 45 \ \text{ksi}
\]

\[E_r = 10000 \ \text{ksi}
\]

\[\eta_r = 0.30
\]

1. Choose standard recommended values of \(f_y, E_r,\) and \(\eta_r\) (Tables 4.1 and 4.2).

\[f_y = 45 \ \text{ksi}
\]

\[E_r = 10000 \ \text{ksi}
\]

\[\eta_r = 0.30
\]

2. Calculate \(\beta_1, V_{fr},\) and \(A_{sl}\).
\( \beta_1 = 0.85 - 0.05 \text{ (500 psi - 4000 psi)} / 100 \text{ psi} \)

\( V_{f1} = \frac{V_f}{N} = 2.29\% / 8 \text{ layers} = 0.286 \text{ per layer of mesh} \)

\[ A_{si} = \eta V_{f1} A_{c} = 0.30 (0.286/100) (5 \text{ in.}) (1 \text{ in.}) = 0.00429 \text{ in.}^2 \]

3. Calculate the depth to each reinforcing layer.

\[ s = (h - (2d'' + db))/ (N - 1) \]

\[ s = [1 \text{ in.} - (2 \times 0.059 \text{ in.} + 0.042 \text{ in.})] / (8-1) = 0.120 \text{ in.} \]

\[ d_1 = d'' + \sqrt{d'b} = 0.800 \text{ in.} \]

\[ d_2 = d_1 + s = 0.200 \text{ in.} \]

\[ d_3 = d_2 + s = 0.320 \text{ in.} \]

\[ d_4 = d_3 + s = 0.440 \text{ in.} \]

\[ d_5 = d_4 + s = 0.560 \text{ in.} \]

\[ d_6 = d_5 + s = 0.680 \text{ in.} \]

\[ d_7 = d_6 + s = 0.800 \text{ in.} \]

\[ d_8 = d_7 + s = 0.920 \text{ in.} \]

4. Determine the distance from the extreme compression fiber to the neutral axis by trial and error. After a number of trials, a distance of \( c = 0.079 \text{ in.} \) is selected.

\( \epsilon_y = 45 \text{ ksi} / 10,000 \text{ ksi} = 0.0045 \)

\( \epsilon_{cu} = 0.003 \)

\( \epsilon_{	ext{strain}} = \left( \frac{0.080 \text{ in.} - 0.079 \text{ in.}}{0.079 \text{ in.}} \right) = 0.003 \) \( \approx 0.00038 \)

\( f_{s1} = 10,000 \text{ ksi} \times 0.00038 = 0.38 \text{ ksi tension} \)

\[ \epsilon_{s2} = \frac{0.200 \text{ in.} - 0.079 \text{ in.}}{0.079 \text{ in.}} = 0.003 > \epsilon_y - f_{s2} = f_y \]

\( T = 45 \text{ ksi} \)

\[ \epsilon_{s3} = \frac{0.320 \text{ in.} - 0.079 \text{ in.}}{0.079 \text{ in.}} = 0.003 > \epsilon_y - f_{s3} = f_y \]

\( = 45 \text{ ksi} \)

\[ \epsilon_{s4} = \frac{0.440 \text{ in.} - 0.079 \text{ in.}}{0.079 \text{ in.}} = 0.003 > \epsilon_y - f_{s4} = f_y \]

\( = 45 \text{ ksi} \)

\[ \epsilon_{s5} = \frac{0.560 \text{ in.} - 0.079 \text{ in.}}{0.079 \text{ in.}} = 0.003 > \epsilon_y - f_{s5} = f_y \]

\( = 45 \text{ ksi} \)

\[ \epsilon_{s6} = \frac{0.680 \text{ in.} - 0.079 \text{ in.}}{0.079 \text{ in.}} = 0.003 > \epsilon_y - f_{s6} = f_y \]

\( = 45 \text{ ksi} \)

\[ \epsilon_{s7} = \frac{0.800 \text{ in.} - 0.079 \text{ in.}}{0.079 \text{ in.}} = 0.003 > \epsilon_y - f_{s7} = f_y \]

\( = 45 \text{ ksi} \)

\[ \epsilon_{s8} = \frac{0.920 \text{ in.} - 0.079 \text{ in.}}{0.079 \text{ in.}} = 0.003 > \epsilon_y - f_{s8} = f_y \]

\( = 45 \text{ ksi} \)

\( C = 0.85 f_y b \quad \beta_1 c = 0.85 (5000 \text{ psi}) \quad (5 \text{ in.}) \quad (0.80) (0.079) \text{ in.} = 1343 \text{ lb} \)

\[ T_{s1} = f_{s1} A_{s1} = 0.38 \text{ ksi} \quad (0.00429 \text{ in.}^2)(1000 \text{ lb/kip}) = 1.6 \text{ lb} \]

\[ T_{s2} = f_{s2} A_{s2} = f_y A_{s2} = 45 \text{ ksi} \quad (0.00429 \text{ in.}^2)(1000 \text{ lb/kip}) = 193 \text{ lb} \]

\[ T_{s3} = f_{s3} A_{s3} = f_y A_{s3} = 45 \text{ ksi} \quad (0.00429 \text{ in.}^2)(1000 \text{ lb/kip}) = 193 \text{ lb} \]

\[ T_{s4} = f_{s4} A_{s4} = f_y A_{s4} = 45 \text{ ksi} \quad (0.00429 \text{ in.}^2)(1000 \text{ lb/kip}) = 193 \text{ lb} \]

\[ T_{s5} = f_{s5} A_{s5} = f_y A_{s5} = 45 \text{ ksi} \quad (0.00429 \text{ in.}^2)(1000 \text{ lb/kip}) = 193 \text{ lb} \]

\[ T_{s6} = f_{s6} A_{s6} = f_y A_{s6} = 45 \text{ ksi} \quad (0.00429 \text{ in.}^2)(1000 \text{ lb/kip}) = 193 \text{ lb} \]

\[ T_{s7} = f_{s7} A_{s7} = f_y A_{s7} = 45 \text{ ksi} \quad (0.00429 \text{ in.}^2)(1000 \text{ lb/kip}) = 193 \text{ lb} \]

\[ T_{s8} = f_{s8} A_{s8} = f_y A_{s8} = 45 \text{ ksi} \quad (0.00429 \text{ in.}^2)(1000 \text{ lb/kip}) = 193 \text{ lb} \]

\[ \Sigma T - \Sigma E = 0? \]

\[ 1.6 \text{ lb} + 7(193 \text{ lb}) - 1343 \text{ lb} = 9.6 \text{ lb} \]

Therefore: \( c = 0.079 \text{ in.} \)

5. Calculate nominal moment capacity \( M_n \).

\[ M_n = \sum_{i=1}^{n} C_{si} or T_{si} \left( d_i - \frac{\beta_1 c}{2} \right) \]

\[ M_n = 1.6 \text{ lb} (0.080 \text{ in.} - 0.0316 \text{ in.}) + (193 \text{ lb})(0.0200 \text{ in.} + 0.320 \text{ in.} + 0.440 \text{ in.} + 0.560 \text{ in.} + 0.680 \text{ in.} + 0.800 \text{ in.} + 0.920 \text{ in.}) - 7(193 \text{ lb})(0.0316 \text{ in.}) \]

\[ = 714 \text{ lb-in.} \]

Example 3-Determine the nominal moment capacity of a 5 x 0.40-in. ferrocement section with two layers of longitudinally aligned expanded metal mesh given the following:

\( N = 2 \text{ layers} \)

\( V_{f1} = 4.50 \text{ percent} \)

\( f_{c} = 5000 \text{ psi} \)

\( b = 5 \text{ in.} \)

\( h = 0.40 \text{ in.} \)

\( d_b = 0.03 \text{ in.} \)

\( d'' = 1.5 \text{ mm (0.059 in.)} \)

1. Choose standard recommended values of \( f_y, E_y \) and \( \eta \) (Tables 4.1 and 4.2).

\[ f_y = 45 \text{ ksi} \]

\[ E_y = 20,000 \text{ ksi} \]

\[ \eta = 0.65 \]

2. Calculate \( \beta_1, V_{f1}, \text{ and } A_{s1} \).
\[ \beta_1 = 0.85 - 0.05 \text{ (5000 psi - 4000 psi)} / 100 \text{ psi} = 0.80 \geq 0.65 \]

\[ V_{fi} = V_f / N = 4.5\% / 2 \text{ layers = 2.25\% per layer of mesh} \]

\[ A_{si} = \eta V_f A_c = 0.65 (2.25/100) (5 \text{ in.})(0.40 \text{ in.}) = 0.02925 \text{ in.} \]

3. Calculate the depth to each reinforcing layer.

\[ d_1 = d'' + \frac{\eta}{2} d_b = 0.059 \text{ in.} + (0.03 \text{ in.}) = 0.074 \text{ in.} \]

\[ d_2 = h - (d'' + \frac{\eta}{2} d_b) = 0.40 \text{ in.} - 0.074 \text{ in.} = 0.326 \text{ in.} \]

4. Determine the distance from the extreme compression fiber to the neutral axis by trial and error. After a number of trials, a distance of \( c = 0.078 \text{ in.} \) is selected.

\[ \epsilon_y = 45 \text{ ksi} / 20000 \text{ ksi} = 0.00225 \]

\[ \epsilon_{cu} = 0.003 \]

\[ C_1 = \left( \frac{0.074 \text{ in.} - 0.078 \text{ in.}}{0.078 \text{ in.}} \right) 0.003 = -0.000154 \]

\[ f_{s1} = 0.000154 \times 20000 = 3.1 \text{ ksi compression} \]

\[ C_2 = \left( \frac{0.326 \text{ in.} - 0.078 \text{ in.}}{0.078 \text{ in.}} \right) 0.003 = 0.0095 > \epsilon_y \]

\[ f_{s2} = f_y = 45 \text{ ksi} \]

\[ T_1 = \sum C_{si} \text{ or } T_{si} \left( d_i - \frac{\beta_i c}{2} \right) \]

\[ M_n = 1316 \text{ lb}(0.326 \text{ in.} - 0.0312 \text{ in.}) = 388 \text{ lb-in.} \]

APPENDIX C—SIMPLIFIED DESIGN AIDS

Example 1  

\[ \left( \frac{5000 \text{ psi}}{5 \text{ in.}} \right)(0.75 \text{ in.})^2 (0.5) = 1519 \text{ lb-in.} \]

This is 1.3 percent larger than the value obtained from exact analysis.

b. Solution using Eq. (4-5)

\[ M_n/[(5000) (5) (0.75)^2 (0.50)] = 0.0049 + 0.4219 (0.56) - 0.07722 (0.56)^2 = 0.217 \]

\[ M_n = 1526 \text{ lb-in.} \]

This is 1.7 percent larger than the value obtained from exact analysis.

Example 2  

\[ V_{f_c} = (0.0229) (45/5) = 0.206 \]

from the nondimensional graph, for 0.206 read, = 0.089, hence

\[ M_n / (f'_c b h^2 \eta) = 0.089 \]

\[ M_n = (0.089) (5000 \text{ ksi}) (5 \text{ in.}) (0.1 \text{ in.})^2 (0.30) = 668 \text{ lb-in.} \]

This is 6.4 percent smaller than the value obtained from exact analysis.

b. Solution using Eq. (4-5)

\[ M_n / (f'_c b h^2 \eta) = 0.0049 + 0.4219 (0.206) - 0.07722 (0.206)^2 = 0.089 \]

\[ M_n = 0.089 (5000 \text{ psi}) (5 \text{ in.}) (1 \text{ in.})^2 (0.30) = 668 \text{ lb-in.} \]

This is 6.4 percent smaller than the value obtained from exact analysis.

Example 3  

\[ V_{f_c} = (0.045) (45/5) = 0.405 \]

from the nondimensional graph, for 0.405, read = 0.160, hence

\[ M_n / (f'_c b h^2 \eta) = 0.160 \]

\[ M_n = 0.160 (5000 \text{ psi}) (5 \text{ in.}) (0.40 \text{ in.})^2 (0.65) = 416 \text{ lb-in.} \]

This is 7.2 percent larger than the value obtained from
exact analysis.

b. Solution using Eq. (4-5)

\[
M_s/(f'_c b h^2 \eta) = 0.0049 + 0.4219 (0.405) - 0.07722
\]

\[
(0.405)^2 = 0.163
\]

\[
M_s = 0.163 (5000 \text{ psi})(5 \text{ in.})(0.40 \text{ in.})^2 (0.65) = 424 \text{ lb-in.}
\]

This is 9.3 percent larger than the value obtained from exact analysis.

APPENDIX D-SURFACE TREATMENT FOR FERROCEMENT STRUCTURES ATTACKED BY COMMONLY USED CHEMICALS*

D.1-General

Ferrocement, like other concrete materials, can be made to perform satisfactorily when exposed to severe weather conditions, to water and soils containing chemicals, and to many common chemicals. There are, however, some chemical environments in which the life of any concrete will be short unless properly protected. When ferrocement is exposed to corrosive chemicals, the thin layer of mortar cover can spall off, exposing the meshes and jeopardizing the composite.

Comprehensive tables have been prepared by ACI Committees 201 and 512, and by Kaiser Cement Company 41 describing the effects of many chemicals on concrete. The tables can be suitably used for ferrocement. The main effects of chemicals are to disintegrate the surface of the concrete matrix, break the bond between matrix and reinforcement, and promote corrosion.

Surface treatment is used widely for the protection of concrete and ferrocement. Application of chemical coatings, resins, bituminous materials, sheet attachment, and the like is suggested by Kaiser Cement Company 41 and ACI Committee 515. The most important methods of surface treatment and the protection provided by these methods are summarized in the following.

D.2-Chemical coatings

D.2.1 Magnesium-zinc fluosilicates-Treatment with a water solution of magnesium or zinc fluosilicates by brush application hardens the surface of ferrocement, makes it more impermeable, and provides resistance to acid water; chlorides of aluminum, calcium, etc.; and light oils, grains, gasoline, coal, and other materials.

D.2.2 Sodium silicate-The treatment is similar to that using fluosilicates; however, due to its higher viscosity this material should be more diluted for penetration. The coating has the same efficiency as fluosilicates.

D.2.3 Resin coatings

D.2.3.1 Synthetic resins and plastics-Usually ther-
D.2.4.5 *Bituminous emulsions*-These materials are made using either asphalt or coal-tar base binders dispersed in water, mineral, or chemical stabilizers. When applied in thin films, or sometimes in hot layers, they provide protection against water penetration, strong acids, sulphates and nitrates of ammonia, and caustic soda.

D.2.5 *Miscellaneous methods of coating*

D.2.5.1 *Drying oil coatings*-Diluted raw or boiled oils, i.e., wood, tung, soybean, linseed oil, applied with brushes penetrate in the concrete/ferrocement and provide good protection for acid waters, phosphoric acid, chlorides, fluorides, sulfates, gasoline, and heavier oils.

D.2.5.2 *Acrylic paints and Varnishes*-Applied in two or more coatings, acrylic paints and coatings including chlorinated rubber or varnishes using chinawood oil, phenolic resins, and the like, give good protection against acetic, lactic, and carbonic acids; caustic soda; fluorides; light oils; gasoline; phenols; grains; milk molasses; and vinegar.

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This report was submitted to letter ballot of the committee and approved in accordance with ACI balloting procedures.