

ACI 549.1R-18

Design Guide for Ferrocement

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Design Guide for Ferrocement

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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

Design Guide for Ferrocement

Reported by ACI Committee 549

Antonio Nanni*, Chair

Corina-Maria Aldea, Secretary

Nemkumar Banthia
Dale P. Bentz
Christian Carloni
Paolo Casadei
Antonio De Luca
Michael E. Driver

Ashish Dubey
Usama A. Ebead
Mahmut Ekenel
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Barzin Mobasher

Hani H. Nassif
James E. Patterson
Bekir Yilmaz Pekmezci
Alva Peled
Larry Rowland
Surendra P. Shah

Yixin Shao
Lesley H. Sneed
J. Gustavo Tumialan

Consulting Members

Gordon B. Batson
James I. Daniel

John Jones†
Antoine E. Naaman*

Paul Nedwell*
P. Paramasivam

Parviz Soroushian

*Members of subcommittee that prepared this report.

†Chair of subcommittee that prepared this report.

This guide provides technical information on physical and mechanical properties, design criteria, and testing of ferrocement. The objectives are to promote the most 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.

Keywords: composite materials; construction materials; ferrocement; fibers; reinforcing materials; structural design; welded wire fabric.

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ACI 549.1R-18 supersedes ACI 549.1R-93 was adopted and published September 2018.

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CHAPTER 1—GENERAL

1.1—Scope

This guide is based on technical information assembled from current practice, developments, and advances in the field of ferrocement around the world. It represents a practical supplement to **ACI 549R**. This guide covers physical and mechanical properties, performance and design criteria, and testing.

The objectives of this guide, in conjunction with **ACI 549R**, are to promote the effective use of ferrocement in 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 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, small-diameter rods completely infiltrated with mortar, or encapsulated in mortar, or both. 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 also used for housing units, water tanks, grain silos, flat or corrugated roofing sheets, and irrigation channels (**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—NOTATION AND DEFINITIONS

2.1—Notation

- A_c = cross-sectional area of ferrocement composite
- A_s = total effective cross-sectional area of reinforcement in the direction considered
- $A_s = \sum_{i=1}^N A_{si} A_s = \sum_{i=1}^N A_{si}$
- 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_s = elastic modulus of steel reinforcement
- f'_c = specified compressive strength of mortar
- f_{si} = stress in reinforcing layer i
- f_{su} = strength of mesh reinforcement or reinforcing bars
- f_y = yield strength of mesh reinforcement or reinforcing bars
- h = thickness of ferrocement section
- M_n = nominal moment strength
- N = number of layers of mesh; nominal resistance
- N_n = nominal tensile strength
- n_r = modular ratio of reinforcement
- S_r = specific surface of reinforcement
- S_{rl} = specific surface of reinforcement in the longitudinal direction
- S_{rt} = specific surface of reinforcement in the transverse direction
- s = mesh opening or size
- V_f = volume fraction of reinforcement
- V_{fi} = volume fraction of reinforcement for mesh layer i
- V_{fl} = volume fraction of reinforcement in the longitudinal direction
- V_{ft} = volume fraction of reinforcement in the transverse direction
- β_1 = factor defining depth of rectangular stress block
- η = global efficiency factor of embedded reinforcement in resisting tension or tensile bending loads
- η_l = value of η when the load or stress is applied along the longitudinal direction of the mesh system or rod reinforcement
- η_t = value of η when the load or stress is applied along the transverse direction of the mesh reinforcement system or rod reinforcement
- η_θ = value of η when the load or stress is applied along a direction forming an angle θ with the longitudinal direction

- ϵ_{ci} = strain of mesh reinforcement at layer i
 ϵ_{cu} = ultimate compressive strain of mortar (generally assumed to be 0.003)
 ϵ_y = nominal yield strain of mesh reinforcement = f_y/E_r
 Σ_o = total surface area of bonded reinforcement per unit length
 σ_{cu} = stress in ferrocement composite at ultimate strength in tension
 σ_{cy} = stress in ferrocement composite at yielding of the reinforcement

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, ACI Concrete Terminology. Definitions provided here complement that resource.

longitudinal direction—roll direction (longer direction) of the mesh as produced in plant.

skeletal reinforcement—framework of widely spaced tied steel bars that provides shape and support for layers of mesh or fabric attached to either side.

transverse direction—direction of mesh normal to its longitudinal direction; also, width direction of mesh as produced in plant.

CHAPTER 3—PHYSICAL AND MECHANICAL PROPERTIES

3.1—Introduction

Many of the properties unique to ferrocement derive from the relatively large amount of two-way reinforcement made up of relatively small elements with a much higher surface area than conventional reinforcement. In the words of **Nervi (1956)**, “Ferrocement’s most notable characteristic is greater elasticity and resistance to cracking given to the cement mortar by the extreme subdivision and distribution of the reinforcement.” The recognition of parameters defining the subdivision and distribution of the reinforcement is fundamental to understanding many of the properties of ferrocement. Two such parameters are the volume fraction and the specific surface of reinforcement. The volume fraction of reinforcement is the volume of reinforcement per unit volume of ferrocement and the specific surface is the bonded surface area of reinforcement per unit volume of ferrocement (5.3, 5.6). Limiting values of these parameters are found in **IFS 10-01**. Unfortunately, despite the generality of the definition of ferrocement, a lack of appropriate data precludes meaningful comparison of the properties of various forms of ferrocement except those using steel wire reinforcement. The order of discussion of properties in the subsequent paragraphs is as follows: mechanical properties under static loading (ultimate strength, elasticity, and stress-strain behavior), mechanical properties under dynamic loading (fatigue and impact), crack development and its relationship to serviceability, shrinkage and creep, and durability.

3.2—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.

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

3.2.2 Specific surface of reinforcement S_r — 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 and equal size wires in each direction, S_r is divided equally into S_{rt} 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

$$S_r = \frac{\Sigma_o}{bh} \quad (3.2.2)$$

where Σ_o is the total surface area of bonded reinforcement per unit length.

3.2.3 Relation between S_r and V_f —The relation between S_r and V_f when square-grid wire meshes of equal diameter are used is

$$S_r = \frac{4V_f}{d_b} \quad (3.2.3)$$

where d_b is the diameter of the wire. For other types of reinforcement, such as expanded metal, S_{rt} and S_{rt} may be unequal.

3.2.4 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 aforementioned effects, the term “effective modulus of the reinforcing system” E_r is used. For welded steel meshes, E_r may

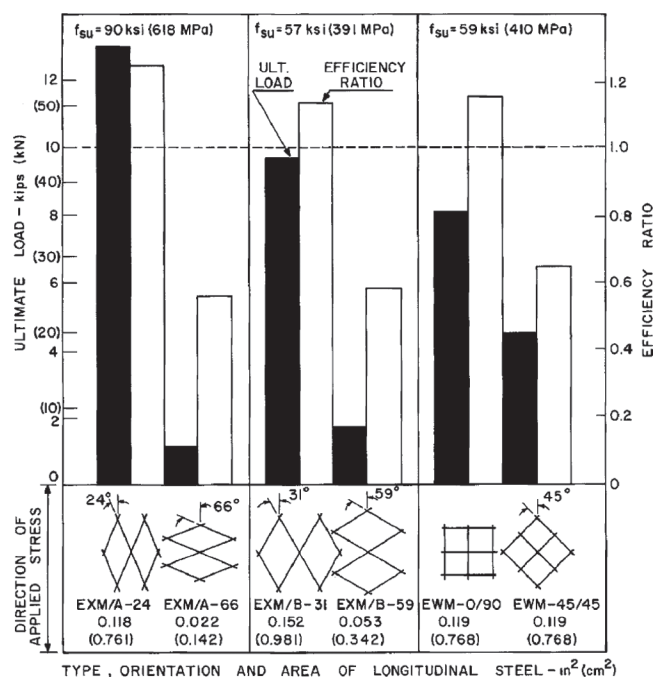


Fig. 3.3—Influence of orientation of reinforcement on the ultimate tensile strength of ferrocement and the efficiency ratio for: Types A (left) and B (center) expanded metal, EXM, and square welded mesh, EWM (right) (Romualdi and Batson 1963a).

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 6. Design values for common meshes used in ferrocement are recommended in Chapter 5.

3.3—Ultimate strength under static load

Throughout this section, parameters associated with the orientation and total amount of reinforcement and the effective area of steel in a particular direction are introduced. The orientation is defined as the angle in degrees between the reinforcing elements and the direction of the applied stress; for example, Type A expanded mesh with all the elements at ± 24 degrees to the applied stress EXM/A-24, or electro-welded mesh with wires at 0 degrees (parallel) and 90 degrees (transverse) to the applied stress EWM 0/90 (Fig. 3.3). The effective area of steel in a particular direction is based on the cross-sectional area of the elements multiplied by the cosine of the angle between the elements and the direction of the applied stress (Fig. 3.3). The total amount of reinforcement is expressed either as a percentage of the volume of ferrocement or as a weight of steel per unit area or volume of ferrocement as appropriate.

3.3.1 Ultimate tensile strength—In tension, the load-carrying capability is essentially independent of specimen thickness because the matrix cracks before failure and does not contribute directly to composite strength. Therefore, material performance is often expressed in terms of load rather than in terms of stress. Generally, the tensile strength (load) of ferrocement using expanded metal, welded, or woven

mesh in their normal orientations corresponds very closely to the tensile load capacity of the reinforcing elements, that is, the product of ultimate steel strength and cross-sectional area effective in the direction considered (Walkus and Mackiewicz 1977; Naaman and Shah 1971; Johnston and Mattar 1976; Pama et al. 1974). The corresponding tensile strength (stress) is equal to the tensile load capacity divided by the cross section of ferrocement. There are notable exceptions occurring when welded mesh is oriented at 45 degrees to the applied load, or when expanded metal is used with the longer axis of the diamond-shaped holes perpendicular to the applied stress (Johnston and Mattar 1976; Pama et al. 1974). For example, for 0.5 in. (13 mm) welded mesh (Fig. 3.3—right), ultimate strength for the 45-degree orientation is 50 to 60 percent of that for the normal orientation, whereas for two types of expanded metal (Fig. 3.3—left and center), strength in a direction perpendicular to the normal orientation is only 15 to 35 percent of that for the normal orientation (Johnston and Mattar 1976). Hexagonal mesh (chicken wire) has also been shown to induce anisotropic strength characteristics in tension, with the higher strength observed when the direction of the twisted wires is parallel to the applied stress (Greenius and Smith 1972).

To distinguish strength differences associated solely with orientation from those arising directly from changes in the effective cross-sectional area (number of elements per unit width multiplied by their cross-sectional area multiplied by the cosine of the angle of inclination of the applied stress), it is useful to eliminate the latter by calculating the ratio of actual strength of ferrocement, determined by tests, to the product of the effective area and actual tensile strength of the reinforcement, termed the efficiency ratio. This gives a true indication of the effectiveness of the various reinforcements in different orientations (Fig. 3.3) and shows that the observed strength differences are strongly associated with the orientation of the reinforcing layers, not just with differences in effective cross-sectional area of the reinforcement.

In general, the optimal choice of reinforcement for ferrocement strength in tension depends on whether the loading is essentially uniaxial or significantly biaxial. For example, Fig. 3.3 shows that expanded metal in its normal orientation is more suitable than other reinforcement meshes for uniaxial loading because a higher proportion of the total steel is effective in the direction of applied stress (Johnston and Mattar 1976). For biaxial loading, square mesh is more effective because the steel is equally distributed in the two perpendicular directions, although the weakness in the 45-degree direction may govern in this case. However, under biaxial conditions, the anisotropy associated with expanded metal or hexagonal mesh can be countered by alternate orientation of successive layers, just as the anisotropy of wood is overcome in the fabrication of plywood.

3.3.2 Ultimate compressive strength—In this mode, unlike tension, the matrix contributes directly to ferrocement strength in proportion to its cross-sectional area, so strength and amount of reinforcement are most appropriately defined in terms of stress and volume fraction of reinforcement. Obviously, matrix strength, governed primarily by its water-

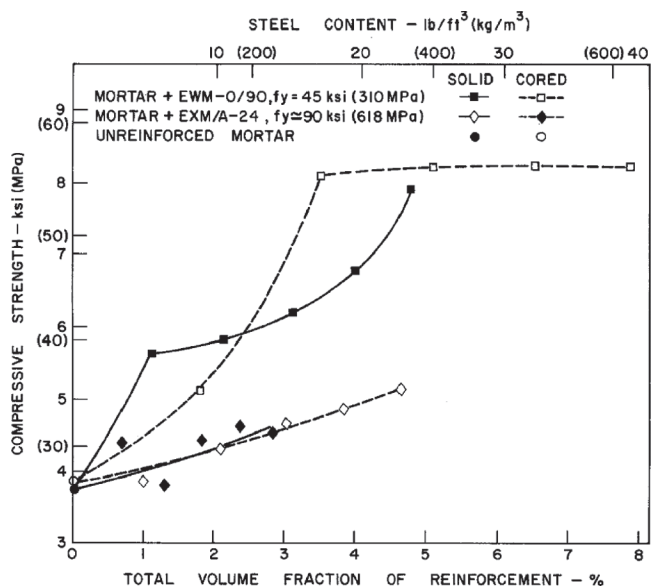


Fig. 3.3.2a—Relationships between compressive strength and steel content or volume fraction for ferrocement columns reinforced with expanded metal or welded mesh (Romualdi and Batson 1963a).

cement ratio (w/c), is a major factor, as for conventionally reinforced concrete. However, the type, orientation, and mode of arrangement of the reinforcement are also important. For example, solid and hollow (identified as cored in Fig. 3.3.2a because they are formed with the aid of a soft polystyrene core) columns peripherally reinforced with welded mesh are significantly stronger than their counterparts reinforced with expanded metal (Fig. 3.3.2a) (Johnston and Mattar 1976). This is attributed to the lateral wires in the mesh acting in a manner similar to conventional helical reinforcement by restraining the enclosed matrix, while the expanded metal undergoes a scissors action, visually apparent in the failure mode, that prevents effective triaxial restraint and renders the ferrocement little stronger than the unreinforced matrix. The drastic change of slope in the upper two curves of Fig. 3.3.2a is attributed to general yielding of the mesh system, as observed by substantial increase in Poisson's ratio (3.5.2). When mesh reinforcement is arranged parallel to the applied load in one plane only (as opposed to the closed peripheral arrangement), no improvement in strength is observed (Pama et al. 1974; Mansur and Paramasivam 1985, 1990).

When axial compression is associated with bending, the resulting interaction relationship is similar to that for conventional reinforced concrete as shown in Fig. 3.3.2b (Mansur and Paramasivam 1990). Based on rigid-plastic material behavior, a method is proposed by Mansur and Paramasivam (1990) to obtain bending moment-axial load interaction curves for ferrocement.

3.3.3 Ultimate flexural strength—Ultimate strength in flexure naturally reflects the combined influence of factors governing tensile and compressive strength, that is, the amount, type, orientation, and intrinsic geometry of the reinforcing layers. Several investigators (Logan and Shah 1973; Balaguru et al. 1977; Johnston and Mowat 1974; Kumar

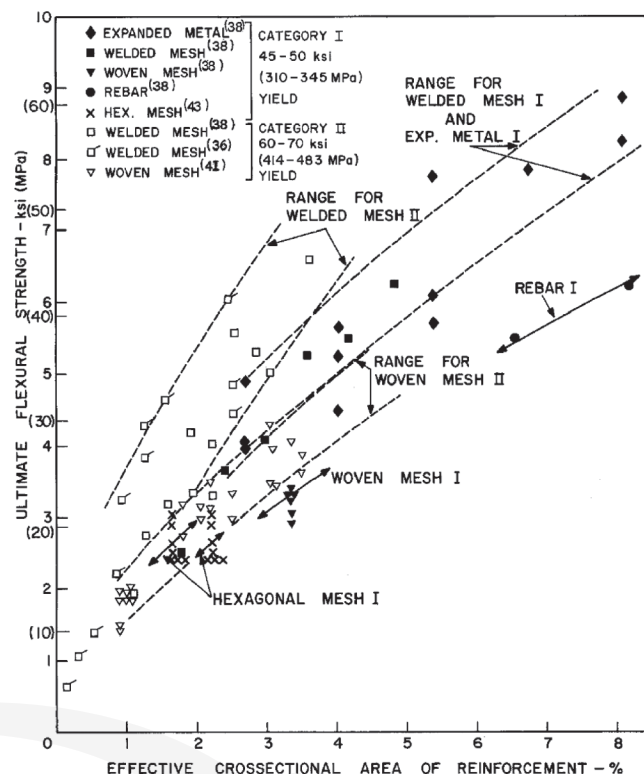


Fig. 3.3.2b—Relationships between ultimate flexural strength of ferrocement and effective cross-sectional area of reinforcement in the direction of applied stress (Naaman and Shah 1971; Pama et al. 1974; Logan and Shah 1973; Johnston and Mowat 1974).

and Sharma 1976; Naaman and McCarthy 1985) have used the principles of conventional ultimate strength analysis for reinforced concrete to compute the strength of ferrocement specimens. In the work of Mansur and Paramasivam (1986), a rigid-plastic analysis was proposed. It gave a very simple means of estimating the ultimate strength of ferrocement. These methodologies, although satisfactory in many cases, take account only of the effective cross-sectional area and position of the reinforcing layers with respect to the depth. The type of reinforcement and the orientation, spacing, and geometry of the layers are additional important variables unique to ferrocement. In addition to comparing absolute strength, it is useful to establish a general indicator of performance applicable to all data that eliminates the influence of differences in matrix and reinforcement strengths, specimen size, and position of the reinforcing layers. This isolates the importance of these variables and highlights the circumstances where a conventional ultimate strength analysis is inadequate. The indicator chosen is the efficiency ratio and is the equivalent of that selected for tensile strength, that is, the ratio of the actual ultimate moment determined by test to the value of the ultimate moment computed by the ultimate strength method. The actual computation of the ultimate strength, however, depends to some extent on the strain distribution and mode of failure assumed (Rajagopalan and Parameswaran 1975), the type of mesh/training function chosen for the reinforcement (Logan and Shah 1973), and

the stress block coefficients and ultimate strain selected for the mortar (Balaguru et al. 1977). However, efficiency ratios based on any particular method of computation are comparable in a relative sense regardless of the method used.

Before considering the efficiency ratios of various systems, it is instructive to compare the performance of various reinforcing systems in terms of the relationship between actual ultimate flexural strength measured by test and the effective area of reinforcement in the longitudinal direction. A comparison was made with the various reinforcements in their normal orientations (as previously defined for expanded metal, square mesh, and hexagonal mesh) at two levels of reinforcement strength (Fig. 3.3.3a). The distribution of the reinforcing layers was assumed uniform throughout the depth of cross section, and skeletal reinforcing bars were not considered. The comparison showed that expanded metal and square welded mesh perform significantly better than woven meshes or conventional bars with end anchorage. Conventional bar reinforcement was included for comparative purposes only and would not be permitted by the ACI 318 because it would not meet cover requirements. Also, woven mesh, conventional bars, and hexagonal mesh perform similarly. Clearly, based on effective longitudinal area of reinforcement, expanded metal and square welded mesh in their normal orientations are more effective in flexure than are other types of reinforcement, despite differences in test specimen size, mortar cover, and the specific surface and spacing of the reinforcing layers. The use of the efficiency ratio gives a truer indication of the effectiveness of the various reinforcements. Despite minor differences in the methods of applying ultimate strength analysis to the computation of ultimate moment, the general consensus is that efficiency ratios for expanded metal and welded mesh in their normal orientations are higher than those of woven meshes and are in the range 1.05 to 1.20 (Logan and Shah 1973; Johnston and Mowat 1974; Naaman and McCarthy 1985; Rao and Gowdar 1971). Similar efficiency ratios have also been obtained for both simple uniaxial (Pama et al. 1974; Austriaco et al. 1975) and biaxial (Greenius 1975a) loading (circular slabs with a central load) using hexagonal mesh laid in alternate layers with skeletal bars between them. The performance of these reinforcing systems meets and slightly exceeds expectations based on strength analysis. Some additional strength is apparently imparted by the two-way nature of the reinforcements, as already noted for tensile strength.

There are three reasons for the greater flexural effectiveness of square welded mesh and expanded metal over woven mesh. First is the possibility of debonding promoted by premature straightening of the longitudinal wires that in woven meshes are not initially straight due to the weave. This straightening also reduces the apparent modulus of the mesh system. Second is the resistance to bond failure associated with anchorage of the longitudinal elements by the transverse or oblique elements in welded mesh and expanded metal. Third is the effect of the transverse component of the reinforcement restraining lateral expansion of the matrix in the compression zone due to inherent fixity with the longitudinal reinforcement, thereby strengthening the matrix

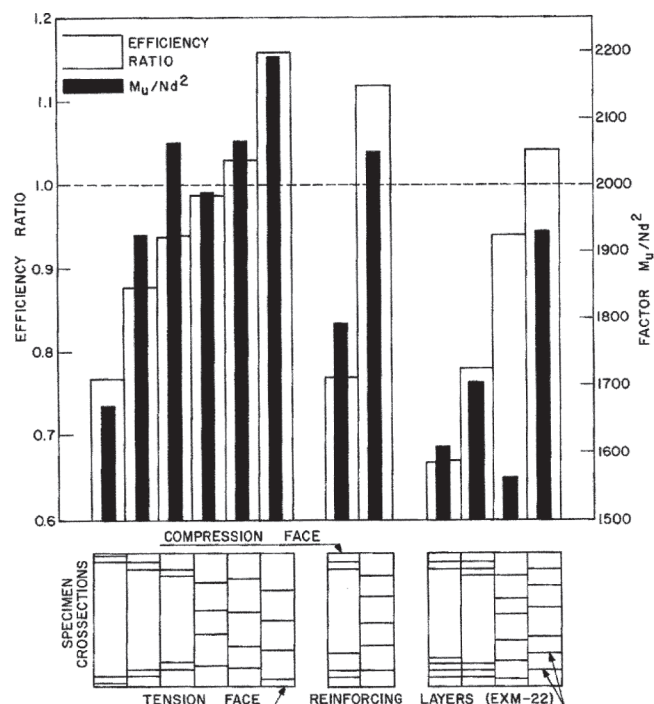


Fig. 3.3.3a—Effect of spacing of the reinforcing layers (four, five, or six layers of expanded metal) on flexural performance and efficiency ratio, where N is the number of reinforcing layers and d is the effective depth (Pama et al. 1974).

by creation of a biaxial stress condition. Because all three considerations also apply to some extent to hexagonal mesh, they may influence its performance in a similar manner.

The orientation of the reinforcement is just as important for flexural strength as it is for tensile strength, particularly when strength under biaxial loading is considered. Whereas square meshes offer equal strength in both directions parallel to the wires, strength in the 45-degree orientation is 67 to 80 percent of that parallel to the wires for welded mesh, with less difference for woven mesh (Logan and Shah 1973; Naaman and McCarthy 1985). With expanded metal and hexagonal mesh, an even greater degree of strength anisotropy is possible. For expanded metal, strengths in the transverse direction are particularly low—11 to 15 percent, (Kumar and Sharma 1976) 23 percent (Greenius 1975b), and 33 percent (Iorns and Watson 1977) of the values for the normal orientation—and are somewhat dependent on the nature of the reinforcement. For hexagonal mesh, strengths in the transverse direction average 57 percent of those in the normal orientation (Greenius 1975b). These reductions are greater than expected on the basis simply of decreases in the effective cross-sectional area of the reinforcement. Efficiency ratios for expanded metal in the transverse direction are of the order of 0.5, clearly indicating another case in which performance is well below that expected from ultimate load analysis.

The specific surface of the reinforcement—a parameter that depends on both the diameter of the reinforcing elements and their elemental (as opposed to interlayer) spacing (Fig. 3.3.3b)—has been shown to influence ultimate strength for relatively large

woven meshes up to 6 in. (150 mm) square (Bezukladov et al. 1968). However, examination of comparable data for both welded (Logan and Shah 1973) and woven (Rao and Gowdar 1971) meshes smaller than 1 in. (25 mm) shows no evidence of the influence of specific surface on ultimate strength (Logan and Shah 1973). Apparently, an increase in specific surface is only beneficial as long as bond failure at the wire-matrix interface is a factor affecting ultimate strength (Johnston and Mowat 1974). When bond failure is not a governing factor—for example, in welded mesh and expanded metal where effective anchorage is provided by the transverse reinforcement, or in very fine meshes of all kinds—specific surface greater than the minimum required to prevent bond failure is of no benefit. In fact, it can even be disadvantageous because of reduction in strength, apparently caused by inability to achieve full penetration of a fine mesh by the mortar matrix (Rao and Gowdar 1971).

The spacing of the reinforcing layers in ferrocement is normally fairly uniform throughout the available depth of cross section, except when the skeletal bar reinforcement is present. Nevertheless, the idea that concentrating the layers at the top and bottom faces of a flexure specimen increases the flexural strength because of their greater distance from the neutral axis is not unreasonable (Paramasivam and Ravindrarajah 1988). However, such an arrangement may reduce the absolute strength and efficiency ratio by promoting horizontal shear failure, which normally is not a problem in ferrocement units with uniformly and closely spaced reinforcement and a large span-depth ratio (Johnston and Mowat 1974) (Fig. 3.3.3b). When expanded metal mesh is used, optimal efficiency ratios and compliance with the expectations of conventional ultimate strength analysis seem to result when the reinforcing layers are spaced uniformly through the effective depth (Fig. 3.3.3b).

In general, the optimal choice of reinforcement for flexural strength, as already noted for tensile strength, depends on whether the loading is essentially uniaxial or significantly biaxial. For uniaxial loading, the cost-effectiveness of different reinforcements is illustrated by the relationship between flexural strength and steel content or volume fraction (Fig. 3.3.3b). Clearly, expanded metal is the best choice on this basis. Also, it generally costs less per unit weight (Iorns and Watson 1977). Alternating layers of hexagonal mesh with skeletal bars in both directions seems equally effective for the same yield strength (Greenius 1975b) (note the lower yield strength in Fig. 3.3.3c for this system). Under biaxial conditions, welded mesh is probably the best choice, although the inherent weakness on the 45-degree diagonal axial should be considered. When expanded metal or hexagonal mesh are employed under these conditions, the orientation of the successive layers should be alternated to counter their anisotropic characteristics.

Another consideration governing the choice of reinforcement is the ability to easily adopt the curvature of the unit to be constructed. Hexagonal mesh is particularly suited to complex doubly-curved sections, square mesh to singly-curved sections, and expanded metal to planar sections.

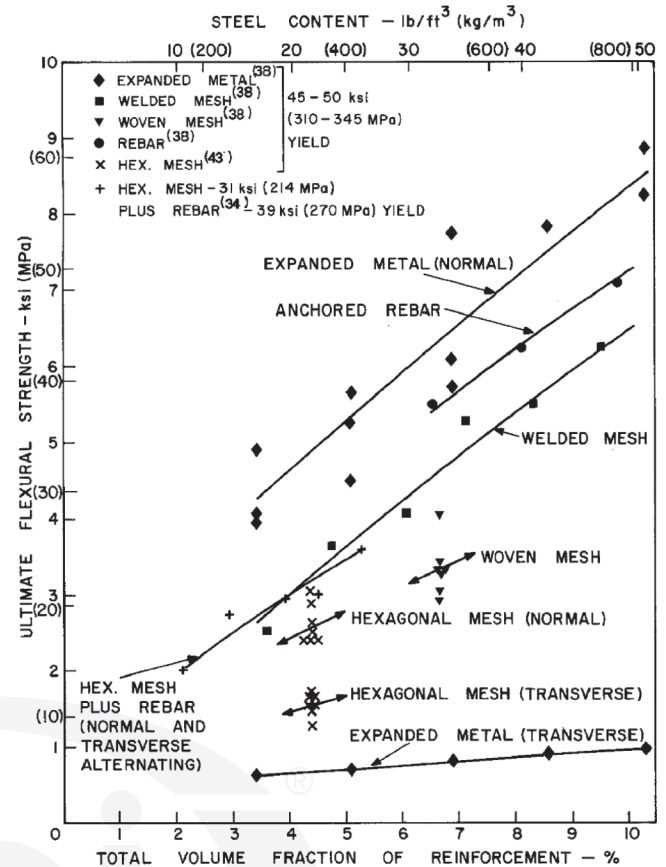


Fig. 3.3.3b—Relationships between ultimate flexural strength of ferrocement and total amount of reinforcement (Bezukladov et al. 1968; Pama et al. 1974; Johnston and Mowat 1974).

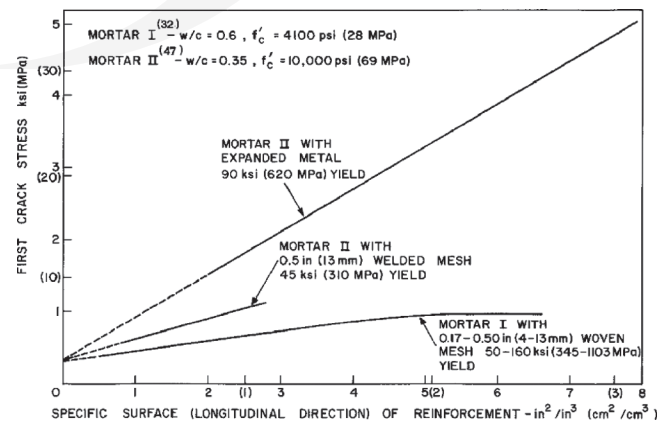


Fig. 3.3.3c—Relationships between first-crack strength of ferrocement in direct tension and the specific surface of the reinforcement (Romualdi and Batson 1963b; Rajagopalan and Parameswaran 1975).

3.3.4 Shear strength—Remarkably few of the many studies of ferrocement have included shear strength evaluation, perhaps because ferrocement is used primarily in thin panels where the span-depth ratio in flexure is large enough that shear is not the governing failure criterion. Parallel longitudinal alignment of the reinforcing layers in ferrocement effectively precludes the inclusion of shear

reinforcement equivalent to the bent-up bars or stirrups used in reinforced concrete, so ferrocement is not particularly suited to resisting shear. However, this is not required in most applications. Shear strength has been determined for specimens reinforced with woven mesh and skeletal bars, tested in bending at a shear span-depth ratio of 2.5 (Collen and Kirwan 1959). Whereas the test values reflect the characteristics of the steel and mortar used, the shear strength remains at a constant fraction of approximately 32 percent of the equivalent flexural strength for a wide range of steel contents: 18 to 35 lb/ft³ (288 to 480 kg/m³). Tests conducted in bending on specimens reinforced with welded mesh at span-depth ratios ranging from 1 to 3 indicate that failure in transverse shear is possible for specimens with a high volume fraction of reinforcement and low strength of mortar only at a small span-depth ratio (Mansur and Ong 1987). However, in general, shear failure is preceded by the attainment of flexural capacity of ferrocement. In the case of in-plane shear, similar to that existing in the web of an I-beam under transverse loading, the Truss Model Theory has been found to give a good estimate of the ultimate shear strength (Mansur and Ong 1991).

Some ferrocement boat builders have demonstrated qualitatively the toughness of the material in punching shear through accidental and deliberate tests involving collisions with rocks or other boats (Iorns and Watson 1977).

3.4—First-crack strength under static load

The term first-crack strength, or its equivalent, appears frequently in literature on the behavior of ferrocement under tension and flexure, but its use without qualification is unfortunate because it can be defined in various ways and, therefore, can carry different meanings. In a comprehensive discussion of this problem (Walkus 1975), it is noted that microcracks are inherent in the mortar matrix even before it is loaded. As the microcracks widen, propagate, and progressively join under load, they are detected by some means, visual or otherwise, and termed first cracks. However, in Walkus (1975), first cracking is defined by a crack width ranging from 2×10^{-4} in. (0.005 mm) to a size visible to the naked eye, 1.2 to 3.3×10^{-3} in. (0.03 to 0.1 mm). Consequently, a cracking strain in these studies ranges from the cracking strain for the unreinforced matrix (100 to 225 microstrain) to values established in other ways and ranging from 800 to 2000 microstrain (Walkus 1975). In other studies, first cracking is defined as the first deviation from linearity of the load-elongation function in tension (900 to 1500 microstrain) (Naaman and Shah 1971) or the corresponding deviation of the load-deflection curve in flexure (Balaguru et al. 1977; Austriaco et al. 1975). First cracking is also defined as a crack width under flexural loading of 0.003 in. (0.075 mm) (Logan and Shah 1973), the point at which the matrix at the tension face of flexural specimen reaches a strain equal to the cracking strain of the unreinforced matrix (Rao and Gowdar 1971) or simply as the first visible crack (Johnston and Mowat 1974; Greenius 1975b; Johnston and Mattar 1976).

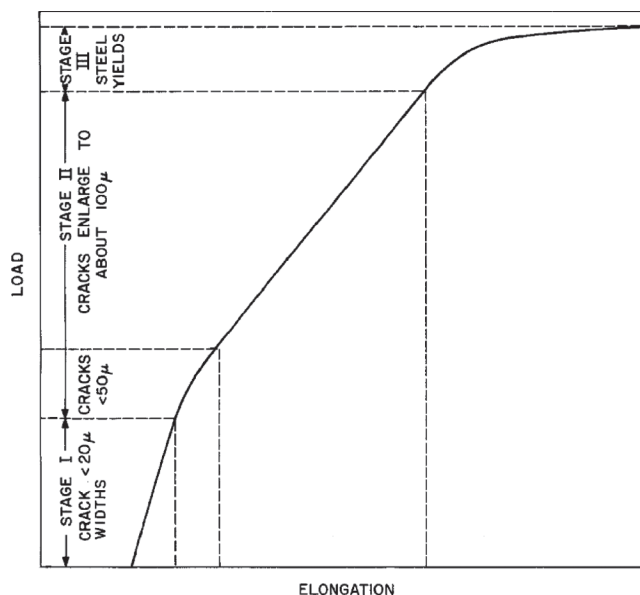


Fig. 3.4—Schematic three-stage load-elongation relationship for ferrocement in direct tension (Pama et al. 1974).

Until a generally accepted definition of “first crack” is adopted, associating a stress or strength with this condition is fraught with difficulty and misunderstanding. A more useful approach may be, in the future, to relate load or stress to average crack width and arrive at an allowable design stress corresponding to the average crack width considered permissible in service (4.8).

Despite the problem of definition, there is a general agreement (Mattar 1971; Johnston and Mattar 1976) that, in direct tension at least, resistance to cracking increases with an increase in the amount or degree of subdivision of the reinforcement defined in terms of the specific surface of the longitudinal component of the reinforcement—that is, its surface area per unit volume of ferrocement (Fig. 3.4). The difference between welded and woven mesh is apparently minor. However, the difference between expanded metal and the aforementioned types of mesh is very significant and is obviously associated with factors other than specific surface. Specimens reinforced with expanded metal resist visible cracking to approximately 80 percent of their ultimate strength, while cracking in mesh-reinforced specimens starts at a much lower percentage of ultimate strength. The cracking develops gradually to a point where the spacing of the cracks corresponds to the spacing of the transverse wires in the mesh (Mattar 1971).

In flexure, relationships linking cracking with specific surface are less well defined, and considerable data scatter reflects the possible influence of other variables, such as location of the reinforcement with respect of the tension face and reinforcement architecture (Logan and Shah 1973; Mansur and Paramasivam 1986; Austriaco et al. 1975; Walkus 1975; Mowat 1970). Specific surface in these cases is defined as the surface area of total reinforcement per unit volume of ferrocement located in the tension zone only. This is, perhaps, questionable on the basis that cracking is primarily controlled by the layer in the immediate vicinity