Structural Analysis and Design of Ferrocement Slabs

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Abstract

Ferrocement is probably one of the many old-style materials for construction which, in spite of the brilliant economic and technical advantages that it offers, has not found extensive application in developed nations. Unfortunately, the material has constantly been looked upon as a material fit for third world economies, which it surely is, but this theory covers an absence of understanding of the possible characteristic in the manufacture of the material. The idea of closely spread out and regularly dispersed reinforcing elements in a relatively visco-elastic matrix may be traditional and old-styled, but it is surely important to reinforced concrete and the most positive way to impart outstanding crack control to the concrete matrix, and through this crack control, develop brilliant properties mechanically, toughness, energy absorption characteristics, and impact resistance unique to a reinforced concrete element. Ferrocement has proven itself to be an outstanding material for construction. Several theoretical and experimental researches on ferrocement have been accepted throughout the world for many years. Ferrocement is workable because of existence of its essential materials, durability and corrosion, mechanical properties, earthly and marine applications and on applications as a strengthening and repair.

Contents

List of Figures

FERROCEMENT

١-INTRODUCTION

١,١ DEFINITION

Ferrocement is another type of reinforced concrete which is different from ordinary reinforced or pre-stressed concrete principally by the style in which the reinforcing elements are dispersed and arranged. It consists of closely, multiple spaced layers of fine rods or mesh completely submerged in cement mortar or concrete. It can be formed into thin sections or panels, generally less than ٢٥mm (١ in.) thick, with only a thin mortar cover over the outermost layers of reinforcement. Finally, ferrocement can be defined as "*Ferrocement is a type of thin wall rein- forced concrete commonly constructed of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small size wire mesh. The mesh may be made of metallic or other suitable materials.*" [١]

Fig. ١. ١Ferrocement roof under construction.

١.٢-HISTORY

The search for the ferrocement origins and its development along the time is a trial of understanding the route of this technology. It can be observed that there are three separate stages in the ferrocement's history amid the ١٨٥٠'s, ١٩٤٠'s and ١٩٦٠'s periods. In ١٨٥٠'s Lambot started the history of reinforced concrete and ferrocement, but only concrete structure, in its massive form, was done with a great success, as a usual growth of that time current Masonry Architecture. This phase had its period for nearly ١٠٠ years, with no considerable acquirements. In the ١٩٤٠'s Nervi revived ferrocement, and he gave it a size ever seen. In the post-war condition, nevertheless, rebuilding was strongly needed and man labor cost was not so substantial in Europe. Ferrocement application continued up to ١٩٦٠'s period, when its use went to a deterioration, mainly because cost of man-labor had been increasing and other materials to thin-walled components were developed, as explained Mario, Nervi's son. In the ١٩٦٠'s time, Nervi's activities stimulated the beginning of another phase, the worldwide application of ferrocement, but mostly in the developing countries. This phase comes till the current days on age near ٣٥ years. The most single property of ferrocement emphasized along its development has been associated with its high structural performance, which has permitted the application of the material in fairly different thin-walled structures, from ship hulls to housing panels. However, the world economy has been coming still more competitive and two words govern the manufacturing: productivity and quality. Among other properties, quality of a structure means durability, an acceptable service lifetime without special repair and maintenance. Production is powerfully associated with the cost of the product, and this last nearly ever is the final principle of choice. Technology of ferrocement does not have adequate knowledge about its production and durability costs are competitive only in special conditions. As comment Hanai and Debs, "looking at the background of ferrocement technology, there were no important developments in the construction and material composition procedures since Nervi’s experiences. Despite the impressive work performed by many study groups and construction enterprises, no considerable progress was extended to characterize a *second generation ferrocement*”. The start of a new phase, either the *second technological generation* or the *fourth historical generation,* must be discussed to begin suitable guidelines for new achievements [٢].

١.٣-COMPOSITION

١.٣.١—General

Ferrocement contains a Portland cement mortar mixture, steel rods and wire mesh reinforcement, admixtures, and coatings. This chapter studied the properties of the basic materials and contains a short explanation of the construction procedure as shown in Fig. ١,٢.

١.٣.٢—Matrix

The mortar matrix mainly used in ferrocement contains hydraulic cement and inert filler material. Portland cement is commonly used, sometimes mixed with a pozzolan. Usually the filler material is a well-graded sand passing a No. ٨ (٢,٣٦ mm) sieve. However, depending on the characteristics of the reinforcing material (mesh opening, distribution, etc.), a mortar contains some small-size gravel.

The physical characteristics and microstructure of mortar matrix depend upon the chemical composition of the cement, the water-cement ratio, the nature of the sand, and the curing conditions of the completed structure. Then the matrix represents approximately ٩٥ percent of the volume of ferrocement, its characteristics have a great effect on the final properties of the product. There are frequent references relating to detail of the effects of various mix of matrix proportion parameters on the properties and microstructure of hydraulic cement mortars. [٣, ٤]

The use of portland cement in ferrocement matrix is considered to have some tensile strength. It gives the idea that composite action between the reinforcement and matrix the is more noticeable in ferrocement than in ordinary reinforced concrete with steel bars. The use of various types of fibers will also have an effect on the tensile properties of the producing matrix. The used water should be clean and somewhat free from organic matter. Water-cement ratios in ferrocement matrix changes between ٠,٣٠ and ٠,٥٥, by weight. In general, a workable mix will totally penetrate and embed the wire mesh reinforcement and will have satisfactory amounts of porosity and shrinkage. Admixtures may be used to reduce water-cement ratio and improve mix plasticity

Fig. ١. ٢ wall ferrocement construction.

١.٣.٣—Reinforcement

Commonly layers of continuous mesh made from single strand filaments used as a reinforcement for ferrocement. Specific mesh types as woven or interlocking mesh (like chicken wire mesh), woven cloth mesh in which filaments are interwoven and their connections are not tightly connected, welded mesh in which a rectangular arrangement is formed by intersecting wires perpendicularly welded together at their joints, two other shapes of mesh reinforcement are in use as expanded metal lath produced by slitting thin gage steel plates and stretching them in perpendicular direction to the slits [٥,٦]. Several examples of welded and woven wire mesh are shown in (Fig. ١.٣ to Fig. ١.٥).

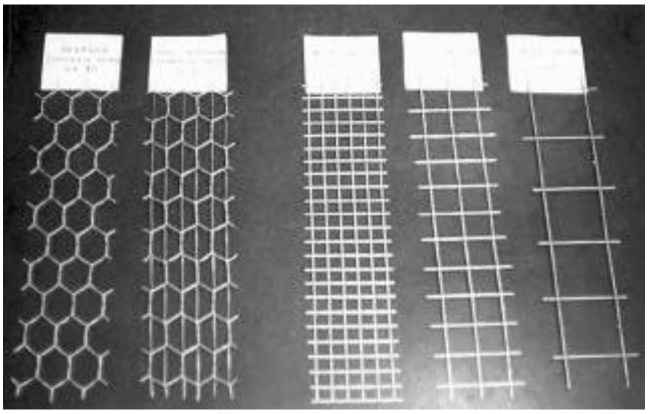

Fig. ١. ٣—Samples of hexagonal and welded wire mesh

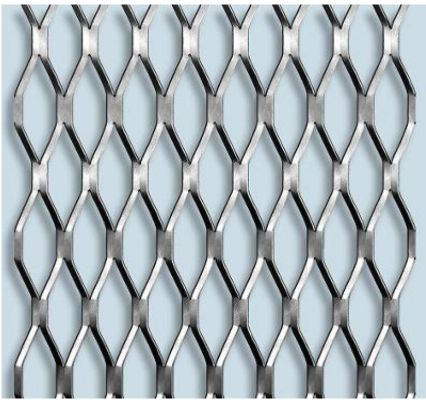

Fig. ١. ٤ —Samples of expanded metal wire mesh

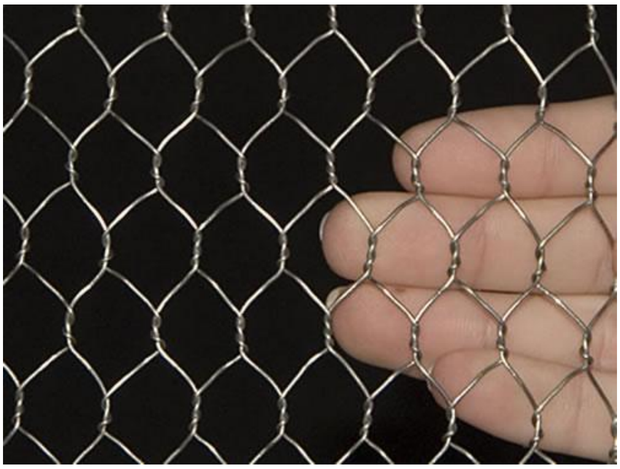

Fig. ١. ٥—Samples of chicken wire mesh.

١.٣.٤—Admixtures

Ferrocement may need chemical additives for reduction of the reaction between the galvanized reinforcement and matrix while addition to the frequent admixtures normally used in the producing ferrocement and normal reinforced concrete. Adding chromium trioxide to the mix water has been reported to be useful in this regard. [٧,٨] Solution concentration recommendation depends upon the water-cement ratio used.

١.٣.٥—Matrix mix proportions

Mix mortar for ferrocement proportioned as:

١- Sand-cement ratio (١.٤ to ٢,٥) by weight.

٢- Water-cement ratio (٠,٣٠ to ٠,٥) by weight.

Minimum water should be used to consist compactibility. This is normally reached by using a rounded well-graded, natural sand with a maximum size about one-third of the smallest opening in the reinforced ferrocement to ensure appropriate penetration. A sand passing a No. ١٦ (١.١٦ mm) sieve has given acceptable results in many applied applications

٢ – Structural Analysis and Design of Ferrocement

٢,١ General

Knowing that concrete is the basic, most public material for the structure of thin shells, the characteristics of such definite codes as those of the American Concrete Institute (ACI) must be followed. Unfortunately, for many years these codes did not converse in specific terms the exclusive problems associated with thin shells, so that in the lack of special supplies only the public rules on concrete structures could in general be followed. One major result has been a great thickness for shells being imposed by minimum cover requirements for steel reinforcement. Naturally, code requirements vary from code to code, so that although ACI limitations were required in the United States, shells only (٣/٤) of an inch thick were officially possible in Mexico, as established by the many thin shells there by Felix Candela. The ACI's design provisions for shells and folded plates are enclosed in (ACI ٣١٨,٢-١٤), "Building Code Requirements for Concrete Thin Shells". These include such main topics as definitions, standards for structural and model analysis, reinforcement, pre-stressing, and construction. In separating the secondary members of a thin shell structure from its whole, the code clearly specifies that (ACI ٣١٨,٢-١٤) provisions apply only on the thin shell portion of the structure. The edge beams, columns, footings, and other supporting members are explained by other chapters in the code. Naturally, thin shell designs should also be controlled by the rest of the code, excluding the provisions that may struggle with those in (ACI ٣١٨,٢-١٤). [٣].

٢,٢ Necessary requirements for analysis and design of ferrocement according to (ACI ٣١٨,٢-١٤) [٣].

- Elastic behavior shall be an accepted basis for determining internal forces, and displacements, of thin shells. This behavior may be established by computations based on an analysis of the untracked concrete structure in which the material is assumed linearly elastic, homogeneous, and isotropic. Poisson's ratio of concrete may be assumed equal to zero (٣,١,١ of ACI ٣١٨,٢-١٤).
- Equilibrium checks of internal resistance sand external loads shall be made to ensure consistency of results. (٣,١,٣ of ACI ٣١٨,٢-١٤).
- The thickness *h* of a thin shell, and its reinforcement, shall be proportioned for the required strength and serviceability of (ACI ٣١٨). (٣,١,٧ of ACI ٣١٨,٢-١٤)
- Specified compressive strength of concrete f_c' at ٢٨ days shall not be less than ٣٠٠٠psi (٤,١,١ of ACI ٣١٨,٢-١٤).

- Specified yield strength of non-pre-stressed reinforcement f_y shall not exceed ٦٠،٠٠٠ psi (٤,١,٢ of ACI ٣١٨,٢-١٤).
- Shell reinforcement shall be provided to resist tensile stresses from internal membrane forces, to resist bending and twisting moments, to control shrinkage and temperature cracking, and as special reinforcement at shell boundaries, load attachments, and shell openings (٦,١,١ of ACI ٣١٨,٢-١٤).
- The minimum area of shell reinforcement at any section as measured in two orthogonal directions shall be at least ٠,٠٠١٨ times the gross area of the section for Grade ٤٢٠ reinforcement or ٠,٠٠٢٠ for Grade ٢٨٠ or ٣٥٠ reinforcement (٦,١,٣ of ACI ٣١٨,٢-١٤).
- Reinforcement for shear and bending moments about axes in the plane of the shell slab shall be calculated in accordance with the analysis requirements of (ACI ٣١٨-١٤M), (٦,١,٤ of ACI ٣١٨,٢-١٤)
- The area of shell tension reinforcement shall be limited so that the reinforcement will yield before crushing of concrete in compression can take place (٦,١,٥ of ACI ٣١٨,٢-١٤)
- In regions of high tension, membrane reinforcement shall, if practical, be placed in the general directions of the principal tensile membrane forces. Where this is not practical, itis permitted to place membrane reinforcement in two or more component directions (٦,١,٦ of ACI ٣١٨,٢-١٤).
- If the direction of reinforcement varies more than ١٠ deg. from the direction of principal tensile membrane force, the amount of reinforcement may have to be increased to limit the width of possible cracks at service load (٦,١,٧ of ACI ٣١٨,٢-١٤)
- If the magnitude of the principal tensile membrane stress within the shell varies greatly over the area of the shell surface, reinforcement resisting the total tension shall be permitted to be concentrated in the regions of largest tensile stress where it can be shown that this provides a safe basis for design. The ratio of shell reinforcement in any portion of the tensile zone shall be at least ٠,٠٠٣٥ based on the overall thickness of the shell (٦,١,٨ of ACI ٣١٨,٢-١٤).

- Reinforcement required to resist shell bending moments shall be proportioned with due regard to the simultaneous action of membrane axial forces at the same location. Where shell reinforcement is required in only one face to resist bending moments, equal amounts shall be placed near both surfaces of the shell even though a reversal of bending moments is not indicated by the analysis (٦,١,٩ of ACI ٣١٨,٢-١٤).
- Shell reinforcement spacing in any direction shall not exceed the lesser of ٥h and ٤٥٠ mm. Where the principal membrane tensile stress on the gross concrete area due to factored loads exceed ٠,٣٣ϕλ√fc′, reinforcement spacing shall not exceed the lesser of ٣h and ٤٥٠ mm (٦,١,١٠ of ACI ٣١٨,٢-١٤).

- Shell reinforcement at the junction of the shell and supporting members or edge members shall be anchored in or extended through such members in accordance with the requirements of Chapter ١٢ of (ACI ٣١٨-٨٩), except that the minimum development length shall be ١,٢ℓ_d but not less than ٤٥٠ mm. (٦,١,١١ of ACI ٣١٨,٢-١٤).
- Lap splice lengths of shell reinforcement shall be at least the greater of ١,٢ℓd and ٤٥٠ mm. The number of principal tensile reinforcement splices shall be kept to a practical minimum. Where lap splices are necessary, they shall be staggered at least ℓd with not more than one-third of the reinforcement spliced at any section (٦,١,١٢ of ACI ٣١٨,٢-١٤).

٢,٣ Design Methods according to: (ACI ٥٤٩R-٩٧), (State-of-the-Art Report on Ferrocement)

- **Allowable tensile stress:** The allowable tensile stress in the steel reinforcement maybe generally taken as ٠,٦٠ *fy*, where *fy* is the yield strength measured at ٠,٠٠٣٥ strain or obtained by using the procedure described in ACI ٥٤٩,١R. However, for liquid restraining and sanitary structures it is preferable to limit the tensile stress to ٣٠ ksi (٢٠٧ MPa) unless crack width measurements on a test model indicate that a higher stress will not impair performance. The above values are appropriate provided the weaving pitch of the mesh system is moderate, approximately٣ in. (٧٥ mm), in order to insure an adequate effective modulus [١].

- **Allowable compressive stress:** The allowable compressive stress in ferrocement may be taken as ٠,٤٥ *fc'* where *fc'* is the specified compressive strength of the mortar measured from tests on ٣ × ٦ in. (٧٦ ×١٥٢ mm) cylinders [١].
- **Volume fraction and specific surface of reinforcement:** the total volume fraction of reinforcement V_t in each direction should not be less than ١,٨ percent. The total specific surface of reinforcement, S_r, in both directions, should not be less than ٢ in.٢/in.٣ (٠,٠٨ mm٢/mm٣). About twice these values are recommended for water-retaining structures. In computing the specific surface of the reinforcement, any skeletal steel may be disregarded, but it should be considered in computing V_t. It is tentatively recommended that for a given ferrocement material (without skeletal reinforcement) of thickness *h* the recommended spacings of transverse wires *s* should not be larger than *h*. Furthermore, the number of layers of mesh, *n*, should preferably be such that:

$n \geq$ ٤h where *n* is in inches

$n \geq$ ٠,١٦h where *h* is in mm (٢,١)

If skeletal reinforcement is used, it is recommended that the skeletal reinforcement not occupy more than ٥٠ percent of the thickness of the ferrocement material. If *h'* is the thickness in which the meshes are distributed, the number of layers of mesh should preferably be such that [١]:

$n \geq$ ٤h' where *h'* is in inches

$n \geq$ ٠,١٦h' where *h'* is in mm (٢,٢)

- **Cover requirements:** The recommended average net cover of the reinforcement is about ١/١٢ in. (٢ mm). However, a lesser value can be used provided the reinforcement is galvanized, the surface protected by an appropriate coating, and the crack width limited. It is also recommended that for thicknesses greater than ١/٢ in. (١٢ mm), the net cover should not exceed١/٥ of the thickness *h* or ٣/١٦ in. (٥ mm), whichever is smaller, in order to insure proper distribution of the mesh throughout the thickness [١].
- **Crack width limitations:** It is recommended that the maximum predicted value of crack width be less than ٠,٠٠٤ in. (٠,١٠ mm) for noncorrosive environment and ٠,٠٠٢ in. (٠,٠٥ mm) for corrosive environments or water-retaining structures. [١].
- **Stress range:** For ferrocement structures to sustain a minimum fatigue life of two million cycles, the stress-range in the steel should be limited to f_{sr} = ٣٠ ksi (٢٠٧ MPa). A value of f_{sr} = ٣٦ ksi (٢٤٨ MPa) can be used for one million cycles and ٥٥ ksi (٣٨٠MPa) for ١٠٠,٠٠٠ cycles [١].

- **Durability**:

١. Ferrocement liable to be subject to freezing and thawing while moist should contain about ١٠ percent entrained air.

٢. Only protective coatings proven by test or past performance should be used.

٣. Admixtures should be free from chlorides or other materials found to promote steel corrosion. Common lignosulfonate water-reducing admixtures assist in protection of steel and in reducing permeability of the ferrocement.

٤. In designing ferrocement for corrosive environments, consideration should be given to: (a) the use of galvanized reinforcement; (b) steps to minimize water content; (c) use of chemical and mineral admixtures to reduce permeability; and (d) use of proven appropriate coatings [١].

٣. Example of Slab Design

Analysis, Design and Behavior of Prefabricated Modular Ferrocement Floor Slab System for Interior Application

This design is for an interior floor slab system, which can be manufactured in modular form with ferrocement technology. The design of the slab is outlined using the mechanics of materials and the theory of plates, and the American Concrete Institute guide for ferrocement design (ACI ٥٤٩,١ R-٩٣). All basic materials were tested to follow to the ACI and applicable American Society for Testing and Materials (ASTM) standards. The water-cement ratio of cement mortar was ٠,٤٨٥, cement-sand ratio of ١:٢,٧٥, and the wire mesh reinforcement used was a galvanized square welded mesh (١٩×١٩) mm opening of ٠,٩٥mm diameter. The results from materials tests were used in the design, modeled to meet the geometric, serviceability, and strength requirements. A (٦٠٠mm x ٦٠٠mm x ٤٠mm) is the final design output, with ٨mm skeletal steels that served as connection studs with two layers of wire mesh. The slab modules were tested to a central load using a universal testing machine (UTM) and based on the results, the behavior of the ferrocement modules conforms to the theoretical formulations and the requirements for serviceability and flexural strength are attained [١٠].

٣,١. Frame work

- The slab assumes the typical square area of (٦٠٠mmx٦٠٠mm) as shown in. However the thickness of the element is determined based on the requirement of strength and serviceability.

- The matrix is reinforced with square mesh of which openings must not exceed ٢٥mm, in the case of this paper a galvanized square welded wire mesh with opening of (١٩×١٩) mm and an actual strand diameter of ٠,٩٥mm was used as shown in (Fig. ٣,١, ٣,٢, ٣,٣).
- Dead and live loads are determined assuming the basic occupancy rating from the NSCP ٢٠١٠ (National Structural Code of the Philippines ٢٠١٠) , including the dead weight of the slab.
- The design ultimate moment is calculated in accordance with the load factors suggested by the NSCP ٢٠١٠.

Fig. ٣. ١ Galvanized square welded wire mesh with opening of (١٩× ١٩) mm and an actual strand diameter of ٠,٩٥mm

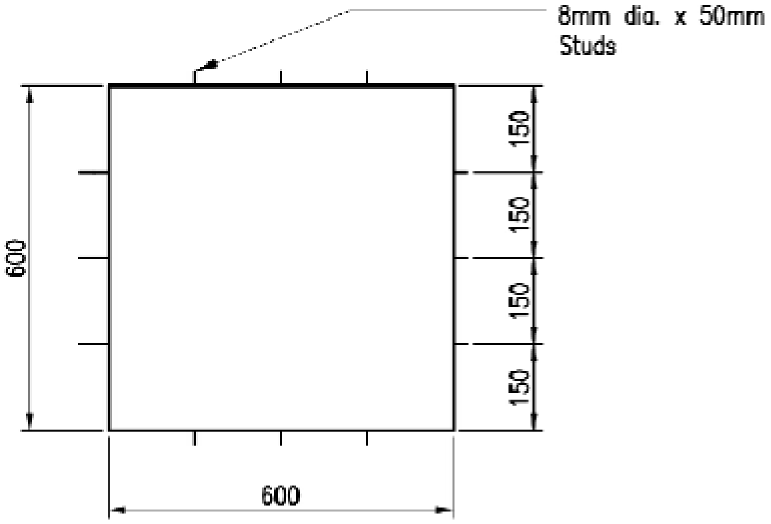

Fig. ٣. ٢ Typical Slab Used in the Design for Modular Ferrocement Slab Element

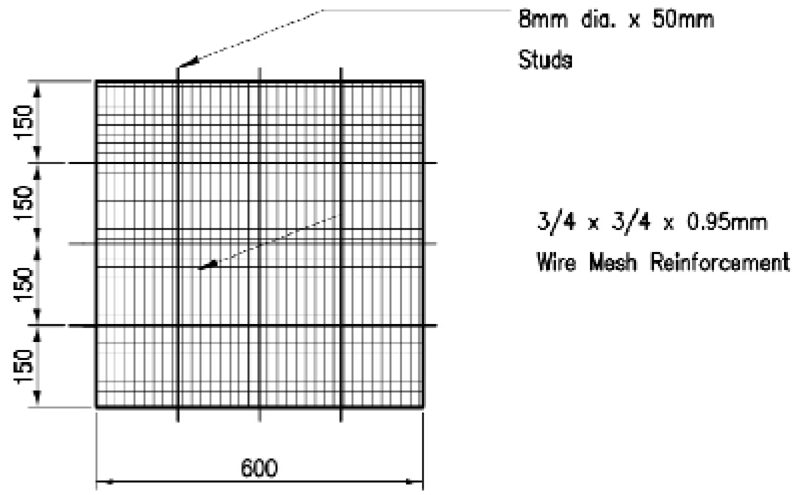

Fig. ٣. ٣ Typical Reinforcing Arrangement

The main assumptions, which were the basis of the ultimate strength theory, used the exact method for nominal bending resistance, a method similar to that followed in the reinforced concrete columns. The applicable theory of plates was also incorporated in the formulation of the design criteria, because of the geometric properties of the ferrocement panels.

The design of the modular ferrocement slab was done by stages. The first stage dealt with the condition where the slab was reinforced with mesh alone to determine the minimum number of mesh layers required. The second stage took into account the influence of skeletal bars in the analysis considering the number of mesh layers obtained in the first phase [١٠].

٣,٢. Design of Modular Ferrocement Slab

The design approach employed was the exact method for nominal bending. The ultimate strength theory as applied to this framework has the following assumptions:

- The distribution of stress across the section is linear.
- The strength of mortar in tension is neglected.
- Failure occurs only by breaking of the mesh reinforcement.

In summary, the order of design began with determining the right thickness that complied with the three major requirements, namely: the geometric requirement, the serviceability requirement and lastly the requirement for strength [١٠].

٣,٣. Geometric Requirement

To ensure good behavior of the ferrocement modules, the following figure shows the suggested placement of skeletal steel bars as well as the thickness required for a ferrocement panel as shown in Fig. ٣,٤ .

$$h = ٤\ (\Phi bar) \qquad (٣.١)$$

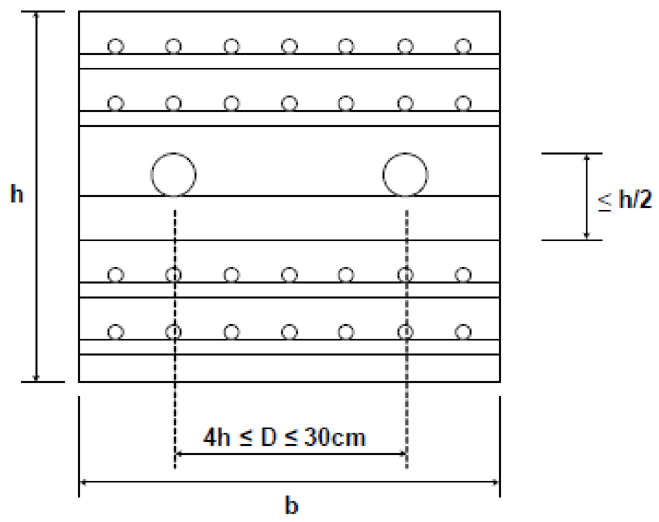

Fig. ٣. ٤ The Geometric Requirement to Ensure Good Behavior

٣,٤. The Serviceability Requirement

The serviceability requirement provided the deformation induced to the panels by the service loads as well as the combined loads, in the form of deflection. The thickness required to meet the condition for serviceability is given by the following equations for uniform load and equivalent central load, respectively.

$$h = ٢.٧٧L \left(\frac{p_U}{E}\right)^{١/٣} \quad \text{(in meters)} \qquad (٣.٢)$$

$$h = ٣.٩٣ \left(\frac{VL}{E}\right)^{١/٣} \quad \text{(in meters)} \qquad (٣.٣)$$

٣,٥. Provision for Shear

Although, the ACI ٥٤٩R Section ٤,٢,٤ stated that no test data are available on the shear capacity of ferrocement slabs, this paper used the conventional analysis for ordinary reinforce concrete due to the similarity of the design process.

The design involves no shear reinforcement much like the ordinary reinforced slab design. From this analysis the following thickness is achieved, for uniform load.

$$V_{max} = ٠,٤٢٠\ P_u\ LW = ٠,٤٢٠\ V \qquad (٣.٤)$$

$$h = \frac{٦\ V_{max}}{\sqrt{fc'}bw} \qquad (٣.٥)$$

For an equivalent central load, it is assumed to be distributed over some small circular area of radius c >٢h as shown in Fig. ٣,٥.

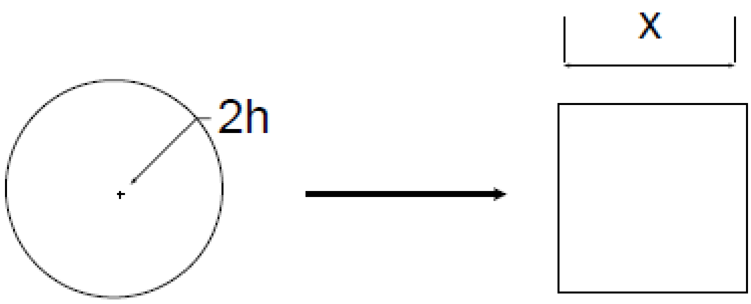

Fig. ٣. ٥ Circular Area Replaced by Equivalent area of the UTM.

The following equations show the thickness of the modules, for this condition.

$$v_u = \frac{١}{٣}\sqrt{fc'} \cdot b.h \qquad (٣.٦)$$

$$h = \left(\frac{v_u}{٦.٠٦\sqrt{fc'}}\right)^{١/٢} \qquad (٣.٧)$$

٣,٦. Strength Requirement

The strength criteria of the modular ferrocement slab design was evaluated using flexural strength analysis wherein a Maximum Bending Moment induced to the panel by the assumed load becomes the basis for calculating the Nominal Moment Capacity of the module itself [١٠].

The following equation is the maximum bending moment of the slab panels as calculated in the theory of plates for uniformly loading section simply supported on all sides.

$$Mu = ٠,٠٤٨\ Pu\ L^{٢} \qquad (٣.٨)$$

٣,٧. Exact Analysis of the Section

The following figure illustrates the nature of the exact method for rectangular element, Fig. ٣,٦.

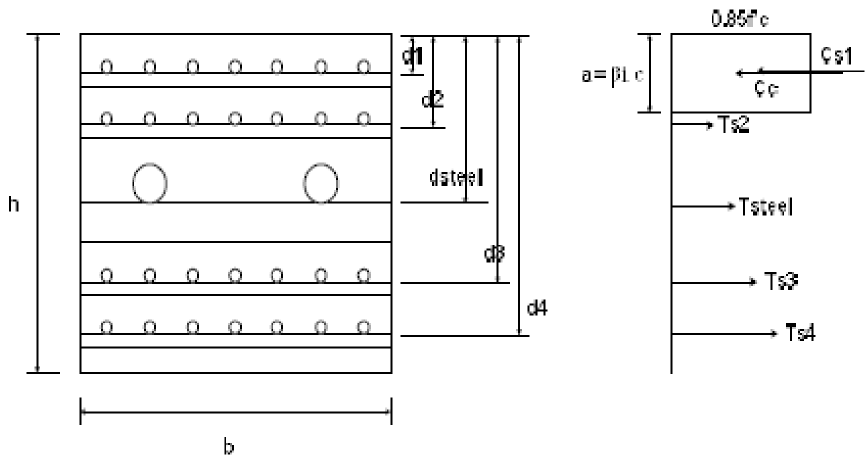

Fig. ٣. ٦ Force Diagram of the Transformed Area for the Exact Analysis

The first step in the exact analysis of the ferrocement panel was done by calculating the volume fraction of the mesh reinforcement, *Vf* mesh, and the Skeletal

Steel reinforcement, *Vf* steel, of the section. In this part, a trial number of mesh layer *i* was assumed. The following expression details how the volume fraction of mesh and skeletal steel reinforcement is computed [١٠].

$$Vf\ mesh = \frac{Ndbmesh^{٢}}{٤h}\left[\frac{١}{Dlmesh} + \frac{١}{Dtmesh}\right] \quad (3.10)$$

$$Vf\ steel = \frac{Nsteel\ \pi\ dbsteel^{٢}}{٤h}\left[\frac{١}{Dlmesh} + \frac{١}{Dtmesh}\right] \quad (3.11)$$

The Ns for the above equations was taken as one (١), as there was only a single layer of steel for the ferrocement module in this design. The reader is reminded that the skeletal steel was not designed to contribute to the theoretical capacity of the ferrocement slab modules, and could be neglected in the exact analysis. However, because of its inevitable contribution in the actual performance of the slab to applied loading, it is shown here how its contribution can be computed together with the mesh layers.

After determining the volume fraction, the volume fraction per layer of mesh and the skeletal steel can be computed by the equations below.

$$Vf\ mesh' = \frac{Vf\ mesh}{N} \quad (٣.١٢)$$

$$Vf\ steel' = \frac{Vf\ steel}{Nsteel} \quad (٣.١٣)$$

Asmesh = ηmesh Vfmesh’ b h (٣.١٤)

As steel = Ns (Asbar) (٣.١٥)

C = ٠,٨٥ fc’ a b (٣.١٦)

C = ٠,٨٥ fc’ β١ c (٣.١٧)

Er which is the effective modulus of the reinforcement taken as Er steel = ٢٠٠،٠٠٠MPa, however Er mesh is taken from the actual tensile test of the mesh reinforcement.

ηmesh = ٠,٥٠, this is the global efficiency factor for welded square mesh taken from ACI ٥٤٩R, ηsteel = ١,٠, this is the global efficiency factor for bars taken from ACI ٥٤٩R, Table ٤,٢.

The depths of each reinforcing layer is determined as is shown in Figure ٣,٦, d١, d٢, …, dN, with dsteel reserve for the skeletal steel reinforcement. A trial and error method is employed at this point in which the distance from extreme compression fiber to the neutral axis, c, is assumed. With the assumed value of c, the strain of the reinforcement layer i, can be calculated as:

$$\varepsilon y\ mesh = \frac{fy\ mesh}{Er\ mesh} \qquad (٣.18)$$

$$\varepsilon y\ steel = \frac{fy\ steel}{Er} \qquad (٣.19)$$

$$\varepsilon s\ mesh\ i = \left[\frac{di-c}{c}\right]\ \varepsilon u \qquad (٣.20)$$

Ɛsmeshi = Ermesh fsmeshi (٣.٢١)

if Ɛsmeshi ≤ Ɛymesh

fsmeshi = fymesh (٣.٢٢)

if fsmeshi > fymesh

$$\varepsilon s\ steel = \left[\frac{d\ steel-c}{c}\right]\ \varepsilon u \qquad (٣.٢٣)$$

Ɛs steel = Er fs steel (٣.٢٤)

if Ɛssteel ≤ Ɛysteel

Ɛs steel = Ɛy steel (٣.٢٥)

If the resulting value of the stress from the above expressions is negative, it signifies compression; otherwise tension.

$$Ts\ meshi = fsmeshi\ Asmesh \qquad (٣.٢٦)$$

$$Ts\ steel = fs\ steel\ As\ steel \qquad (٣.٢٧)$$

Whenever a compression stress is present for the reinforcement, the compression force can be evaluated as:

$$Cs\ meshi = (fsmeshi - ٠,٨٥\ fc')As\ mesh \qquad (٣.٢٨)$$

$$Cs\ steel = (fs\ steel - ٠,٨\ fc')\ As\ steel \qquad (٣.٢٩)$$

The Compression and the Tension Forces are added using the following equations, such that both forces should be theoretically equal.

$$\Sigma\ C = C + Cs\ meshi + Cs\ steel \qquad (٣.٣٠)$$

$$\Sigma\ T = Ts\ meshi + Ts\ steel \qquad (٣.٣١)$$

If C = T results in the process, the nominal moment capacity, Mn computed, can be determined using the following expressions. However, it might not be the case. In the event when $C \neq T$, the value of c should be changed until an equality condition is met.

$$Mn\ computed = \sum_{١}^{N} *\ Csi\ or\ Tsi \left[di - \frac{\beta_{١}\ c}{٢}\right] \qquad (٣.32)$$

The following expression can be used to calculate Mn computed using the mesh and steel reinforcement.

$$Mn\ computed = \sum_{١}^{N} *\ (Cs\ meshi + Ts\ meshi)\left[di - \frac{\beta_{١}\ c}{٢}\right] + (Cs\ meshi + Ts\ meshi)\left[d\ steel - \frac{\beta_{١}\ c}{٢}\right] \qquad (3.33)$$

If Mn computed is greater than or equal to Mn required, then the design is satisfactory. In the event that it falls below the required value, the author suggests considering another mesh layer until this condition is fully satisfied [١٠].

٣,٨. Results

٣,٨,١ Prototype Module Load Test Result

٣,٨,١,١ ١٤-day old ferrocement slab prototype module there were a total of six prototype ferrocement floor slab modules load tested using a universal testing machine by applying a central load to the slabs induced by the plate of the UTM.

Three of these slabs were tested to determine the ١٤th day strength of the modules and the rest were tested for the ٢٨th day strength.

From the test it can be observed that the first crack based on the arithmetic average of the three samples appeared at the application of ٢٠,٥٠kN load, with a corresponding deflection of ٨,٠٧mm.

The ultimate load that the slab can carry for ١٤th day curing period is ٣٦,٩٩kN with a corresponding deflection of ٢٠,٠٨mm.

With respect to the design load of ٧,٦٨٤ KN/m٢ with an equivalent concentrated load of ٢,٧٧kN, the following figures illustrates that at such amount of applied load the prototypes were able to effectively handle it without so much deflection [١٠]. as shown in Fig. ٣,٧.

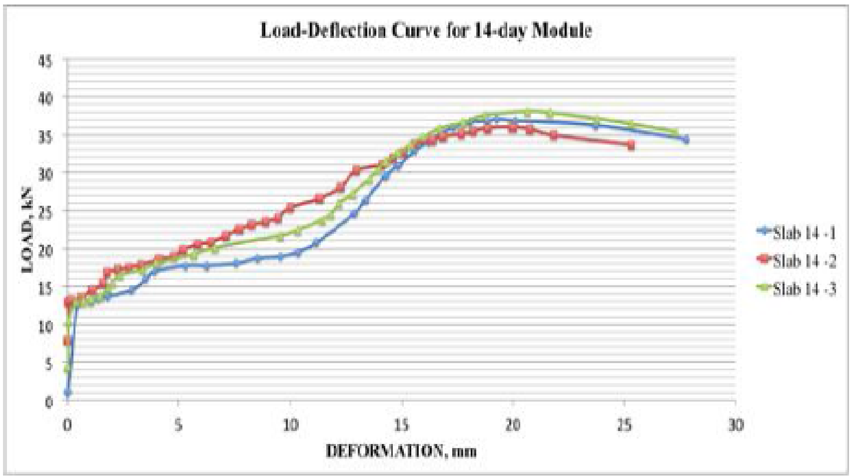

Fig. ٣. ٧ Load-deflection Curve of the ١٤-day old Prototypes

٣,٨,١,٢ ٢٨-day old ferrocement slab prototype module three prototype samples were load tested by way of central loading applied using the loading plate of the UTM for the ٢٨-day curing period. From the test it can be observed that the first crack appeared upon the application of ٢٥,٢٤kN load on the center of the module, which is the arithmetic average of the three modules, with a corresponding deflection of ٧,٥٦mm on the average. The ultimate load recorded is٣٣,٦٩kN with a deflection of ١٦,٧٩mm.

The designed equivalent central load for the prototype is ٢,٧٧kN, and with this load, the theory of plate suggested a maximum deflection limit of ٠,٠٨٠٢mm. With respect to the three modules that were tested for the ٢٨ day curing period slab samples١, ٢ and ٣, based on the following figure for a ٢,٧٧kN loading deflected at ٠,٠٠mm, ٠,٠٠٧٩mm, ٠,٠١٢٢mm linearly interpolated between values containing ٢,٧٧kN. It can be inferred that the theory has been satisfactorily satisfied by the result of the load-testing phase as shown in Fig. ٣,٨.

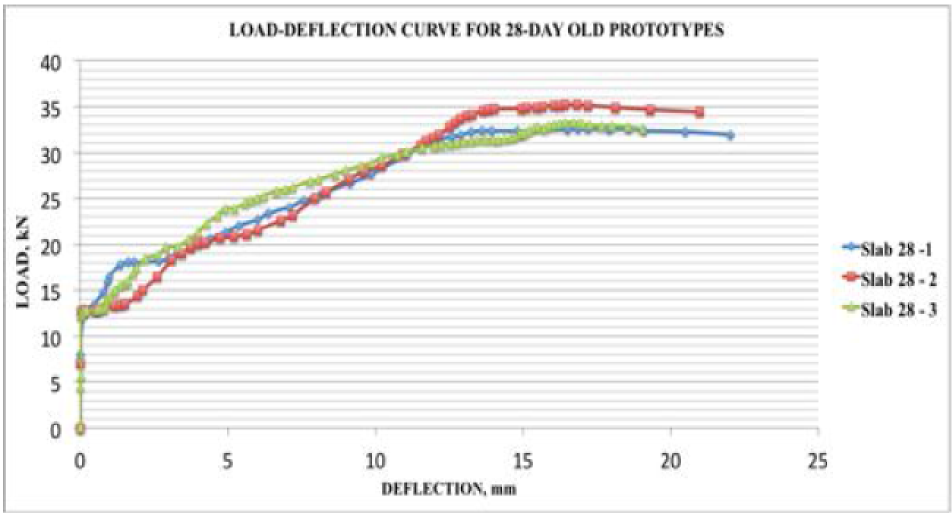

Fig. ٣. ٨ Load-deflection Curve of the ٢٨-day old Prototypes

٣,٩ Comparison

Continued loading of the specimen resulted in the crushing of the compression face of the ferrocement module prototypes and this phenomena was due to the compressive strength of the mortar matrix has been reached. Further loading only increased the deflection of the specimen but the force required to produce such deflection decreased after the ultimate load has been recorded.

The section used in this study has a moment capacity of ١,٠٥٣kN-m, with this capacity a section was expected to carry an equivalent central load of١٩,٧٢٤kN at ultimate state, which has been surpassed by the two load-tested prototypes slabs which recorded a ٣٦,٩٩kN and ٣٣,٦٩kN, for the ١٤th and٢٨th day old modules, respectively.

However, it could be seen through the test result of the ٢٨th-day old prototypes that the carrying capacity of the slab has been increased to ٧٠,٨٠٪.

With respect to the deflection limit set forth by the NSCP ٢٠١٠ in this case a maximum deflection of L/٤٨٠ was used as a limiting value for serviceability, equal to ١,٢٥mm, the ١٤th-day old prototypes recorded a capacity in tern of the central load for the samples ١, ٢, and ٣ were ١٣,٢٩kN, ١٣,٧٩kN, and١٣,٥٠kN respectively, with an average arithmetic value of ١٣,٥٣kN.

For the ٢٨th-day curing period, the resulting capacity based on the deflection limit set forth by the NSCP٢٠١٠ for the prototype samples ١, ٢, and ٣, are, ١٧,٣٤kN, ١٣,٣٣kN, and ١٥,١٧kN respectively, with an average arithmetic value of ١٥,٢٨kN.

This average value is almost twice as that of the designed load, which means that the section is very satisfactory to carry the projected load [١٠].

٣,١٠ Behaviour of Cracks

Figure ٣,٩ shows a sample of the behavior of cracks of the prototypes. Crack patterns appeared in a circular manner around the inner radius of the slabs and radiating out towards the edges of the slabs. The bottom of the prototype modules showed more severe and larger crack sizes because the bottom of the slab is under tensile forces.

Close inspection of the prototypes modules for both period of tests showed that some of the meshes reached their failing stages as indicated by the broken strands of wire mesh visible inside the bottom cracks.

In both tests, it could be observed also that the modules although infested by large cracks, the parts were still intact because of the presence of the meshes that tend of arrest the action of separation [١٠], as shown in Fig. ٣,٩.

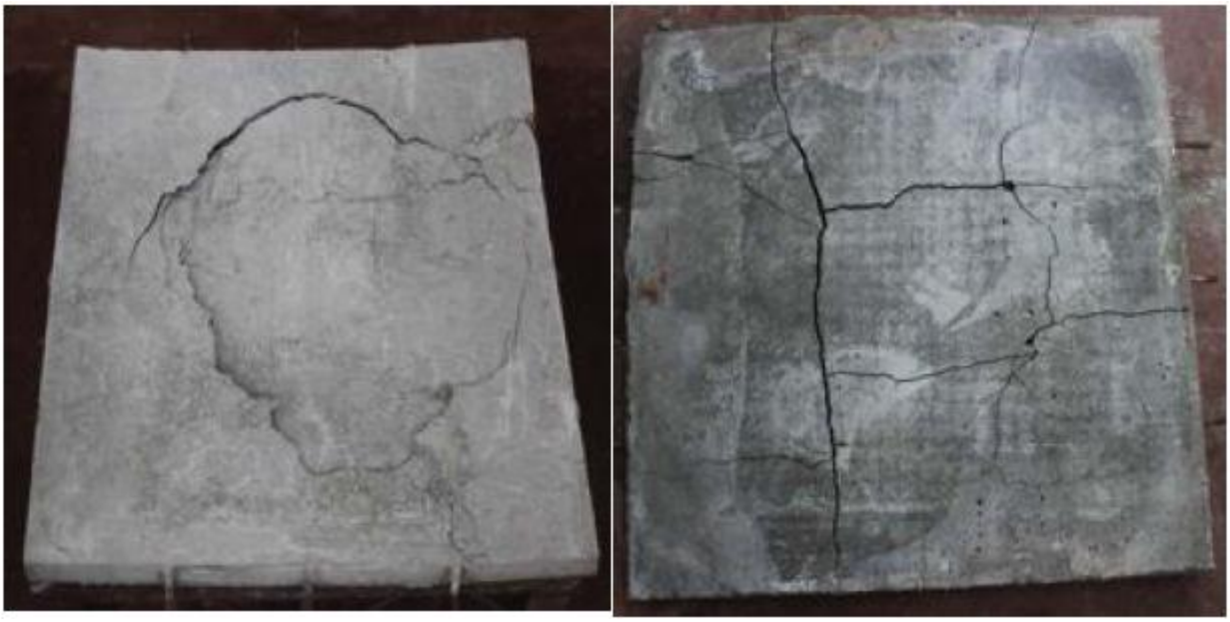

Fig. ٣. ٩ The Crack Patterns of the Top (Left) and Bottom (Right) of the Prototypes

٣,١١ Actual Application Phase

٣,١١.١ The Actual Construction

The first part that was done before the installation of the ferrocement floor slab system was the construction of the floor beams needed to hold the slab structure into place. This type of system employed another type of technology, which allowed the floor joist to be welded into its sides. However, the discussion of such work was not included in this paper. The following installation procedures were used on the actual construction.

١. The ferrocement modular slabs were constructed offsite at Dalipuga, Iligan City. An average of twenty (٢٠) to twenty-four (٢٤) modules can be produced in a day for a gang of one laborer and a semi-skilled individual as shown in Fig. ٣,١٠.

Fig. ٣. ١٠ The Molded Prefabricated Slabs Readied for Curing

٢. The floor joists were fabricated off site through a local steel fabricator and were transported to site for installation and were then painted for protection. The rate of joist installation based on the actual performance of the gang of single welder and a helper is about ١١m٢/day as shown in Fig. ٣,١١.

Fig. ٣. ١١ The Application of the Red Metal Oxide to Joists

٣. The slabs from stock were then individually welded for installation by welding. The installation part used a gang of a welder and a helper with a combined productivity rate based on actual observation of ١٥m٢/day as shown in Fig. ٣,١٢.

Fig. ٣. ١٢ Installation of the Modules by Welding

٤. After the first slab was installed that served as guide for the level of other slabs, another single slab was brought and placed adjacent to the first slab that was already installed. The figures below show the interconnections that were created by fully welding the studs at the edges of the slab as shown in Fig. ٣,١٣.

Fig. ٣. ١٣ Installation of another Adjacent Slab

٥. For corner slabs, and for slabs that did not fit the desired position, the remedy that was used was trimming and cutting some parts of the slab using a stonecutter as shown in Fig. ٣,١٤.

Fig. ٣. ١٤ Trimming of the Slab by using Stone Cutter

٦. Methods ٤ and ٥ were repeated in cycle until all floor area was covered with the modules. This type of installation left an average of٥٠mm space between the slabs, which were filled with mortar [١٠], as shown in Fig. (٣,١٥, ٣,١٦, ٣,١٧).

Fig. ٣. ١٥ Re-application of Red Metal Oxide to weld Connections

Fig. ٣. ١٦ The Application of the Grout to the Spaces between the Modules

Fig. ٣. ١٧ The Finished System showing Freshly Placed Grout

٣,١٢ Direct Cost Analysis

Based only on direct cost analysis of the two slab system it could be easily determined that for the floor area of ٢,٥٢m x ٢,٩٥m used in the example the prefabricated modular ferrocement floor slab system was lower by about ٧,٤٧٪ of the direct cost got for the conventional system. This small difference in cost might be due to the rates used in the evaluation of the prefabricated system, which was also based on the actual output of the labor that was required to construct the floor system. Because the system was new to the labor hired for the purpose of evaluation, thus the ordinary productivity rates were greatly affected and consequently the direct cost of the whole system.

With the conventional system, its total dead weight is about ١٨,٣٩kN, whereas the prefabricated modular ferrocement slab system is about ٧,١٢kN, which was only about ٣٨,٧١٪ of the weight of the conventional system. This means that the new prefabricated system need not have large supporting structure compared to the conventional system. The effect would be savings on the beams, the supporting pedestal or concrete columns, and on the structure’s footing requirement [١٠].

٤. Conclusions

١. The requirements for Strength and Serviceability in order to support normal household loadings as prescribed in the National Structural Code of the Philippines has been adequately attained and exceeded by the carrying capacity of the samples.

٢. There was considerable agreement between the theoretical method made by the author and that of the results of the tests.

٣. By mechanical test the samples, it was found out that a manufactured modular slab made out of ferrocement technology for interior purposes was a viable and safe system that can address the basic house loading requirements.

٤. There was adequate economic savings in the ferrocement modular slab system.

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