Ferrocement Prefabricated Housing: The Next Generation

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Ferrocement is a construction material ideally suitable for high levels of prefabrication. However, in order for ferrocement prefabricated products to successfully penetrate the housing sector, it should be demonstrated that high quality housing can be produced with ferrocement, in as an effective way as for low cost housing. This paper describes part of an ongoing investigation which attempts to address this concern. In a first study, published earlier, advanced manufacturing techniques were considered for the production of ferrocement housing units; this led to the development of a ferrocement housing system using standardized prefabricated U and box-shaped panels for the walls, floors, and roof of a typical house. It was assumed, in all cases, that joining of the panels can be properly achieved with bolted type connections. After a brief review of existing ferrocement housing systems (which address primarily the low-cost housing sector), this paper provides a brief summary of the progress achieved so far on the study of bolted connections. Two types of connection are identified, a shear-type and a moment-type connection. Test arrangement and test set-up designed to identify various failure modes are described. Typical load-deformation response curves are presented. It is hoped that experimental results will provide the basis for calibrating analytical models of the connections. Such models can be implemented in a computer program in order to investigate a large number of parameters, and eventually develop optimum connection configurations.

INTRODUCTION

Ferrocement has been successfully used in marine applications, with a wide range of material characteristics, qualities, and finishes. However, there is a common perception that terrestrial applications such as in housing, are generally low cost, thus of a lower quality. One of the main advantages of ferrocement is that it can be constructed with a very wide range of qualities, properties, and cost, according to customers demand and budget. While most ferrocement housing applications have been so far directed toward low cost housing solutions, this does not imply that good quality housing products cannot be achieved with ferrocement. In fact some of the first applications of ferrocement used by Nervi were to replace intricate ceiling decorations usually made with gypsum lath. Indeed ferrocement can, should, and eventually will address the high quality housing sector. It is a construction material that lends itself to easy manufacturing and transportation. What is needed above all is: 1) to change the perception of architects, engineers, building authorities, and users about ferrocement, and 2) to bring the level of technology in ferrocement construction to the level of progress achieved in other industries such as the manufacturing, automobile and aerospace industries.

Today, an extraordinary confluence of new technologies and a large market for housing products worldwide can bring a revolution in the way ferrocement is used. Advanced technologies can help

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expand the applications of ferrocement and greatly improve its subjective acceptance as a high quality, high technology, luxurious, durable and cost competitive construction material.

Ferrocement is ready for new technologies. Most of its properties have been documented, and guidelines for its analysis and design have been developed [1,10,13]. While ferrocement housing components can be built using advanced manufacturing techniques, there is need to develop entire housing packages where the ferrocement structural sub-system is integrated harmoniously as part of the whole housing system and occupies a well balanced portion of it. Current advances in robotics, computerized manufacturing, machine vision, expert systems, and the like allow us to project that such advanced technologies which are already in use in the auto industry can be successfully utilized in the production of manufactured housing systems where ferrocement is the primary structural material.

OBJECTIVES AND SCOPE

It has been one of the objectives of the research on ferrocement at the University of Michigan to address advanced production technologies for ferrocement, while taking advantage of the characteristics offered by ferrocement such as strength, lightweight, fire resistance, durability, ease of transportation and erection, ductility for seismic zones, and adaptability to high levels prefabrication.

In two previous studies by Naaman [9,11], ferrocement was considered and evaluated in prefabricated housing systems. In Ref. (9), ferrocement panels were considered the primary material for flooring and roofing, to reduce the total weight of the prefabricated modular box systems investigated. Ref. [11] describes a feasibility study where advanced manufacturing techniques were considered for the production of single family housing units using prefabricated ferrocement panels. One of the constraints considered was, that the housing system so produced, should be of equal if not better quality than standard single family housing units currently found on the U.S. market. The study suggested that most common housing requirements could be satisfied from a pool of about fifteen standard panel configurations. Although the ferrocement sub-system can occupy a wide range of structural and protective functions within the housing unit, it was shown that the same group of panels could be used for the skin (outside bearing wall), the floors, and the roof of the house. In all cases the connections between the various elements were assumed satisfied by bolting. The main features of the system are schematically described in Figs. 1 to 3.

The above study [11] showed that the ferrocement system developed is a technically feasible system suitable for a highly industrialized production facility at a competitive cost. It also indicated that the most pressing problem is that of the connections between the various ferrocement elements. The properties of the connections between ferrocement elements is the least documented in the technical literature and should receive high priority in future research. Connections, allowing the use of bolts to join ferrocement elements produced with high precision surfaces, can save substantial time and money, if proven structurally acceptable.

After a brief review of various ferrocement housing systems of interest as a background to the current investigation, a progress report on the status of the study of connections is given.

REVIEW - BACKGROUND ON FERROCEMENT HOUSING SYSTEMS

Numerous conceptual and developmental studies have been undertaken on prefabricated housing systems made from ferrocement [3-7,9,11,15-24]. Such systems can be as simple as a wall panel proposed for use in many non-specialized situations [7,22,23], or, as complete as the entire structural system of a house (walls, roof, floors, and foundation) [5,15,16,19,23]. However, to the best of the
author's knowledge, some systems were only conceptual and never used in practice, while others led to one or a small number of prototype units. In some systems, the term ferrocement is used generically and may imply thin reinforced concrete members. In other words, the reinforcing parameters do not satisfy the minimum recommendations of the ACI Guide on Ferrocement [1] and other guidelines [10,13], such as particularly for the minimum amount of reinforcement and its specific surface.

Following is a brief description of five ferrocement housing systems which are relevant to the present study. They are reviewed by chronological order.

In 1979, Castro [3] reported on the use of prefabricated ferrocement panels to build as many as 350 low cost housing units in Mexico. The panels were reinforced with two to three layers of chicken wire mesh sandwiching a grid of 6 mm reinforcing bars, placed 250 mm center to center. The panels were joined using nuts and bolts. The joints were observed to behave properly even in the seismic areas of Mexico. No further report on the long term behavior of these units is available.

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Fig. 1. Typical panels for prefabricated ferrocement housing units.
In 1981, Tatsa et al. [20] described a composite building system where ferrocement panels were joined together with cast-in-place concrete. The system consists of three basic precast ferrocement elements: 1) a horizontally spanning unit for one-way bending, 2) a two-way bending unit, and 3) a vertical shear panel unit. The beams and columns are cast in place. Continuity is assured by reinforced concrete poured in place between the ferrocement elements. The primary feature of the panels is that they incorporate a styrofoam insulation which is used as a permanent form. A system based on bolted connections instead of poured ones, was also developed later using the same concept. However, little can be found to date about the application of the system to real housing units.

Gokhale (1983) described the Castone housing system [5] developed in India. The system consists of wall panels attached to a floor slab. The panels are 3 ft x 9 ft (0.91 m x 2.73 m) with a thickness of 1.25 in. (32 mm). The first floor slab (or ceiling of the ground floor) is a lattice girder hollow block.

![Panel assembly in a typical house cross-section.](image-url)
type, capable of anchoring to the top of the wall panels. The panels have ribs around their periphery with preformed holes to accept bolts. According to Gokhale, the system was used in several one or two-story houses in the Bombay area, however, we do not have any further information about the behavior of these ferrocement units during service and in the long term.

In 1985, at the Second International Symposium on Ferrocement, the F. Davis system was presented [21]. The system consists of prefabricated ferrocement U and box-shaped panels and number of other shapes that could be used for windows, water channels, and the like. For the outside walls, the ribs of the panels were positioned toward the outside. A couple of rooms (demonstration units) were built for a housing fair in France to illustrate the strength, appearance, and feasibility of the system. Very high quality panels were used. It is not known if the system was ever used in any small or large scale project.

Sandowicz (1985) described four housing systems utilizing three basic types of ferrocement channel elements; he named them the ELSA, CEE, ELWO, and Mixed Systems [19]. The ELSA panel system is used either for partitions or as a permanent formwork for cast in place concrete such as spandrel beams, columns, and floor bearing elements. The main intent of the ELSA system is to combine ferrocement with reinforced concrete to result in a monolithic structure. In the CEE system the whole house is made out of panels connected with screws and especially designed steel corner elements. There is no cast-in-place concrete and no need for foundations since the wall panels are dug directly into the ground. The system is recommended for one story houses. In the ELWO system, ELWO type ferrocement channels are joined with screws and separated by lath. The roof is covered with roof paper to allow construction of summer houses and bungalows. In the mixed system, the three previously described systems are used, namely: the framework is made of ELSA channels filled with concrete, the floor and roof are made of CEE channels, and the external walls are made of ELWO elements. It is not clear at the time of this writing, if the above systems were ever used in real applications.

Fig. 3. Panel assembly for a typical wall and corner.
In 1988 [16] Rivas described the first ferrocement house built in Cuba in 1986. It was constructed of prefabricated ferrocement panels using hand woven wire meshes. Following the success of this first effort, Rivas reports that three factories producing ferrocement elements for housing have been set up in Cuba. Since then, numerous high quality one and two-story houses have been built using ferrocement panels, roofs, and mezzanines.

No ferrocement prefabricated system has ever been used extensively in applications other than very low cost housing, such as described by Castro in Mexico [3]. This may explain the reasons why the users and building authorities are reluctant to allow such ferrocement systems in the production of higher quality housing units. One of the main goals of the current investigation is to show that high quality, high levels of prefabrication, and competitive cost can be indeed achieved for ferrocement housing. The most pressing technical problem is that of the connections and it is being addressed.

CURRENT PROGRESS ON CONNECTIONS AT THE UNIVERSITY OF MICHIGAN

As mentioned earlier, the research at the University of Michigan has focused on developing a highly industrialized ferrocement panel system for housing, where connections are achieved by bolting. The system is described in Ref.[11] and typical details are shown in Figs. 1 to 3. While the analysis and design of the panels for bending, axial, and shear loadings has been already investigated, the primary focus, at the time of this writing, is on the connections between the prefabricated panels. Very little information can be found at present on ferrocement connections [14,25]; however, useful background on the design of joints and connections can be obtained from studies of steel joints [2,8].

In this study, ferrocement connections are classified into two main types, namely, a primarily "shear-type" connection, and a primarily "moment-type" connection. Of course a connection is generally subjected to combined loads, but the above definition attempts to identify the load that is most critical to the connection. Typical loads transmitted by bolted connections are illustrated in Fig. 4.

A shear-type connection between two plates joined by a bolt is one where the applied external loads are parallel to the plane of the plates, and perpendicular to the axis of the connecting bolt. A typical shear-type connection is shown in Fig. 5. Note that the load is transferred by two mechanisms, friction and bearing. Understanding and quantifying the contribution of each mechanism is one of the essential goals of the current experimental investigation. Once friction is overcome under load, the bearing resistance is engaged. Five different failure modes (Fig.5) can then be observed 1) tensile failure of the critical net section of the plate, 2) shear failure or tear-out of the plate portion close to the edge of the plate, 3) crushing of the plate ahead of the hole, 4) cleavage or fracture of the plate between the hole and the plate edge, and 5) shear fracture of the bolt. This last mode of failure can always be avoided by using larger diameter and/or stronger bolts.

In the moment-type connection, the connection is subjected to a bending moment (with vector normal to the axis of the connecting bolts) that induces axial forces in the bolts. Such loading occurs frequently in L-shaped joints where the bolted portion is called joined flange, while the free portion is called web. Most common failure modes of moment-type connections are: failure of the bolts due to axial loads, failure of the section of the joined material located in the corner between the flange and the web, and excessive surface separation between the two connected plates. Here also, the bolt size and pre-load can be designed in such a way that one of the failure modes can occur first.

An extensive experimental program is being carried out on the above types of connections. Parameters include the number of mesh layers in the ferrocement plates, the distance of the bolt to the edge of the plates, and the type of mesh. Details of the experimental program and results will be given
in a future publication. Here only typical preliminary results are provided.

The testing arrangement and set-up for a shear-type connection are shown in Fig.6. The corresponding load deformation curves are shown in Fig.7. It should be noted that the specimens tested in Fig.7 had the following characteristics: standard 1/2 in. (12.5 mm) diameter bolt, 1/2 in. (12.5 mm) thick ferrocement plates, with a distance of 2 in. (50 mm) from the center of the bolt to the edge of the plate. The reinforcement for Fig.7 top and Fig.7 bottom consisted of eight layers and four layers of square welded mesh respectively, with a wire spacing of 0.25 in. (6 mm) and a wire diameter of 0.025 in. (0.62 mm). A cleavage type failure (Fig.5) was observed at a maximum load of 2693 lbs (1220 kg or 11806 N) and 1318 lbs (599 kg or 5796 N) for the 8 layer and 4 layer specimens respectively. Other types of failure have been observed by varying the reinforcement and the end

Fig. 4. Typical forces transmitted by bolted connections.
distance. The performance of the specimens have been satisfactory and further tests are being carried.

The test arrangement and set-up for the moment-type connection are shown in Fig.8. Typical load-deflection curves are shown in Fig.9. Here, the ferrocement plates had the same reinforcement as described above for the shear-type connection. Failure occurred by failure of the corner between the plates and was preceded by a small separation between the plates. The corresponding moment was of the order of 0.449 k-in (5.07 x 10^4 N-mm) and 0.306 k-in (3.46 x 10^4 N-mm) for the 8 layer and 4 layer specimens respectively. It seems that in this type of connection, the strength and spacing of the bolts can always be adjusted so that failure occurs in the plates, i.e. at the corner edge. The test results indicate that the moment resistance of the edge is smaller than in the ferrocement plate. Further tests are being carried to quantify this difference and to try strengthening procedures.

The testing program is ongoing, while simultaneously a finite element model is being developed for the connections. Once the model is calibrated, it may become possible to simulate analytically the

![Diagram of shear failure](image)

**Fig. 5. Typical shear-type connections and corresponding plate failure modes.**
response of any connection configuration, and thus study the effects of a large number of parameters. This will open the way to analyzing the response of an entire house to various externally applied loads. A computerized evaluation will then allow the identification of optimum housing solutions and configurations.

CONCLUDING REMARKS

While sufficient information can be found in the technical literature on the properties, analysis, design, construction, and maintenance of ferrocement structural elements, no building code provisions or guidelines are available to address the question of ferrocement joints and connections. The connection problem is paramount to the technical feasibility and eventual success of prefabricated ferrocement housing. Thus, there is, first, a genuine need to solve the technical aspects related to the connection problem in ferrocement, and then there is need for developing related design and code recommendations. This is the main and ultimate goal of the above described investigation.

Architects, engineers, users, and building authorities are reluctant to consider ferrocement
systems for the large scale production of high quality prefabricated housing units, primarily because of the lack of prior experience in that sector. On the other hand, unless a large number of housing units are built with one system or another, no prior experience can be developed. This is a vicious circle which must be overcome. What may be needed is a large developer willing to take the responsibility for the planning, design, building, and maintenance of a large housing project, until satisfactory performance is proven without any doubt.

Finally, there is the question of prefabrication. How much prefabrication is optimal or necessary depends on a large number of regional and geographic factors. Available technology and manpower, site access, the means sought for transportation and erection are all issues that must be weighted in considering what level of prefabrication is needed for a given project. However, there is real ground to believe that a high level of prefabrication can also guarantee a high quality, low cost product that can

![Graph 1](image1)

![Graph 2](image2)

*Fig. 7. Typical load-displacement response of pin-loaded plate with shear-type connection.*
be competitive not only in developing countries, but also in highly industrialized countries as well.

REFERENCES

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3. SP-61. 143-146, Detroit: American Concrete Institute.
5. 37-42.

Fig. 8. Test arrangement and set-up for moment-type connection.
Fig. 9. Typical load-deflection response of L-shaped joined plates simulating moment type connections.


