DEVELOPMENT AND ASSESSMENT OF A REFINED CONCRETE MASONRY SYSTEM

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ABSTRACT

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Masonry, though one of the oldest forms of construction, is still not a perfect system, nor can it ever be. It can only be continuously improved, as has been done over centuries. The effort presented here is an attempt to improve the masonry industry, specifically concrete masonry. It first identified the different ways that concrete masonry can be improved. It then incorporated a selection of those methods into a new masonry system. Last, it measured and compared the refined system against a benchmark using a productivity study.

The refined system was designed with all aspects of concrete masonry in mind. The material, the actual blocks, how they would be manufactured, and even the method of assembly were designed in an integrated fashion. The result is a lightweight, interlocking, concrete block that is larger than standard concrete masonry units. The system consists of three types of blocks, namely a stretcher, a half, and a universal corner to increase the speed of construction.

Physical tests on masonry prisms, theoretical structural checks using a model structure, and a productivity study were conducted. With 27.6 N/mm^2 (4,000 psi) grout the average load sustained by the prisms was 430.5 kN (96,733 lb). Nearly all structural checks passed, however, certain load combinations exceeded the axial load-moment interaction diagram envelope, prompting for further investigation. The productivity study produced consistent results, showing that the assembly time of the refined system is shorter than that of the traditional system. This demonstrates the potential the refined masonry system has for improving concrete masonry.

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I would also like to give recognition to those within academia: Mr. Eric Krebs, co-director of the World Center for Concrete Technology, for providing valuable input concerning masonry manufacturing methods and technologies; Mr. Tom Longman, machining technology director at Kellogg Community College’s Regional Manufacturing Technology Center, for all the assistance and valuable suggestions during the fabrication of the block mold; and finally to each and every member of my graduate committee who have invested so much of their limited time to provide valuable support and guidance.

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CHAPTER 1

INTRODUCTION

Masonry has changed relatively little considering how long the practice has been in existence, and how widely it is used around the world. The basic concept still remains under the façade of advancements in technology and material. The range of products might have grown, the quality and consistency might have improved, yet a brick, block or stone still, for the most part, gets placed in a bed of mortar by the skillful hands of a mason. One by one, they are stacked, checked for plumb, and leveled similar to the way our ancestors have done so many generations ago. Despite the continuation of a strong, time-honored tradition, we cannot ignore the fact that changes and improvements have occurred, and efforts by many and those described here are a testament that efforts to improve the masonry industry will continue.

It should be apparent then that there stands a reason or reasons for this effort to change the industry. There must be faults in the system, flaws in the materials, deficiencies in the methods used. The reason may also be rooted in obsolescence as caused by advancements in technology, creation of new materials, or changes in conditions caused by exterior factors. These reasons become the driving force that promotes change; that beckons researchers to find or create new solutions. The reasons for the current research came about through simple observations over the course of several trips to the Philippines.

There in the archipelago, where most structures are built using concrete masonry blocks, several shortcomings can be recognized almost immediately. The blocks are heavy and construction is slow. Workers have to thread the blocks over vertical reinforcement placed prior to the assembly of the wall. Chases for utility lines are cut using a hammer and chisel. The use of hand tools forces crude cuts when blocks need to be shortened. The quality of the blocks in general is low, and so too is the assembly which is typically concealed by a thick layer of cementicious plaster. Insulation is another issue, especially considering the tropical climate. It was the collection of these shortcomings, and several others not mentioned, that have become the driving force for the current research, and have prompted the question, “how can concrete masonry construction be improved?”

Having seen the problems and wondered why things are done the way they are, it has then become the goal of this research to, in broad terms, improve concrete masonry construction. To do so, several objectives have been identified as necessary steps. First, define the current state of masonry technology and methods. Second, identify ways that masonry can be improved. Third, select appropriate parameters to act as guides. Fourth, redesign the masonry block and its entire system. Finally, test the effectiveness of the design changes. These steps should result in progress towards achieving the goal.

CHAPTER 2

LITERATURE REVIEW

To improve concrete masonry construction, it is necessary to identify in what ways it can be improved, what improvement methods have been attempted, and which of the methods have been successful. Figure 2.1 shows many of the ways mentioned in literature that concrete masonry can be improved. This diagram is by no means complete, and shows only many of the major methods. Some can be distinctly divided into different approaches, and then further subdivided. After finding and evaluating the many different strategies, it was found that not all could be pursued. The importance of the method and the likelihood of achieving it had to be weighed during the selection process. A discussion of those selected follow.

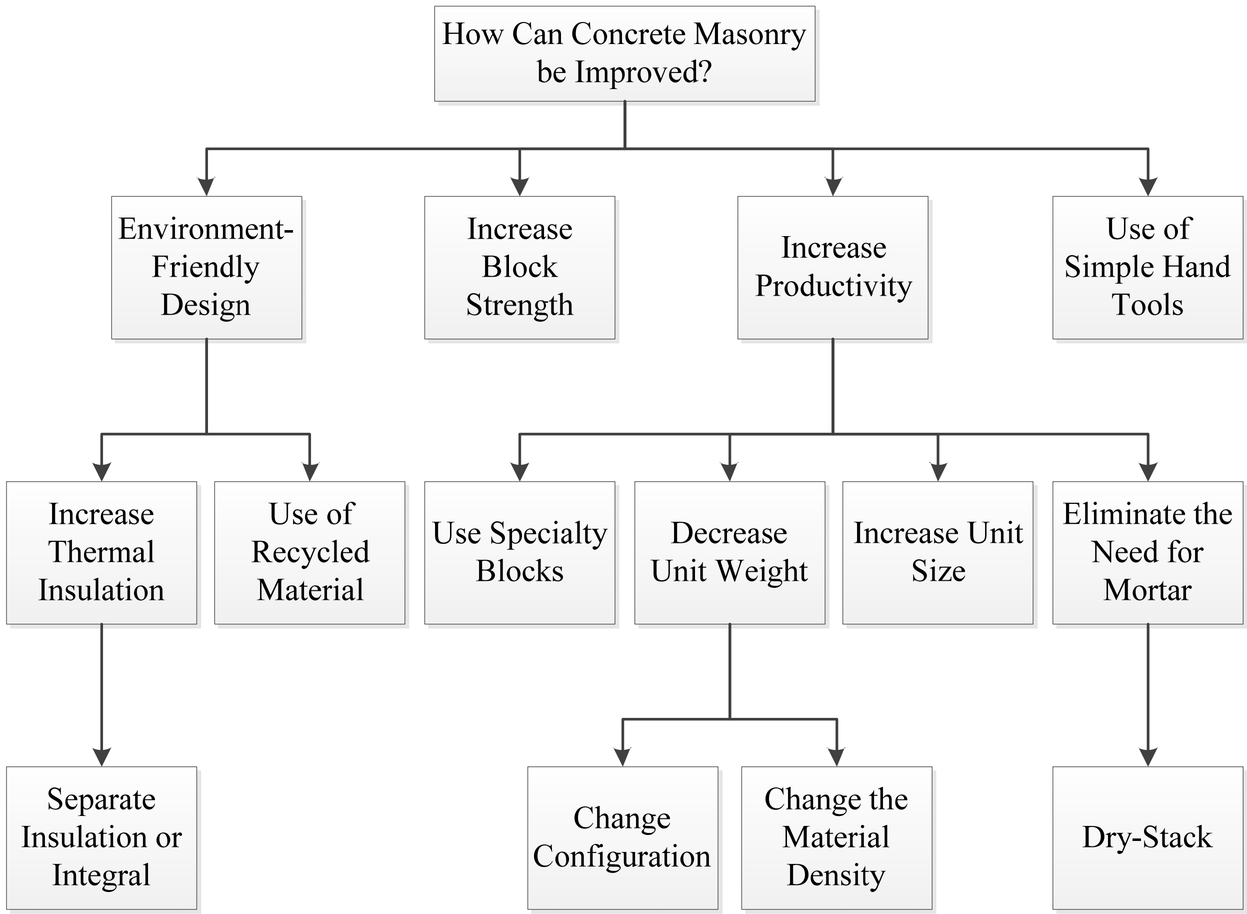

Figure 2.1: Various ways that concrete masonry can be improved. (For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis.)

2.1 Improve Productivity

Perhaps the most important improvement method is to increase productivity. Anand and Ramamurthy present three reasons for the existing need to increase masonry construction (*Techniques for Accelerating*, 1999):

1) Improving productivity of general building construction
2) Post-disaster reconstruction activities
3) Mass housing schemes

Increasing the rate of masonry construction can be divided into several distinct approaches, the more effective and practical ones being: increasing the unit size, decreasing the unit weight, offering different block shapes for common wall configurations, and decreasing or eliminating altogether the use of mortar between joints. Each is discussed separately below.

2.1.1 Increase Unit Size

Naturally, brick masonry has experienced a great amount of research concerning increases in the unit size. Of the extensive research on improving brick-laying productivity, Mortlock and Whitehead (1970) placed much emphasis on the early works by Gilbreth who contributed greatly to increasing brick masonry productivity. Bricks are small and require many more joints than do concrete masonry. So by increasing the size, the number of joints that must be mortared is decreased, and the number of motions that a mason must make is also decreased. Mortlock and Whitehead (1970) have demonstrated through an extensive compilation of literature research that increasing the unit size of bricks and concrete masonry blocks can increase productivity.

The technique of using larger-than-standard sizes for units has been tried on concrete masonry but with limited adoption, despite the fact that it has been shown to increase productivity (Anand and Ramamurthy, 1999). Concrete masonry units (CMU) are already much larger than bricks to begin with, and despite their hollow core, increasing their size is limited by the resulting increase in weight. The average weight of a standard 2-core 400 mm x 200 mm x 200 mm (16”x8”x8”) CMU is 16.8 kg (37 lb) (Amiri *et al*., 1994). Thanoon *et al.* (2004) mention that for workers in certain countries anything over 20 kg (44 lb) is considered “unduly”. Because of this, only a marginal increase in size is possible, which may only be accompanied by a marginal increase in productivity. Therefore, increasing the size of CMUs is not practical unless the unit weight can be made the same or less, which brings up the next approach to increasing productivity.

2.1.2 Decrease Unit Weight

It has been found that the unit weight of masonry inversely affects the productivity of a mason (Amiri, *et al.*, 1994); the heavier the unit the less productive the mason. Two practical methods to decrease the unit weight are to change the unit configuration or to change the density of the material being used. Some bricks were produced with vertical hollow cores. This decreases the amount of material which also decreases the unit weight (of course the cores serve another purpose concerning dimensional stability). That is an example of a configuration change. An example of using a lighter material would be to incorporate expanded, lightweight aggregate in the production of CMUs. This practice has also already been adopted by industry and one such block is the Durisol system (Murray, 2007).

2.1.3 Complete or Partial Elimination of Mortar

Yet another method found effective in increasing productivity is to decrease or eliminate the need for mortar entirely (Anand and Ramamurthy, 2003). Masonry that doesn't use mortar is said to dry-stack. In lieu of mortar joints, which bond units as well as compensate for height variations of the blocks, dry-stacked blocks join by a means of physical interlocking mechanisms such as a tongue-and-groove arrangement.

Having blocks with more intricate shapes has, however, created a major disadvantage because in the absence of mortar the blocks require much smaller dimensional tolerances and more complex molds (Crofts, 1993). Several methods are currently employed to address this issue. Grinding the top and/or bottom of the blocks during production appears to be the most common (Thanoon et. al., 2004; and Thallon, 1983). Sariisik and Sariisik (2012) used a masonry saw to cut their blocks that resulted in a smooth surface finish. A last known option is to place a thin layer of fine cement on top of freshly molded blocks as they pass under a calibration unit (Crofts, 1993). Alternative to these manufacturing measures, dimensional variations can be dealt with during construction by using shims or placing mortar on every forth course (VanderWerf, 1999). In light of this setback, care must be taken when designing the block to ensure that manufacturing costs do not offset the productivity benefits that can be gained from dry-stacked systems.

2.1.4 Use of Special Block Configurations

Lastly, productivity can be increased through the use of special block configurations to speed assembly of common wall layouts such as regular corners, 45-degree corners, T-intersections, and full or cruciform intersections. Rather than taking additional time to carefully place or modify standard blocks, known as stretchers, to form a corner or intersection, specialty blocks act more like prefabricated subassemblies. They help decrease the number of field cuts and adjustments that would otherwise have to be made.

Research has produced a vast variation of specialty blocks but of the many designs, the more common specialty blocks are corner blocks, bond beam blocks, and half blocks. Some corner blocks are designed to be universal, i.e. they are capable of forming full- and T-intersections. Bond beam blocks have a U-shaped channel along the top that when filled with grout produces an embedded, horizontal beam. Lintels can also be easily formed using this type of block. It can be argued that half blocks aren't considered specialty blocks since they don't form any special wall configurations. However, half blocks are an important necessity as will be pointed out later.

2.2 Compatibility with Hand Tools

Another approach to improve concrete masonry is to design the blocks so that simple hand tools can be utilized during construction. In the use of expanded polystyrene to make lightweight concrete masonry, the ease of cutting and the ability of the block to accept screws and nails are recognized as advantages (Cook, 1983). Avoiding the need to take a block to a powered saw can decrease travel and wait time. Having the ability to drive regular screws or nails into a block using nothing more than a typical hammer would remove the need to carry a power drill or powder-actuated fasteners. A general contractor using insulating concrete forms, which also are easily amendable with nothing more than simple carpenter tools, also mentioned they no longer needed a power generator on-site (Calvert, 2010). In further regards to insulating concrete forms, *Industry Comparison Chart* mentions that because composite-type blocks will readily accept nails and screws, finishing the interior or exterior is far easier.

2.3 Environment-Friendly Design

With the burgeoning concern over environmental issues, making concrete masonry more environment-friendly has garnered much attention. Certifying programs such as LEED have added another impetus for becoming "green" if concrete masonry wish to remain competitive against rival industries. From research, two of the more prominent ways to improve masonry in this field is to increase its thermal resistance and to use recycled material.

2.3.1 Increase Thermal Insulation

The energy used to heat homes and buildings is a significant percentage of the total energy consumed. Standard concrete masonry units have been shown to provide very little thermal resistance, requiring more energy to heat (or cool) than what should be required (Rao and Chandra, 1970). Kosney and Christian (1995) point out that even the mortar that the blocks are set in contributes to this heat transfer, and it can be as high as 12%. One of the ways to combat this is to incorporate insulation, either as a separate material or as an integral component of the masonry units. The use of lightweight concrete to produce masonry units can increase thermal efficiency to as high as 90% (Kosny and Christian, 1995). An abundant amount of research has been conducted on various lightweight mix designs and the results are very promising.

2.3.2 Use of Recycled Material

The reuse and recycling of material plays a large role in reducing the need for virgin resources and additional space for waste disposal. Already being practiced in the US and in many other coal-burning countries, fly ash captured from coal-fired power plants is being used as a partial substitute for cement. This serves a multitude of purposes such as aiding the disposal of a by-product and improving certain qualities of concrete. Aggregate too can come from waste resources. Crushed concrete can be reincorporated into fresh concrete, as well as slags from metal production and certain household items. Lightweight concrete made using lightweight aggregate can increase thermal resistance as mentioned above. Some researchers have experimented with recycled expanded polystyrene as aggregate which can account for a vast majority of the total volume of concrete (Laukaitis et al., 2005; and Zurauskas et al., 2001).

There are several other ways that concrete masonry can be improved, but those in the aforementioned sections will be the focus of the research.

2.4 Design Parameters

After reviewing the different ways that a block can be improved it became apparent that parameters will be needed to act as guides during the design phase. There needs to be some formal process or mechanism to decide when a block is too heavy, or the design is too complex. Without such limits any effort to improve a concrete masonry unit can become counter-productive. The degree to which something was changed may become inappropriate for its intended purpose. In essence, parameters will be the rules to observe. After extensive consideration those selected are as follows:

1) Size: What size and dimensions should be used?
2) Weight/Density: What should the target weight or density be?
3) Manufacturability: How can the blocks be manufactured?
4) Constructability: How will walls be constructed?
5) Material: What materials are available and can contribute in achieving the other parameters?
6) Overall Simplicity: Is the shape design simple and how many different block configurations should be included in the system?
7) Strength: What should be the minimum target strength?

Each parameter will be discussed in more detail later, but it needs to be pointed out that it was recognized that there is an existing relationship between many of the parameters. The degree of this relationship varies in intensity and the corresponding effect on the parameter under study. It can be a strong relationship such as changing the size of a block will definitely change the weight of it. It can also be a weak relationship such as changing the constituent material of the block may have a small impact on strength. The effect of the relationship is whether it will have a positive or negative impact. For instance, decreasing the density of the block material will typically decrease the strength. Integration of these parameters is necessary, but a holistic mind-set is also needed to understand and be attentive to the impacts decisions will have. A graphical depiction is presented in Figure 2.2.

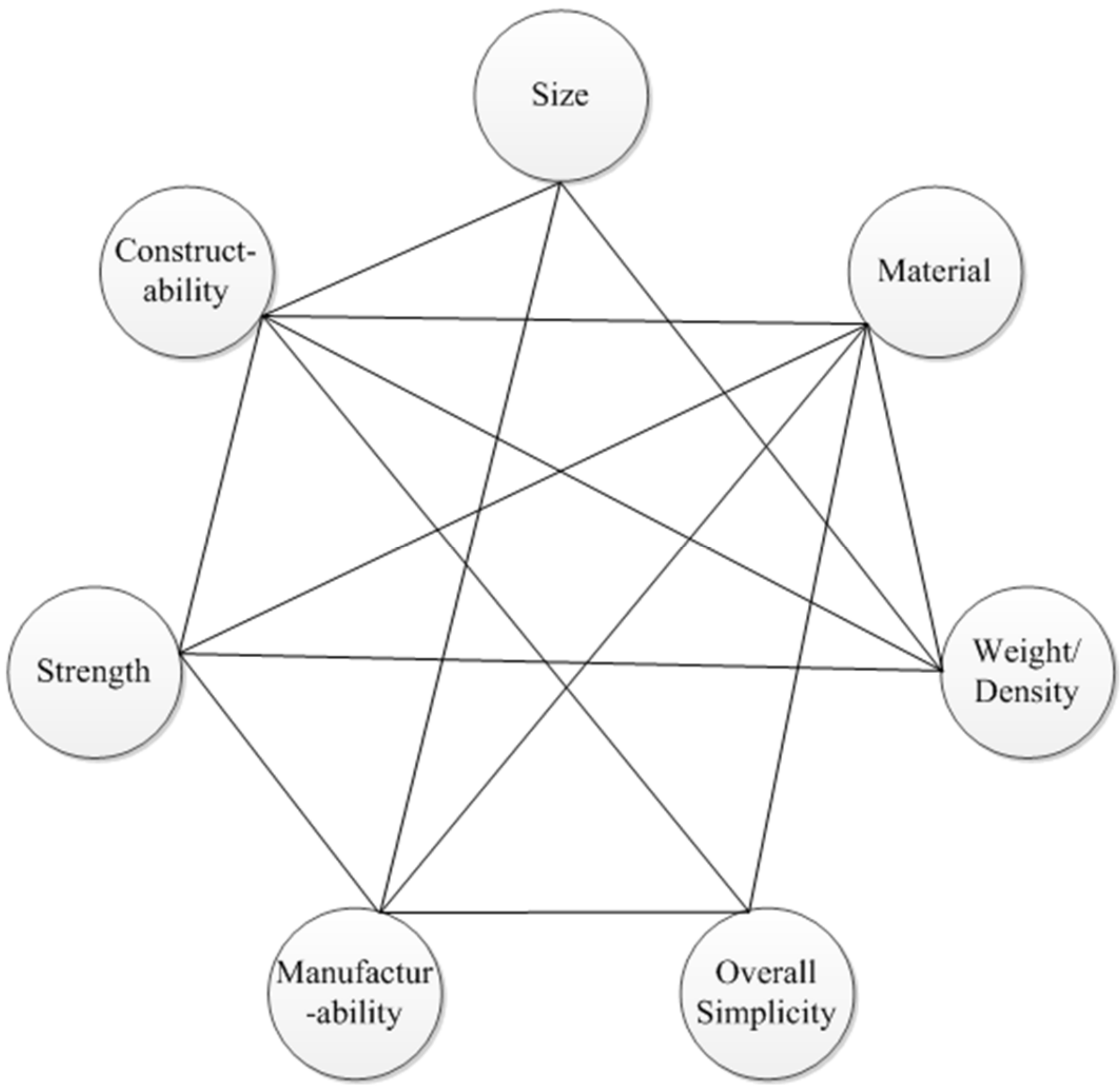

Figure 2.2: Interdependency of parameters.

CHAPTER 3

DESIGN AND EXPERIMENTAL METHODOLOGY

To go about designing a new masonry system, several disciplines became involved. Material science was the first when selecting what materials to use, anticipating how they will interact with each other, and calculating the proportions to use. Designing of the block and checking its structural integrity comes under engineering. Finally, comparing the productivity of the refined system to a traditional system is a construction management-related field. Because this research involved several disciplines, it was decided to segment it into respective modules, namely material science, engineering, and construction management. This was done for organizational purposes.

3.1 Module 1: Material Science

The goal of this module is to create the median of which the refined masonry system will be comprised of while complying with the set parameters. The objectives that must be met to achieve this goal are, namely, select appropriate materials, define quantities of each material, and test the material to ensure parameter limits have not been exceeded.

3.1.1 Material Selection

Concrete masonry units are produced using a combination of cement, aggregates (usually subdivided into coarse and fine), water, and sometimes various admixtures. Concrete has many advantages as a construction material. First, it is available in most parts of the world making sourcing a non-issue. Second, cement does not require any catalyst to begin the chemical reaction with water that transforms it into the effective binder that it is known to be. Third, concrete, under the right conditions, is a very durable material. Finally, when concrete is in its plastic state, it can be shaped to almost anything imaginable. Only when it hardens does it become difficult to change. For these advantages, and for the fact that the concrete masonry industry is already familiar with concrete, choosing cement as the binder became an easy choice. In order to meet the objectives of this module the other constituents of concrete (the aggregate, admixtures, and water) will be altered.

The aggregate in concrete accounts for 60-80% of the total volume. Because of this, aggregate has the most profound effect on the density of concrete (Mehta and Monteiro, 2006). Therefore, by using an aggregate with a lower density the unit weight of the concrete can be lowered, and subsequently so too can the weight of a block. Aggregate densities of 1,121 kg/m^3 (70 lb/ft^3) and less are typically considered lightweight, and many different types are currently used in the concrete industry today. By substituting any of these lightweight aggregates for normal weight aggregate the density will be lowered, and in order to know which aggregate would be best a target density needs to be selected.

At this point in the material selection a junction has been reached. Due to the interplay between the various parameters discussed earlier, a specific target density cannot be selected without knowing what the target weight of the block is. Furthermore, the weight could not be derived from the volume of the block since the block itself has not been designed. The target weight, therefore, would become one of the defining attributes for many subsequent characteristics, and would have to be defined otherwise.

It can be recalled from earlier that a standard concrete masonry unit is approximately 16.8 kg (37 lb). This already is a considerable amount of weight and wishing to be less than or equal to it, the target weight was somewhat arbitrarily set at 13.6-15.9 kg (30-35 lb). This weight can be considered a reasonable target considering the fact the size of the block would be larger than that of traditional CMUs.

As for defining the volume of the block, preliminary design work, which was conducted in Module 2, had to be completed in parallel prior to doing so. This yielded a volume of 0.023 m^3 (0.82 ft^3) which can now be used to continue calculations.

Using the now defined preliminary weight and volume of the block, the appropriate target density can be calculated, and work in this module may continue. This came to be approximately 640 kg/m^3 (40 lb/ft^3). A chart from ACI 213R-79, is partially reproduced in Figure 3.1 showing what densities can be achieved by using one of several aggregates. From this, one can quickly see that in order to achieve a density of 640 kg/m^3 (40 lb/ft^3), expanded vermiculite or expanded perlite could be used. This raised concerns regarding the availability of the material (perhaps perlite or vermiculite are available but the capital for expanding it is not, or perhaps neither are available), and an alternative was searched.

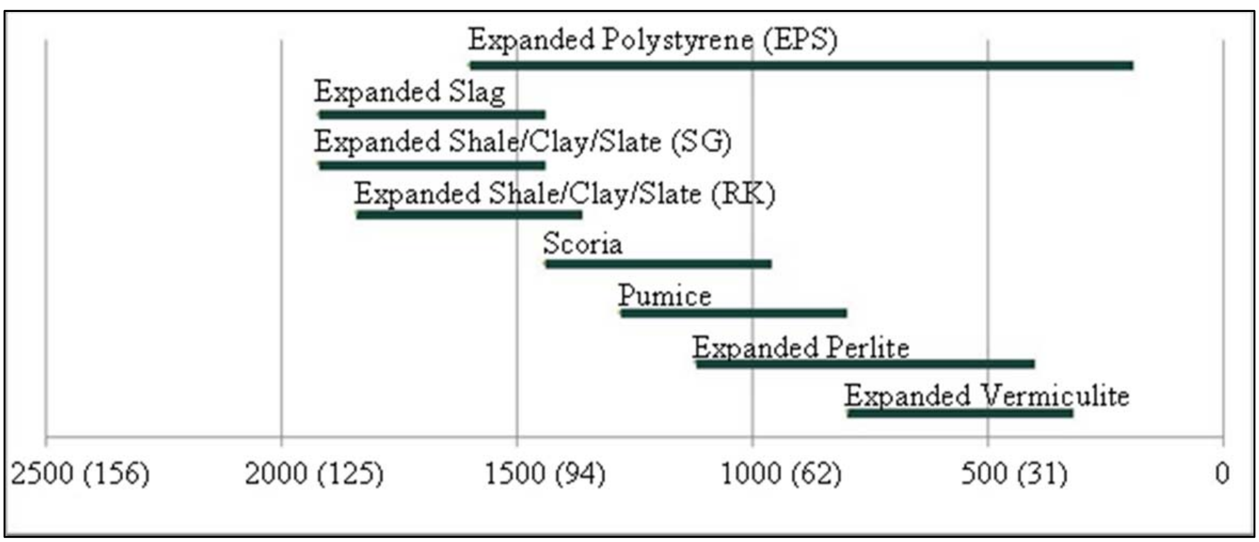

Figure 3.1: Various lightweight aggregate and corresponding concrete densities. (kg/m^3 (lb/ft^3))

Initial research experimenting with expanded polystyrene (EPS) beads as aggregate for producing lightweight concrete was conducted by Kohling and also BASF (Cook, 1983). Extensive work by Cook during the 1970's showed the viability and potential of EPS as an aggregate for lightweight concrete. The concrete density range that can be achieved using EPS was added in Figure 3.1. Subsequent researchers explored various possible applications, and surprisingly numerous studies have already been conducted on EPS concrete masonry units (Gazzola and Drysdale, 1989; Godwin, 1982; and Drysdale and Gazzola, 1993). Seeing the positive results and finding that EPS can meet the criteria for the purpose of this research, it was selected as an acceptable aggregate alternative.

The remaining ingredients for the lightweight concrete mix followed in selection. Sand was originally selected as the fine aggregate but Cook pointed out that for concrete densities under 600 kg/m^3 (37.5 lb/ft^3) sand is usually omitted. A high range water reducing admixture was used to decrease the amount of mixing water. This is because of the inverse relationship between the strength of concrete and the amount of mixing water (Abrams, 1919). Also, a Class F fly ash was used as a partial replacement for the cement which is already widely practiced around the world. This serves two purposes; first it improves several qualities of the concrete in both its plastic and hardened state, and second, it has a positive impact on the environment (creating a more environment-friendly design). Now that all the ingredients have been selected the next objective is to determine the quantity ratio of each.

3.1.2 Mix Design

To begin determining the quantity of each material a benchmark mix would have to be formulated. ACI 211.3R-02, Guide for Selecting Proportions for No-Slump Concrete, was used to calculate the base mix design. From there, visual observations were made during mixing, placing, and after removal of the samples from the molds. Observations such as how well it mixed, how easy it was to place, if there was excessive bleeding or segregation, and the general quality of the surface finish. The weight was also recorded and the density calculated for each sample. Based on these observations the quantities would be adjusted until a favorable mix design that also had the correct density was achieved.

Once the mix design was properly proportioned, three replica samples were produced for compressive strength testing in in accordance with ASTM C39-11. The samples were moist cured for three weeks in plastic bags and finally moved to a fog room where they continued to cure for another 7 days. They were capped with a Sulphur-based capping material using ASTM C617/C617M-11 just prior to testing. The results of the testing, which were conducted at Michigan State University, will be presented in Chapter 4.

3.2 Module 2: Engineering

Module 1 created the material to be used in making the blocks. In Module 2, the block design and assembly steps were completed. In addition, a preliminary structural check was conducted to indicate the feasibility of the design from a structural standpoint. To reach these two goals the objectives are to establish standard dimensions to use for designing the block, create a preliminary block design and method of assembly by drawing ideas from numerous sources, cross-check the preliminary design against respective parameters to derive a final design and method of assembly, design and fabricate a temporary mold to cast prototype blocks, conduct strength tests of block prisms, design a model structure for calculating loads, and identify and conduct proper means of calculating the theoretical strengths within the context of the model structure.

3.2.1 Modular Design

The first step taken to designing the new block system was to establish the basic outer dimensions and to ensure they agree with international practices. The use of modular coordination was similarly one of the guiding parameters used by Thanoon *et al.* (2004) in the development of their new masonry system, and by Nasly and Yassin (2009) for yet another new masonry system in Malaysia. Some of the practical purposes for complying with such modularity rules are to increase compatibility between construction materials and design, and to reduce waste of material and effort. Modular coordination identifies ideal dimensions and multiples thereof. The established guidelines for practicing modular coordination are comprehensively covered by a set of ISO standards. The specific standards selectively used from the set for the purpose of this research are ISO 1791, 1006, 1040, 2848, 6511, 6513, and 6514. These particular standards define the foundation for using modular coordination.

3.2.2 Basic Configuration

For the next objective an extensive, but not exhaustive, review of different block designs and masonry technologies was conducted. From this review, inspirations for ideas were drawn from three major categorical sources: research on concrete masonry technology/techniques, the insulating concrete forms industry, and the autoclaved aerated concrete industry. Similarities exist between each, yet they are still very distinct from one another. New ideas spawned from existing ones that helped shape a new preliminary block design.

With the preliminary design at hand, it was necessary to cross-check this design against the parameters discussed earlier. Weight was one of the first parameters checked because a very strict weight limit was imposed during work in Module 1. The volume and size of the block then became dependent parameters. They are limited by the restriction imposed on the weight of a single block. Manufacturability (how feasible and practical it is to manufacture a product), was then checked. It does not make sense to develop a masonry system that cannot be manufactured within reason of capability. It is also recommended that the blocks be designed so that they can be produced by "conventional means" (Ramamurthy and Nambiar, 2004). Thanoon *et al.* (2004) went further by suggesting that "production is similar to that of normal hollow blocks so that the manufacturing machinery is easily fabricated." Finally, the preliminary design was checked for constructability. Similar to manufacturability, this parameter ensures that the method of assembly has been thoroughly investigated. It is not enough to just design a block and ensure it can be manufactured; how it will be used in the field must also be designed. This was recognized during the development of the Putra Interlocking Block System in Malaysia (Thanoon *et al.*, 2004). Changes in the design were made to remedy any issues that were discovered during the cross-checking phase until a final design was reached.

3.2.3 Temporary Mold Development

Once commitment on a final design was made a mold could be designed and fabricated. Researchers who have also developed new concrete masonry systems produced temporary molds using different materials and methods. Harris *et al.* (1992) at Drexel University fabricated a seven-piece mold from brass that disassembles during use. They also fabricated another, more inventive mold using aluminum that had a mechanized means of consolidation and made it convenient to remove the block once cast. Both molds were contrived at one-third scale, which is assumed to be due to costs and practicality. For reasons later discussed in Module 3, it is necessary to be able to produce full-scale prototypes. Researchers in Malaysia were able to produce full-scale models of their proposed block design using wood forms. Wood is not as durable as the metal used by Harris *et al.* (1992), but it proved sufficient enough to cast well over 1,000 blocks (Anand and Ramamurthy, 2000).

Wood, having the advantage of lower cost than metal, was considered, however it was foregone for a more promising alternative. By chance, a special type of resin was found that is cast into large, flat slabs. These plastic slabs are purposefully made for milling, as if they were metal. Along with their available sizes and thicknesses, it was possible to fabricate a full-scale mold with very small dimensional tolerances. Preliminary trials on different coating arrangements were conducted to find which combination worked best to safeguard against adhesion between the concrete mix and the new plastic mold material.

Following the completion of the mold, blocks were made one by one. They were wrapped individually in large, plastic bags to moist cure for at least 28 days. The mix design was altered based on how easy placement was, what the actual weight of the block came out to be, and the quality of the surface finish. Enough blocks were produced to make prisms for testing and to conduct the productivity study in Module 3.

3.2.4 Structural Check

The next objective is to use a model structure to calculate loads as part of the structural check. A related procedure was used by Thanoon *et al.* (2004), where they used a five-story building to conduct a structural check of their concrete masonry system. Recalling that the original motivation for this research stemmed from observations made in the Philippines, the model structure was designed by a practicing architect in the Philippines, and it is representative of homes found there. Although a different design from a different country could have been used, the one from the Philippines was kept. Considering the presence of typhoons, landslides, volcanoes, and seismic activity, keeping with the decision can perhaps be considered a conservative one.

Now the actual procedure for checking the structural integrity had to be outlined. The blocks themselves appear very similar to that of traditional concrete masonry blocks, however, categorically they would be classified as insulating concrete forms (ICF). Because of this designation, ACI 318, Building Code Requirements for Structural Concrete, would be more appropriate than ACI 530, Building Code Requirements for Masonry Structures. This was pointed out through discussion with Jason Thompson of the National Concrete Masonry Association. Despite this, compressive strength testing will be conducted on masonry prisms following ASTM 1314-11 testing procedures, which is usually used for standard masonry units. This will provide additional insight on the expected strength characteristics of the proposed masonry system.

The procedure for applying ACI 318 on the refined masonry system used by VanderWerf *et al.* (1997) was closely followed. The book was written for insulating concrete forms (ICF) and includes a section on structural design. Their example uses a simple residential layout in order to calculate the different loads, which is actually very similar to what is intended for the refined system. The ICF block chosen for the example also had a very similar configuration. The major difference was the load levels used. Other minor differences were the block core size, characteristics of the model homes being used, and the load combinations. Results of the structural check should show where major weaknesses, if any, exist.

3.3 Module 3: Construction Management

The final module deals with concerns related to construction management than other disciplines as productivity can affect the duration and schedule of a project. The goal of this module is to conduct a time comparison between constructing masonry walls using standard concrete masonry units and using the refined concrete masonry system. In order to do so a study was designed, and volunteer masons were recruited for the construction process.

3.3.1 Productivity Study

The productivity study was kept relatively simple and direct. It was decided that each mason would construct two identical walls. Each wall measured 3 m (10 ft) long by 1.2 m (4 ft) high, and was a nominal 200 mm (8 in) thick. One wall was built using standard 400 mm x 200 mm x 200 mm (16"x8"x8") CMUs while the other was built using the new blocks. The study was conducted indoors on a flat, smooth, concrete surface. There was ample lighting and the space was heated. The time it took a mason to build each wall was measured as the primary endpoint to compare the two block systems. Summary statistics (mean, standard deviation, median, minimum and maximum) and 95% confidence interval were computed using SAAS version 9.2.

The use of a controlled environment helped reduce variation. Another measure that was taken to help reduce variation was setting up the study to be as close as possible to an actual job site. Mud boards and other common tools of the trade were used, the masons were tended by a laborer, and the blocks were placed as they would be in the field. Consistency is yet another means to help control variation. To save on cost of materials, the blocks were cleaned and reused. After each use they were returned to the same location and in the same orientation as they were at the beginning of the study. Mason order assignment was performed at random using cards, which were also set up to ensure that both walls would have an equal number of starts. Finally, the volunteer masons were required to meet certain eligibility criteria in order to participate in the study. Taking these measures helped reduce variation which in turn helped increase the accuracy of the results.

It was expected that there will be a learning curve in order to use the refined masonry system. To help reduce this effect, each mason was briefed prior to the start of the study on how the new system is assembled. It was assumed that by keeping this briefing short the times recorded for the refined masonry system will remain conservative because the masons will have had a relatively minimum amount of exposure.

CHAPTER 4

RESULTS AND DISCUSSION

In keeping the format consistent, this section of the report will again be subdivided in the same modules as used when discussing the methods used. Results are gathered for each section and conclusions are compiled in the following chapter.

4.1 Module 1: Material Science

The goal of Module 1 was to create the material comprising the refined masonry system. It had to meet certain criteria, perhaps the most important being the density. It was decided, because of numerous advantages, that concrete would be used. However, to meet the density requirement a lightweight aggregate had to be utilized.

4.1.1 Mix Design

The concrete industry has identified several lightweight aggregates available for achieving a wide range of concrete densities. An unlikely alternative, however, was selected which is expanded polystyrene (EPS). The original mix proportion, as calculated using ACI 211.3R-02, is presented in Table 4.1. Initially sand was chosen as the fine aggregate but as Cook (1983) pointed out, EPS concretes with similar densities usually omit sand. This mix was adapted multiple times until a final sample that met the density requirement and exhibited favorable characteristics was obtained. The final mix design is presented on the same table as the original.

Table 4.1: Original and final concrete mix designs.

Mix	Amounts are per Cubic Meter of Concrete						
	Cement kg (lb)	Fly Ash kg (lb)	W/C	EPS kg (lb)	Sand kg (lb)	HRWR ltr (oz.)	Density kg/m^3 (lb/ft^3)
Original	193 (425)	48 (106)	0.40	8.48 (18.7)	264 (582)	4.32 (146)	935 (58.4)
Final	240 (529)	80 (176)	0.36	6.82[1] (15.04)	-	4.58 (155)	636 (39.7)

Notes:
[1]The second batch of recycled EPS had a lower density resulting in a lower weight even though the volume of EPS increased.

4.1.2 Material Testing

The final mix design was used to make triplicate samples for compressive testing. These 150 mm by 300 mm (6" by 12") cylindrical samples were tested after 28 days. They were moist cured for 21 days in plastic bags followed by 7 days of curing in a fog room. Figure 4.1a shows the mechanism used for capping the samples, and Figure 4.1b shows the three samples after they had been capped using a Sulpher-based capping compound. The results of the test are listed in Table 4.2.

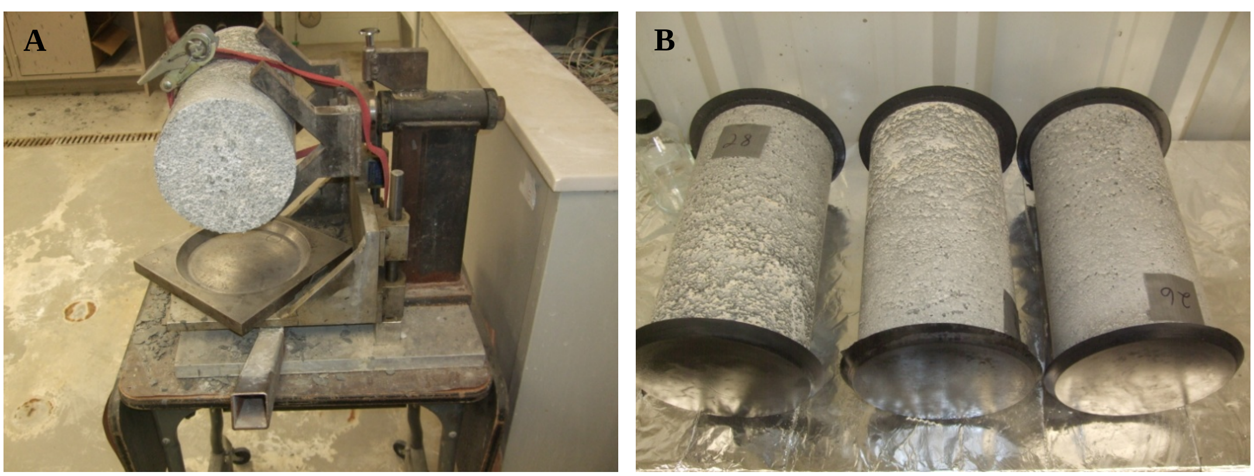

Figure 4.1: Capping of cylindrical concrete samples. (a) mechanism used for capping samples; (b) triplicate concrete samples after they had been capped.

Table 4.2: Concrete cylinder test results.

Sample	Test Result, kN/m^2 (psi)
1	8.62 (180.0)
2	8.69 (181.4)
3	7.56 (157.8)
Average	82.88 (173.1)

During testing, the cylinders did not fail in the usual fashion that normal-weight concrete samples do. Rather, they compressed a considerable amount without any distinct indication of failure. According to the testing equipment readout, the resistance of the sample reached a maximum followed by a gradual decline. It was not an abrupt failure that usually marks the failure of normal concrete samples. The residual resistance is an interesting note, and after removal of the load the sample would "spring" back slightly. See Figure 4.2a for a picture of the testing equipment, and Figure 4.2b for one of the samples recently removed (notice the "mushroomed" bottom and slight signs of failure).

Figure 4.2: Testing of cylindrical concrete samples. (a) hydraulic testing equipment loaded with sample; (b) sample after testing.

The average compressive strength doesn't compare to that of standard concrete, however, the blocks themselves will not be carrying any superimposed loads. The refined masonry system is designed to be fully grouted which will be the structural component. There is no maximum strength limit, but a minimum strength was established as one of the parameters. This is because the blocks must be at least strong enough to withstand handling, placing, and general wear during its life.

The minimum compressive strength was set equal to a category of insulating concrete forms product that is similar in makeup. Composite type ICFs are made by incorporating cement with the steam during the expanding process of polystyrene beads. The two fuse together in a mold where it cures as a solid mass. Both the density and compressive strength is similar, whereas the production process differs. The reported strength for this type of ICF from several manufacturers is 2.68 kN/m^2 (56 psi) and 2.54 kN/m^2 (53 psi) from Rastra Technologies, Inc. and Millennium Manufacturing, Inc., respectively; which is much lower than the average achieve with the new mix design.

4.2 Module 2: Engineering

There were two goals for this module. The first was to design the block and the method of assembly. The second was to conduct a preliminary structural check to demonstrate the refined masonry system's potential and to try to identify major structural issues. During the design of the block and the method of assembly research focused on three major areas from which ideas were stimulated. These were concrete masonry advancements, the insulating concrete forms industry, and the autoclaved aerated concrete industry.

When reviewing research concerned with concrete masonry a vast variety of designs and ideas surfaced; originating from numerous countries around the world. Over 70 different block designs were found. Some were just drawings, others were already in the market, while the development progress of the remaining designs fell somewhere between the two ends of the spectrum. Most are designed to dry-stack and interlock, showing the large interest in increasing the production rate of concrete masonry. To emphasize the prolific output of designs and the immense creativity, some of the blocks have been illustrated in Figure 4.3 while the remaining blocks are included in a non-exhaustive figure in Appendix C.

Almost every block illustrated is part of a complete system, meaning two or more different block configurations are part of the design as a whole. What have been illustrated here and in the appendix are the main units of their respective systems. The number of units that make up a system has no limit and at times can be quite high. For example, the Intralock block system is made up of six different block configurations. What kind of configuration is included in each system differs from one design to the next, but the common ones are the corner block and the half block. Identifying system design trends was beneficial during the design of the current new system.

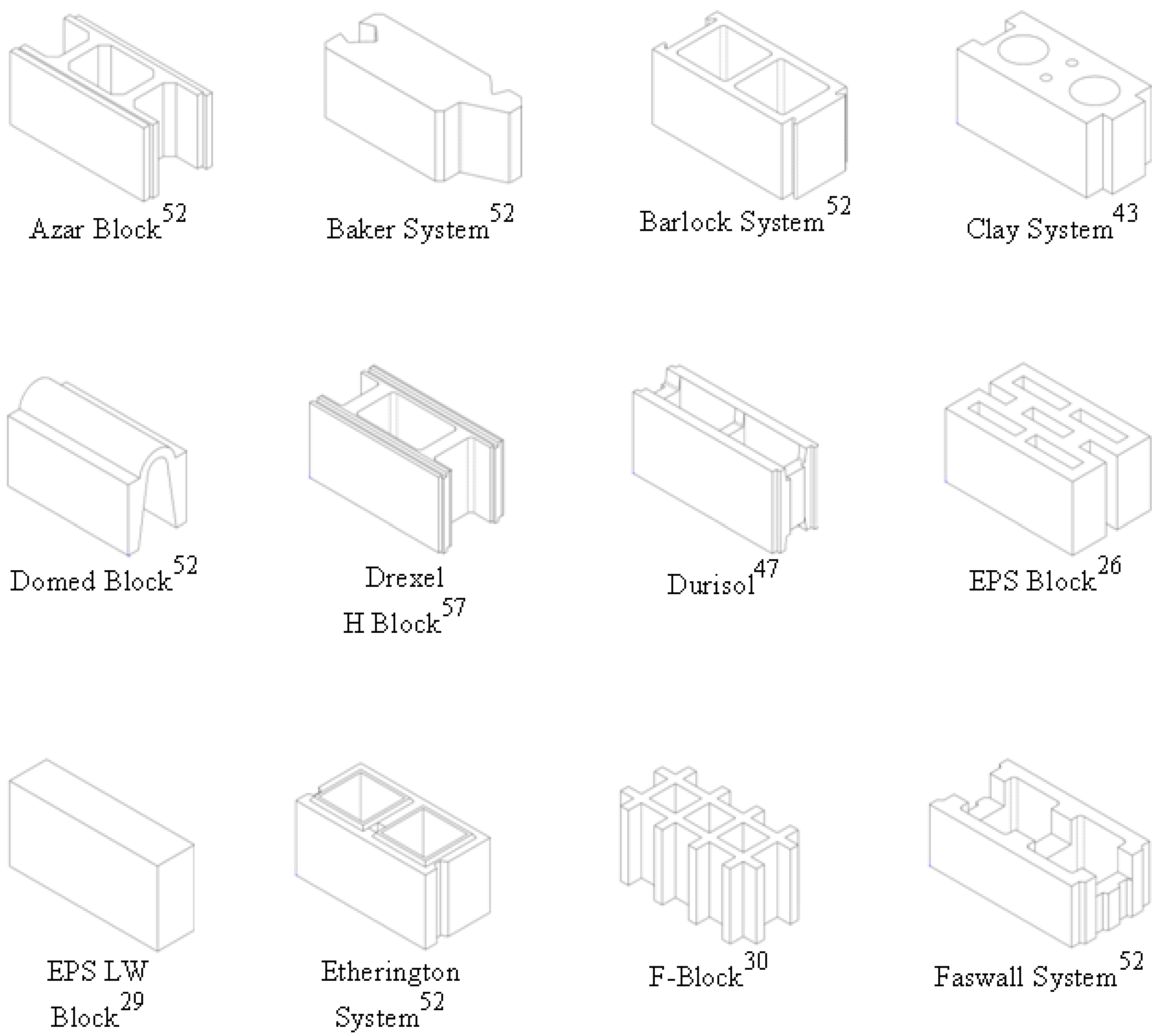

Figure 4.3: Various new block designs from around the world.

Insulating concrete forms (ICF) is a relatively new building system. Invented in 1967 (Quain, 2010), ICFs have matured as a product and as an industry with over several dozen existing companies (*Industry Comparison Chart,* 2008). The basic concept of ICFs is that an insulating material, most commonly a type of plastic foam, is used as stay-in-place forms for casting concrete walls. They can be categorized in several different ways: by what type of material they are made from (expanded polystyrene, polyurethane, composite, etc.), by their mode of assembly (blocks, planks, panels, etc.), or by the shape of the concrete wall formed within. The most common category used to distinguish between the different systems is the latter of those mentioned. Within this category there are four wall shapes: flat, screen-grid, waffle-grid, and post-and-beam (Figure 4.4; post-and-beam is not included because it is not very common).

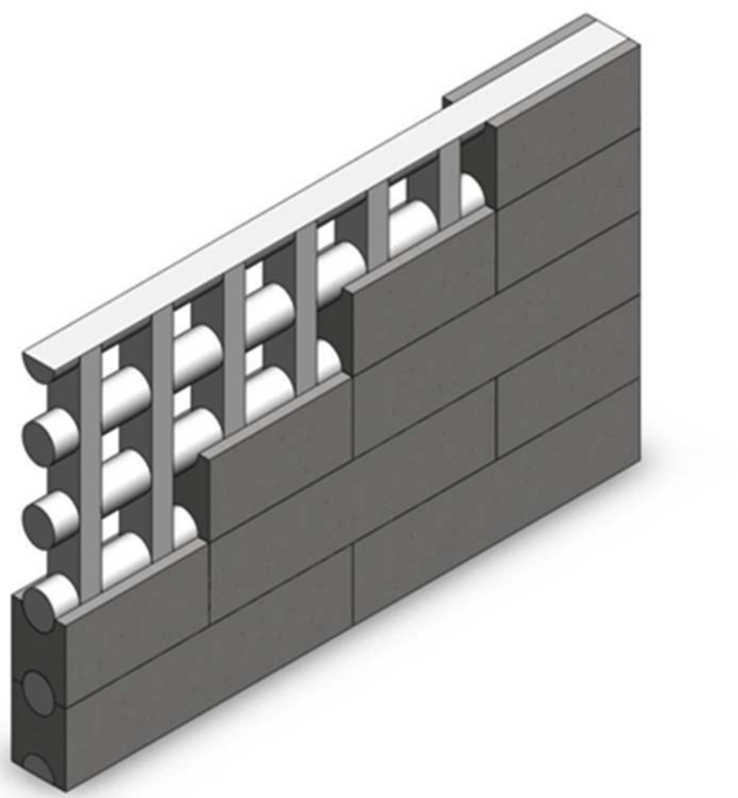

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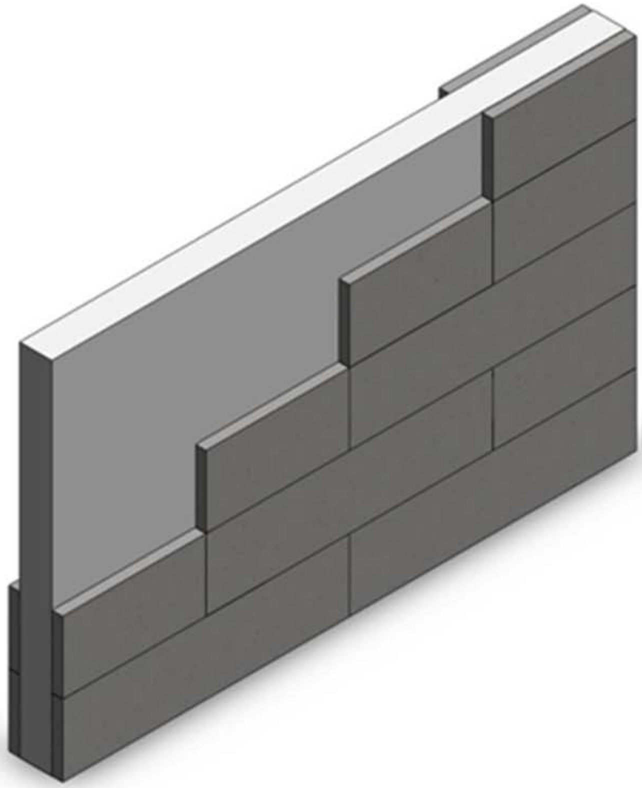
Figure 4.4: Different categories of ICF walls. (a) Screen-grid; (b) Flat; (c) Waffle-grid.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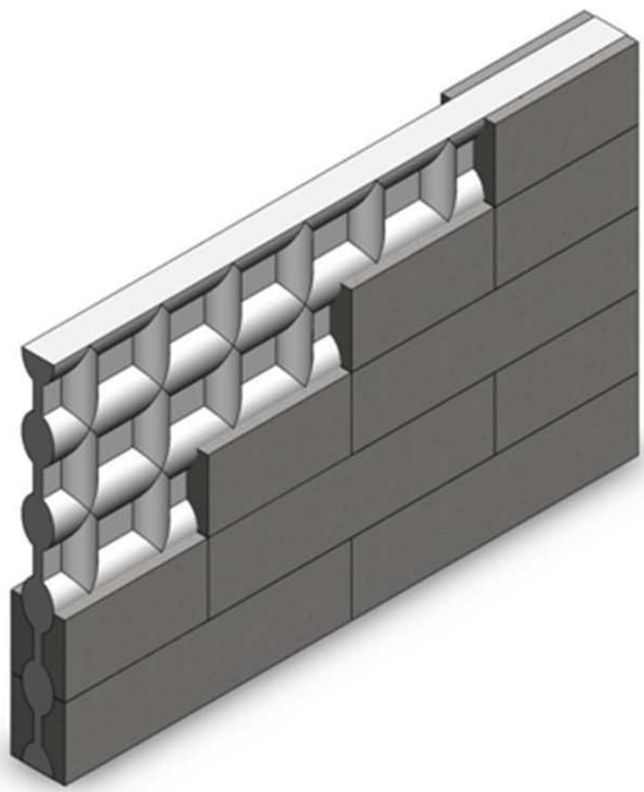
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Figure 4.4: (cont'd)

Autoclaved aerated concrete (AAC) masonry has been the last major source of help during the design of the new masonry system. Invented in the mid-1920's by Johan Axel Eriksson, AAC blocks are produced by adding aluminum powder to a concrete mix containing only fine aggregate. The powder reacts with calcium hydroxide to produce microscopic hydrogen gas bubbles which become trapped as the concrete sets. After cutting into large blocks, it is further hardened in a pressurized chamber using heat and steam, after which, the hydrogen gas escapes to the atmosphere and is replaced by ambient air. The process is analogous to yeast used to make bread rise, and the resulting density of the material is usually a fraction that of regular concrete.

The three major areas of research; state-of-the-art of concrete masonry, the insulating concrete forms industry, and the autoclaved aerated concrete industry, each have been valuable resources for the design process of the new system. In addition, many more design guides were also used, as will be discussed.

4.2.1 Modular Design

The first step during the design process was to define what modular dimensions should be used. ISO standard 1006:1983 established 100 mm (3.94 in) as the base dimension, and it is represented as 1M. ISO standard 1040-1973 further expounded by recommending common multiples, or multimodules, for lateral dimensions. The values are reproduced in Table 4.3. For practical reasons, 6M was selected as the length of the block. 3M was considered for the width of the block, however, 200 mm (7.87 in) is nearly a universal standard and is a reasonable width for walls. For the vertical dimension, 3M was selected because the floor heights specified in the National Building Code of the Philippines for residential construction are multiples of 300 mm

(11.81 in) [i.e. 2.4 m (7.87 ft), 2.7 m (8.86 ft), and 3.0 m (9.84 ft)]. Therefore, the final face dimensions of the refined masonry system were set at 6M by 3M, or 600 mm (23.6 in) length by 300 mm (11.81 in) height. These modular dimensions agree with the modular parameters of 3M and 1M for lateral and vertical dimensions, respectively, used by Thanoon *et al*. (2004) during the development of their masonry system. Dimensions were purposely kept in metric units, and now that a "box" has been defined the finer details of the block can be developed.

Table 4.3: Recommended multimodules for lateral dimensions.

Designation	3M	6M	12M	15M	30M	60M
Equivalent mm (ft)	300 (0.98)	600 1.97	1200 (3.94)	1500 (4.92)	3000 (9.84)	6000 (19.69)

4.2.2 Basic Configuration

What vertical and horizontal cores were incorporated, and what kind of stacking bond to use were decided following the selection of the outer dimensions for the unit. Knowing the blocks will be fully grouted for strength means that all the cores need to align with one another. It would also be best to have multiple horizontal cores to stabilize the vertical concrete cores against the effects of slenderness (just in one direction). Furthermore, a running bond, where the blocks of one course are offset from the adjacent course, was selected because it is a strong stacking pattern, and provides additional stability during construction. To incorporate this running bond (set at one-half) it was easiest to have two vertical cores.

The horizontal channel was more difficult to establish because of the additional manufacturing hurdles. Manufacturability was one of the parameters that would impact the design of the block. Huizer and Ward (1982) contacted Besser Company, an international producer of masonry manufacturing equipment, for recommendations on how their new masonry system could be manufactured. Besser happened to be the same company that was contacted for manufacturability feedback of the different design iterations of the current system. From this, a single horizontal channel was placed along the top of the block. Each design decision, including incorporation of horizontal channels, was crossed-checked with constructability.

Having a semi-circular channel along the top, corresponded with a decision of how the blocks would be placed during construction. With the first course placed with the channel oriented upward, the second course of blocks would be placed with the channel oriented downward. This pattern would continue on; each course a mirror image of the next. The now circular, horizontal channel occurs at every other course.

How the blocks would interlock together in the absence of mortar was the next concern. A simple tongue and groove arrangement was selected for the head joints. The bed joints were more difficult to conceive, and several conditions played a role in finalizing a design. First, in order to incorporate an interlocking mechanism on the bed plane, the manufacturer would have to go to great lengths to make it possibly. Second, having blocks that stack completely without any mortar would require very small dimensional tolerances in the vertical direction. As stated by Vanderwerf, "variations of 1/16-inch [1.6 mm] are enough to cause a freestanding, mortarless, running-bond wall to deviate from plumb after just three or four courses" (*Mortarless Block Systems*, 1999). Murray further pointed out how gaps can also be caused by height variations. Even 2 mm (0.08 in) is not considered accurate enough, but instead 0.2 mm (0.008 in) is more acceptable (Croft 1993). The blocks developed by Thallon *et al.* (2004) achieve a tolerance of 0.12 mm (0.005 in) after an additional grinding process. To circumvent some of the intrinsic manufacturing issues of dry-stacked masonry, an idea sourced from the autoclaved aerated concrete industry appealed as a viable solution.

Autoclaved aerated concrete (AAC) blocks are stacked using a thin-bed mortar joint. The joint measures approximately 3.2 mm (0.125 in) as opposed to the standard 9.5 mm (0.375 in) used for CMUs. By choosing this option for the bed joints of the refined masonry system, extra manufacturing steps or complexities were avoided. Also, height variation concerns during construction are reduced. Several other more minor advantages exist that made AAC's thin-bed mortar joints an attractive solution. With this decision, the bed planes of the block were designed as flat surfaces, while a simple tongue-and-groove arrangement was incorporated into the head planes.

4.2.3 Special Blocks Configurations

Now that the block has been designed (Figure 4.5), attention was turned to deciding how many and what kind of specialty blocks should be included in the refined masonry system. To conform with the simplicity parameter, the number of different block configurations was kept to only three. Having just three different block configurations was selected as a practical number for both manufacturing and constructing purposes. The two additional blocks are a half block and a corner block (Figure 4.5). These are some of the most common types among the different systems investigated.

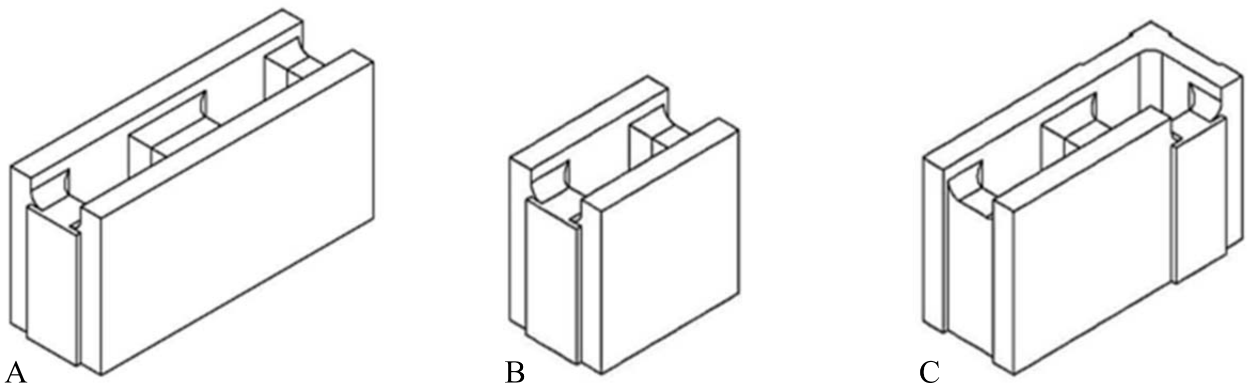

Figure 4.5: Refined concrete masonry system. (a) stretcher; (b) half; (c) universal corner.

The half block is as it sounds. It is half the length of a normal block, or stretcher. Since the stretcher has two cores the half will have one, and it will have the same tongue-and-groove ends. The half block helps to save time by not having to cut a stretcher in half to create that offset running bond. Most courses could expect to require a half block.

The last of the three blocks that comprise the refined concrete masonry system is a corner block. It is used to quickly form 90-degree wall corners. However, this particular corner block has been designed to also assist in forming T-intersections, and full wall intersections or cruciforms. Because of this ability, which is demonstrated in Figure 4.6, the block has been titled universal corner block. The block is similar to a half block, in that it has one full-sized core within the leg portion of the block. In addition to this, it has another, smaller core that acts as the pivot point.

The leg alternates accordingly to continue the running bond pattern of the wall. In a normal wall corner, the leg alternates equally between both legs of the wall. In a T-intersection, the leg alternates in a particular pattern so that it is in the leg of the T on every other course (Figure 4.6). This particular, but necessary, stacking sequence was discovered using computer models, which was an imperative step in the constructability cross-check. In a full wall intersection, the leg of the universal corner block simply rotates 90-degrees in either direction from one course to the next.

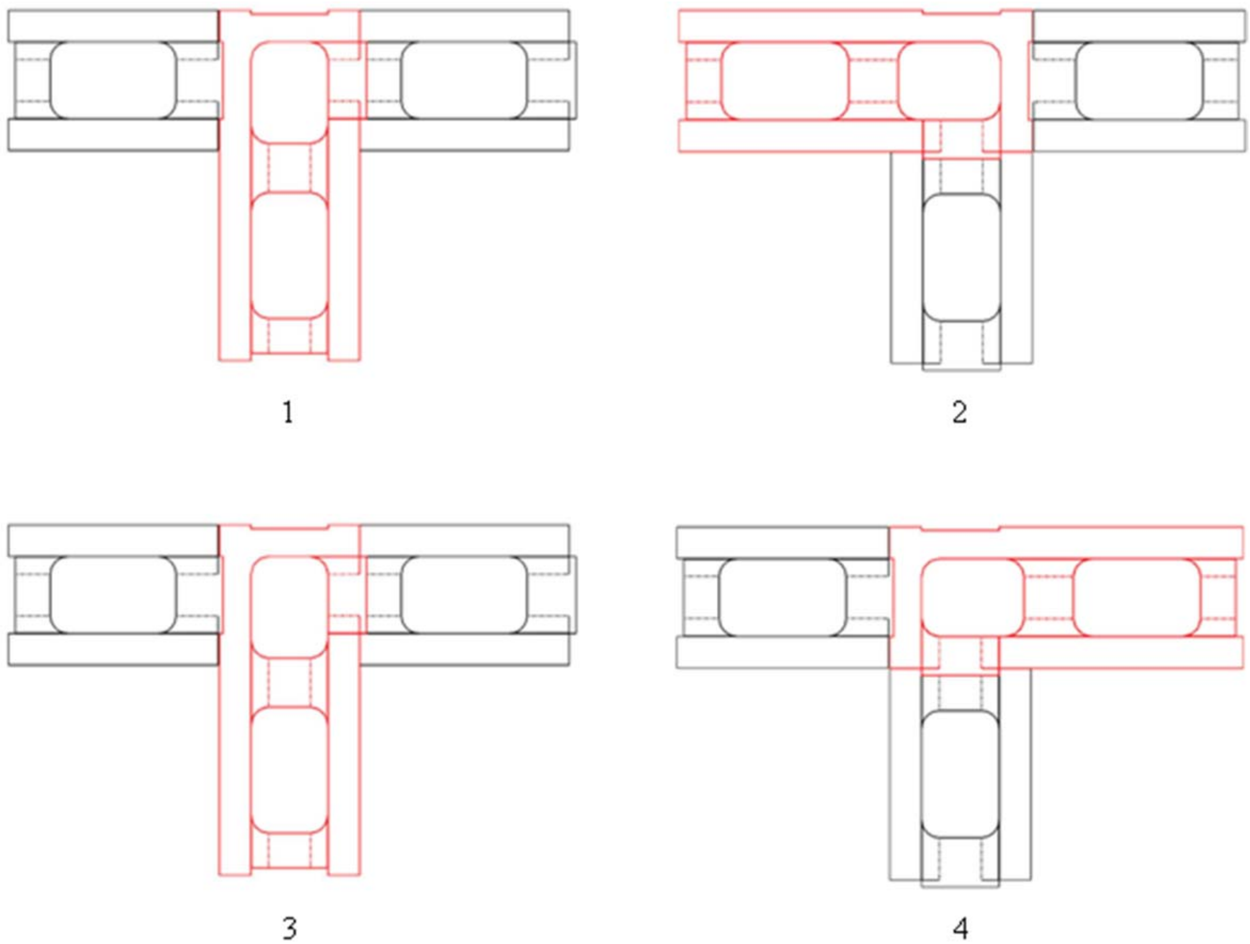

Figure 4.6: Stacking sequence demonstration for universal corner block.

The impact of alternating the corner block as described above can best be seen by visually studying the resulting concrete grid that is formed. The horizontal beam that enters in a common wall corner alternates with the corner block. This series of beams acts as the interconnection between the two individual walls. There is a fewer number of interconnecting horizontal beams in each individual wall of a T-intersection, and still even a fewer number in a full wall intersection. This decreased number is balanced by the fact that the addition of each wall helps to strengthen the intersection, and whenever needed additional "bond" channels can be field cut to allow grout to flow in the direction needed.

A final touch to the design of the universal corner block is the additional of grooves on each side of the pivot point. This is to facilitate construction of corners and wall intersections in the event the tongue-side of a block happens to meet the pivot point of the corner block and needs a groove.

4.2.4 Temporary Mold Development

Once final commitment was made on a single design the prototypes (of the stretcher only) could now be produced for strength testing and for the productivity study that was conducted in Module 3. As discussed earlier, the blocks were produced in a pre-cast method using a mold fabricated out of a special type of plastic. The polyurethane-based, machinable plastic is intended to be milled in a metal machine shop setting as if it were metal. It was chosen over other mold materials, such as wood and metal

The mold consists of three main sections, namely: the box, the core, and the shoe (Figure 4.7). The box is a 4-sided rectangle with both the top and bottom open to allow the block to "slip" out. The longer sides are referred to as the faces and the short sides are referred to as the ends. The interior of the faces has a draft of 1-degree to lessen the effort needed to remove the blocks. The ends are milled accordingly to form the tongue and groove of each block. The face and end pieces were joined using machine bolts placed in counter-bored and tapped holes. Locating pins were friction fitted into the end pieces to help align the pieces exactly as they were in case disassembly is needed.

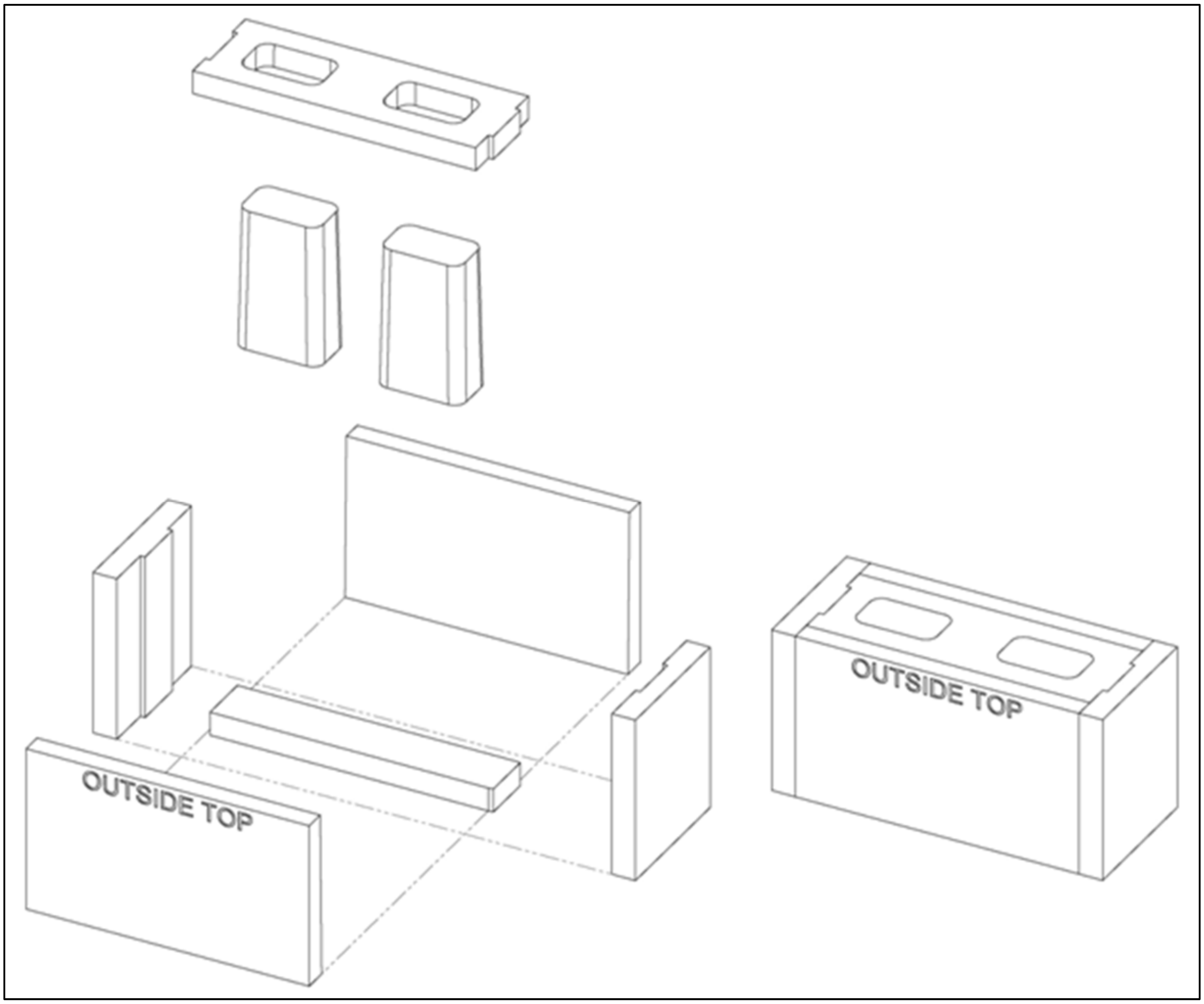

Figure 4.7: Mold assembly.

The core will form the hollow cores of the block as well as the horizontal channel. The two uprights were attached to the base using machine bolts and locating pins in the same fashion as the box section. These also have a draft of 1-degree. The radius found on most of the edges will form the fillets of the prototype block.

The last section is the shoe, and it is the closing piece of the mold once the concrete has been placed. The long edges and the two holes have an inverted 1-degree draft to mate with the sides of the box and the uprights of the core section. The holes were milled using a CNC machine whereas the rest of the mold was milled using a vertical milling machine (Figure 4.8). Cross pieces were placed to keep the shoe flush with the top of the box. The shoe is critical in that it determines the height of the blocks.

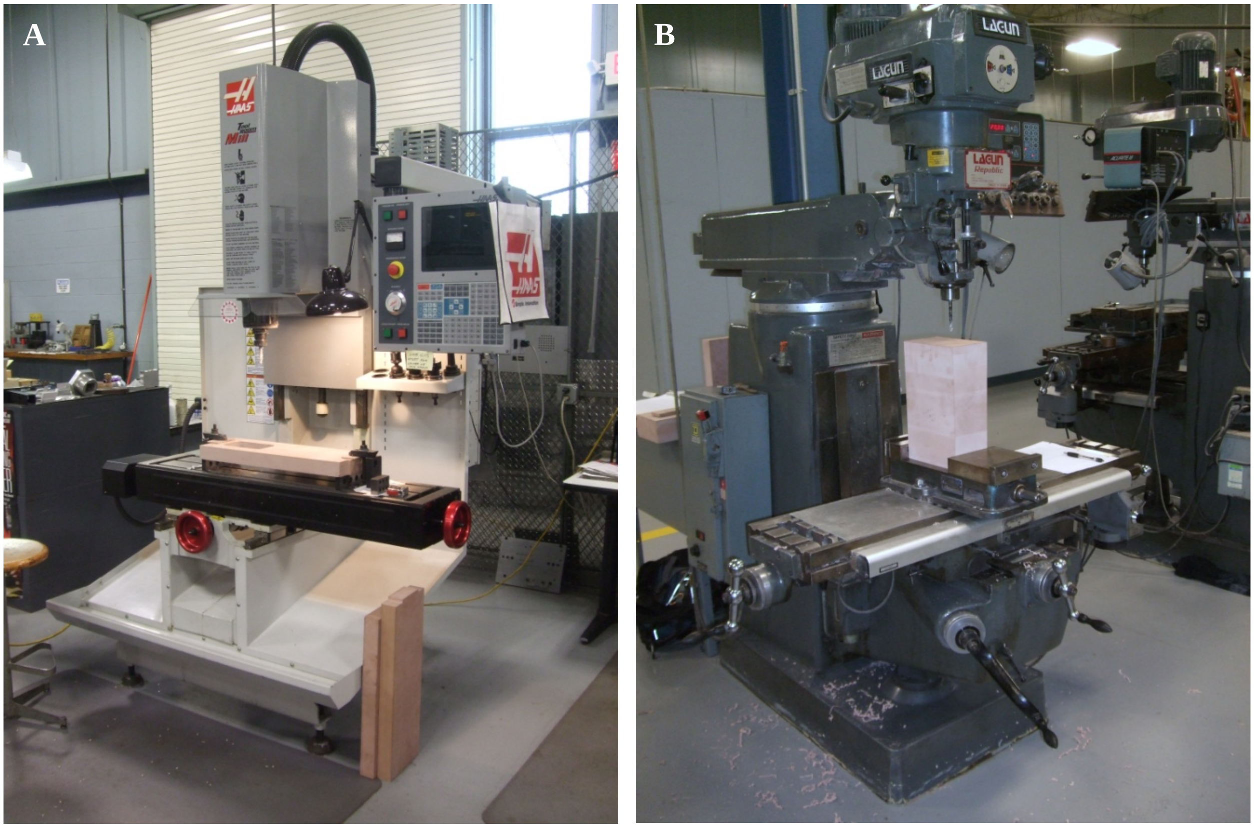

Figure 4.8: Equipment used to fabricate the mold. (a) CNC machine; (b) vertical milling machine.

During a side study, it was discovered that concrete will greatly adhere to the bare plastic. Technical suggestions for various surface treatments, coatings, and form release agents were given by the manufacturer of the plastic slabs (Axson, 2010). They also were the ones who suggested incorporating the draft. Through further testing of each type of surface treatment, coating, form release agent, and the different possible combinations it was found that a well-cured coat of epoxy paint and fresh floor wax worked best.

4.2.5 Prototype Block Production

The blocks were produced one by one; 30 in all. The ingredients were weighed using a digital scale accurate to 0.5 grams (0.001 lb). Then they were mixed by hand in a large plastic tub; first the foam and the high-range water reducer diluted in the mixing water. After the EPS beads were well coated the cement and fly ash were added. Mixing would continue for at least five minutes. Placement of the mix was done in several lifts using a flat tamping rod for consolidation.

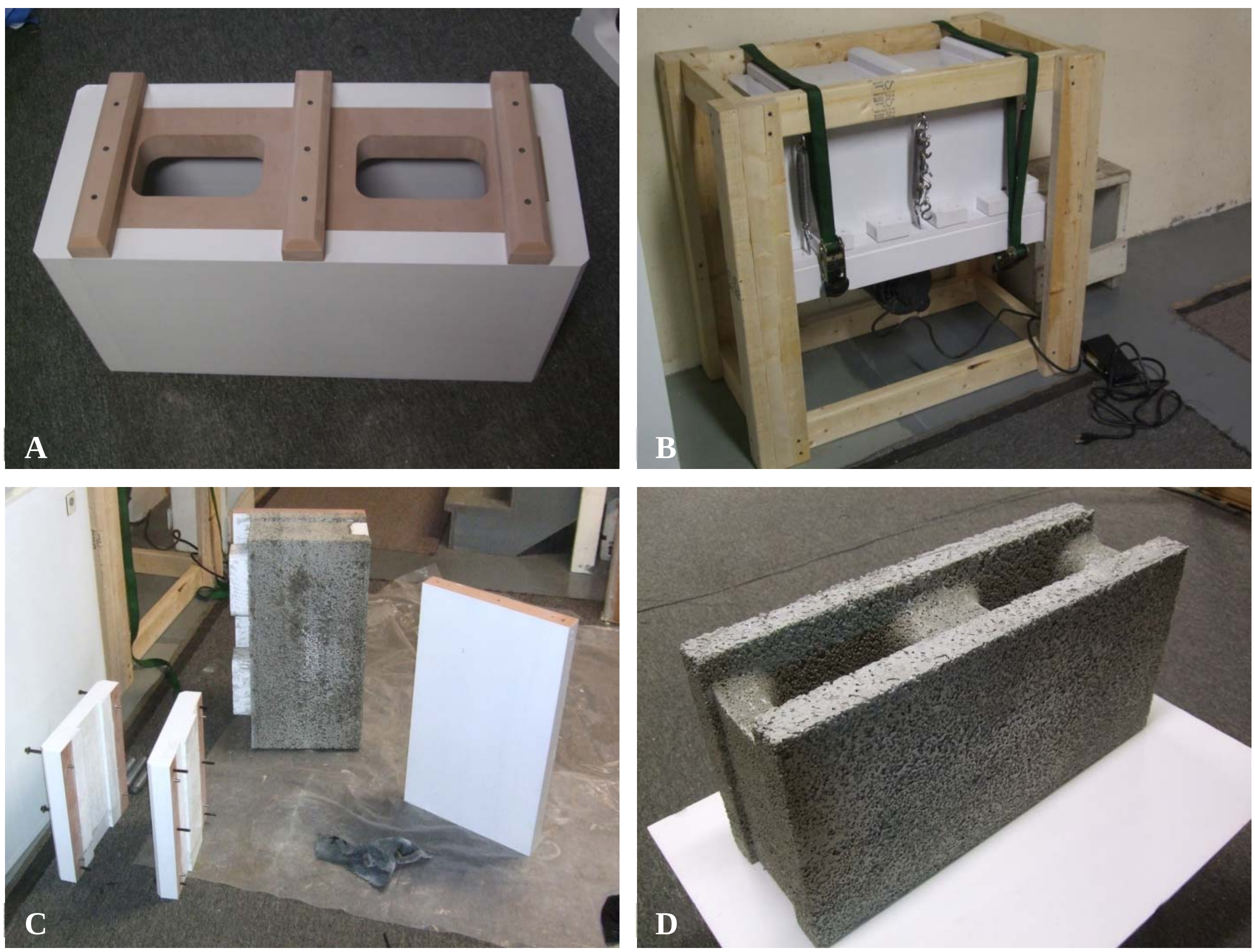

Figure 4.9: Various stages of block production. (a) nearly completed mold with unpainted shoe section; (b) mold loaded on vibrating table; (c) mold disassembled to remove completed block; (d) block shortly after removal from mold.

Originally, a consolidating table built from modified plans (Panagos, 2011) was going to be used to consolidate the mix. Because of the low density of the mix, a weight surcharge (as prescribed by ASTM C192) applied using something nearly identical to the mold's shoe was going to be used in conjunction with the table. However, consistency became an issue and a flat-end tamping rod was opted for. Each block was cured for 12-24 hours prior to removal. Figure 4.9 shows different stages of block production.

Removing the blocks from the mold was more difficult than anticipated. Each time the mold had to be mostly disassembled and thoroughly cleaned. Then before placing material for production of another block wax had to be reapplied. Despite this effort, the mold proved to be durable enough to fulfill production needs

After each block was removed from the mold, they were moist-cured in large trash bags for 28 days (Figure 4.10). Then they were allowed to air dry until the time they were to be used. Prior to their use, each block was weighed and measured. Table 4.4 summarizes their physical characteristics.

Figure 4.10: Curing method for the blocks.

Table 4.4: Summary of physical characteristics of the blocks.

	Length mm (in)	Width 1 mm (in)[1]	Width 2 mm (in)[1]	Height mm (in)	Weight kg (lb)
Target	600 (23.62)	200 (7.87)	205 (8.07)	300 (11.81)	14.81 (32.7)
Actual (avg.)	600.46 (23.64)	199.69 (7.86)	205.6 (8.09)	300.64 (11.84)	-
Minimum	599 (23.58)	198 (7.80)	204 (8.03)	299 11.77	13.7775 (30.4)
Maximum	601 (23.66)	201 (7.91)	207 (8.15)	302 (11.89)	15[2] (33.1)

Notes:

[1]Two values for the width are caused by the 1-degree draft incorporated in the mold.

[2]At least half the blocks were marginally over the 15 kg (33.1 lb) limit of the scale used.

4.2.6 Prism Testing

For strength testing, six blocks were used to construct and test three replicate masonry prisms following ASTM 1314-11. Figure 4.11 shows the cutting of the blocks to the proper length. One entire core plus the entire center web was needed while the rest was discarded, therefore, six blocks were needed to make three prisms. The prisms were fabricated indoors by a professional mason using thin-bed mortar and 27.6 N/mm^2 (4000 psi) grout. They were enclosed in plastic bags and cured for 28 days prior to testing (Figure 4.11).

Figure 4.11: Prism test preparation. (a) block ready for cutting on masonry saw; (b) recently stacked prism prior to grouting.

On the day of testing, the prisms were capped using Hydro-Stone, a fast-setting, gypsum cement. They were tested on a machine with a 4450 kN (1,000,000 lb) rated capacity (Figure 4.12). During testing, no distinct indication of failure was exhibited other than what was shown on the digital readout. After the rapid drop in bearing capacity, the speed of the testing machine was increased to examine the result of further displacement. Each prism eventually showed signs of cracking as the inner concrete core fragments began to shift significantly (Figure 4.12). The faces of the prisms continued to remain intact, and only after breaking them apart using a large hammer was the concrete core exposed. This made it difficult to assess the mode of failure. One of the core fragments with part of the block still attached is shown in Figure 4.12. Grout prisms were also tested and proved to be adequate in strength. Results of both the masonry prisms and the grout prisms can be seen in Table 4.5. Using 27.6 N/mm^2 (4,000 psi) grout, the average compressive capacity of a single grouted core is 430.5 kN (96,733 lb), resulting in an average compressive strength over the gross area of the prism (area of the core and block) of 5.81 N/mm^2 (842 psi).

Figure 4.12: Prism testing. (a) recently capped prisms; (b) hydraulic testing equipment; (c) prism after testing with signs of failure in the face; (d) remaining segment of prism with block material still intact with part of the core.

Table 4.5: Masonry prism test results.

Prism	Gross Area mm^2 (in^2)	Load kN (lb)	Strength N/mm^2 (psi)	h_p / t_p [1]	CF[2]	f'_m [3] N/mm^2 (psi)
001	75,827 (117.4)	436.2 (98,020)	5.75 (834)	3.0	1.07	6.14 (890)
002	72,806 (112.9)	437.4 (98,290)	6.01 (872)	3.0	1.07	6.41 (930)
003	73,937 (114.0)	417.8 (96,890)	5.65 (820)	3.0	1.07	6.07 (880)
Average	74,190 (114.8)	430.5 (96,733)	5.81 (842)	-	-	6.21 (900)

Notes:
[1]This is the prism height to prism thickness ratio; it's used to select CF from ASTM C1314.
[2]Correction Factor as defined by ASTM C1314; accounts for prism height and thickness.
[3]Masonry compressive strength.

Continuing with the calculations outlined in ASTM C1314 the net compressive strength averaged over the entire area of the prism doesn't meet ACI 530 requirements for standard CMUs. This is because the compressive strength of the inner concrete posts is diluted over the large surface area of the shells and webs of the block. These results are included to demonstrate that ACI 318 standards are more appropriate as discussed with Jason Thompson of the National Concrete Masonry Association, and also to give readers an impression of what kind of structural strength can be expected of the refined system as demonstrated by actual test results.

4.2.7 Structural Check

The theoretical, structural performance check using ACI 318 will now be discussed. VanderWerf *et al.* (1997) outlined an example of a structural check done on an insulating concrete form (ICF) system that produces a concrete grid very similar to the new system developed here. Also similar to this new system is the model structure that the authors based their load calculations on. To limit the scope of this particular segment of Module 2, only the same procedure described therein will be conducted as the structural check for the refined masonry system.

For ICF structures, VanderWerf *et al.* (1997) mentioned that there are several basic structural checks completed for a wall. ICF walls are commonly checked for shear parallel to the wall, shear perpendicular to the wall, lintel bending, lintel shear, axial compression, and wall moment. Loads are calculated based on the concerned structure and the existing conditions.

Figure 4.13 and 4.14 presents the ground floor and second floor plans, respectively, of the residential structure that will be used for the structural check. It was designed by an architect in the Philippines and utilizes traditional materials and methods typically found there.

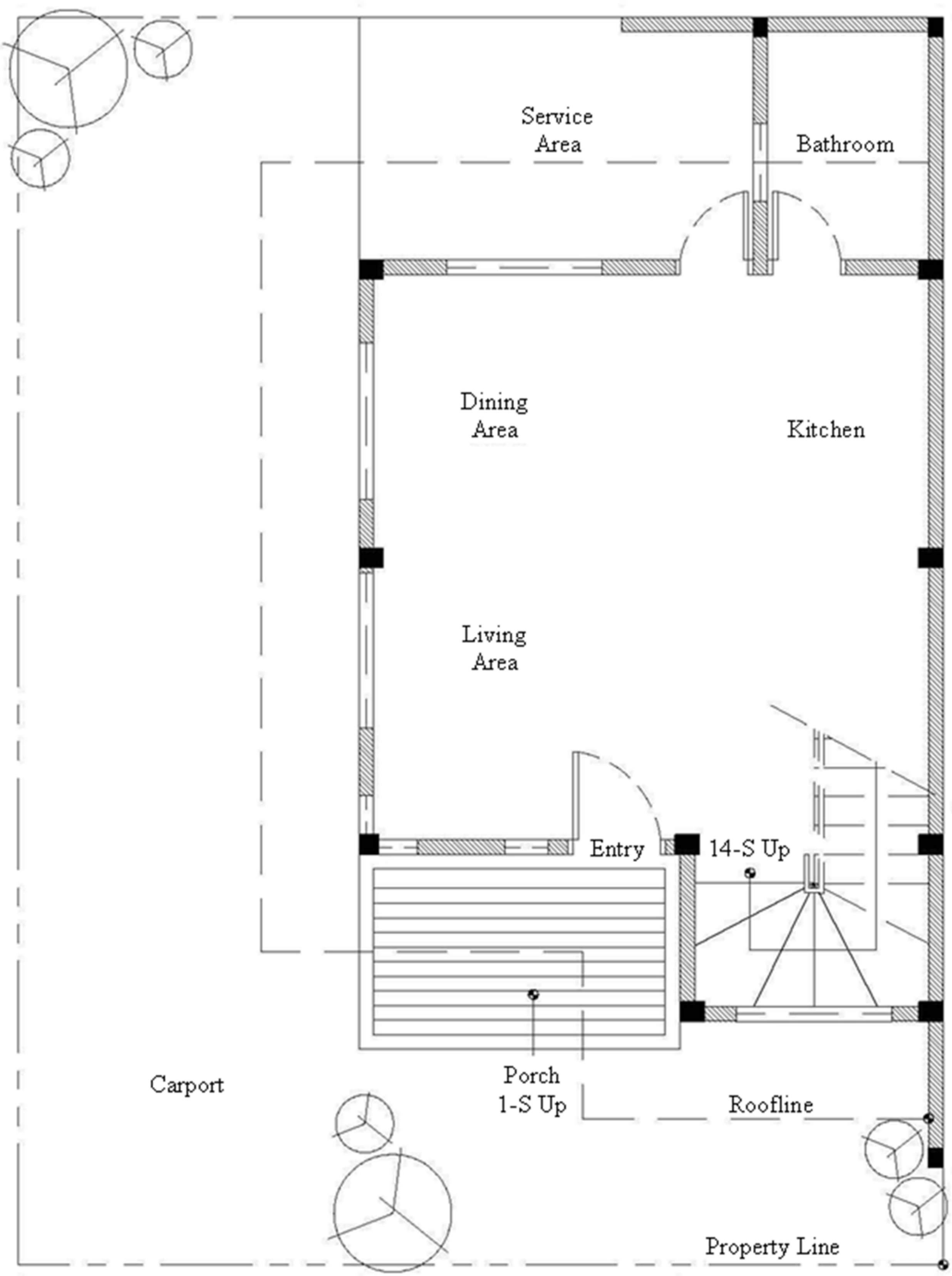

Figure 4.13: Ground floor plan of model house used to conduct structural check.

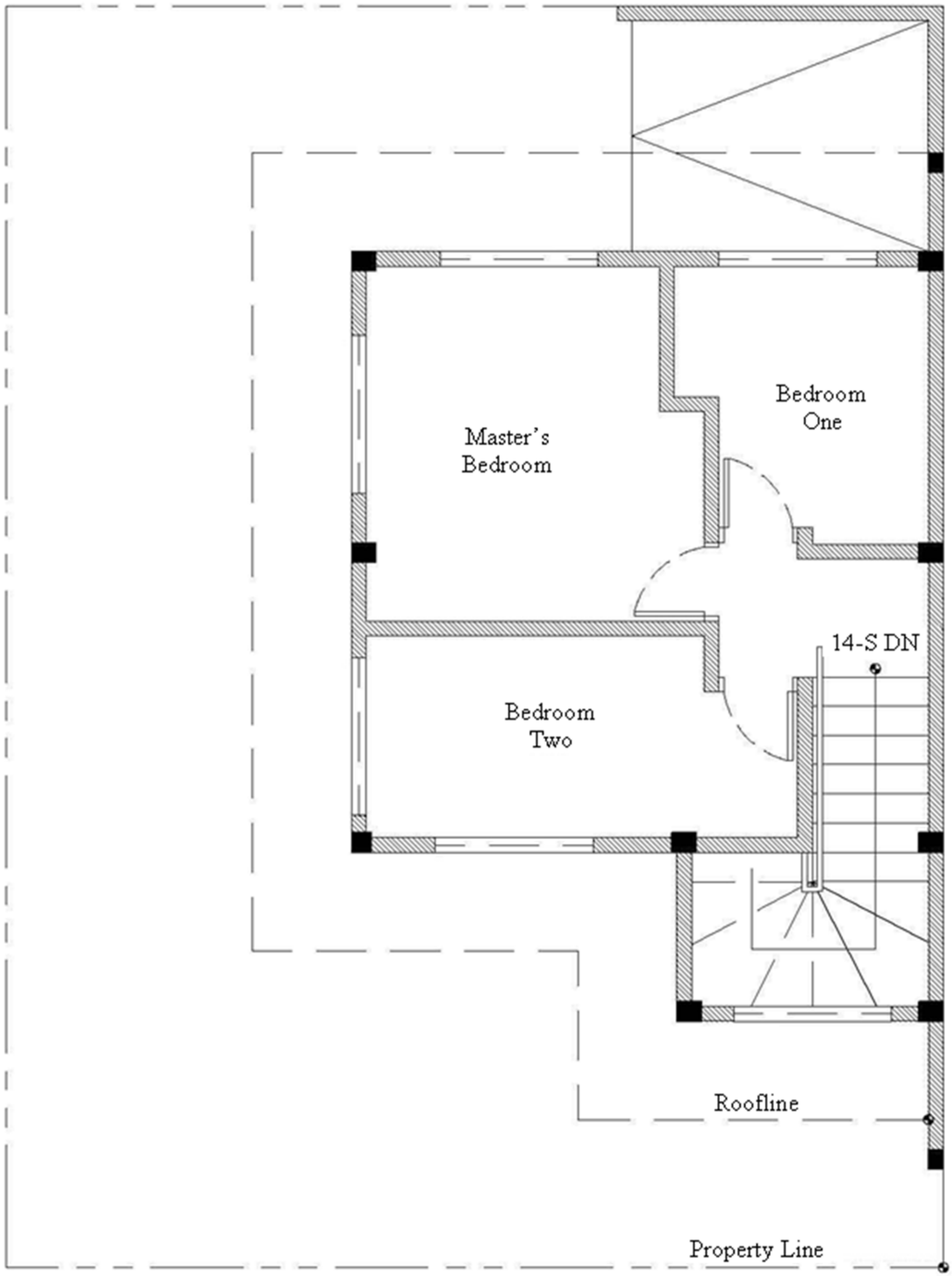

Figure 4.14: Second floor plan of model house used to conduct structural check.

The traditional masonry system used in the plans has been substituted for the refined masonry system, which resulted in a few minor alterations. The beam and composite floor specified in the plans was also substituted for a cast-in-place floor using temporary forms. The beams would normally transfer the loads to the columns which would then transfer the loads to footings and so on. The space between the columns would be filled in with non-loadbearing CMUs. The refined system does away with the beams and columns, and instead spreads the load among the multitude of concrete posts formed by the refined masonry system. A cutaway of the wall (Figure 4.15) reveals the concrete core formed within the refined masonry system. Both horizontal beams and vertical posts of the concrete core are visible.

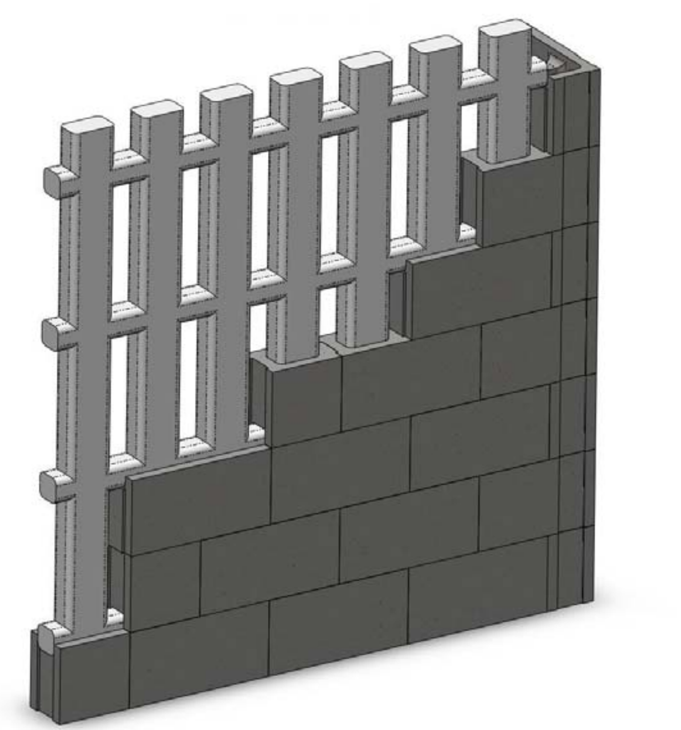

Figure 4.15: Cross-sectional view of the refined masonry system exposing the concrete core.

Table 4.6 presents the unit load and material values used. Some values are assumed while the others are taken from the Association of Structural Engineers of the Philippines' *National Structural Code of the Philippines*. Because the sample outlined by VanderWerf *et al.* (1997) is in imperial units, the structural check performed here was kept in imperial units for ease of relative benchmarking.

Table 4.6: Load and material values.

Load	Value, N/mm
Wind Load	2.01 kN/m^2 (42 psf)
Roof Live Load	1.01 kN/m^2 (21 psf)
Roof Dead Load	0.96 kN/m^2 (20 psf)
Floor Live Load	1.92 kN/m^2 (40 psf)
Floor Dead Load	4.79 kN/m^2 (100 psf)
Vertical Rebar Size	#4 (12.7 mm, 0.5 in)
Vertical Rebar Spacing	600 mm (23.6 in) on center
f'c	143.6 kN/m^2 (3,000 psi)
fy	1,915.2 kN/m^2 (40,000 psi)

Figure 4.16 shows a detailed diagram of the block cores as viewed from the top and corresponding dimensions necessary for calculations. The values in the diagram correspond to equation variables as follows:

$$h = 4.3 \text{ in}$$

$$d = 2.15 \text{ in}$$

$$b = 7 \text{ in}$$

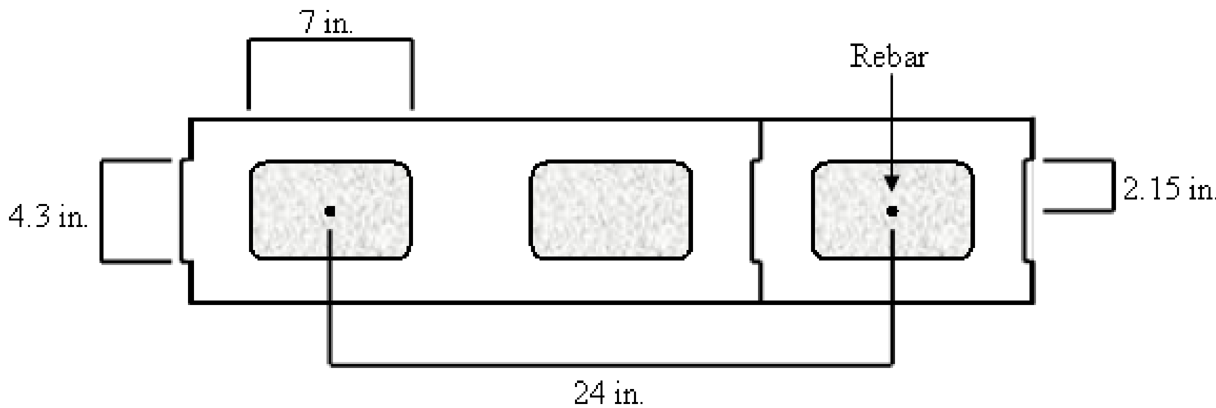

Figure 4.16: Plan view of refined masonry system with values for structural check

In order to speed up some of the calculations, a few preliminary calculations have been completed and their results will be referenced for subsequent calculations. These are dead load, live load, and wind load calculations, as well as a slenderness check.

Dead Loads:

P_{roof} = 11.2 ft *x* 20 psf = 224 lb

P_{floor} = 10.3 ft *x* 100 psf = 1,030 lb

P_{wall} = 10.8 ft + 8.4 ft *x* 49 psf = 941 lb

Total = 2,195 lb

$P_{wall2} = (10.8\text{ ft} + (\frac{8.4\text{ ft}}{2}))\ x\ 49\text{ psf} =$ 735 lb

$M_{floor} = \frac{1{,}030\text{ lb x 0 in}}{2} =$ 0 in-lb

Notes:

Each P value is viewing a 1 ft wide strip of the structure

The P_{wall2} is the weight of the walls at midheight of the lower level.

49 psf is the weight of the wall per square foot of wall area.

0 in is used as the eccentricity caused by the floor deck.

Live Loads:

P_{roof} = 11.2 ft *x* 21 psf = 235 lb

P_{floor} = 10.3 ft *x* 40 psf = 412 lb

Total = 647 lb

$$M_{floor} = \frac{412\text{ lb}}{0\text{ in}} \div 2 = \qquad 0\text{ in-lb}$$

$$M_{roof} = \frac{235\text{ lb}}{3.9\text{ in}} = \qquad 917\text{ in-lb}$$

Wind Load:

$$M_{wind} = \frac{wL^2}{8} \rightarrow \frac{(42\text{ psf})(8.4\text{ ft})^2}{8} = \qquad 4{,}440\text{ in-lb}$$

Notes:

0 in is used as the eccentricity caused by the floor deck.

3.9 in is the assumed eccentricity caused by the roof.

The moment calculation is divided by 2 for midheight of the wall.

Check for Slenderness in Lower Level:

$$\frac{kl_u}{r} = \frac{(1.0)(8.4\text{ ft x }12\text{ in})}{(0.3)(4.3\text{ in})} = \qquad 78$$

78 > 34; therefore slenderness must be considered

Notes:

k is assumed to be 1.0

l is the unsupported length of compression member *r* is the radius of gyration set to 0.3 as per ACI 318-11

M1 is assumed to be 0, therefore $\frac{M1}{M2}$ was omitted.

For the structural check, it needs to be pointed out that several assumptions and limitations were used. These assumptions and limitations are listed in Table 4.7

Table 4.7: Structural check assumptions and limitations.

Assumption:	Limitation
Hooke's Law is applicable	Seismic effect was not considered
The concrete does not contribute to the tensile strength	
Blocks are included for finding the total dead load, but ignored for structural calculations	

One final step before commencing with the structural check will be to make necessary calculations to create an axial load-bending moment interaction diagram. An example is included here as Figure 4.17. This diagram graphically demonstrates the interaction between axial load and wall moment. It shows the limitation envelope for a structural system; anything within the boundary of the line is within the structural capacity of the wall, and anything beyond the line is likewise beyond the structural capacity of the wall. In essence, it serves as a design tool.

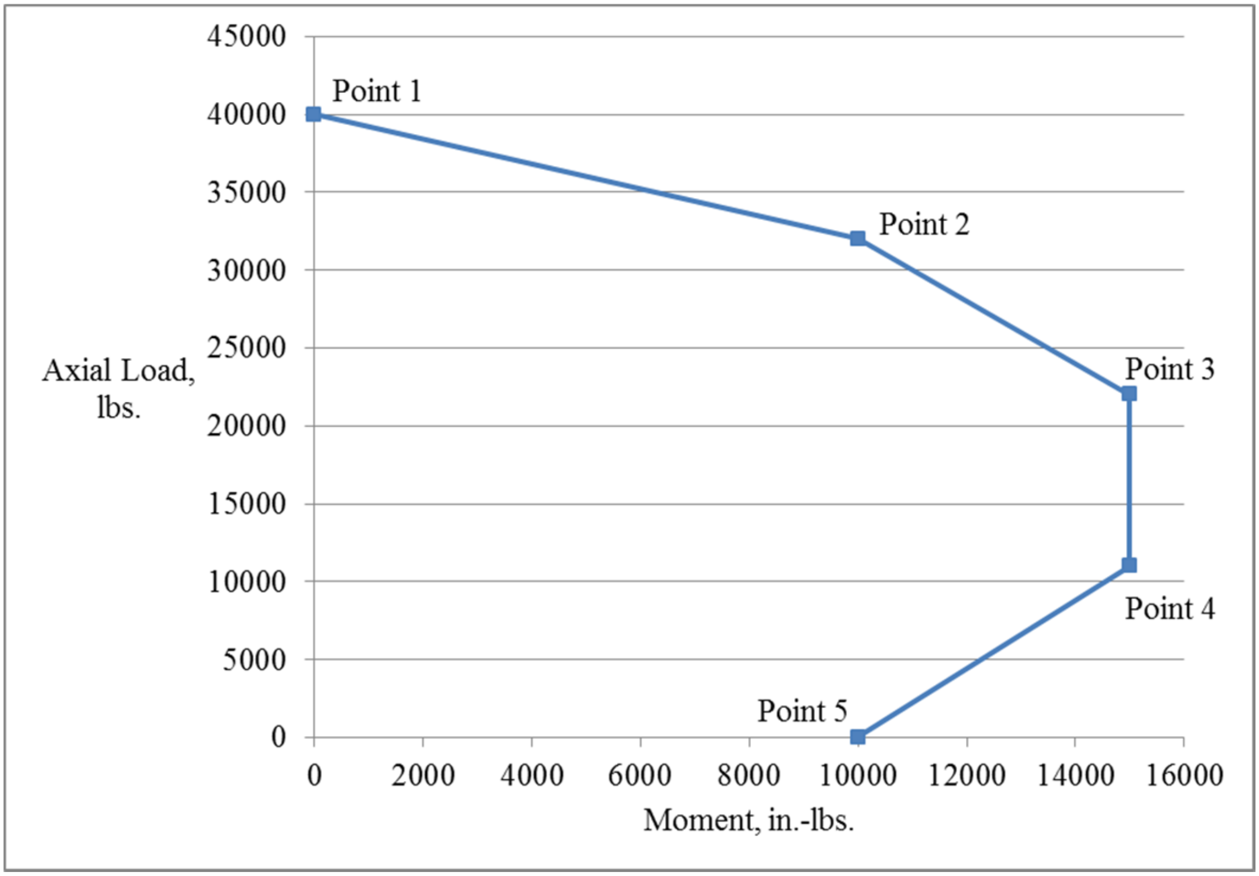

Figure 4.17: Axial-Load/Moment Interaction Diagram example.

In order to plot the line, five important, load transitional points are plotted first, then the points are connected, usually by a straight line rather than a curved one for simplicity. In practice however, only points 4 and 5 are needed because of the low axial loads typical of residential structures. The calculations that follow are for point 4, representing the balanced condition, of the axial load-bending moment interaction diagram.

Point 4 of the Interaction Diagram:

$C = \left(\frac{\epsilon_c}{\epsilon_c+\epsilon_y}\right)d;$

where ϵ_c = 0.003 (ACI 12.2.3) and $\epsilon_y = \frac{f_y}{E_s}$

Then; $\epsilon_y = \frac{40{,}000 \text{ psi}}{29{,}000{,}000}$ (ACI 10.2.4)] = 0.0014

$C = (\frac{0.003}{0.003+0.0014})$ *x* 2.15" = 1.47 in

a = 0.85 *x* 1.47 in (ACI 10.2.7.1) = 1.25 in

C_c = (0.85)abf'c

C_c = (0.85)(1.25 in *x* 7 in *x* 3,000 psi) = 22,313 lb

$T_s = A_s f_y$ (ACI 10.2.4)

T_s = 0.2 in^2 *x* 40,000 psi = 8,000 lb

The Factored Axial Load:

$\Phi P_b = \Phi(C_c - T_s)$

ΦP_b = (0.7)(22,313 lb – 8,000 lb) = 10,019 lb (Plot)

The Factored Bending Moment:

$\Phi M_b = \Phi C_c(d - \frac{a}{2})$

ΦM_b = (0.7 *x* 22,313 lb)(2.15 in - $\frac{1.25 \text{ in}}{2}$) = 23,819 in-lb (Plot)

Point 4 is plotted in Figure 4.18. Point 5, which represents a pure moment condition (no axial load), is calculated next.

<u>Point 5 of the Interaction Diagram:</u>

$$a = \frac{A_s f_y}{0.85 f_c b}$$

$$a = \frac{(0.2)(40{,}000\ \text{psi})}{(0.85)(3{,}000\ \text{psi})(7\ \text{in})} = \qquad 0.448\ \text{in}$$

$$\Phi M_n = \Phi A_s f_y\left(d - \frac{a}{2}\right)$$

$$\Phi M_n = (0.9\ x\ 0.2\ \text{in}^2\ x\ 40{,}000\ \text{psi})\left(2.15\ \text{in} - \frac{0.448\ \text{in}}{2}\right) = \qquad 13{,}867\ \text{in-lb (Plot)}$$

P = 0 lb (Plot)

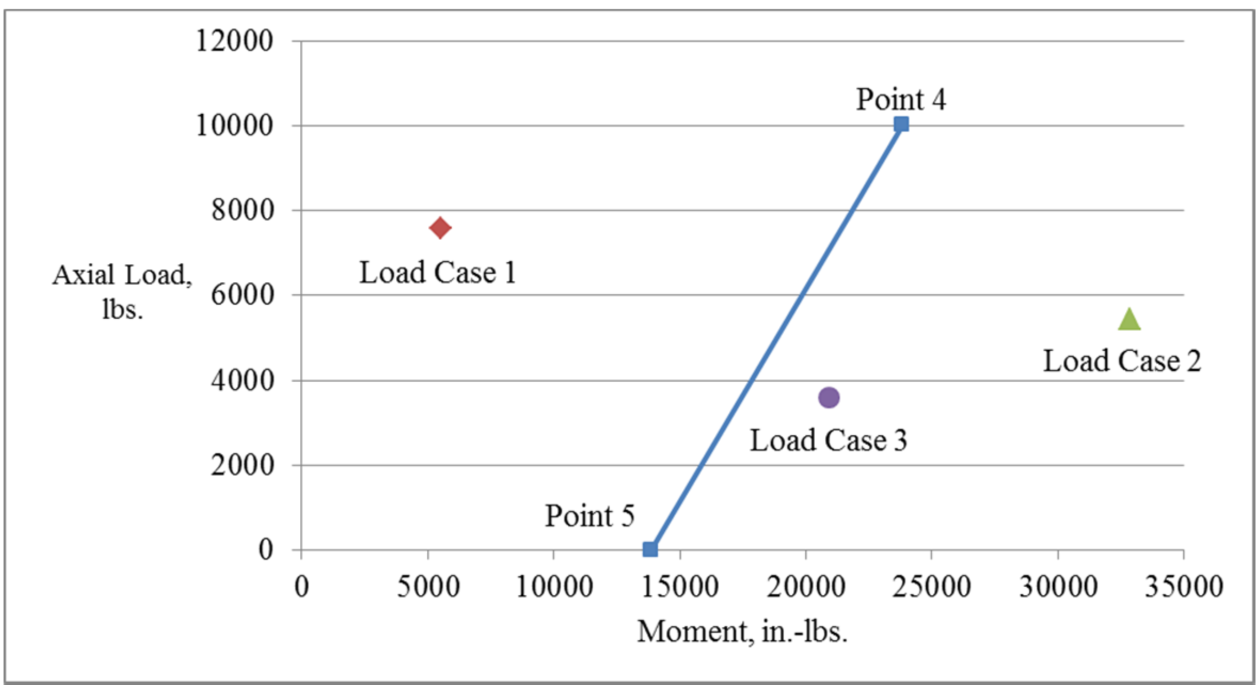

Figure 4.18: Axial-Load/Moment Interaction Diagram for refined masonry system.

With the preliminary calculations for the loads and the interaction diagram complete, the actual structural check can begin. It follows the same principles that many other structural elements follow during design. Loads and forces are calculated for the respective structural elements. The structural elements are checked using various formulas to determine whether or not they have the capacity to resist those loads and forces. In the event that their capacities do not satisfy that which is needed, revisions are made until an adequate design is obtained.

The first calculation will be to check the shear parallel to the walls. To save time only one wall is checked, the one perceived as having the worst conditions in regards to shear parallel to it. This would be caused either by the wall configuration, the amount of load it has to carry, or a combination of these. For this check, the tallest wall with no openings was selected, and the shear force caused by the wind load is used.

VanderWerf *et al.* (1997) indicated that the common practice for grid-type ICF concrete walls is to only consider the concrete posts that have reinforcement. This means that every reinforced concrete post must make up for the unreinforced concrete posts and the spaces between. With vertical reinforcement placed every 24 in, the load is calculated for a 2 ft wide strip of wall. In other words, the cross-sectional area of that post alone must have enough shear strength for 24 in of wall. This is done as a conservative measure, and in addition, the wind load was factored by 1.3 using the load combination from the Association of Structural Engineers of the Philippines' *National Structural Code of the Philippines*.

Lower Story:

$V = (42 \text{ psf } x \text{ 2 ft strip})(\frac{8.4 \text{ ft}}{2}) =$ 352.8 lb

Factored Required Shear Force:

U = 1.2D + 1.3W (NSCP 2001)

$Vu = (1.3 \ x \ 352.8 \text{ lb}) =$ 458.6 lb

Concrete Shear Capacity:

$\Phi V_c = 2\sqrt{f'_c} * bwd$

$\Phi V_c = (0.85 \ x \ 2)(\sqrt{3{,}000} \text{ psf})(7 \text{ in } x \text{ 2.15 in}) =$ 1401.3 lb

Check:

$1401.3 \geq 352.8 \ (V_c \geq V_u)$ OK

The next structural check is for shear perpendicular to the wall. Again, the wall selected is the one perceived the weakest. This is the north wall that includes the bathroom door, the back entrance door, and one window (Figure 4.13). The openings in the wall, two doors and a window, disqualify the inclusion of the discontinuous concrete posts found at those locations. Also, the greatest lateral load caused by the wind will come from the broad firewall on the east side of the structure (Figure 4.19).

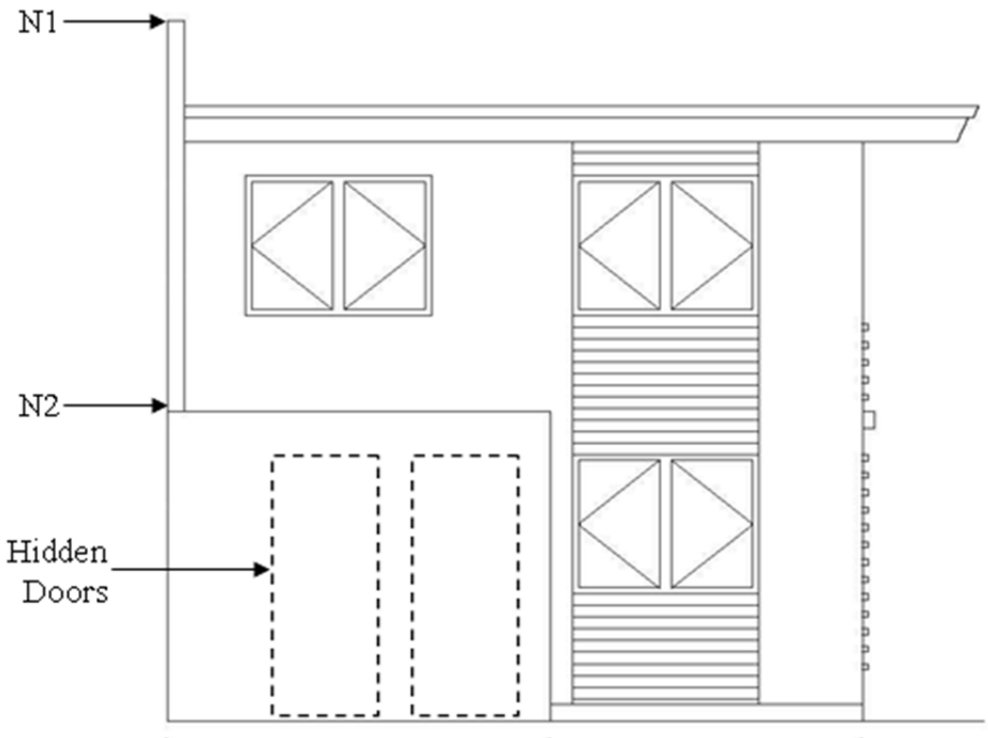

Fig 4.19: Rear elevation (south view). There are two hidden doors in the north main wall.

The calculation is as follows:

Lateral Load from Wind:

$$N1 = 42 \text{ psf } x \left[\left(\frac{10.8 \text{ ft}}{2}\right) x \left(\frac{25.9 \text{ ft}}{2}\right) + 3 \text{ ft})\right] = \qquad 3{,}618 \text{ lb}$$

$$N2 = 42 \text{ psf } x \left[\left(\frac{10.8 \text{ ft}}{2} + \frac{8.4 \text{ ft}}{2}\right)\right] \text{x} \left[\left(\frac{25.9 \text{ ft}}{2} + \frac{8.2 \text{ ft}}{2}\right)\right] = \qquad 6{,}875 \text{ lb}$$

Shear in Lower Story:

N1 + N2 = 3,618 lb + 6,875 lb = 10,493 lb

Factored Required Shear Force:

U = 1.2D + 1.3W

V_u = 1.3 *x* 10,493 lb = 13,640 lb

Concrete Shear Capacity:

$$\frac{13{,}640 \text{ lb}}{9 \text{ concrete posts}} = \qquad 1{,}516 \text{ lb per post}$$

$\Phi V_c = 2(\sqrt{f'_c})hd_1$

$\Phi V_c = 2(\sqrt{3{,}000 \text{ psi.}}) \, x \, 4.3 \text{ in } x \, 5.6 \text{ in} =$ 2,242 lb per post

Check:

$2{,}242 \geq 1{,}516 \; (V_c \geq V_u)$ OK

It should be noted that the wind load on the firewall was appropriately divided among the other walls that will be resisting it, including the north bathroom wall. Also, despite only being able to consider the shear capacity of nine concrete posts, the strength of the wall was found to be adequate.

The calculation checks for the shear and bending capacity of the lintels would be next, however, VanderWerf *et al*. (1997) pointed out that concrete grid wall systems cannot effectively resist moment caused by long spans over openings. They suggest using other types of forms or modifying the existing ones. Further investigation beyond the scope of this structural check is required, and so calculations addressing the lintels are not included here.

The last forces to be checked, wall axial load and wall moment, will be conducted together. Again, following a similar framework to that used by VanderWerf *et al.* (1997), three different load combinations will be used in three different examples. Each result will be plotted on the axial load-wall moment interaction diagram created earlier (Figure 4.18) to determine whether the structural strength will be adequate or not. The calculations for Load Case 1 are presented here, whereas the calculations for Load Case 2 and 3 are omitted but the results are included.

<u>Load Case 1:</u>

Axial Load:

$U = 1.2D + 1.6L + 0.5L_r$

$U = (1.2 \, x \, 2{,}195 \text{ lb}) + (1.6 \, x \, 647 \text{ lb}) + (0.5 \, x \, 235 \text{ lb}) =$ 3,787 lb

$P_u = 3{,}787 \text{ lb} \, x \, 2 \text{ ft width between rebar} =$ 7,574 lb (Plot)

Moment:

$M_U = 0$ at the bottom of the wall (minimum moment value must be used);

$M_{2,\,Min} = P_U(0.6 + 0.03h)$

$M_2 = (7{,}574 \text{ lb})(0.6 + (0.03 \, x \, 4.3 \text{ in})) =$ 5,521 in-lb

Moment Magnifier Calculations:

$E_c = 57{,}000\sqrt{f'_c} = 57{,}000(\sqrt{3000}) =$ 3,122,019 psi

I_g = Moment of inertia for concrete post cross-section

$I_g = \frac{bd^3}{12} = \frac{(7 \text{ in})(4.3^3)}{12} =$ 46.4 in^4

$e = \frac{M}{P} = \frac{5{,}521 \text{ in-lb}}{7{,}574 \text{ lb}} =$ 0.73 in

$B_d = \frac{\text{Dead Load}}{\text{Total Load}} = \frac{1.2(2{,}195 \text{ lb})(2)}{7{,}574 \text{ lb}} =$ 0.70

$p = \frac{\text{Area of vertical rebar}}{\text{Area of concrete post}} = \frac{0.2\ in^2}{(7\ in)(4.3\ in)} =$ 0.0066

$\beta = 0.9 + 0.5B_d^{\ 2} - 12p \geq 1.0$

$\beta = 0.9 + (0.5\ x\ 0.70^2) - 12(0.0066) =$ $1.065 \geq 1.0$

$EI = \frac{E_c I_g}{\beta}\left(5 - \frac{e}{h}\right) = \frac{(3{,}122{,}019\ psi\ x\ 46.4\ in^4}{1.065}(0.5 - \frac{0.73}{4.3\ in}) =$ 44,918,351 in^2-lb

$P_c = \frac{\pi^2 EI}{(kl_u)^2} = \frac{\pi^2(44{,}918{,}351\ in^2\text{-lb})}{1.0(8.4\ ft\ x\ 12\ in)^2} =$ 43,632 lb

$C_m = 0.6 + 0.4(\frac{M1}{M2}) \geq 0.4 = 0.6 + 0.4(\frac{0}{5{,}521\ in\text{-lb}}) =$ 0.6

$\delta_{ns} = \frac{C_m}{1\text{-}P_u/0.75P_c} = \frac{0.6}{1\text{-}(\frac{7{,}574}{0.75(43{,}632)})} =$ $0.78 \neq\geq 1.0$

So the moment magnifier minimum must be used which is = 1.0

$M_c = \delta_{ns}(M_2) = 1.0(5{,}521\ in\text{-lb}) =$ 5,521 in-lb (Plot)

Check (based on graph) = OK

Load Case 2:

Factored Load = 5,422 lb (Plot)

Factored Moment = 32,848 in-lb (Plot)

Check (based on graph) = NOT OK

Load Case 3:

Factored Load = 3,580 lb (Plot)

Factored Moment = 20,895 in-lb (Plot)

Check (based on graph) = NOT OK

The calculation framework for each load case was the same. First, the required factored axial load was calculated using one of the prescribed load combinations. Just like the other structural checks, only the reinforced concrete posts were considered. Therefore, the calculated required axial load is the superimposed load that rests on 2 ft of linear wall that must be supported by a single concrete post (for a conservative estimate). Next, the required factored moment is found. In Load Case 1, there was no moment, in which case, a minimum moment is calculated (i.e. $M_{2, min}$). This is followed by several equations used to find the elasticity of concrete (E_c), the moment of inertia (I_g), the critical buckling load (P_c), and a correction factor (C_m). Each equation supplements the succeeding equation until what is called a moment magnifier is found.

The moment magnifier is one of the two ways that ACI 318 provides in order to consider the effect of slenderness on a structural member. It is the less accurate but simpler method. The approach used in each load case is specific for non-sway frames, which most residential structures built using grid ICF wall systems are non-sway frames (VanderWerf *et al*., 1997).

Finally, after having found the required factored axial load and magnified factored moment values, they can be graphed on the axial load-wall moment interaction diagram to determine the strength adequacy of the structure. The load combination used in Load Case 1 yielded results that fell within (to the left of) the curve of the interaction diagram. This means that the strength capacity of the walls was not exceeded. However, this was not the situation in Load Case 2 and 3. Both points fell beyond the interaction diagram curve meaning the strength capacity of the walls did not suffice for the load combinations used.

The results of the structural check are beneficial. They demonstrate the potential the refined concrete masonry system has within the context of structural performance. They also reassure the efforts of the development of this refined masonry system. At this stage of progress it is useful to have an early indication of how well the system may work to support day-to-day loads. The results of Load Case 2 and 3 have also prompted the need for further investigation. The level of conservation may be too extreme, and perhaps a more thorough review is necessary. Possible incremental improvements may be found by increasing the grout strength, widening the core spaces of the blocks, or arranging the reinforcing steel differently. However, by examining one of the equations used for the interaction diagram it will be found that the area of steel reinforcement has a direct relationship with the moment value. Therefore, the most pronounced improvement can be realized by increasing the area of steel reinforcement.

4.3 Module 3: Construction Management

The goal of the research is to improve concrete masonry, which means that any changes made must be measured in order to make comparisons to existing metrics of the status quo. It is within Module 3 that the culmination of efforts will now be tested to gauge the effects of the refined masonry system; tested against one of the most time-honored construction methods known.

As mentioned earlier, of the various ways suggested to improve concrete masonry, reducing construction time received the most attention. With resource constraints and wishing to keep the scope of the study within reason, it was fitting then to use time as the measure of comparison. A direct and simple productivity study was designed and conducted.

4.3.1 Productivity Study

The general framework involved ten masons. Each mason had to build two walls; one using traditional CMUs and the other using the refined masonry system. The entire study was conducted within a controlled environment, and the time to construct each wall was recorded. Table 4.8 presents the times collected for each wall.

Table 4.8: Productivity time results.

	Time in Minutes:Seconds		
Mason	Traditional Wall	New Wall	Time Difference
1	37:23	25:05	12:18
2	39:47	22:15	17:32
3	37:24	29:12	8:12
4	28:33	16:21	12:12
5	47:59	26:00	21:59
6	47:26	34:31	12:55
7	32:25	21:51	10:34
8	29:00	16:41	12:19
9	38:15	26:03	12:12
10	47:22	16:07	31:15
Average	38:33	23:25	15:08
Std. Deviation	±7:17	±6:01	±6:50

From the results, it can be seen that the construction times vary between each mason. However, for every individual mason the time to construct using the refined masonry system was always less than the time to construct using traditional CMUs. The average difference in construction time between the two walls is about 15 minutes with a 95% confidence interval of (10:26, 20:02; minutes:seconds). This equated to an improvement of 39%.

With this decrease in construction time the natural question to arise is, "how would this impact cost?" To analyze the financial ramifications of the changes implemented into the refined masonry system would be well beyond the scope of the present research, however, a very basic cost comparison of material only has been conducted to provide some general idea. For the cost comparison, most values have been sourced from existing cost data (RSMeans, 2010), while the unit cost of expanded polystyrene was provided by industry. Other values are assumed as noted. Because the blocks differ in size, the cost per unit are of wall was the basis of comparison. Table 4.9 lists the results.

Table 4.9: Material cost comparison.

Material	Unit cost	Refined Block	Standard CMU (not grouted)[1]	Standard CMU (fully grouted)[2]
Cement (Type I)	$17.20/cwt kg ($7.80/cwt lb)	$1.91/block	-	-
EPS (regrind)	$1.32/kg ($0.60/lb)	$0.67/block	-	-
Mortar (Type M)	$170.57/m^3 ($4.83/ft^3)	$0.03/block	-	-
Grout	$86.06/m^3, assumed ($75/yd^3)	1.26/block	-	$0.69/block
Steel Reinforcement[3]	$1.32/kg ($0.40/lb)	$0.27/block	-	$0.13/block
Cost per block	-	$4.14	-	-
Cost per m^2 (Cost per sf)	-	**$23.00 ($2.13)**	**$39.50 ($3.67)**	**$49.43 ($4.59)**

Notes:

[1] Final cost is directly from RSMeans and it is the cost of material including mortar.

[2] Final cost is the sum of the standard CMU in previous column plus the steel and grout.

[3] Steel reinforcement is vertical reinforcement only spaced at 600 mm (23.62 in) on center.

Construction time was the only data planned to be collected, but during the study there were other observations noted that are worth mentioning. Perhaps the most significant was the minor learning curve present. This was mostly because the masons had to remain attentive to the orientation of the blocks, both in the vertical and horizontal directions. It is important for structural reasons that the blocks are placed correctly, therefore, how fail-safe the system is may have an impact on the design of the block. The masons also mentioned how quickly the “back pains” went away using the refined system. This is because the time spent working on the lower courses is shortened by the greater height of the refined blocks and shortened stacking duration.

Several masons also noted that the thin-bed mortar joint reduced the amount of room available to level and plumb the blocks. They recommended perhaps using a 6.35 mm (0.25 in) joint rather than a 3.2 mm (0.125 in) joint. The masons also suggested that the refined system has the potential for non-loadbearing applications such as partition walls; perhaps in combination with surface-bonding. For placing the thin-bed mortar, a special trowel borrowed from the autoclaved aerated concrete industry was offered to the masons for use in the study. They preferred to use their own trowel and they were actually just as effective with it on the refined masonry system as they were on the traditional system. Yet another observation was how well the lightweight blocks withstood handling for ten sessions. The blocks were reused each time because it was not practical to produce enough blocks to be used once each. Finally, it is interesting to note that even though the refined blocks are approximately the same weight as the 400 mm x 200 mm x 200 mm (16”x8”x8”) traditional blocks, nearly every one of the ten masons expressed their opinion that the refined blocks are lighter.

CHAPTER 5

CONCLUSIONS

An effort to improve concrete masonry has been presented here. Originally motivated by deficiencies observed with the masonry industry in the Philippines, a refined concrete masonry system was developed. Starting nearly from nothing, guiding parameters helped lay the foundation for the refined system. It was necessary to address what basic dimensions would be used, what materials would be most appropriate, what improvements would be incorporated, how the blocks would be manufactured, and how the blocks would be assembled. In essence, an integrated approach was used during the design of the entire system. Any aspect that could impact the design of the system was included as a factor.

To design a refined system, however, does not suffice. Impacts caused by changes must be measured, and these measurements then must be compared to existing benchmarks. Care is needed to ensure that the measurements taken are accurate, and that direct comparisons are made using a common unit of measurement. In this case it was time. It is only then that substantial claims can be drawn from the data collected.

In conclusion, the results of the productivity study indicate that the refined system requires less time for assembly as compared to traditional concrete masonry. It must be cautioned that the results alone cannot substantiate whether or not overall construction time will be reduced with the new system. It should also be noted that despite the fact that many concrete masonry walls require some grouting, the refined system developed here requires full grouting, which may increase overall construction time.

5.1 Limitations

Several limitations exist for the current study which are as follows. The sample size for the productivity study was small. Furthermore, the productivity study does not fully represent all the different possible work environments that exist in actual construction projects. In fact, the conditions for the productivity study were near optimum, i.e. it was dry, the ground was level, the wall being constructed was straight and short, it was conducted indoors where the space was heated, and the work area was not elevated. There were neither field issues nor logistical complications. Also, every component of the refined system was not incorporated into the productivity study. Half blocks were quickly made by sawing the stretchers into two even pieces, but the corner blocks, which are intended to increase the speed of construction, were never fabricated. Another limitation is that only time was considered when comparing the refined system to traditional concrete masonry. It was the aim of the research to improve several other qualities other than just construction time. Finally, the amount of physical testing of the refined masonry system was limited by resource availability.

5.2 Suggestions for Further Research

There are several more areas for possible research specifically related to the new system. These areas concern crew and site choreography, ergonomics, physical characteristics, and construction economics.

First, there may be a different optimum crew choreography. The volunteer masons noticed that after placing mortar along the bed plane they were able to set their trowel aside, allowing for handling of the blocks with both hands. This prompted the thought of whether or not efficiency could be gained by rearranging crew positions, or having dedicated tasks. For example, have a crew member dedicated to placing mortar while another crew member is dedicated to stacking blocks. After some time they could trade positions to avoid possible injury from repetitious motions.

Site layout of materials, equipment, and tools may be another area for further research. The blocks of the refined system are not only larger, but they also come in three different configurations. These conditions may require a different arrangement on the project site. The rate mortar is used, how the mortar is staged (mud bucket versus mud board), how the mortar is mixed, what additional tools are required and which ones are no longer needed, are some of the factors that may impact how the site is arranged.

The effect that these blocks have on overall ergonomics may be an additional topic of research. It was noted earlier that many of the masons perceived the refined concrete masonry block to be lighter in weight versus the traditional blocks, despite the fact that they weigh nearly the same. Could this perception become a hidden danger if masons overexert themselves due to a heightened confidence?

Physical testing was limited, so there is potential for further work such as testing actual structural performance. The structural values could be compared to the theoretical values calculated here as a means of validation. Thermal performance may also be evaluated which would have appeal to energy conservation efforts. Hydrostatic grout pressure capacity of the blocks would dictate at what rate and in what amount grout could be placed in the cores of the refined system.

Finally, the economic impact of the refined masonry system is unknown. This impact could be part of a life cycle costing analysis. It would also be interesting to explore the impact on labor costs, either as per project or per unit area of wall.

APPENDICES

APPENDIX A

MATERIAL DESIGN AND TESTING

This appendix provides additional information concerning the development of the mix design used for the refined masonry system. A table was created to aid in the mix design process and is reproduced in part here as an example. Additionally, pictures of some of the concrete samples produced are presented.

Table A.1: Mix design worksheet.

					Designed Proportions		Test Sample Proportions		Safety Proportion: 14 %			
	Mix ID:											
	Mix Date:											
	Samples: (1) 150x300 Cylinder			Specific Gravity	Amount (kg per c.m.	Volume (c.m.)	Amount (kg)	Volume (c.m.)	Amount (kg)	Volume (c.m.)	% by Volume	% by Weight
	Cementitious Material											
1	ASTM Type I Ordinary Portland Cement			3.15	336	0.11	1.87	0.0006	2.1293	0.0007	10.7	50.7
2	Class F Fly Ash (Note 2)			2.25	84	0.04	0.47	0.0002	0.5323	0.0002	3.7	12.7
3												
	Total Cementitious Materials				420	0.14	2.33	0.0008	2.66	0.0009		
	Aggregates											
1	Expanded Polystyrene (EPS) Regrind (Coarse) (Note 3)			0.014	13.98	0.97	0.078	0.0054	0.0886	0.006	97.0	2.1
	Absorption	9.90	%									
	Batched Moisture Content	0.00	%									
	Ratio & Mass (Fine :Coarse)	0	100						0.0000	0.0886		
2	Mortar Sand (Note 4)			2.67	80.10	0.03	0.45	0.0002	0.5076	0.0002	3.0	12.1
	Absorption	0.7	%									
	Batched Moisture Content	5.4	%									
	Total Aggregates				94	1.00	0.52	0.0056	0.596	0.006		
	Water											
1	Water			1.00	151.2	0.1512	0.84	0.0008	0.9582	0.0010		
2	Additional Water for Aggregate Absorption			1.00	1.9	0.002	0.01	0.0000	0.0123	0.0000		
3	Less Water from Admixtures (Note 5)			1.00	1.43	0.001	0.01	0.0000	0.0091	0.0000		
4	Less Batched Moisture Content			1.00	4.3	0.004	0.02	0.0000	0.0274	0.0000		
	Total Water				147.4	0.1	0.8	0.0008	1.0070	0.0010	14.7	22.2
	Fiber											
1	(None)											
	Total Fibers											
	Admixtures	**Dosage Rate**			Amount (L)	Vol. (c.m.)	Amount (ml)					
1	Riteks Inc SP 7000 (Note 6)	3.405	ml/kg cem.	1.00	1.43	0.001	7.95		9.06		0.1	0.2
	130-975 ml/100 kg	340.5	ml/100 kg							0.1031	114.5	100.0

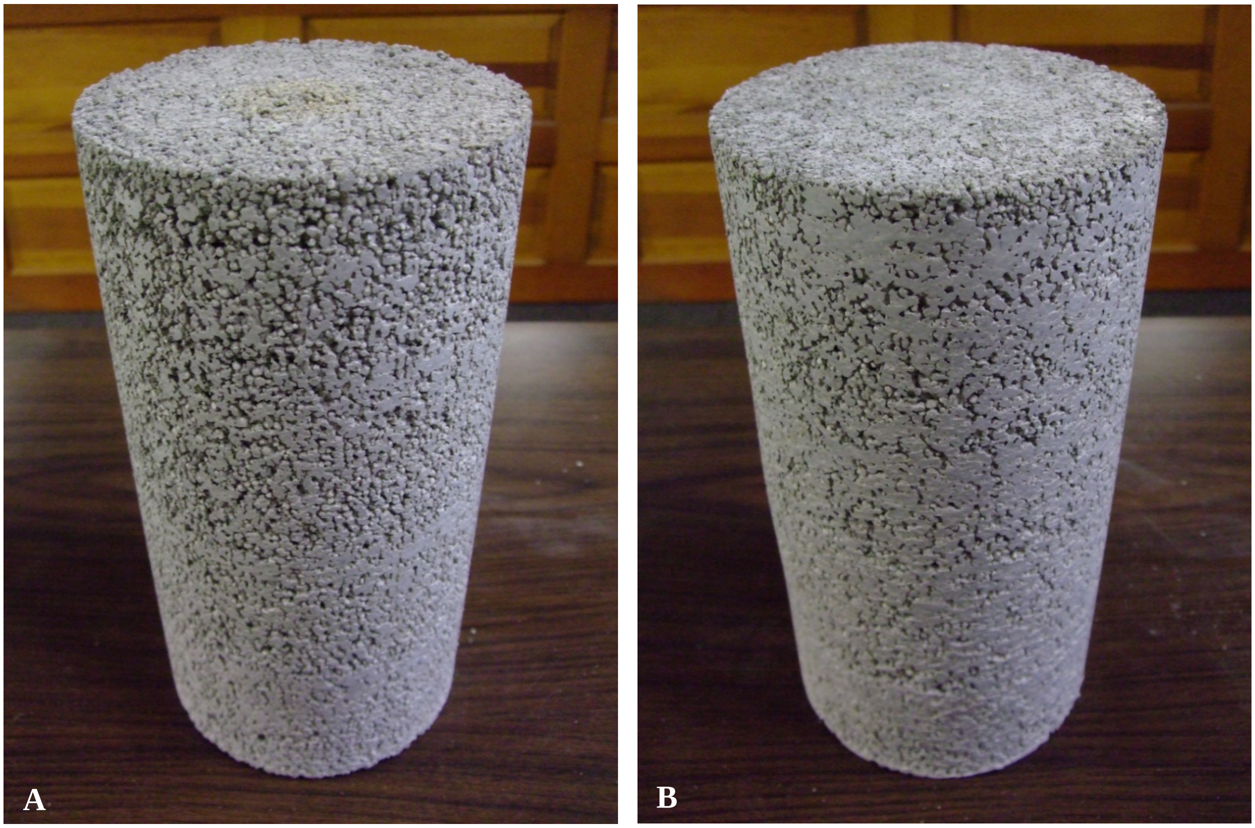

Figure A.1: Additional cylindrical concrete samples. (a) more porous surface finish from one mix design; (b) smoother surface finish with a different mix design.

These two samples are from different mix designs, and from appearance alone it can be seen that the surface textures are slightly different.

APPENDIX B

MOLD DESIGN AND FABRICATION

This appendix provides further information concerning the temporary mold used to produce prototypes of the newly developed concrete masonry system. Detailed design drawings are presented followed by additional pictures taken during mold fabrication. The mold was used to produce a total of 30 blocks.

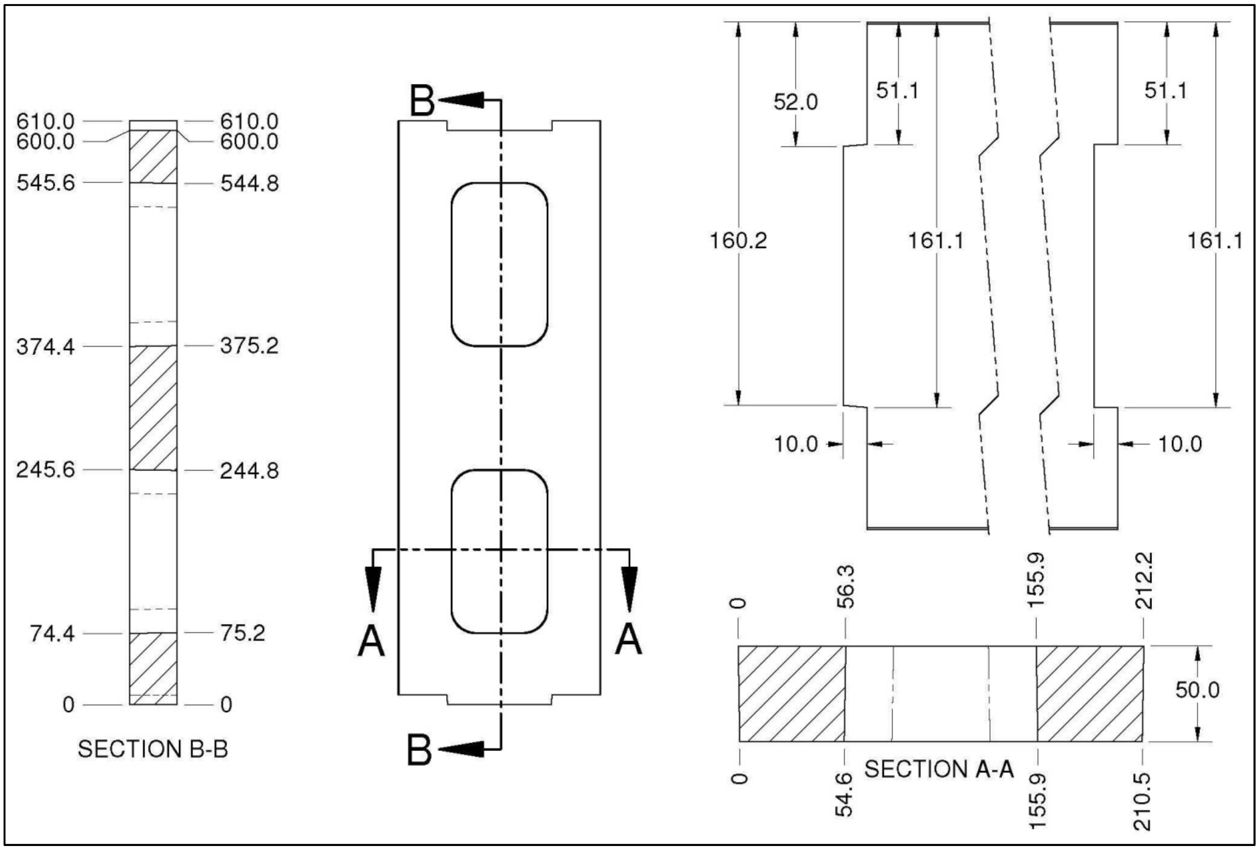

Figure B.1: Design plans for the shoe.

Figure B.1 shows plans for the shoe section of the mold. The holes incorporate a 1-degree draft to properly match the draft of the core section. All measurements are in millimeters (1 in = 25.4 mm).

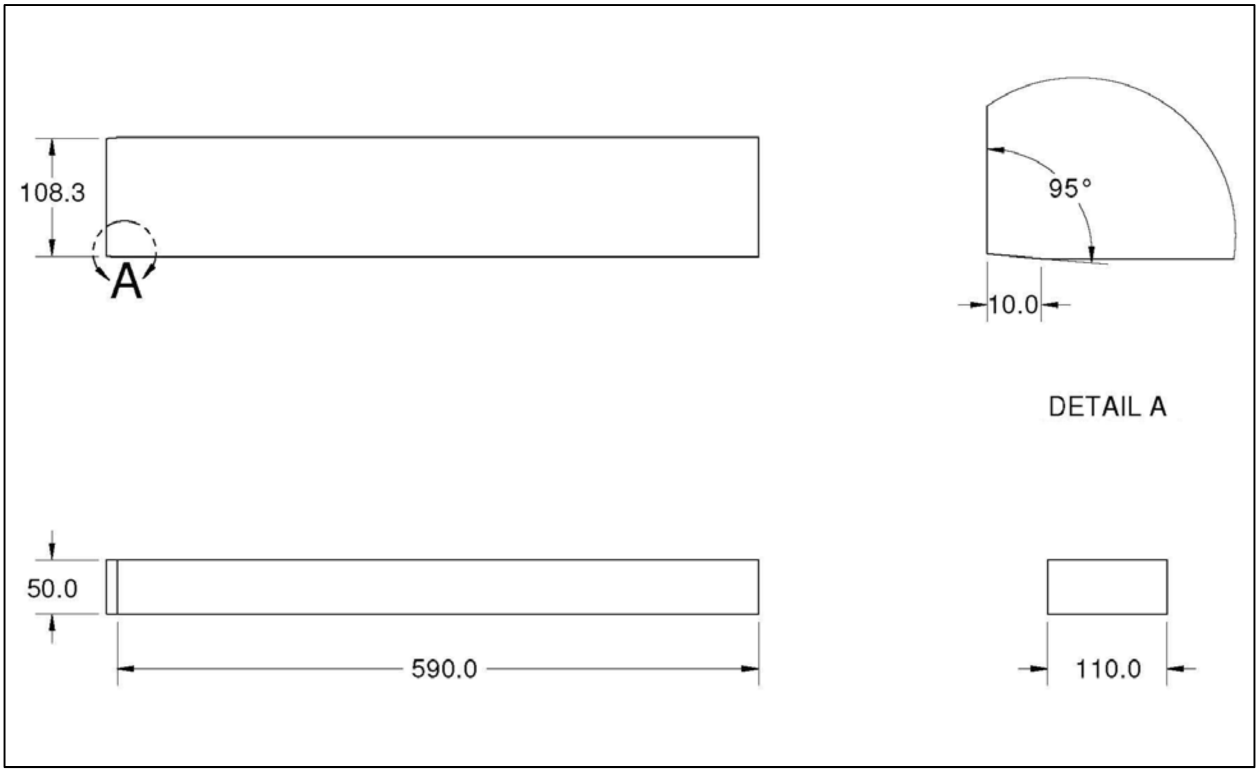

Figure B.2: Design plans for the core base.

Figure B.2 shows plans for the base piece of the core section. The 95-degree cut on the end is to properly match the groove on the box section of the mold. All measurements are in millimeters (1 in = 25.4 mm).

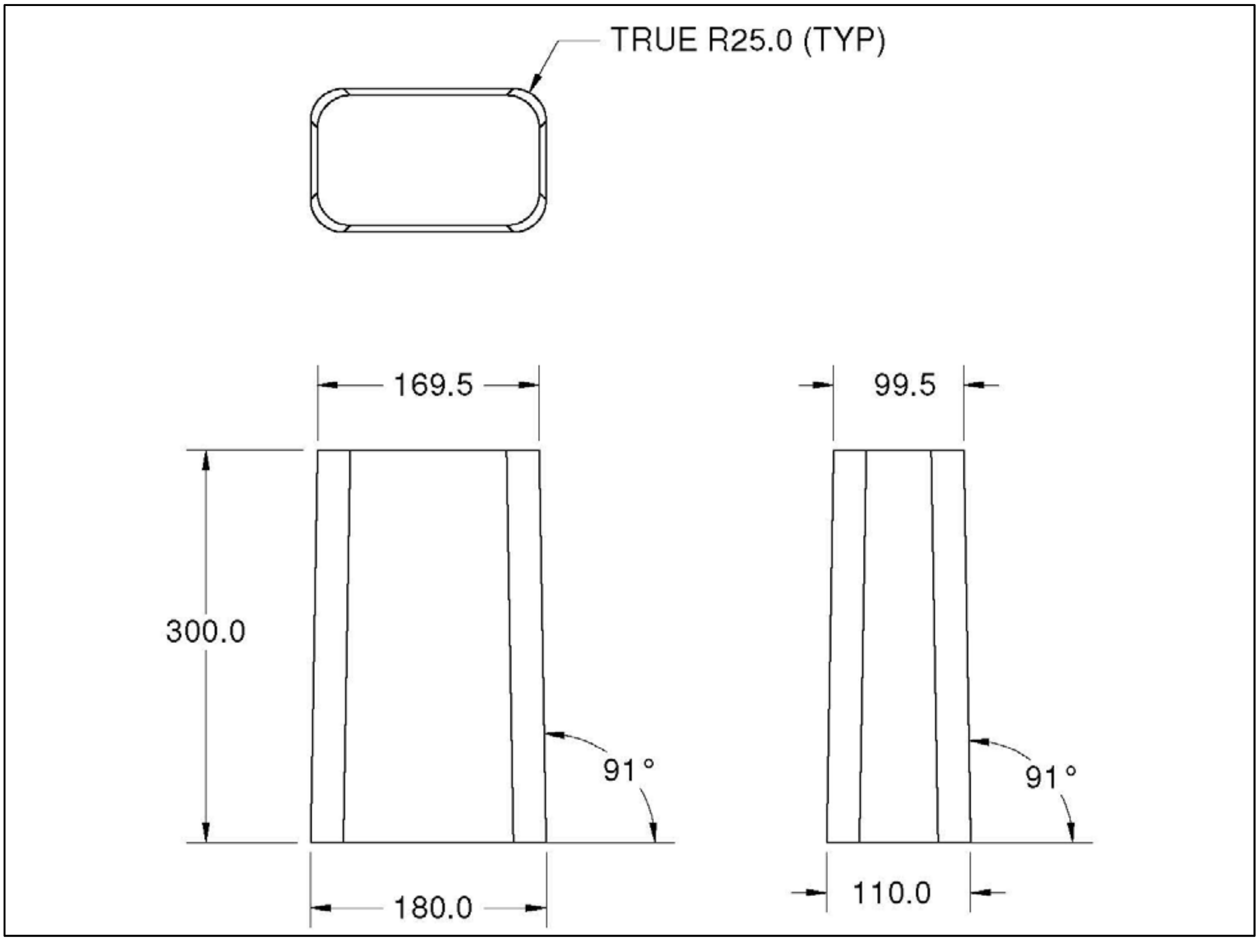

Figure B.3: Design plans for the core uprights.

Figure B.3 shows the plans for one of the upright pieces of the core section of the mold. A 1-degree draft was incorporated to allow for easier block extraction, hence 91-degrees. All measurements are in millimeters (1 in = 25.4 mm).

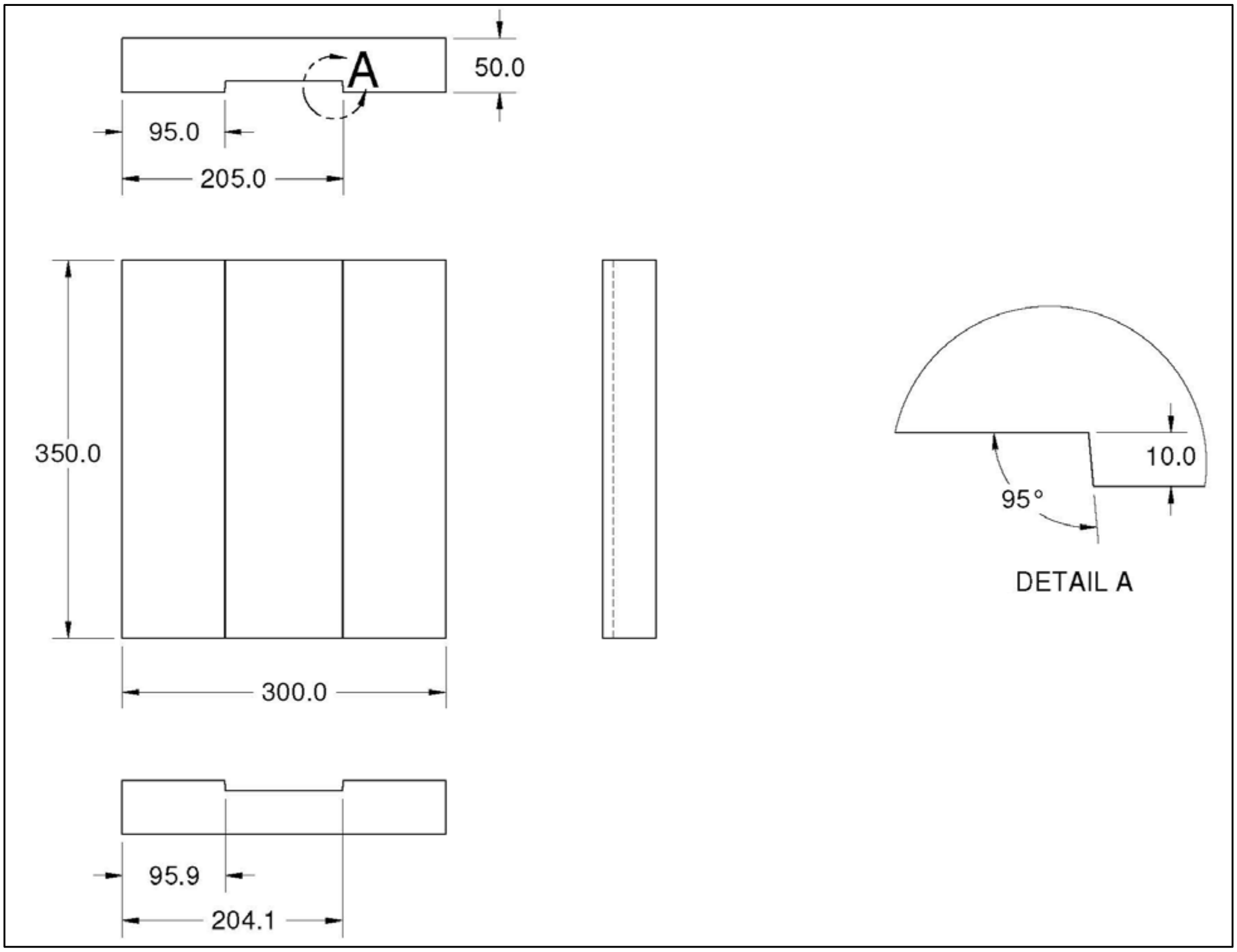

Figure B.4: Design plans for the left segment of the mold box.

Figure B.4 shows the plans for the left piece of the box section of the mold. The 95-degree angle is to form a tongue of the block that will more easily insert into its corresponding groove. All measurements are in millimeters (1 in = 25.4 mm).

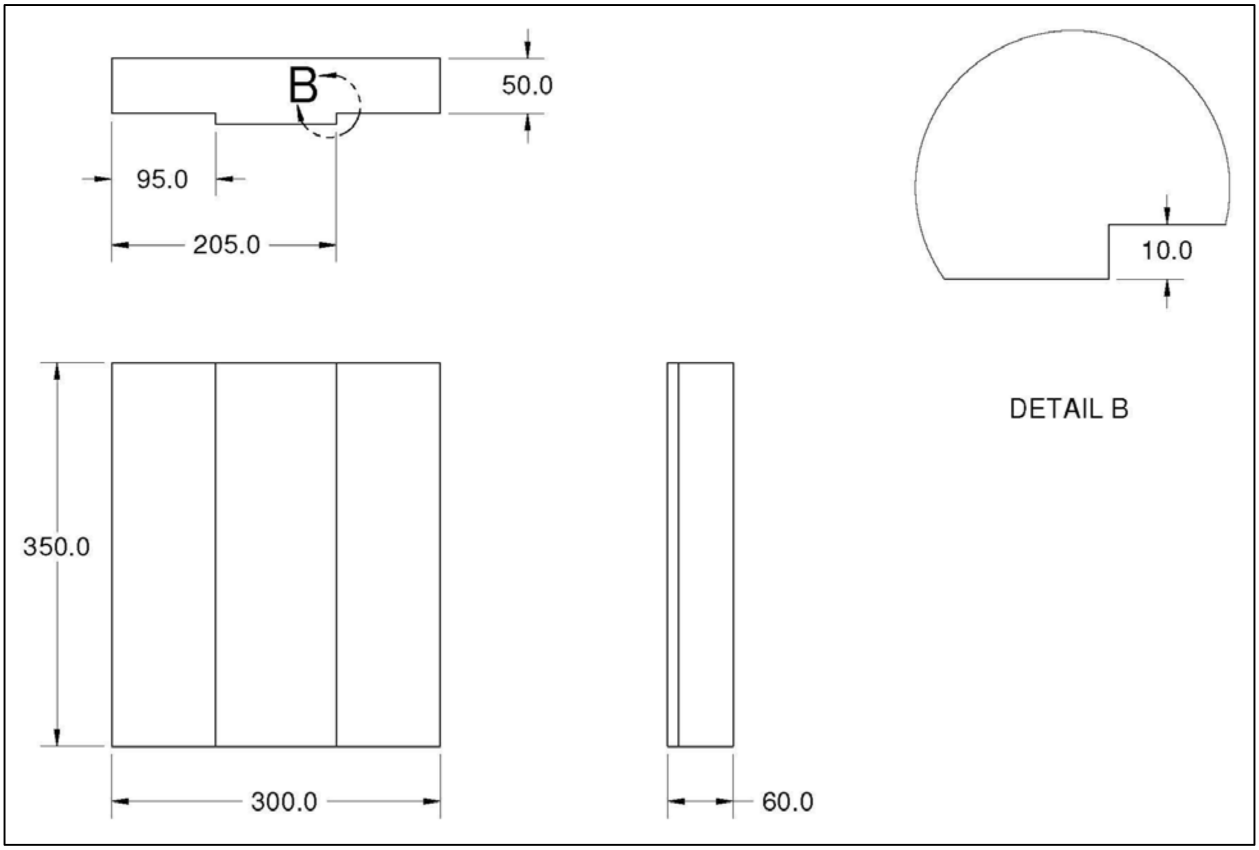

Figure B.5: Design plans for the right segment of the mold box.

Figure B.5 shows the plans for the right piece of the box section of the mold. It will form the interlocking groove of the block. All measurements are in millimeters (1 in = 25.4 mm).

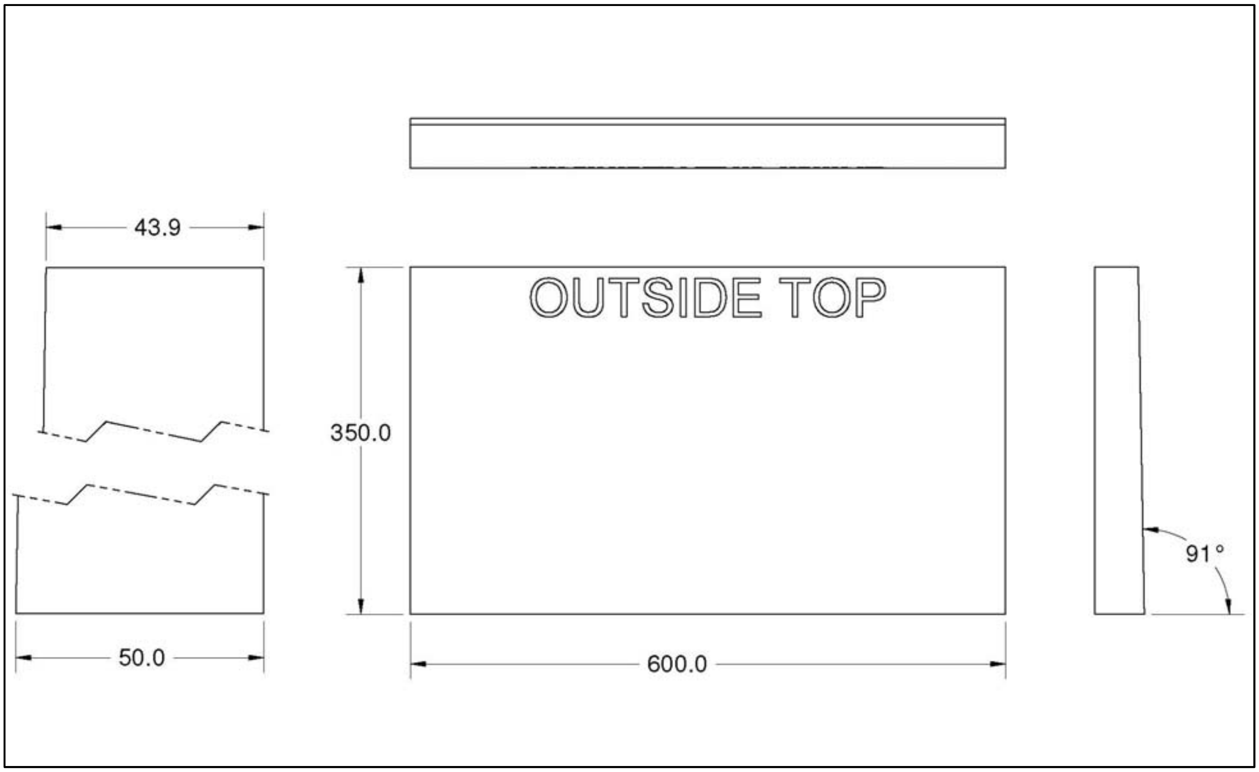

Figure B.6: Design plans for the long segments of the mold box.

Figure B.6 shows the plans for the long pieces (they are identical) of the box section of the mold. A 91-degree draft was incorporated to allow for easier block extraction. All measurements are in millimeters (1 in = 25.4 mm).

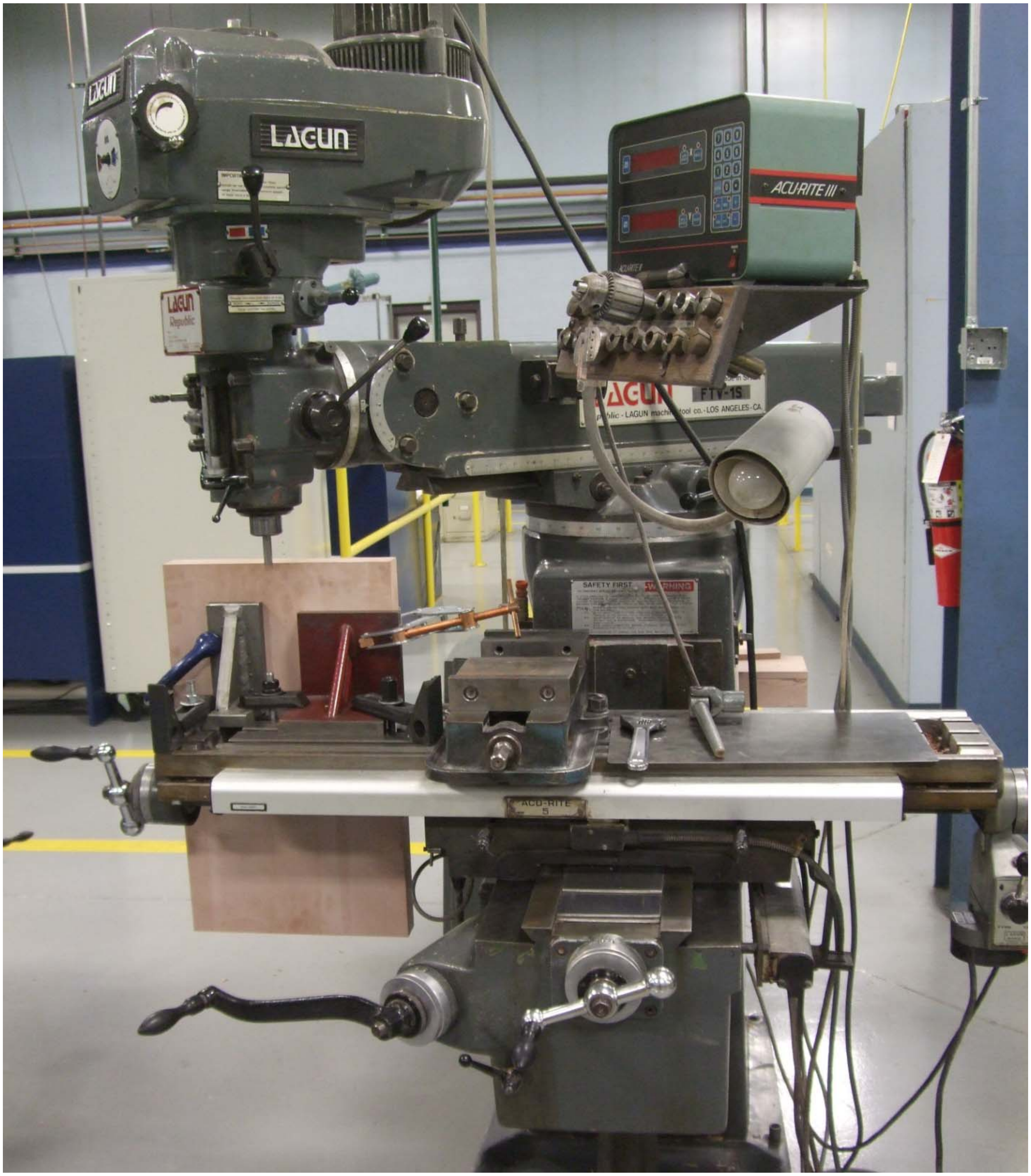

Figure B.7: Vertical milling machine.

At times complex setups were required on the vertical milling machine.

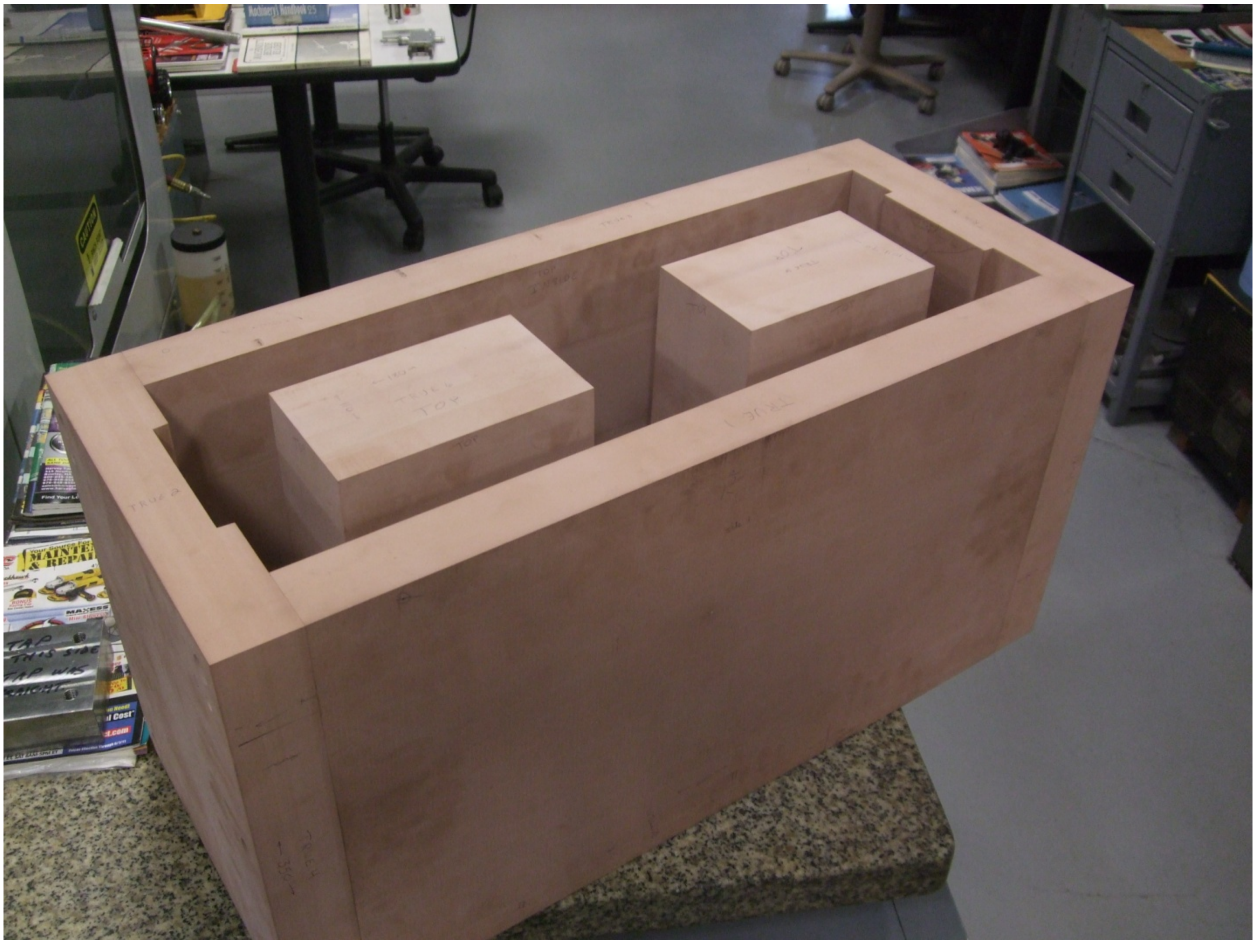
Figure B.8: Partially complete block mold.

Pictured are the box and core sections prior to cutting the radius on the core. The tan appearance is the natural color of the plastic.

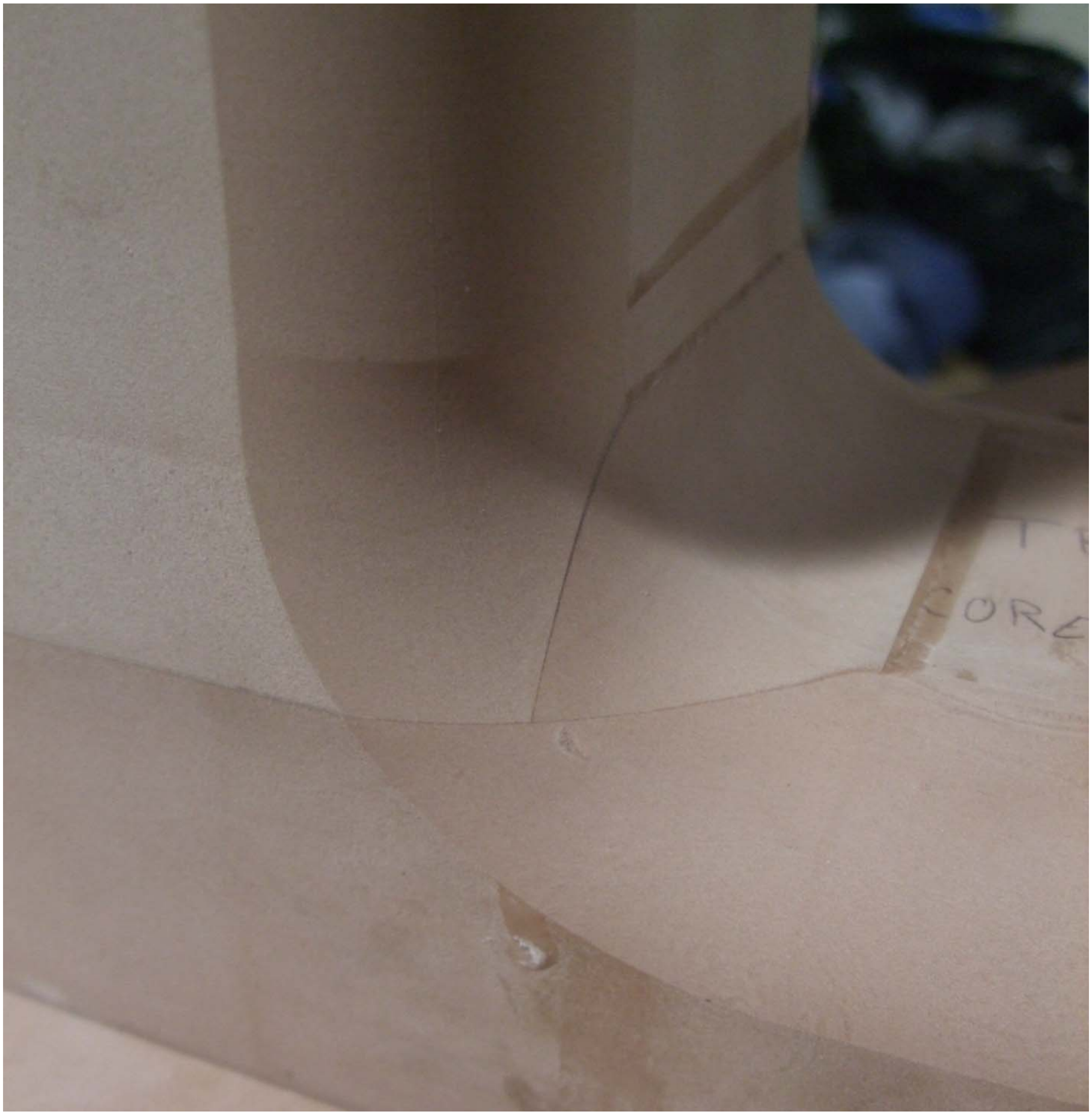

Figure B.9: Radius close-up on core.

This is a close-up on the radius of the core section. The 25 mm (approx. 1 in) radius was cut using a hand-held router.

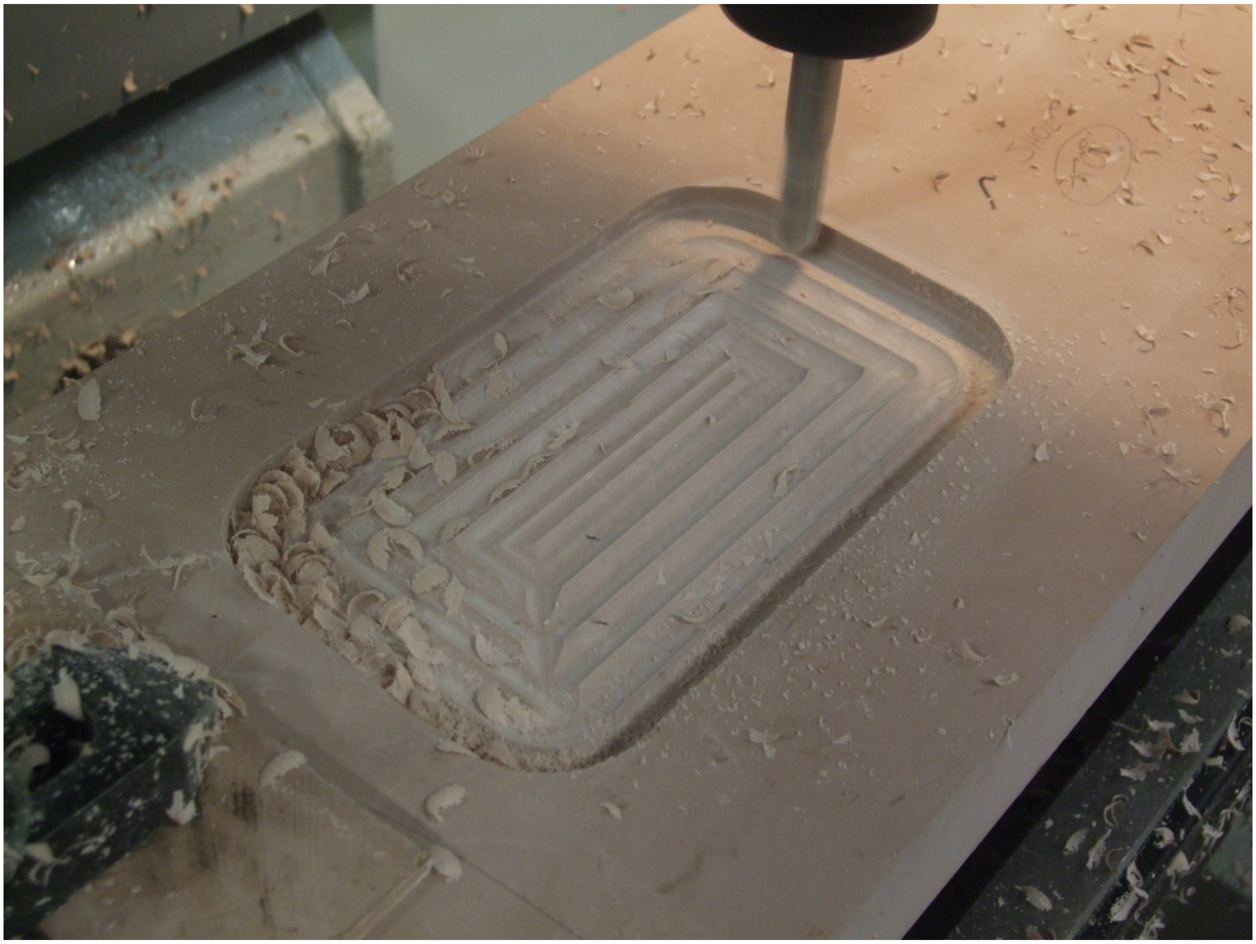

Figure B.10: CNC milling machine during cutting.

One of holes in the shoe of the mold is being cut by a CNC machine. The plastic material was designed to chip away in small pieces, which is favorable during cutting.

APPENDIX C

BLOCK DESIGN AND PRODUCTION

This appendix provides additional information concerning the design and production of the blocks of the refined concrete masonry system. Detailed drawings of each block are provided. An example of the computer model used to cross-check the constructability of the system is also included. Lastly, there is a complete table of several different block characteristics, followed by additional pictures taken during block production.

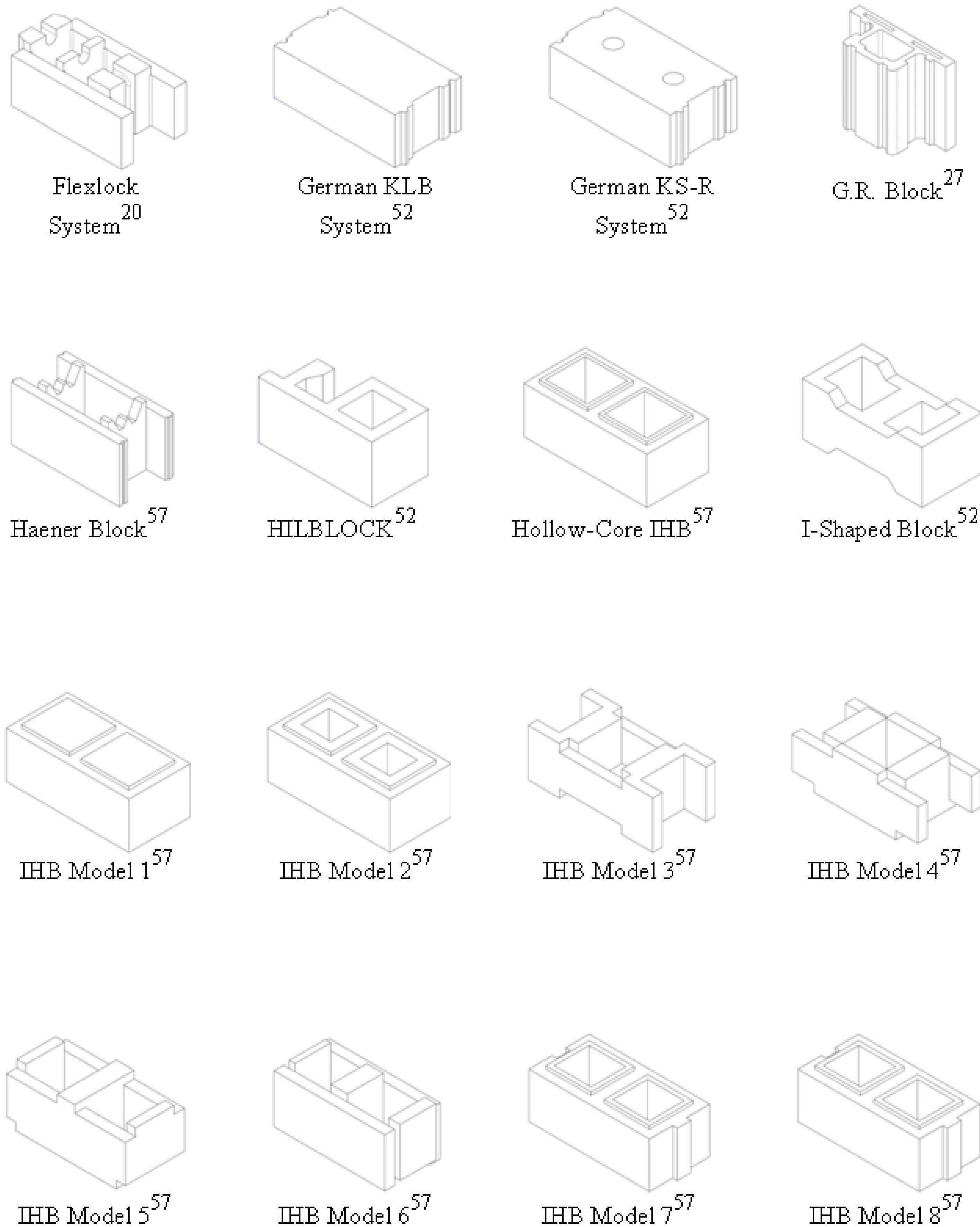

Figure C.1: Various new block designs from around the world.

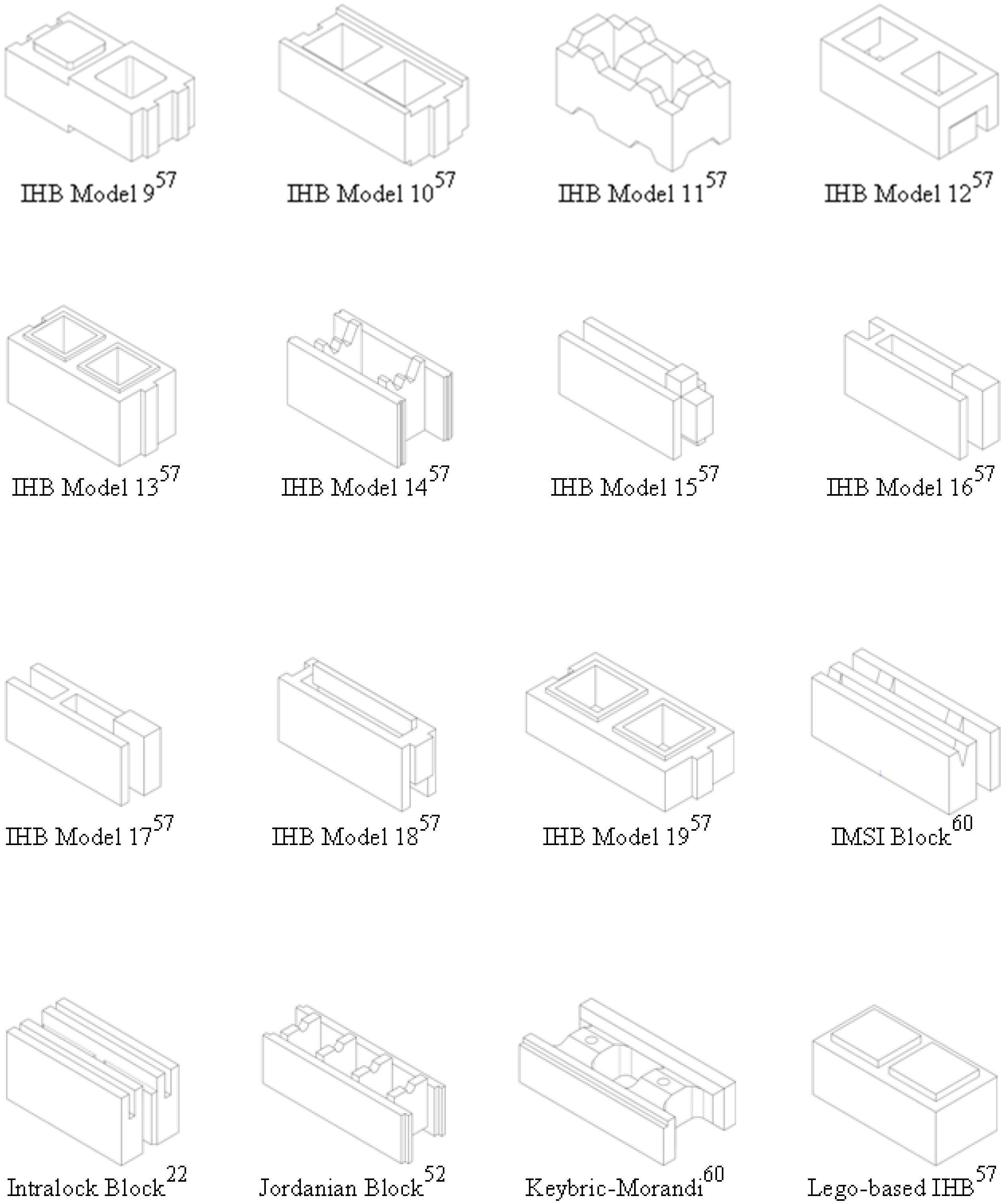

Figure C.1 (cont'd)

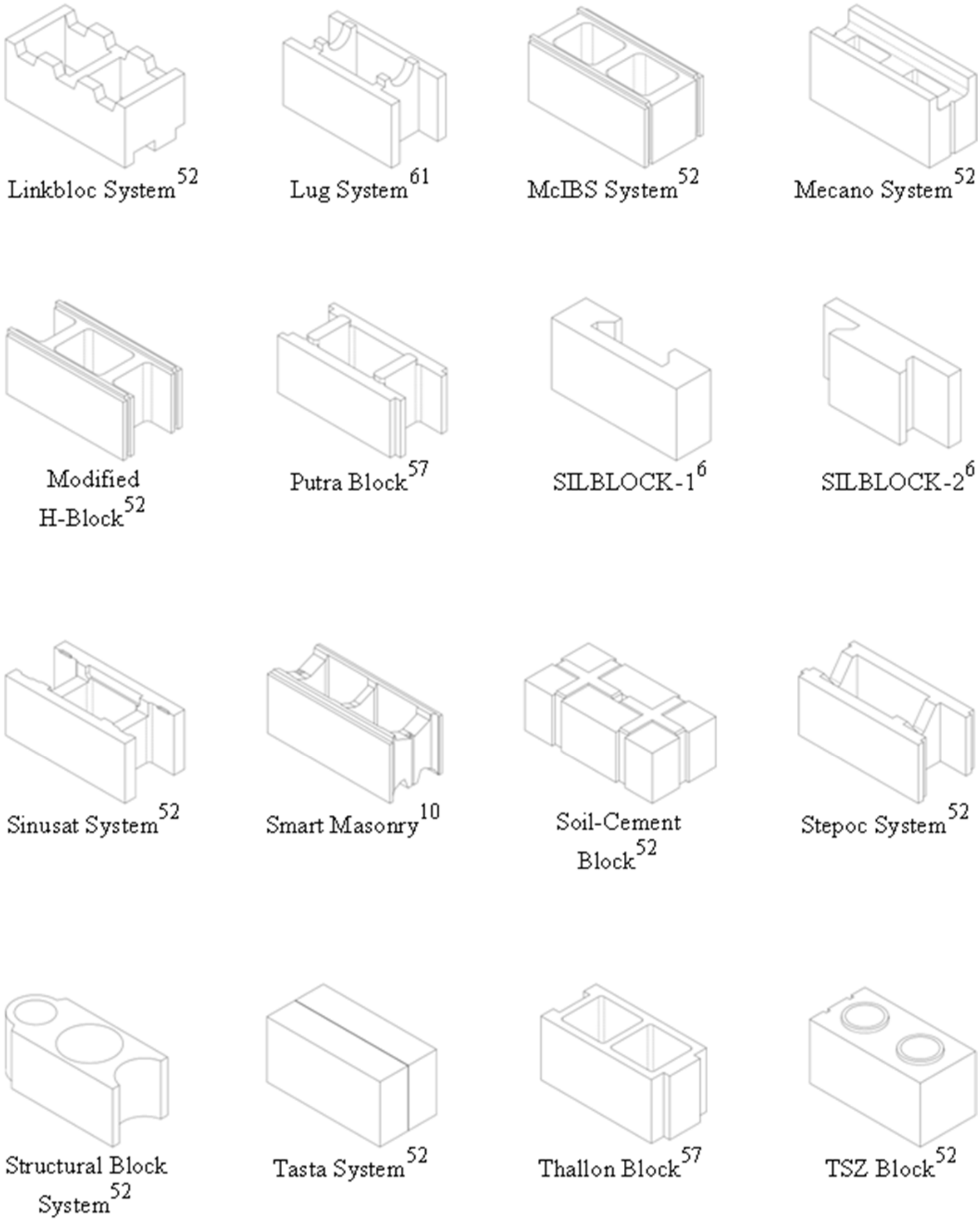

Figure C.1 (cont'd)

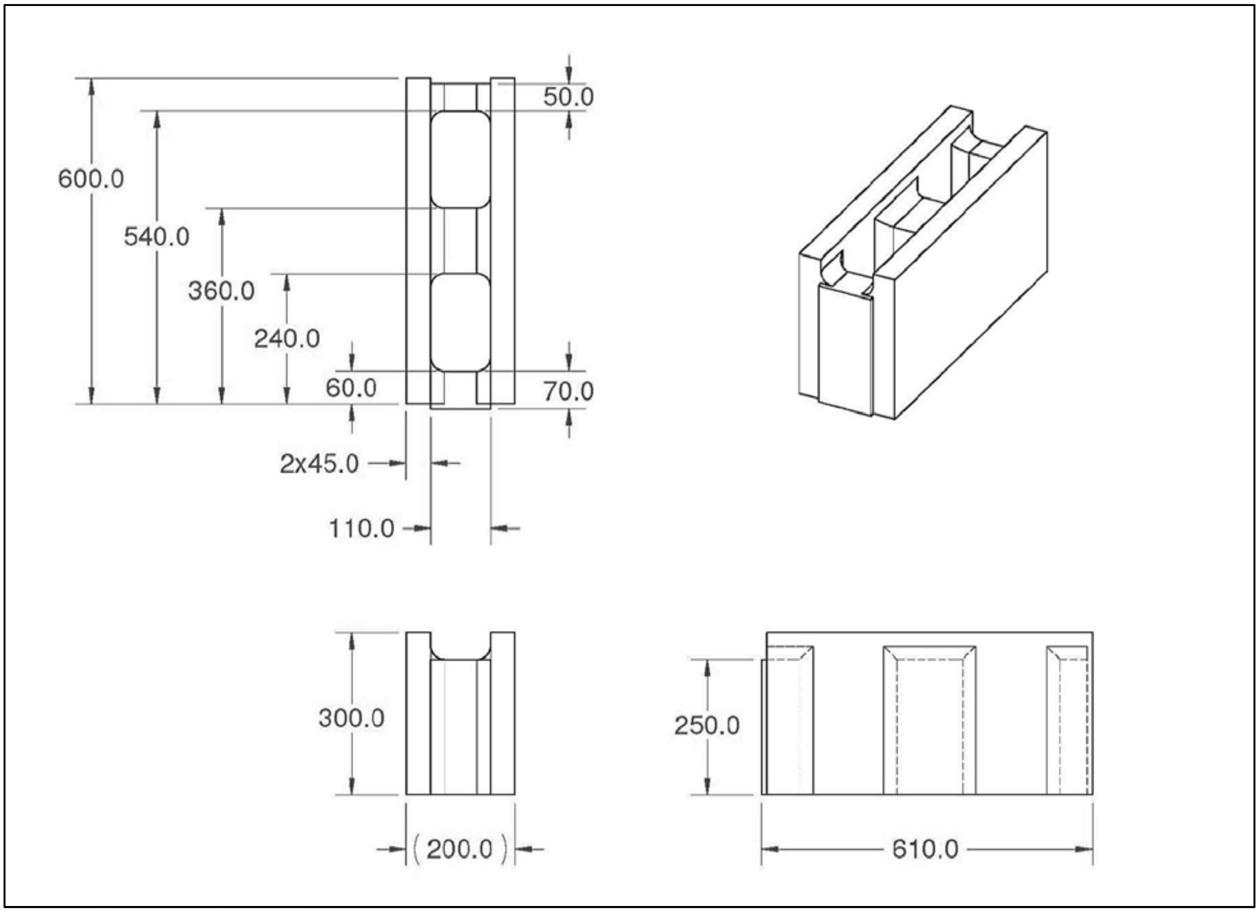

Figure C.2: Design plans for the stretcher block.

Depicted in Figure C.2 is the standard block, or stretcher. It is the central piece of the system. The length is 600 mm (23.62 in), the width is 200 mm (7.87 in), and the height is 300 mm (11.81 in). The core dimensions are 110 mm (4.33 in) wide by 180 mm (7.1 in) long, while the length of the center web is 120 mm (4.7 in). Its principle operation can be likened to a bond beam block; a block that produces a horizontal channel for creating interconnectedness between grouted, vertical cores. However, unlike that of a traditional bond beam block, the horizontal beams are produced throughout the entire wall.

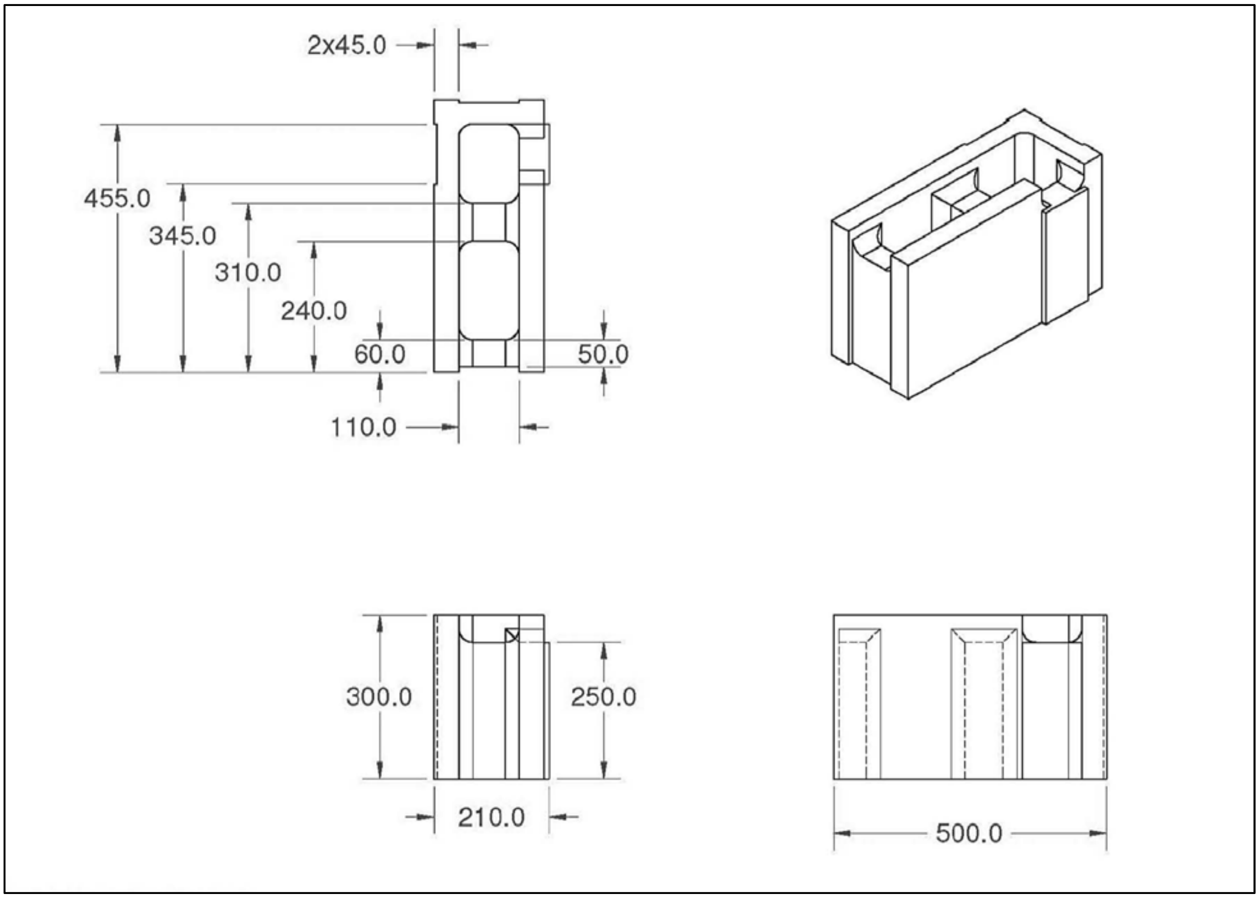

Figure C.3: Design plans for the universal corner block.

Figure C.3 shows the detail of the universal corner block. It too incorporates a horizontal channel to maintain continuity. The core of the leg has the same dimensions as the cores of the stretcher, but the core at the pivot point is slightly smaller. Grooves are included on the adjacent faces of the pivot point to accommodate an interlocking tongue when erecting wall intersections.

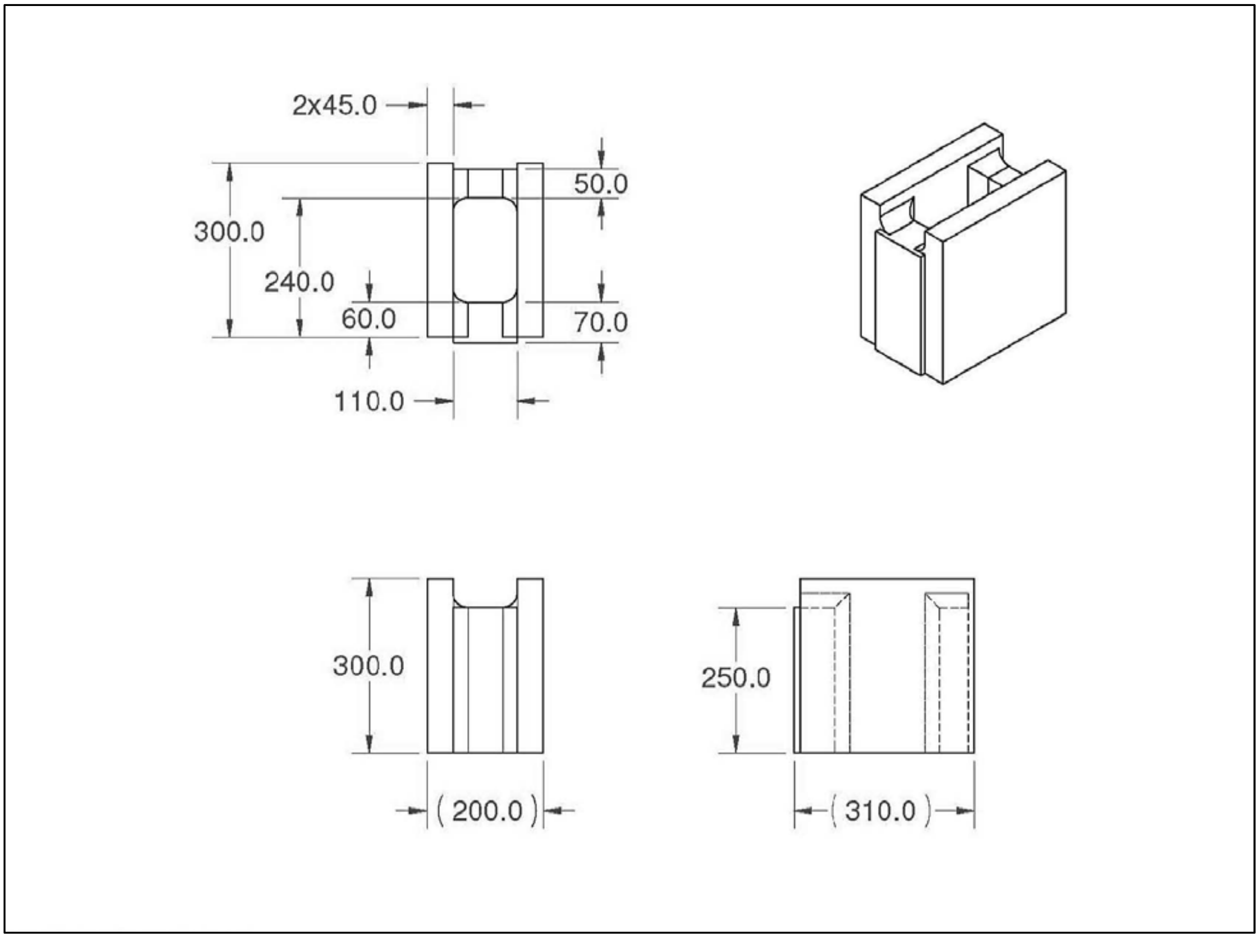

Figure C.4: Design plans for the half block.

Figure C.4 contains the details for the half block; which is exactly half the length of the stretcher. Since the method of assembly calls for a one-half running bond, the intent of this block is to save time during construction.

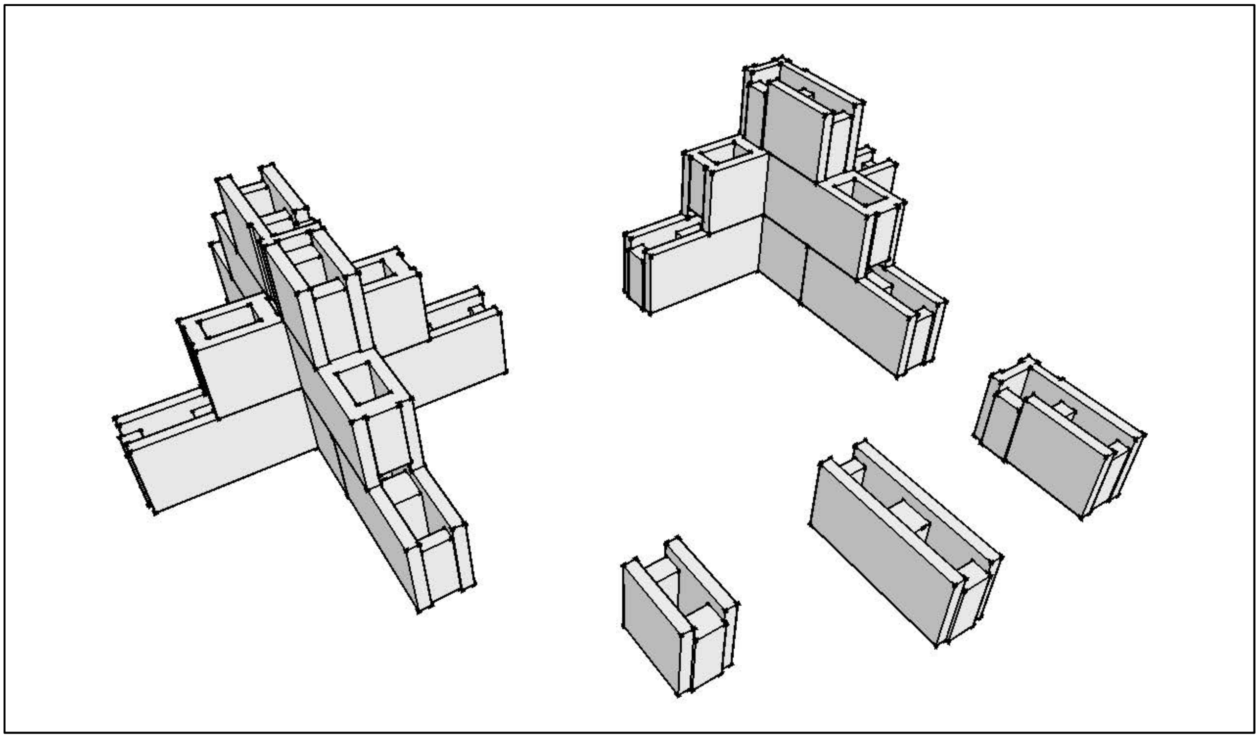

Figure C.5: Constructability check computer model.

Simple computer models were used to check the constructability of the refined concrete masonry system. The three individual blocks are shown in the bottom-right corner. The partial assembly on the left side is a full wall intersection and the other partial assembly is a T-wall intersection. Many issues were discovered with minimal effort and no cost.

Table C.1: Measurement of block dimensions.

Block	$\mathbf{L_1}$	$\mathbf{L_2}$	$\mathbf{L_3}$	$\mathbf{L_4}$	$\mathbf{W_1}$	$\mathbf{W_2}$	$\mathbf{W_3}$	$\mathbf{W_4}$	$\mathbf{H_1}$	$\mathbf{H_2}$	$\mathbf{H_3}$	$\mathbf{H_4}$
001	599	599	600	600	198	199	205	205	300	300	300	300
002	-	-	-	-	-	-	-	-	-	-	-	-
003	-	-	-	-	-	-	-	-	-	-	-	-
004	600	600	600	600	199	199	205	206	300	301	301	300
005	-	-	-	-	-	-	-	-	-	-	-	-
006	-	-	-	-	-	-	-	-	-	-	-	-
007	600	600	600	600	199	199	205	206	301	301	299	300
008	-	-	-	-	-	-	-	-	-	-	-	-
009	-	-	-	-	-	-	-	-	-	-	-	-
010	599	600	600	600	199	199	205	205	301	302	301	300
011	600	600	600	600	199	199	205	206	300	301	301	300
012	600	600	600	601	198	199	205	207	302	302	300	300
013	599	600	601	601	199	199	205	206	301	302	300	300
014	601	601	601	601	200	200	205	206	302	303	300	301
015	600	600	601	601	200	200	206	206	300	301	301	300
016	600	601	601	600	199	199	205	206	302	301	299	301
017	600	600	601	600	199	199	205	207	301	302	300	301
018	600	600	601	601	200	200	205	206	301	299	299	300
019	600	600	600	601	199	199	205	206	302	302	300	300
020	601	601	601	601	200	199	206	206	302	301	301	301
021	601	601	601	601	200	200	205	207	301	302	300	300
022	600	600	601	601	200	199	205	206	301	301	300	300
023	601	601	601	601	200	200	205	206	300	300	300	300
024	601	601	601	601	201	200	205	207	300	300	300	300
025	600	600	601	601	200	201	205	206	301	300	300	300
026	600	600	601	600	200	200	205	206	301	301	300	300
027	600	600	601	600	200	200	205	207	301	301	301	301
028	600	600	600	600	200	200	204	207	301	301	299	300
029	600	600	600	600	200	200	205	207	300	300	301	301
030	601	601	601	601	201	201	205	206	301	302	300	300
Avg.	**600**	**600**	**600**	**600**	**199**	**199**	**205**	**206**	**301**	**301**	**300**	**300**

This is the complete tabulation of the lengths, widths, and heights measured for the blocks. The measurements were taken in a similar fashion as described by ASTM C140-11. The accuracy demonstrates the performance of the temporary mold used. Four points in each direction were measured and averaged. All measurements are in millimeters (1 in = 25.4 mm).

Table C.2: Measurement of block weights.

Block	Initial	Final	Block	Initial	Final	Block	Initial	Final
001	14.282	14.2255	011	15+	15+	021	15+	15+
002	15+	15+	012	15+	15+	022	-	-
003	15+	14.926	013	15+	15+	023	-	-
004	14.32	14.2055	014	15+	15+	024	-	-
005	15+	15+	015	15+	15+	025	15+	15+
006	15+	15+	016	15+	15+	026	15+	15+
007	15+	15+	017	15+	15+	027	14.6475	14.1775
008	15+	15+	018	-	-	028	15+	15.001
009	15+	15+	019	-	-	029	14.307	13.7775
010	-	-	020	15+	15+	030	14.7000	14.1915

The weights of the blocks are presented here in kilograms (1 kg = 2.2 lb). Many were slightly over the 15 kg (33.1 lb) capacity of the digital scale used. The initial weight is the weight of the block immediately after being removed from the mold. The final weight is the weight of the block after extensive air drying, and before use in prism testing or the productivity study. Overall, the consistency and relative proximity to the target weight are considered good.

Figure C.6: Expanded polystyrene (EPS) aggregate.

These bags contain the aggregated used, recycled expanded polystyrene (EPS). Each bag holds approximately 10 cubic feet. The bag marked “Dust” contains fine EPS particles that were filtered from the rest of the EPS. It was used to help achieve the ideal aggregate size grading.


Figure C.7: Block in mold.

This is a view of a block within the mold. The shoe segment of the mold is not present in the picture which is a critical piece in that it creates a consistent block height.


Figure C.8: Completed blocks.

The blocks were moist cured in large plastic bags for 28 days, after which they were allowed to air-dry until they were utilized. The blocks are pictured sitting on-end, and the gray patch on each one is a label for identification.

APPENDIX D

STRENGTH TESTING AND STRUCTURAL CHECK

This appendix provides additional information concerning the strength tests conducted on the blocks and the structural check that was performed. The equations used for the structural check are presented in plain form here with short explanations (they were kept in imperial units). They are reproduced in part from VanderWerf (1997) and ACI 318-11. Different plans of the model structure that served as basis for load calculations have been included here. Additional pictures of the prism testing are also included.

$c = (\frac{\epsilon_c}{\epsilon_c + \epsilon_y})d$

$\epsilon_c = 0.003$

$\epsilon_y = \frac{f_y}{E_s}$

$a = \beta_1 c$

$C_c = 0.85abf_c'$

$T_s = A_s f_y$

$\Phi P_b = \Phi(C_c - T_s)$

$\Phi M_b = \Phi C_c(d - \frac{a}{2})$

Variables	Description	Unit
a	Depth of equivalent rectangular stress block	in
A_s	Area of tension reinforcement	in^2
b	Width of compression face	in
c	Distance from extreme compression fiber to neutral axis	in
C_c	Compression in concrete	lb
d	Distance from extreme compression fiber to centroid of rebar	in
E_s	Modulus of elasticity of steel reinforcement	psi.
f_c'	Specified compressive strength of concrete	psi.
f_y	Specified yield strength of reinforcement	psi.
M_b	Nominal flexural strength at balanced strain conditions	in-lb
P_b	Nominal axial load strength at balanced strained conditions	lb
T_s	Tension in reinforcement	lb
β_1	Factor (defined by ACI as equal to 0.85 for f_c' up to 4,000 psi.)	-
ϵ_c	Strain in concrete	-
ϵ_y	Yield strain of reinforcing steel	-
Φ	Strength reduction factor (set to 0.70 by ACI for combined axial/flexure)	-

Figure D.1: Equations for Point 4 of interaction diagram.

Explanations:

These calculations will produce Point 4 of the interaction diagram. This point represents a balanced condition between moment and axial load; the stress in the steel reinforcement closest to the tension face is equal to its yield stress. Any further tension and the reinforcement will fail.

$$a = \left(\frac{A_s f_y}{0.85 f'_c b}\right) d$$

$$\Phi M_n = \Phi A_s f_y \left(d - \frac{a}{2}\right)$$

Variables	Description	Unit
a	Depth of equivalent rectangular stress block	in
A_s	Area of tension reinforcement	in^2
b	Width of compression face	in
d	Distance from extreme compression fiber to centroid of rebar	in
f_c'	Specified compressive strength of concrete	psi.
f_y	Specified yield strength of reinforcement	psi.
M_n	Nominal flexural strength at condition of no axial load	in-lb
Φ	Strength reduction factor (set to 0.90 by ACI flexure)	-

Figure D.2: Equations for Point 5 of interaction diagram.

Explanation:

These calculations will produce Point 5 of the interaction diagram. It represents a point on the interaction curve with no axial load; just pure moment. In the interaction diagram used for the structural check, Point 5 was lower in moment capacity than compared to Point 4. This is because at times the presence of axial load can help increase the moment capacity of the structure.

$\frac{kl_u}{r} \leq 34 - 12\left(\frac{M_1}{M_2}\right) \leq 40$ (ACI-2011 10.10.1)

Variables	Description	Unit
M_1	Smaller factored end moment	in-lb
M_2	Larger factored end moment	in-lb
k	effective length factor equal to 1.0; ACI	-
l_u	unsupported length of compression member	in
r	Radius of gyration of cross section, = 0.3 times the thickness of the rectangular, vertical members	in

Figure D.3: Equation for slenderness check.

Explanations:

Slenderness must be considered as structural members become longer, and the chance of buckling increases. The degree of slenderness is represented by the part of the equation to the left of the first inequality sign. ACI 318 stipulates that compression members braced against sidesway may neglect the effects of slenderness if the equation above holds true.

$M_c = \delta_{ns}M_2$

$$\delta_{ns} = \frac{C_m}{1 - P_u/0.75P_c} \geq 1.0$$

$$P_c = \frac{\pi^2 EI}{(kl_u)^2}$$

$$C_m = 0.6 + 0.4\left(\frac{M_1}{M_2}\right) \geq 0.4$$

$C_m = 1.0$ for members with transverse loads between supports

$M_{2,\,min} = P_u(0.6 + 0.03h)$

Variables	Description	Unit
C_m	Factor relating moment diagram to equivalent uniform moment diagram	-
E_c	Modulus of elasticity of concrete	psi.
EI	Flexural stiffness of compression members	in^2-lb
h	Thickness of wall	
I_g	Moment of inertia of gross concrete section	in^4
k	Effective length factor equal to 1.0; ACI	-
l_u	Unsupported length of compression member	in
M_1	Smaller factored end moment	in-lb
M_2	Larger factored end moment	in-lb
$M_{2,\,min}$	Minimum value of M_2	in-lb
M_c	Magnified factored moment to be used for designing compression member	in-lb
P_c	Critical load	lb
P_u	Factored axial load	lb
δ_{ns}	Moment magnification factor for nonsway frames	-

Figure D.4: Equations for moment magnifier for non-sway frames.

Explanations:

The moment magnifier is used as part of the approximate method when accounting for slenderness in a wall. The approximate method is the easier of the two methods which are outlined in ACI 318. As can be seen, the moment magnifier is a function of the factored axial load and the critical buckling load.

$$EI = \frac{E_c I_g}{\beta}(0.5 - \frac{e}{h}) \geq 0.1\frac{E_c I_g}{\beta} \text{ and } \leq 0.4\frac{E_c I_g}{\beta}$$

$$\beta = 0.9 + 0.5\beta_d^2 - 12p \geq 1.0$$

Variables	Description	Unit
e	Eccentricity of axial load	in
EI	Flexural stiffness of compression members	in^2-lb
E_c	Modulus of elasticity of concrete	psi.
h	Thickness of wall	in
I_g	Moment of inertia of gross concrete section	in^4
β	As defined in equation	-
β_d	Ratio of dead load to total load	-
p	Ratio of area of vertical rebar to gross concrete area	-

Figure D.5: Equations for flexural stiffness of compression members with one layer of reinforcement.

Explanations:

The first equation is for calculating EI. If the value of $(0.5 - \frac{e}{h})$ is less than 0.1, then 0.1 is used by default in place of that section of the equation.

$\Phi V_n \geq V_u$

$V_n = V_c + V_s$

$V_c = 2\sqrt{f_c'} b_w d$

Variables	Description	Unit
b_w	Web width, or diameter of circular section	in
d	Distance from extreme compression fiber to centroid of longitudinal tension reinforcement	in
f_c'	Specified compressive strength of concrete	lb
V_c	Nominal shear strength provided by concrete	lb
V_n	Nominal shear strength	lb
V_s	Nominal shear strength provided by shear reinforcement	lb
V_u	Factored shear force at section	lb
Φ	Strength reduction factor	-

Figure D.6: Equations for checking shear perpendicular to wall.

Explanations:

The web width determination varies between the different configurations formed by different ICFs. For flat walls it is straight forward since the cross-section is constant; it is the distance between vertical rebar. For a grid ICF system, the most common method, and quite conservative, is to ignore the posts that do not have any steel reinforcement. In other words, use just the cross-sectional area in the posts with reinforcement. Further simplification is done by using an equivalent rectangle for posts with circular or elliptical cross-sections. If additional shear capacity is needed, increasing the concrete compressive strength or thickness of the wall is recommended. Luckily, shear forces rarely result in the need for making increases. Also, V_s is to be set equal to 0 if no shear reinforcement is provided.

$\Phi V_n \geq V_u$

$V_n = V_c + V_s$

$V_c = 2\sqrt{f_c'}hd$

$d = 0.8l_w$

Variables	Description	Unit
d	As in equation	in
f_c'	Specified compressive strength of concrete	lb
h	Overall thickness of wall	in
l_w	Length of wall	in
V_c	Nominal shear strength provided by concrete	lb
V_n	Nominal shear strength	lb
V_s	Nominal shear strength provided by shear reinforcement	lb
V_u	Factored shear force at section	lb
Φ	Strength reduction factor	-

Figure D.7: Equations for checking shear parallel to wall.

Explanations:

Shear is resisted by concrete and steel. Fortunately, shear levels typically are small enough that the capacity from the concrete is enough. An equivalent rectangular cross-section is usually used in placed of the existing circular or elliptical cross-section to make calculation simpler. Calculations are normally done on a 12 in strip of wall, and all posts, reinforced or not, are used in this calculation.

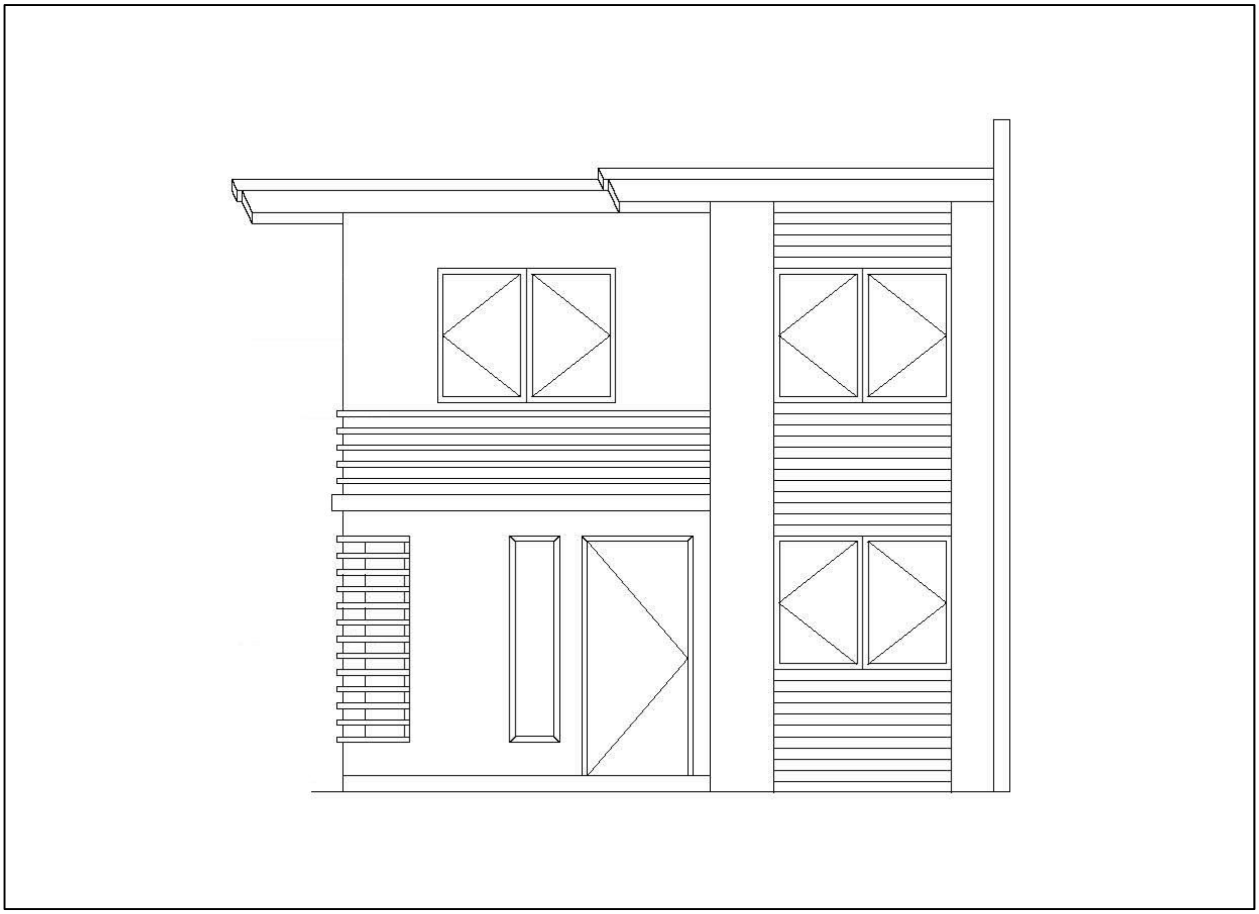

Figure D.8: Front elevation of model building.

The various loads were calculated using this model. It is two a two-story residential building with a slightly sloped, flat roof. The entire wall on the right is a firewall with a height that exceeds that of the roof. Design was created by a Filipino architect and it reflects the styles and methods of the Philippines.

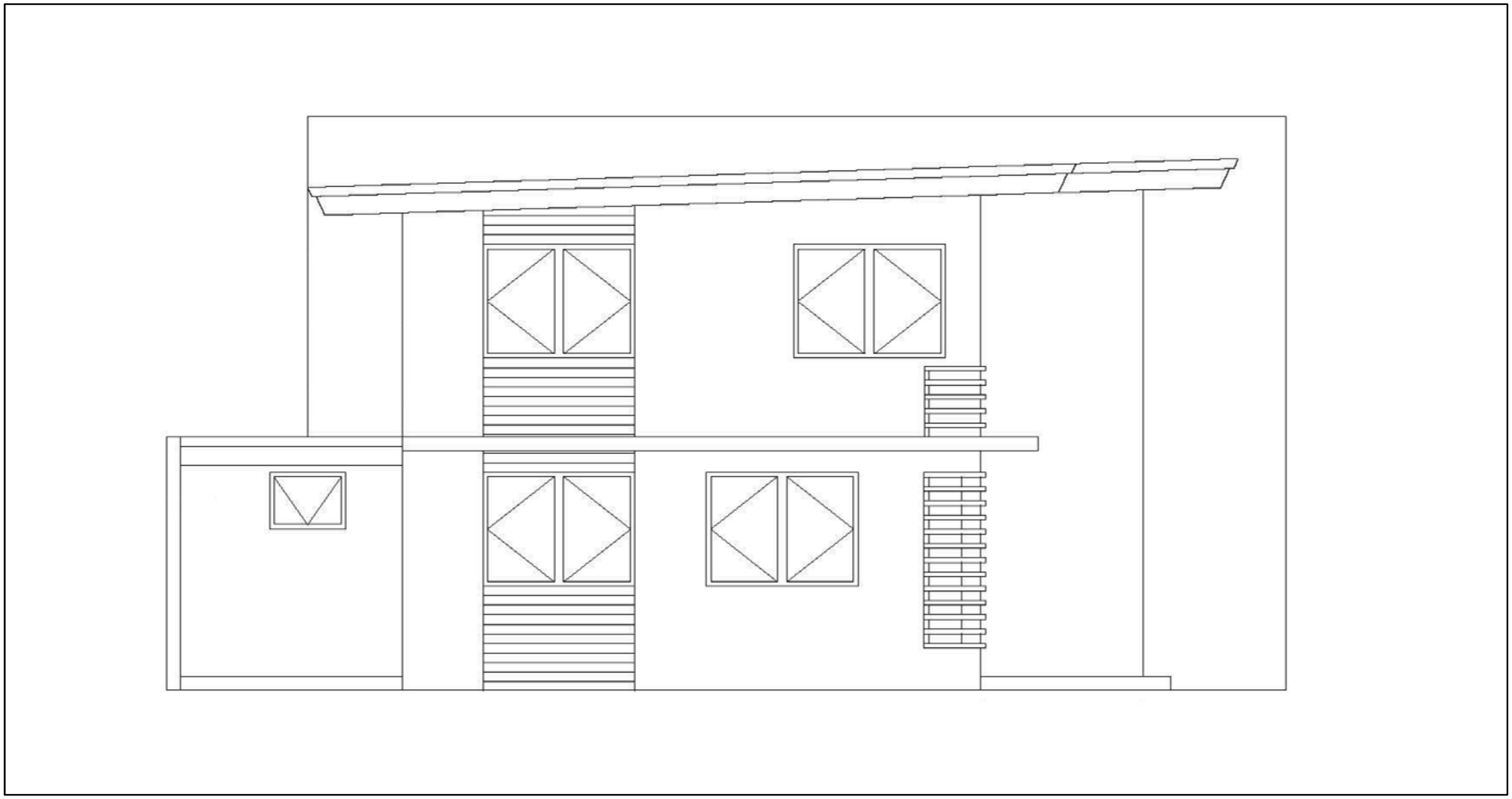

Figure D.9: Left elevation of model building.

The bathroom is visible to the far left, and it is apparent that the second level floor plan is smaller in area than the first. The slightly sloping flat roof meets the firewall that is partially visible in the background.

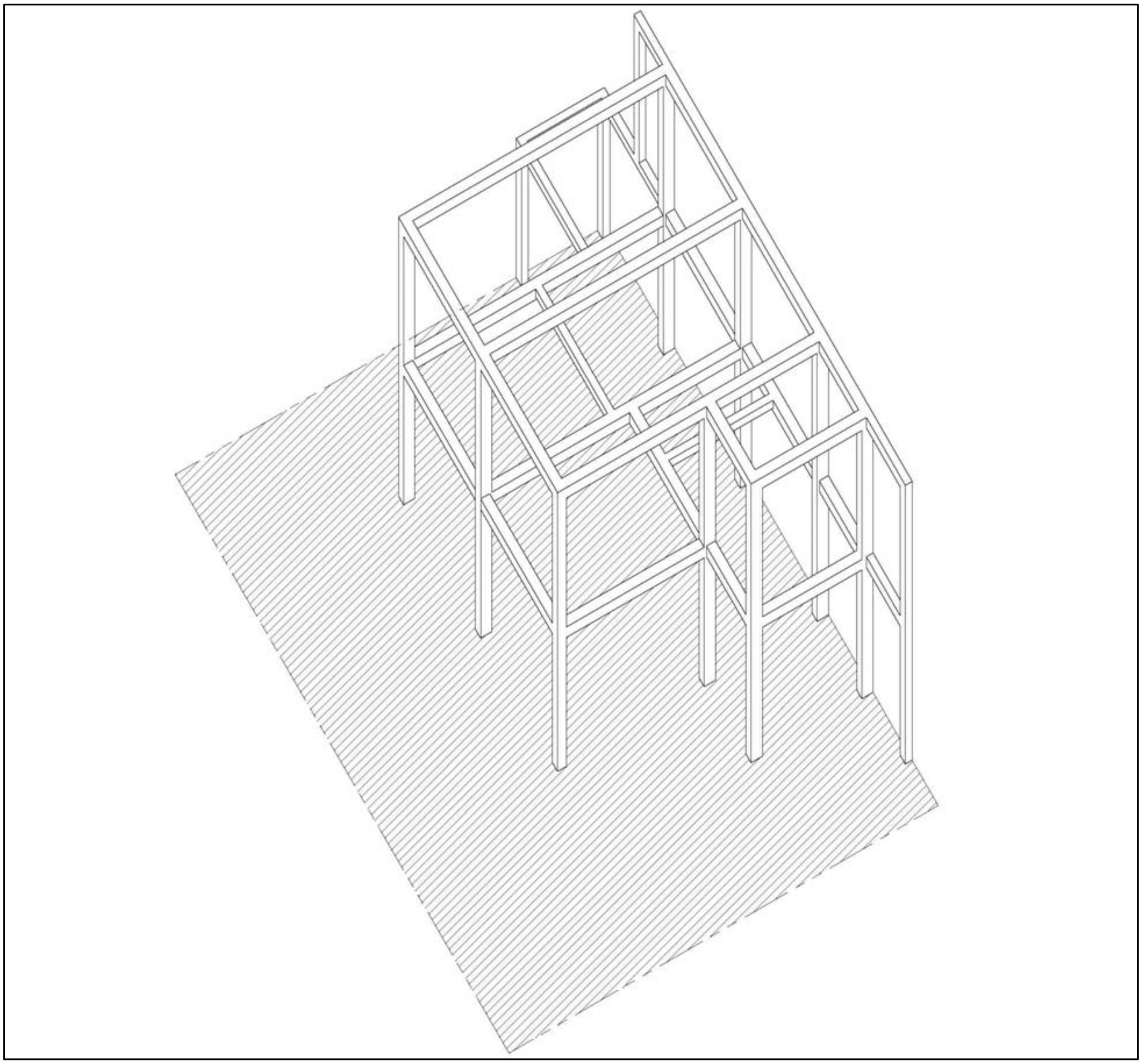

Figure D.10: Structural frame isometric view of model building.

Concrete post-and-beam skeleton and masonry infill is typical of construction methods in the Philippines. The refined masonry system was designed to be loadbearing in order to bypass the need for structural columns. The columns in this figure rest on pad footings while the infill walls rest on continuous footings. The refined masonry system will only require continuous footings. Beams may still be used with the refined masonry system if needed.

Figure D.11: Additional images of masonry prism preparation and testing. (a) blocks after being cut in half for prism assembly; (b) assembled prisms ready to received grout; (c) grout prism sample to ensure grout has reached specified strength; (d) close-up of visible movement of part of the prism after failure.

The horizontal channels of the prisms were plugged using foam panels and duct tape. The plastic bags were pre-positioned so that they could enclose the entire prisms once completed. A cardboard mold was used to make 102 mm x 203 mm (4"x8") grout samples. The samples were cured in the same location as the prisms, and were used to confirm that the specified strength of the grout in the prisms was achieved.

APPENDIX E

PRODUCTIVITY STUDY

This appendix provides additional information concerning the productivity study conducted in Module 3. There is a diagram of the layout used and a short explanation. There are also additional pictures that were taken at different times during the study.

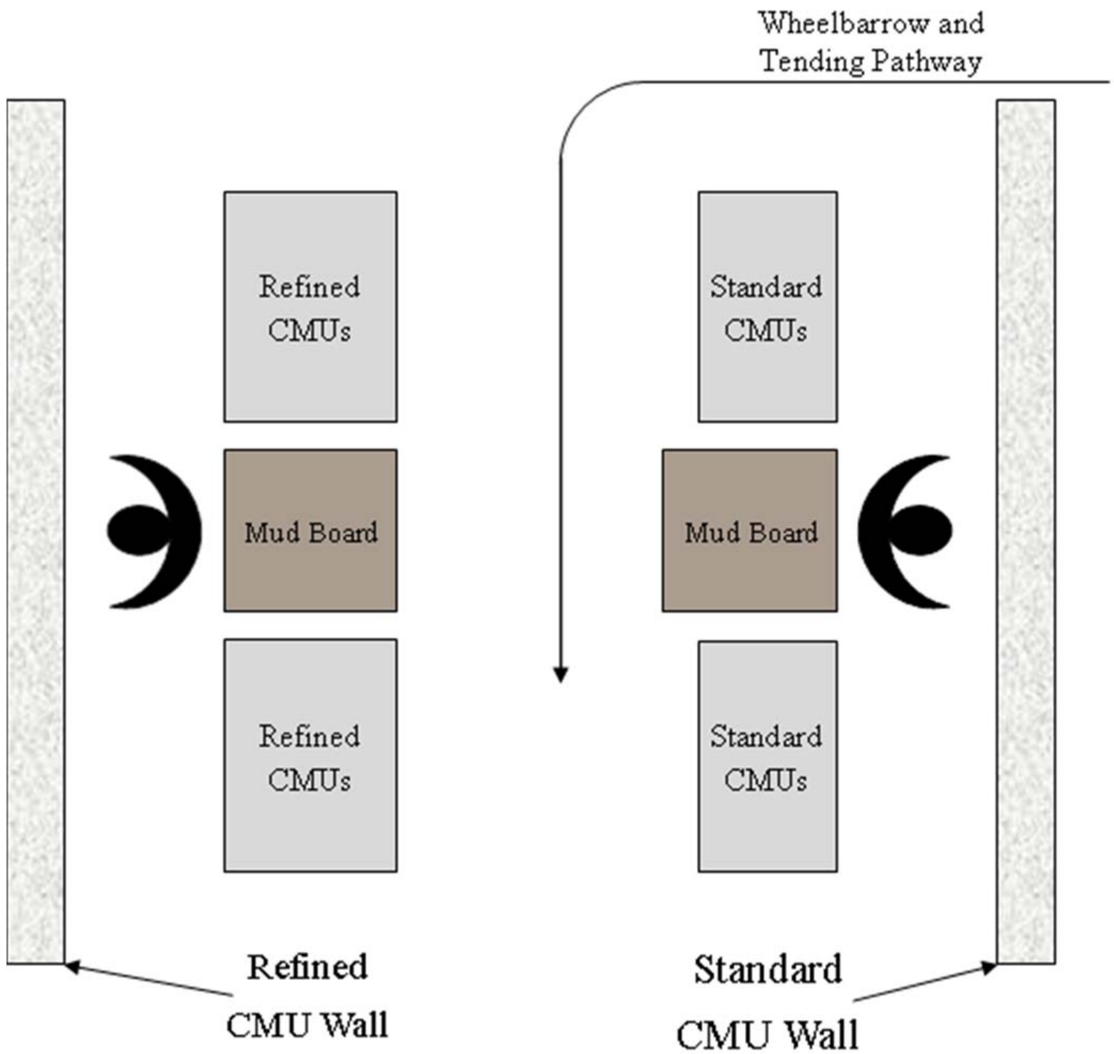

Figure E.1: Productivity study layout model.

The productivity study was setup much like an actual jobsite would be arranged. There were aisles for the masons, and another one to bring more mortar to the mud boards via a wheelbarrow. The person tending would also utilize the central aisle.


Figure E.2: Productivity study layout.

This is the actual layout of the blocks and material except for the mud boards which are not present in the picture. The blocks in the foreground are the refined masonry blocks while the traditional masonry blocks are in the background.

Figure E.3: Mortar staging area.

Both the regular mortar and thin-bed mortar were mixed in the staging area. The orange cart is filled with masonry sand. The electric powered mixer on the left was used to mix the regular mortar while the drill mixer (just visible in the background) was used to mix the thin-bed mortar in a 5-gallon bucket.

Figure E.4: Central aisle of productivity study layout.

The wheelbarrow used for replenishing the mud boards currently positioned in the central aisle. On the right are the refined masonry units and on the left are the traditional masonry units.

Figure E.5: Constructing with refined masonry system.

The second leader block of the last course is being tapped level. Notice that four courses is needed to reach 1.2 m (approx. 4 ft) in height. The first and third courses are oriented with the horizontal channels up while the second and fourth courses are oriented with the horizontal channels down. This creates a 100 mm (approx. 4 in) channel, 600 mm (23.62 in) on center in the vertical direction. The end blocks on the second and fourth courses are half blocks produced from sawing stretcher blocks in half, hence the smooth appearance.


Figure E.6: Constructing with traditional masonry units.

Six courses were required to reach the 1.2 m (4 ft) height specified. Normal 9.5 mm (3/8 in) joints struck flush with the wall were used comprehensively on all walls for consistency. To complete the wall, 42 stretchers and 6 half blocks (jamb blocks) were used.

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