ABSTRACT

RHANI, RAMI AWNI. An Investigation of Critical Success Factors for Robotic Masonry. (Under the direction of Dr. Leonhard E. Bernold.)

Automating masonry wall construction faces several challenging mechanical control issues reaching from the dehacking and delivery of bricks, the application of mortar, to actual placement of bricks to create straight and even elements. The first objective of this research work was to study the complex operations done by hand in order to understand what is necessary to meet standards, what affects the brick-mortar interfaces, and what leads to required bond strengths.

The Critical Success Factor method was used to identify the most relevant problem areas that needed to be addressed and solved. Using this approach, the following six factors were defined: 1) design automation, 2) dehacking, 3) brick quality control, 4) brick placement quality, 5) mortar application quality, and 6) brick-mortar bond strength. Consequently, each factor was studied followed by the design and execution of necessary experiments. The research showed that isolating these factors was useful in identifying a focused list of topics that affect them.

The issue of brick-mortar interaction and its importance in achieving bond strength was especially important in that the skill of a mason had to be replicated with a mechanical approach. Experimental tests showed that the bond strength was affected by the profile of the mortar joint applied and the depth of mortar penetration in the brick holes. The final step of this study included a comparison between robotically and manually placed bricks. Utilizing a standardized Bond Wrench Test apparatus, it was found that the consistency of bond strength values of ten prisms placed robotically matched that of ten prisms laid manually.
Mortar application proved to be the most difficult problem. Consistently smooth pulsation-less mortar joints were not achieved even after many redesigns of the progressive cavity pump setup. Conceptual pressure models demonstrated that the resultant pressure at the end of the pumping apparatus, after friction losses and pressure drops, was critical in producing acceptable mortar joints. A modified pump model was recommended for future research. The experiments highlighted the factors affecting mortar pumping using this kind of pumping mechanism, such factors included: 1) the speed of the pump motor drive, 2) the size of the rotor-stator opening, and 3) the length of the rotor-stator assembly. Measuring the pressure inside the pump lay outside the scope of this research but should be the focal point in future work.

Overall, the work showed difficulty in achieving established quality standards in masonry construction using robotics. On the other hand, the project solved some unique problems by integrating electronics, computing, and mechanical concepts in innovating ways. For example, the problem of dehacking work led to the design of the pneumatic adaptive brick gripper. For the design of the brick quality control work cell, data collected from a photoelectric sensor was manipulated in order to substitute the human sensory skill of detecting different colors. For applying mortar bed joints, a nozzle plate was redesigned, with the same cross-section as that of a manually placed mortar joint, in order to pump mortar where it is most effective.
AN INVESTIGATION OF CRITICAL SUCCESS FACTORS
FOR ROBOTIC MASONRY

By

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APPROVED BY:

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Chair of Advisory Committee
DEDICATION

To my Father and Mother
BIOGRAPHY

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1.0 INTRODUCTION

This chapter discusses the reasons for automating brick masonry followed by a background on masonry, mortar technology, and the concept of Critical Success Factors. The problem statement is also described, in addition to the research objectives, and the methodology adopted to guide this study.

1.1 Reasons for Automating Brick Masonry

Masonry work is a difficult, but in many respects, a perfect process to be robotized. Although it cannot be considered overly dangerous, it is a good candidate for robotization because it is tedious, unpleasant, physically demanding, and is critical to the timely completion of building projects.

1.1.1 Long-Range Driving Forces

In a publication entitled Projects and Competition of the Future, the Construction 2000 Task Force of the Construction Industry Institute (CII) outlined six fundamental driving forces that may shape engineering and construction projects in the coming century (CII 1992). One driving force in particular, rapidly increasing computing capabilities, will provide a means to economically meet future demands for greater quality and expected reductions in the work force through automation. If U.S. contractors are to remain competitive, it is expected that they must embrace automation and robotics for accomplishing both on-site and off-site tasks. In defining the focus for a national research agenda into the next century at the National Civil Engineering Research Needs Forum organized by the Civil Engineering Research Foundation (CERF), one of the major topics was the need for advancement of civil engineering through innovation in emerging technologies such as construction automation (Kramer 1991).

In another publication entitled Vision 2020, the Construction Industry Institute’s (CII) Strategic Planning Committee listed numerous items to guide its long-range
planning process in the 21st century and to stimulate breakthrough thinking in the industry (CII 1999). Some of those concepts were:

1. Innovation will be a driver for global competitiveness.
2. Automation will alter project approaches.
3. Use of information technology will be a significant competitive advantage.
4. Control technologies will permit on-site control of automated equipment.
5. Prefabrication will increasingly be used to minimize site work, and new systems will be developed to combat field delays caused by inclement weather, and to reduce use of scaffolding and other false work.
6. Technology advances will be made to improve productivity.
7. Craft labor availability will become more critical, and minimizing craft labor content of a project will drive design. Labor will be greatly reduced by automation and much more work will be done by far fewer people.

1.1.2 Skilled Labor Shortage

Another area of focus noted by the Construction 2000 Task Force was the need for the industry to reverse the trend of a diminishing work force. One of several approaches cited was placing an emphasis on safety as a top job site priority, even above quality, cost, and schedule (CII 1992).

The Atlanta Business Chronicle (Shelar 1998) reported results from a survey conducted by the National Center for Construction Education and Research (NCCER) which found that 92 percent of respondents nationally reported shortages of skilled labor; 85 percent said their work force is not as skilled as it needs to be; and more than 240,000 jobs went unfilled in 1996. The root of this shortage was attributed to “a complex array of causes that stem back twenty years into open shop organization and reach forward to the social and economic problems of today including technological and educational change. The resultant combination of these factors now has created a record low number of master crafts workers employed in the industry and a stigmatized profession that is not being freshly or properly introduced to the high school-aged children in vocational...
education programs” (Chini et al. 1999). The same author offers a solution that encompasses repairing the construction vocational technical education system and the overall image of construction in the public’s eye. The Wichita Business Journal (Roths 1998) reported that the wage level had always been an issue in construction, and that firms lacked the ability to provide comprehensive benefit packages. This caused many workers to leave the construction field to pursue employment with larger manufacturing companies who provide strong benefit packages for their workers. The U.S. construction industry’s lack of skilled personnel has become so severe that construction firms are using temporary labor agencies to fill the gaps when possible (ENR 2000). This labor shortage is still evident today and is a major concern for owners and construction firms (ENR 2005).

1.1.3 Dangerous Task

Bernold and Guler (1993) showed that frequently lifting and carrying bricks and blocks, leads to permanent back injuries. Masonry contributed to approximately 6.5% of all construction related back injuries by work or trade in 1990 in Ontario, Canada; thereby exceeding some major construction trades such as concrete work. Occupational back injuries are on the rise, resulting not only in pain and suffering but also in significant costs to the economy (Bernold, et al. 2001).

In its Construction Automation Initiative (Stone 1996), the National Institute of Standards and Technology (NIST) stated that “there are many visions that people have had over the years concerning how we might get to that future where the construction process is automated. Certainly, there is an impetus to eliminate dangerous tasks in an arguably risky industry. This is so well known that the Japanese have a saying that captures the essence of the construction workplace: "Kitanai, Kiten, Kitsui" (Dirty, Dangerous, and Difficult). This has secondary ramifications in which the above perception leads to a reduced appeal to the workforce to pursue this type of work, which thereby exacerbates skilled laborer shortages and reduced productivity. What we seek,
ultimately, are ways in which we can automate various construction processes that are presently manually intensive and dangerous”.

1.1.4 Poor Image

According to The 2002 Jobs Rated Almanac (Krantz 2002), the “construction laborer” ranked as the 7th worst job in the U.S. (after lumberjack, commercial fisherman, cowboy, ironworker, seaman, and taxi driver); #1 was biologist. The criteria included environment, income, employment outlook, physical demands, security, and stress. Each occupation was ranked using data from sources including the U.S. Bureau of Labor Statistics, the U.S. Census Bureau, as well as studies conducted by a wide range of trade associations and industry groups. In addition, Rosenthal (1990) stated that “the term “construction worker”, embodied as the unskilled manual laborer, has negative connotations for young people. To youngsters, “construction workers” are ditch diggers they see calling obscenities to passers-by, and loafing on the job. Most commonly associated with dirt, sweat, and a gruff demeanor, the construction worker lacks prestige, class, and respectability.” Moreover, the U.S. construction worker is five times more likely to be killed on the job than other American workers (MacCollum 1995).

1.2 Background on Brick Masonry

A brick is a masonry unit usually made of clay or shale, formed into a rectangular prism while plastic, and burned or fired in a kiln. Brick may also be composed of other materials, such as concrete brick and calcium-silicate brick. Mortar is a plastic mixture of cementitious materials, fine aggregate, and water generally made up of portland cement, lime, sand, and water. Consequently, masonry is the type of construction made up of masonry units laid up with mortar or grout or another accepted method of jointing (BIA 1989).

The fabrication of brick is a complex process that contains many different tasks. First, the raw materials are mined or quarried out of the ground with heavy equipment. The quarrying process is called winning. A wide variety of clays that are suitable for
brickmaking are available. Generally, local clays are used. Clay is created by the breakup and weathering of rocks over millions of years, and consists mainly of silica and alumina. Metallic oxides in the clay create different colors in the fired brick. Shale, which is also used in brick fabrication, is a hard compressed clay. Second, the raw materials must be broken up and ground before it can be used. In the third step of this process, water is added, allowing the mixture to be shaped into brick. The shaped mixture is then fired in a kiln. In the final step, the bricks are formed and cut into rectangular cored units with wire, before a desired texture is achieved in the glazing workstation.

Production of brick is highly automated. For example, the Triangle Brick Company plant in Apex, NC, utilizes several automated material handling systems, and fully computer-controlled conveyors, brick stackers, and a 61 m (200 ft) long kiln with integrated sensory feedback to produce brick cubes of 530 pieces each from extruded clay.

Fig. 1-1 presents a schematic showing some basic terminology for brick masonry. A brick has two faces (joints), a bed joint and a head joint; the same applies to mortar. A wythe is a panel in the wall. A masonry wall can consist of a single or a double wythe.
Masonry patterns or bonds used in walls are laid out to create a strong masonry element. The basic premise of masonry bonds, referred to as "breaking bond" (BIA 1988), is that the masonry head joint should not line up with head joints on the course above or below. This is true of all bonds except the stack bond, which is mainly a decorative bond and usually carries little structural load. Fig. 1-2 displays the most common masonry bonds in use today.

![Masonry bonds](image)

**Fig. 1-2 Common Masonry Bond Types**

Some basic types of masonry bonds or patterns shown in Fig. 1-2 are the Running bond which is the most common masonry bond. In some codes, unless otherwise specified, a standard running bond is required when laying a wall. The Common bond is sometimes called the American Bond. Several courses of running bond are followed by a course of headers. The Stack bond is not strong since head joints line up one over the other. A mainly decorative type, it can, however, be load bearing. The Flemish bond is made up of alternating stretcher and header brick in each
course. And the English bond essentially uses alternate courses of stretchers and headers where headers are centered over stretchers.

Masonry construction requires skill and experience. This is especially evident in its two basic tasks: mortar application and brick placement. Mortar application requires the mason to skillfully execute a series of seven steps (BIA 1988):

1. Testing of mortar quality (e.g., slump).
2. Cupping the mortar, that is, placing the mortar on a wooden board.
3. Loading the trowel.
4. Throwing, or laying, the mortar on the masonry course.
5. Furrowing, or spreading, the mortar bed.
6. Buttering the brick, that is, placing mortar on the brick head joint.
7. Cutting off mortar: When a brick is laid in the mortar bed, some mortar will project out over the edge beyond the face of the brick. This extruded and excess mortar is cut off with the trowel.

Brick placement requires the mason to perform the following three steps (BIA 1988):

1. Holding the brick: Every brick should be held with the thumb and fingers well up from the mortar bed.
2. Laying to the line: It is important that the thumb, fingers, or brick not hit the mason's line when laying the brick.
3. Laying the brick: Bricks should be set or pushed downward into the mortar bed and shoved against the end of the previously laid brick.

The traditional method for building masonry walls is on-site by bricklayers and their helpers. An alternative method is panelization or prefabrication of brick panels in a plant environment to be erected on site with the help of cranes. At present, several companies fabricate brick masonry veneer panels in an in-plant environment. Three of those companies are L. C. Pardue Inc. Masonry Panels of Tualatin, Oregon, Vet-O-Vitz Masonry Systems, Inc. of Brunswick, Ohio, and Keller AG of Switzerland.
There are several advantages of prefabrication over traditional building techniques is simple. On time-critical construction, prefabrication of a building can reduce the construction time dramatically. Panels are constructed in-plant under controlled environment conditions unaffected by the weather. This allows the finished product to be ready for installation when needed. For example, the Seattle First project, a 10-story brick structure in Vancouver, Washington, built by L. C. Pardue Inc., was erected in just 21 working days with the window installation following closely behind (Literature from L. C Pardue Inc. Masonry Panels). Prefabrication also reduces the jobsite congestion on those sites where space is a problem. Masonry panels are often more price competitive than other systems including granite, glass, aluminum, tile, and most architectural pre-cast concrete.

1.3 Background on Mortar Technology

Having a mortar mixture providing acceptable results is critical to robotic masonry since mortar plays a primary role in bond strength of masonry units, and is critical for proper brick placement. The following discussion will address the effects of different mortar constituents on mortar performance.

1.3.1 Effects of Portland Cement on Bonding

The American Concrete Institute (ACI 1985) defines portland cement as “a hydraulic cement produced by pulverizing clinker consisting essentially of hydraulic calcium silicates, and usually containing one or more of the forms of calcium sulfate as an interground addition.” Portland cement by itself, without water, does not bind sand and gravel, it acquires the adhesive property only when mixed with water. This is because the chemical reaction of cement and water, commonly referred to as the hydration of cement, yields products that posses setting and hardening characteristics (Mehta 1986). In other words, the cement itself is not a cementing material; it is the hydration products that have the cementing action.
1.3.2 Effects of Lime on Water Retentivity

ACI (1985) defines lime as “specifically, calcium oxide (CaO)...a general term for the various chemical and physical forms of quicklime, hydrated lime, and hydraulic hydrated lime.” Because it increases plasticity and workability, lime is considered a plasticizer. The greater the absorption of the brick, the greater the use and need for lime. Since lime contributes to plasticity, addition of lime in the mortar mixture allows the addition of more sand to the mixture. This mixture is more economic since sand is only 1/5 to 1/6 as costly as lime and cement combined (Boynton 1980).

1.3.3 Effects of Fly Ash

ACI (1985) defines fly ash as “the finely divided residue resulting from the combustion of ground or powdered coal which is transported from the firebox through the boiler by flue gases; known in UK as Pulverized fuel ash (pfa).” Mixture workability is governed by such factors as the volume of paste, the water-cement ratio, and the proportion, grading, and shape of the aggregates. When fly ash is added, there will normally be an increase in the paste volume. Fly ash particles often contribute to workability of mortar by reducing the friction at the aggregate paste interface (ACI 1985). The rate of slump loss is not affected by the addition of fly ash except to the extent that initial setting time is slightly increased. Fly ash increases the cohesion and plasticity of a mortar mixture due to an increased fines content. As the workability improves, segregation is greatly reduced (Lane 1983).

Fly ash generally slows the setting of a mixture, although both initial and final setting times remain within specific limits. Retardation may be affected by the proportion, fineness, and chemical composition of the ash. Pastes containing fly ash generally result in porosity of about 0.35 in 1 day and about 0.24 in 180 days (Helmuth 1987).
1.3.4 Effects of Admixtures on Workability and Setting Time

ACI (1985) defines an admixture as “a material other than water, aggregates, and hydraulic cement, used as an ingredient of concrete or mortar, and added to the concrete immediately before or during its mixing.” A detailed understanding of flow behavior is required to study the effects of the organic and inorganic admixtures used as plasticizers and stabilizers that change the workability of mortar and concrete (Vom Berg 1979).

The use of admixtures, according to British Standards BS-5075, can be readily divided into two areas: 1) admixtures that facilitate the pumping of the mixture, such as increased workability and lower water retention, and 2) admixtures that are able to produce specific requirements, such as durability of a mortar mixture.

Although there are many types of admixtures available (Cooke 1990), the three main types that are widely used are: 1) water-reducing admixtures (or plasticizers) that either reduce the cement requirement for a given strength or increase the workability which is very important for pumping, 2) water-thickening admixtures that increase the viscosity of the system which in turn has the effect of reducing pressure bleeding by making the mixture more cohesive, 3) air-entraining admixtures for exposed concrete in bridges, roads, and airfields in addition to increasing the durability and permeability of mixtures. Adding an air-entraining admixture creates very small air bubbles throughout the mixture (Helmuth 1987).

1.3.5 Mortar as a Non-Newtonian Fluid

Fluids that behave according to Newton’s law of viscosity are called Newtonian fluids. Fluids that do not, such as mortar, are termed Non-Newtonian fluids. Fig. 1-3 shows a fluid, either a gas or a liquid, contained between two large parallel plates of Area A, which are everywhere separated by a very small distance Y. The system is initially at rest, but at time $t = 0$, the lower plate is set in motion in the x-direction at a constant velocity, $V$. As time proceeds, the fluid gains momentum, and finally the steady-state
velocity profile is established. When the final state of steady motion has been attained, a constant force $F$ is required to maintain the motion of the lower plate.

This force may be expressed as shown in Equation 1.1:

$$\frac{F}{A} = \mu \frac{V}{Y}$$

where:

- $F = \text{force required to maintain motion of lower plate}$
- $A = \text{area of plates}$
- $V = \text{velocity of lower plate}$
- $Y = \text{distance between plates}$
- $\mu = \text{fluid viscosity}$

Fig. 1-3 Steady-State Velocity Profile for Newtonian Fluids
(Source: Bird et al. 1960)
The force per unit area is proportional to the velocity decrease in the distance \( Y \); the constant of proportionality \( \mu \) is called the viscosity of the fluid (Bird et al. 1960). The shear stress exerted in the \( x \)-direction on a fluid surface of constant \( y \) by the fluid is designated as \( \tau_{yx} \), and the \( x \)-component of the fluid velocity vector is designated as \( v_x \). In terms of these symbols, Equation 1.1 may be rewritten as Equation 1.2:

\[
\tau_{yx} = -\mu \frac{dv_x}{dy}
\]  

(1.2)

This states that shear force per unit area is proportional to the negative of the local velocity gradient. This is known as Newton’s law of viscosity. Fluids that do not obey this simple law, including pastes and slurries such as mortar, are termed Non-Newtonian fluids.

Fig. 1–4 shows a plot of shear stress versus shear rate for different fluid types. Newtonian fluids have a straight line or constant viscosity starting at the zero point. All the other curves represent Non-Newtonian fluids. Bingham plastics are those fluids where a finite shear stress is needed to initiate flow. Such fluids are drilling muds, toothpaste, and paper pulp. The majority of Non-Newtonian fluids are considered pseudoplastic like mortar, paint, grease, and detergent slurries. Dilatant fluids, such as PVC pastes, are far less common and show an increasing viscosity with increasing shear rate.
Non-Newtonian fluids are encountered in a multitude of process operations in almost every major industry. Examples of some of these industries include those engaged in the manufacture of rubber, plastics, synthetic fibers, petroleum, paper pulp, soap and detergents, cosmetics, pharmaceuticals, cement, foods, biological fluids, fermentation products, metals refining, printing, and solid rocket propellants (Cheremisinoff 1982). Non-Newtonian fluids often pose difficult handling problems. They make the principles of fluid mechanics more complex since the resistance to flow and viscosity must be defined through a physical model reflecting process conditions. Pumping mortar also proved to be a difficult issue in this dissertation as discussed in Chapter 8.

1.3.6 Mechanics of Mortar Bonding

The issue of creating efficient bond between bricks using mortar has been studied in great detail. Mehrotra (1986) found that the characteristics affecting bond strength are: 1) Initial rate of absorption of water for bricks, 2) brick porosity, 3) brick texture, 4) type of mortar, 5) type of sand, 6) mixture proportions, 7) mortar water content, 8) mortar workability, 9) mortar viscosity, and, 10) use of clay or fly ash in the mortar mixture.
According to Robinson (1986), the brick to mortar bond is a mechanical bond produced by the intrusion of a cementitious paste into the pores of the brick. Therefore, it is vital that the paste flow into the pores. The Initial Rate of Absorption (IRA) of the brick is important because high IRA bricks may draw water from the mortar, preventing the cementitious paste from flowing into brick pores. This can be counteracted by increasing the water content of the mortar or by aggressive placement methods. Low IRA bricks tend not to absorb water and therefore do not obtain sufficient intrusion. Robinson (1986) also examined the effect of different placement methods including pressing the brick into place, placing the brick with load, placing the brick without load, vibrating the brick into place, and tapping the brick. He found that the amount and type of load applied to the brick affects the bond strength. Pressing with force and vibrating were both found to provide a consistently higher bond strength. It was suggested that the placement procedure could mask the effects of IRA and water content of the mortar. For general use, a medium IRA brick was recommended.

1.3.7 Mortar Types

Mortar type also plays a role in bond strength (Mehrotra 1986). Four different types of mortar have been defined by the Brick Institute of America (BIA). They are presented in Table 1-1.

Table 1-1 Mortar Proportions by Volume
(Source: BIA 1988)

<table>
<thead>
<tr>
<th>MORTAR TYPE</th>
<th>PORTLAND CEMENT</th>
<th>HYDRATED LIME</th>
<th>SAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>1</td>
<td>⅛</td>
<td>3</td>
</tr>
<tr>
<td>S</td>
<td>1</td>
<td>½</td>
<td>4 ½</td>
</tr>
<tr>
<td>N</td>
<td>1</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>O</td>
<td>1</td>
<td>2</td>
<td>9</td>
</tr>
</tbody>
</table>
The four types of mortar depend on the ratio of Portland Cement : Lime : Sand by volume. The letters identifying the types are from the words “MaSoN wOrK” using every other letter. Type “M” mortar is a high strength mortar, having nearly four times the compressive strength of type “N” mortar. Robinson (1986) concluded that the relative bond strengths of these mortar types do not, however, follow a similar ratio. Type “M,” while having a greater potential for bond, is less workable than type “N,” thus decreasing its intrusion into the brick, and providing a ratio of relative strengths of one to one.

Table 1-2 distinguishes between the different types of mortar according to their building segment or location.

Table 1-2 Guide for the Selection of Masonry Mortars
(Source: ASTM C270)

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>BUILDING SEGMENT</th>
<th>RECOMMENDED MORTAR TYPE</th>
<th>ALTERNATIVE MORTAR TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior (above grade)</td>
<td>Load-bearing wall</td>
<td>N</td>
<td>S or M</td>
</tr>
<tr>
<td></td>
<td>Non-load bearing wall</td>
<td>O</td>
<td>N or S</td>
</tr>
<tr>
<td></td>
<td>Parapet wall</td>
<td>N</td>
<td>S</td>
</tr>
<tr>
<td>Exterior (at or below grade)</td>
<td>Foundation wall, retaining walls, manholes, sewers, pavements, walks, and patios</td>
<td>S</td>
<td>M or N</td>
</tr>
<tr>
<td>Interior</td>
<td>Load-bearing wall</td>
<td>N</td>
<td>S or M</td>
</tr>
<tr>
<td></td>
<td>Non-bearing wall</td>
<td>O</td>
<td>N</td>
</tr>
</tbody>
</table>

As can be seen from Table 1-2, type “N” mortar is recommended for both exterior and interior load-bearing walls, while type “O” mortar is recommended for both exterior and interior non-bearing walls.
1.3.8 Test Methods

One apparatus used to measure bond strength data is the Bond Wrench Test (ASTM C1072). Fig. 1-5 is a schematic of this apparatus. It consists of a metal frame designed to support a prism. The support system is adjustable to prisms ranging in height from two to seven masonry units. The upper clamping bracket is clamped to the top masonry unit of the prism. It does not come into contact with the lower clamping bracket during the test. After the masonry prism has been placed in the support frame, the lower and upper clamping brackets hold the prism firmly in a locked position. A load is then applied at a slow and uniform rate until failure occurs. Load readings are collected using an electronic load cell (not shown) connected between the upper clamping bracket and the base of the metal frame.

![Fig. 1-5 Schematic of Bond Wrench Test Apparatus](Source: ASTM C1072)
1.4 Background on the Critical Success Factor Method

An increasingly popular approach for identifying “strategically relevant” information is through the Critical Success Factor (CSF) method.

1.4.1 Definition

Critical Success Factors can be events, conditions, circumstances, or activities. Specifically, they are “the limited number of areas in which results, if they are satisfactory, will ensure successful competitive performance of an operation” (Jenster 1987). The identification of these factors provides a vehicle for the design of an effective system of performance measurement and control.

The Critical Success Factor method is considered a top-down approach for planning (Byers and Blume 1994). CSFs are areas that should receive constant and careful attention, and should be constantly monitored. These factors are also useful in prioritizing critical concerns for a project. Sanvido, et al. (1992) define CSFs as those factors predicting success on a project. They also provide a forecasting tool to enable different parties to rapidly assess the possibility of a successful project from their viewpoint.

1.4.2 History of the CSF Method

The concept of identifying and applying CSFs to problems is not a new field of work. It started with the original concept of “success factors” put forth in management literature by Daniel (1961). In the late 1970s and early 1980s, the growth of information systems in organizations resulted in the production of significant amounts of information for analysis and decision making. John F. Rockart of MIT’s Sloan School of Management, expanding on the work of Daniel, recognized the challenge this presented to senior executives. As a result, Rockart’s team concentrated on developing an approach to help executives identify and define their information needs. His work, presented in “A Primer on Critical Success Factors,” detailed the steps necessary to collect and analyze data for the creation of a set of organizational CSFs (Bullen and Rockart 1981).
1.5 Problem Statement

In order to successfully automate masonry panel fabrication, a set of critical success factors have to be defined. This research attempt uses the Critical Success Factor method as a top-down planning process to identify strategically relevant information to help develop a successful competitive final product. Conducting these tests will show how robotics best substitutes human skills.

Determining the Critical Success Factors for robotic masonry requires analysis of the following four aspects:

1. Methods to best substitute human skills with machines: The first aspect, addressed in Chapters 5 and 6, considers the design changes that have to be made to machines to substitute human motor and sensory skills. How well will machines substitute human behavior? Can machines match human skills such as picking up objects, visual inspection, or the sense of touch?

2. Behavior of the brick-mortar interface: The second aspect, discussed in Chapter 7, examines the brick-mortar environment and the way it is controlled and modeled. When a brick is robotically placed onto a mortar bed, how does the mortar react? How does the brick react?

3. Control of mortar output for panel fabrication: The third aspect, tackled in Chapter 8, considers issue of mortar application. Can mortar be applied with different thicknesses? How is position accuracy affected during robotic brick placement?

4. Control of the brick placement operation: The fourth aspect, addressed in Chapter 9, examines the brick placement operation. Can the bond strength of a robotically placed brick prism equal or exceed that of one placed manually? Will the bond strength values be more consistent for robotic placement than for manual placement? What are the factors affecting bond strength?
1.6 Research Objectives

In order to address the questions mentioned in the problem statement scientifically, the following research objectives were defined:

1. Identify the Critical Success Factors affecting the development of a robotic masonry system.
2. Determine the relationship between placement force, mortar thickness, and brick position for robotic brick placement.
3. Develop the relationship between placement force, mortar thickness, and bond strength for the brick-mortar interface.
4. Determine the effect of robotic brick placement on prism bond strength using testing methods listed in ASTM C1072.
5. Develop an understanding of the factors affecting automated mortar application.
6. Examine the potential for designing robots that substitute human motor and sensory skills.

1.7 Research Methodology

The following six-step plan was adopted for this study:

1. Literature Review: In this phase of work, Chapter 2 presents a literature survey is presented on the subjects of brick masonry, mortar technology, the mechanics of mortar bonding, prefabrication, in addition to a review of past approaches to masonry automation. The economical aspects of automation are also highlighted in addition to design and feasibility approaches. A review of robotic control methods is also presented.

2. Use of Critical Success Factors: Chapter 3 will cover the method of Critical Success Factors as a top-down approach for planning to identify strategically relevant information to help develop a successful and competitive final product.
3. Design of Experimental Procedures: Chapters 4 through 9 will introduce the design of experimental work cells in order to investigate the proposed critical success factors.

4. Data Collection and Evaluation: Chapters 4 through 9 will also concentrate on the methods and means adopted for data collection using the designed experimental procedures, and the evaluation of the data collected.

5. Control Framework for Robotic Brick Placement: Chapter 10 will cover the development of a proposed control framework for brick panel fabrication that interacts with the environment.

6. Conclusions and Recommendations: This final phase of research, presented in Chapter 12, will present a summary and conclusions of this research based on the data evaluation phase, the potential impact they may have on the industry, and a list of recommendations for future research endeavors.


2.0 LITERATURE REVIEW

This chapter presents a literature review on total quality management tools, the uses of the Critical Success Factor method, and past approaches to masonry automation. The economical aspects of automation are examined as well as design and feasibility approaches. A review of robotic control methods is also presented.

2.1 Ishikawa’s Total Quality Management Tools

Ishikawa was a key player in the companywide quality control movement which started in Japan around 1955. It necessitated the improvement of quality for every function of a business and by all levels. Ishikawa is perhaps best known from the Ishikawa diagram, otherwise known as the cause-and-effect diagram, or fishbone diagram. Ishikawa saw this diagram as a device to assist groups in quality improvements (Bendell, et al. 1995). In particular, he championed the use of what are commonly known as the seven tools of Total Quality Management (TQM). TQM is defined by Capezio and Morehouse (1993) as "a management process and set of disciplines that are coordinated to ensure that the organization consistently meets and exceeds customer requirements. TQM engages all divisions, departments and levels of the organization. Top management organizes all of its strategy and operations around customer needs and develops a culture with high employee participation. TQM companies are focused on the systematic management of data of all processes and practices to eliminate waste and pursue continuous improvement.” Ishikawa’s seven tools of TQM are:

1. Pareto charts to prioritize action.
2. Cause-and-effect diagrams to identify causes of variation.
3. Stratification to divide data into subsets.
4. Check sheets for data collection.
5. Histograms to display variation graphically.
6. Scatter diagrams to identify relationships between two factors.
7. Shewart control charts and graphs to monitor and control variation.
Ishikawa was also a pioneer of the quality circle movement in Japan. The nature of quality circles varies between companies, although the circles typically consist of small groups of five to ten people who meet on a regular basis to discuss, investigate, measure and, analyze work-related problems. He also highlighted that management commitment, quality of staff, training, measurement, feedback and recognition for positive outcomes are vital for the success of quality improvements (Bendell, et al. 1995).

2.2 Uses of the Critical Success Factor Method

Most of the early work in the Critical Success Factor method was focused on refining the information needs of executives. As a logical outgrowth of this work, Bullen and Rockart (1981) hinted at the usefulness of the method as a component of strategic planning for information systems or technology. The CSF method has found its way into information, business systems, and technology planning methodologies that are still being used today (Caralli 2004).

The CSF method has been used in many ways outside of the information technology planning arena. In their research on the use of CSFs in federal government program management, Dobbins and Donnelly (1998) identify CSFs as being used to: 1) Identify the key concerns of senior management, 2) assist in the development of strategic plans, 3) identify key focus areas in each stage of a project life cycle and the major causes of project failure, 4) evaluate the reliability of an information system, 5) identify business threats and opportunities, and 6) measure the productivity of people.

2.3 Past Approaches to Masonry Robotics

Several efforts are underway worldwide to investigate technology to automate masonry work. They range from partially to fully automated systems. One of the earliest implementations of automation in masonry was by a German entrepreneur who developed a working bricklaying machine for the prefabrication of brick walls (Anliker 1988). The $80,000 semi-automated machine was able to build prefabricated brick walls up to 8 meters long. With the help of two men, it was able to produce approximately 30 - 35
cubic meters of wall section per day. Upon completion, these sections were either loaded onto a delivery truck or lifted directly to their final position in a building. Upgrades to this system have included the use of a computer program to generate CAD diagrams of brick walls with data such as the number of full and half bricks, type of cut on bricks, and the weight, center of gravity, and dimensions of the wall. The system is still in operation and is being sold to brick plants (Bley and Anliker 1994). Another effort was Lehtinen's outline of two masonry robots (Lehtinen et al. 1989) that utilize a special mortar. A thin seam adhesive is used that sticks to the brick after being dipped in it. Lehtinen also found that a masonry robot could be built for approximately $330,000 with an estimated payback period of six years.

Slocum and Schena (1988) produced a robotic machine called the Blockbot which dry-stacked concrete blocks instead of using the traditional mortar bond. Upon completion of the dry stacks, the wall sections would be surface-bonded using spray-applied fiberglass bonding cement on both sides. It was shown that the method was structurally adequate for up to two floors. The system never became commercially available.

Chamberlain, et al. (1991) reported several major developments in masonry robotics. They concluded the following:

1. The accuracy requirements of the robot have to be defined by strength related tolerances of the finished construction such as bow, out-of-plumb, thickness and evenness of the mortar bed, and dimensional tolerances of the units.
2. A mortar mixture can be designed which allows the conflicting requirements of pumpability, stiffness during placing, bedding and strength compatibility with the blocks to be satisfied.
3. Computer-Aided-Design (CAD) modeling can be used to produce a wall project development configuration with the aid of vision sensing.

This research was followed by Chamberlain and Gambao (2002) who described a robotic system for concrete repair preparation that can be used on masonry walls. It utilized
hydro-erosion systems for removal of concrete prior to the placement of replacement materials.

Warszawski and Navon (1991) produced a robot for interior-finishes. The robot could be adapted to several tasks, including painting, plastering, tiling, or building interior partitions, by modification of its effector and control mechanism. The robot had a reach ranging from 2 to 2.3 meters. At this configuration and reach, the robot was well suited to be used in typical residential spaces. It was concluded that the velocity of its arm joints in addition to its economic life cycle affected the productivity of the robot.

Altobelli, et al. (1993) discussed a prototype bricklayer that utilized several principles of robotics. They concluded that the automation of bricklaying in a fixed or semi-fixed production environment is possible. The performance and accuracy of the prototype system was reported to be very satisfactory.

Pritschow, et al. (1993) suggested a possible layout for a mobile robot for on-site masonry construction featuring a configurable robot control system with a task-oriented software structure. The robot was reported to be reliable, cost-efficient, and market oriented with a maximum cost of $150,000 (Pritschow et al. 1994). The successful use of this robot was reported on several different test-sites (Pritschow et al. 1998).

Andres, et al. (1994) reported the development of a conceptual design of a masonry robot called ROCCO (RObotic Assembly System for Computer Integrated CONstruction). Spath, et al. (1997a) described a PC-based masonry programming system that integrated ROCCO with a conceptual robot for interior finishes. They also extended that study to develop a robot system for the manufacturing of wall slits as a preliminary step of wiring and electrical installations in masonry construction (Spath and Andres 1997b).
Forsberg, et al. (1997) developed a robotic system capable of plastering walls and ceilings during the construction of apartment and office buildings. Tests of the system have been successfully performed at an actual construction site. Initial testing concluded that the time required for plastering the walls and ceiling in a room would be less than 50% of that required with manual work. The amount of plaster used was also greatly reduced due to more even spraying.

Heintze, et al. (1996) developed controller hydraulics for a direct drive Brick Laying Robot (BLR) for relining steel converter walls. The robot-erected walls comprised about 12,000 bricks each weighing approximately 35kg. The bricks had to be placed precisely as no mortar was used and the life of the lining was directly influenced by the planeness of the interior.

Established in 1995, the FutureHome project, an industry-led international R&D program, had an objective of developing the next generation of manufacturing and processing technologies. Its main objective was the development of an integrated construction automation (ICA) concept and associated technologies during all stages of the house-building construction process, from architect’s desk to site robots. These stages included the modular design of buildings, keeping in mind robotic construction, automatic planning and real-time replanning of the offsite prefabrication, transportation, and onsite assembly, and onsite automatic and robotic transportation, manipulation, and assembly of the buildings’ prefabricated parts (Balaguer et al. 2002).

Khoshnevis (2004) described research done in the area of contour crafting; a layered fabrication technology reported to have a great potential in automated construction of entire structures as well as subcomponents. Using this process, a single house or a colony of houses, each a different design, may be automatically constructed in a single run, including the embedment of all the conduits for electrical, plumbing and air-conditioning. Automated tiling of floors and walls may be integrated by robotically delivering and spreading the material for adhesion of tiles to floors and walls. Another
robotic arm can then pick the tiles from a stack and accurately place them over the area treated with the adhesive material.

Approaches to brick masonry robotics have included new methods either related to materials used or fabrication processes. However, studies (U.S. Congress 1987) have shown that codes and standards are central obstacles to the introduction of new technologies. The final product must conform to existing codes to avoid delays in implementation.

2.4 Feasibility of Using Automation

In order to assist construction managers in systematically evaluating whether to opt for a conventional construction process or an automated system for a given project, Hastak (1996) developed a decision support system (DSS) called AUTOCOP (AUTomation Option evaluation for COnstruction Processes). The system analyzed the tangible and intangible set of criteria involved in the decision including need-based criteria, economic criteria, technological criteria, project specific criteria, and safety or risk criteria. Although incentives exist, the reality in the marketplace hinders construction managers from investing in new technologies.

The criteria cited by Hastak (1996) are based on a study conducted by Kangari and Halpin (1989) that examined issues relating to the feasibility of using robotics in the construction industry. They distinguished between need-based feasibility, technological feasibility, and economic feasibility. The robotization of masonry was rated by the authors on a scale from 1 to 10: need-based feasibility received 6.8, technological feasibility was given a 7.2, and economic feasibility was rated as 7.3. The study recommended eight processes as viable candidates for robotization including steel fabrication, painting, and concrete placement. Masonry was not included. It must be noted that the ratings were based on an assessment by the authors in 1987 and were also based on the available technology at the time.
2.5 Economical Aspects of Automated Systems

Drees, et al. (1991) stated the following limits to profitability of automated masonry systems:

1. The product must be in line with market conditions, i.e. sellable.
2. Costs of production of the automated system must be lower than those of manual on-site bricklaying.
3. Organization and logistics must be in line with the working environment in construction firms and on construction sites.
4. The technology used should be universally applicable and adapted to building conditions.

Warszawski and Rosenfeld (1997) presented a simplified model for the economic analysis of robot employment on building sites. Four types of building robots were analyzed: 1) exterior finishing, 2) horizontal finishing, 3) interior finishing, and 4) assembly-handling. The analysis referred to the cost of robot employment versus the economic benefit of the improved productivity in the particular task performed by the robot. The model was able to project the cost of such systems per square meter of work area.

2.6 Designing for Automation

In order for automation to be fully realized in the construction industry, architects and engineers need to use more standardized designs that allow for easier automation, and designers must try to simplify projects as much as possible. They need to look for more repetitiveness and standardized components. The use of prefabrication also allows for better automation. In addition, unions must accept that automation is important to the industry’s well being. They need to rectify jurisdictional work disputes and be willing to accept new job descriptions. Unions should also fully participate in the development and implementation of new training programs (Stein et al. 2000).
Traditionally, the U.S construction industry operates differently than other engineering disciplines. It is customary for the design and construction operations to be handled by two different companies. According to Wing (1992), this is one of the main reasons for the delay of adopting robotics in the construction sector. In the manufacturing industry, the link between design and fabrication is a strength. Howe (1997) stated that the majority of automated construction research and development has been bottom-up, from the construction side rather than top-down from the technology end. In order to optimize the use of automated technology, it is important that design principles based on the technology are considered.

Slaughter (1997) stated that technologies adapted from manufacturing applications are often not robust enough to function within the construction environment. Costs of operation and maintaining advanced construction technologies in the adverse conditions of the construction site are often not accurately known. The current structure of investment and financing within the construction industry limits the application of advanced construction technologies to sufficiently profitable construction projects, which can recover costs on expensive equipment within a short time period. Given these risks and uncommon economic benefits, few private companies have been willing or able to commit the resources necessary to develop and use robotic technologies. This resistance could be diminished if the technologies can be developed and assessed relative to the perceived opportunity for acceptance in the industry, and if cost savings and productivity gains are evident.

Richard (2005) argues that in order to deliver quality architecture, the building industry should move to full industrialization. He recommends pushing the process of reproduction in front of the first four processes of industrialization (prefabrication, mechanization, automation, and robotics). Reproduction is defined as the introduction of an innovative technology capable of simplifying the multiplication of complex goods. The purpose of reproduction is to short cut repetitive operations which are the trademarks of the craftsmanship approach, like nailing and bricklaying.
2.7 Robotic Control Methods

Although the end product in masonry construction looks simple, the process and control of building quality brick walls requires significant skill and practice. In particular, the proper application of mortar and the placement of bricks can be considered an “art.” Since humans have developed skills that fit their capabilities, robots have to be adapted to attain such capabilities in order to emulate human behavior. Thus, in the exploration of ways to automate brick masonry, controlling the placement of brick units represents one of the most critical hurdles.

In a general sense, control can be defined as a cyclic sequence of observing, planning, and executing new actions. Similar to the human body, robotic devices are equipped with a wide variety of sensors for the purpose of acquiring the needed information for planning and replanning (Bernold 1993). Leigh (1985) defined a control system as "a system in which some physical quantity is controlled by regulating an input in a dynamic environment." In addition, a control system should have the ability to handle unexpected developments, insufficient initial knowledge, and a changing setting. The main characteristics of control systems are stability, accuracy, speed of response, and sensitivity. Stability is the ability to attain a certain value in a finite time after an input is applied. The deviation of the actual output from its desired value is indicated by accuracy. Speed of response measures how quickly an output attains a steady-state value after an input is applied. Sensitivity is a measure of how sensitive the system output is to changes in the value of physical components, as well as to environmental conditions.

According to Goertz (1963), three distinct states of a robot manipulator can be identified: motion in free space, contact, and exertion of a force. All three states are present during brick placement. The first state occurs when carrying the brick from a conveyor belt to the placement position, the second state occurs when the brick starts to touch the existing mortar layer, and the third state occurs while placing the brick onto the mortar layer. Generally, three basic force-and-motion dependent control structures are discussed in the literature: position control, force or compliance control, and impedance
control (Hogan 1985; Paul 1987; Goldenburg 1988). Position control is based on the assumption that resistance to the robot movement is negligible (e.g. movement in free space). The more successful industrial robots use this type of control (e.g. robot welders). Force or compliance control requires a leading edge for a force sensor to touch as a guidance for manipulator movement. Both of these control systems make it impossible to allow dynamic interaction between the robot manipulator and the environment. More specifically, if the robot is required to exert a certain amount of force on the environment (e.g. rotate a bolt to a specific torque) the first two control concepts are not sufficient. Impedance control, which also uses the relationship between position and force, provides a mechanism for dealing with these situations. “The objectives of this control can be loosely defined as: 1) exerting a desired force on the environment by the robot, and 2) generating a desired (target) relationship between the force and the relative location of the point of interaction (contact) with respect to the commanded robot location” (Goldenburg 1988).

Learning control is suitable for dynamic systems performing repetitive operations, because an adaptation algorithm can be designed to improve the controller’s performance from one trial to the next by updating the control input based on the error signals from the previous trials (Horowitz 1993). For non-repetitive tasks, traditional learning control schemes have limits. Efforts have been made to seek other intelligent learning control techniques. One technique that has gained more and more popularity is the artificial neural network (ANN). This is a composite system consisting of a larger number of nonlinear and linear activation functions called neurons. An ANN is built from many of these neurons and has several inputs and outputs. Learning is attained by back-propagating the errors between the actual control signals and the predicted ones (Albus 1975).
3.0 FRAMEWORK FOR THE DEVELOPMENT OF CRITICAL SUCCESS FACTORS

This chapter uses the Cause-Effect Diagram method to offer a listing of factors that may prove critical to the success of this effort.

3.1 Cause-Effect Diagram

Given the problem statement and objectives defined in Chapter 1, a successful robotic brick panel fabrication system would have to construct a structurally strong and aesthetically acceptable masonry panel, with minimum human intervention, that meets specifications and standards.

One method of identifying the critical success factors is by using the Cause-Effect Diagram (CED) which is one of the total quality management tools developed by Ishikawa. The tool helps identify and document the causes and sub-causes of a specific problem or effect. Ishikawa (1968) outlined the following steps in order to develop a CED:

1. Identify and clearly define the outcome or EFFECT to be analyzed.
2. Using a chart, draw the spine and create the EFFECT box.
3. Identify the main CAUSES contributing to the effect being studied. These are the labels for the major branches of the diagram that become categories under which to list the many causes related to those categories.
4. For each major branch, identify other specific factors which may be the CAUSES of the EFFECT.
5. Identify increasingly more detailed levels of causes and continue organizing them under related causes or categories.
6. Analyze the diagram and identify causes that warrant further investigation.

Given the definition of success offered earlier, a cause-effect diagram was designed according to Ishikawa’s method. The main EFFECT to monitor was defined as
“A ‘successful’ robotic masonry system.” The three causes or inputs that impact this effect were aligned according to the following sections: 1) Product Quality, 2) Enabling Technologies, and 3) System Control. Sub-causes were also linked to the main causes.

Fig. 3-1 outlines the causes affecting “a successful robotic masonry system”. The causes and their sub-causes are aligned as follows:

1. Enabling Technologies:
   a. Design Automation: The software control mechanism as caused by the system design and unit controls.
   b. Dehacking (Brick Delivery): The method of delivering the bricks from their manufacturing output state to the robotic system.

2. Product Quality:
   a. Brick Quality: The quality of the brick product as caused by the different variables in the manufacturing process. Properties that are affected include the brick thickness, color, and texture.
   b. Brick Mortar Bond Strength: The bond strength between the brick and mortar layers.

3. System Control:
   a. Brick Placement: The quality of the brick-mortar layer as caused by the mortar and brick thicknesses in addition to the quality of brick placement method.
   b. Mortar Application: The quality of the mortar layer as caused by the thickness of the mortar applied, which is affected by the mortar placement method.
3.2 Test Bed for CSF Investigation

The test bed to investigate the above CSFs is the Experimental Robotic Masonry System (ERMaS). This system resides in the Construction Automation and Robotics Laboratory (CARL) at North Carolina State University (NCSU). It was built to serve the following functions: 1) a facility to test various technologies such as mortar extrusion, brick placement, and impedance control, 2) an experimental mechanism to study the operational relationship between mortar, brick, and mechanical machinery, and 3) a vehicle to robotically build masonry walls for structural experiments such as mortar bond and wall strength. While it represents an entire assembled facility, ERMaS is comprised of partial modules that will be utilized as experimental setups for CSF investigation.

Having defined the CSFs, the following chapters will analyze these factors, including presentation of experimental work cells and tests conducted to generate experimental data. Conducting these tests will attempt to examine robotic benefits, and
to help determine the critical success factors for robotic masonry. The modules for analyzing CSFs are:

1. Design Automation: Module for the analysis of the control framework, where 3D masonry wall representations are generated with quantity takeoff sheet and brick position coordinates. This is key in the preplanning stage of automating the construction of a masonry panel.

2. Dehacking: Module for the analysis of brick delivery. This is the process of unstacking a brick cube into individual bricks, and their delivery to a brick panel fabricator without human intervention.

3. Brick Quality Control: Module for the analysis of brick quality. Specifically, the measurement of brick thickness, color, and texture. This is necessary to insure a quality brick product.

4. Brick Placement Quality: Module for the analysis of mortar thickness quality and the achievement of a horizontal level. Specifically, the position and force control of placing masonry units without human input. This provides an understanding of the brick-mortar material interactions.

5. Mortar Application Quality: Module for the analysis of mortar delivery. Specifically, pumping mortar for various brick thicknesses in a pulsation-less output. This is fundamental for bond strength development and brick positioning.

6. Brick-Mortar Bond Strength: Module for measuring and comparing robotic vs. manual bond strength. This is essential in determining the feasibility of this study and provides a quantitative analysis highlighting the ability of mechanical capabilities to replace human skills.
4.0 AN INTEGRATED SYSTEM FOR DESIGN AUTOMATION

In order to provide a dynamic interface in designing a brick panel, a 3D representation is needed. This representation provides a visual depiction of the panel, in addition to estimating the number of bricks and their positions. This is key for integrating the system at an end-user level.

Some of the most significant developments in computer-based technologies have occurred in the areas of visual display and non-procedural man-machine interaction. Highly realistic 3D color displays can be produced in real time, and the visual display can be manipulated by a variety of mechanisms (Fenves 1991). Two objectives were proposed by Fenves (1991) to set a framework whereby technological changes in civil engineering processes may be evaluated: 1) every human activity should be naturally and conveniently supported by suitable computer aids, and 2) every activity burdensome for individuals and society should be relegated to computers and computer-controlled robots. The automation of masonry design that also feeds data to planning and construction is one specific application for assisting traditional human activities.

4.1 Integrated Information System

Fig. 4-1 shows the components of an integrated information system developed as part of this research in order to provide the dynamic interface to design a brick panel. This system is composed of the AutoCAD engineering software (Release 11), the AutoLISP computer programming language which is embedded in AutoCAD, the QuickBASIC programming language, and the “dBase III Plus” database system. These were all integrated to automatically generate 3D-masonry wall drawings and quantity takeoff sheets for panels built using the running masonry bond.

The end-user, launching an embedded AutoLISP program in AutoCAD, would specify the length and height of a masonry panel. The program then uses pre-drawn full and half brick shapes in the brick diagram library to produce a CAD drawing
representation of the panel. The end-user is then prompted to select an opening in the generated CAD drawing if desired. Once this is completed, a flat text file is generated by AutoCAD that includes the coordinates of the resulting brick shapes. Thereafter, a QuickBASIC executable program extracts these coordinates from the flat text file generated by AutoCAD, and produces a delimited file that is passed on to the “dBase III Plus” database system. Once the database program is opened, the end-user is presented with a menu offering several options to produce quantity takeoff sheets for the drawn masonry panel.

Fig. 4-1 Components of the Integrated Information System

These quantity takeoff sheets provide the following information about the designed masonry panel drawing:

1. Classification of each brick (i.e., full or half).
2. Position in wall: a coordinate point (such as an edge point) for each brick (full or half) drawn. This is especially useful for future integration with a masonry robot to initiate movements to determine the position of each brick.
3. Total number of full and half bricks needed.
4. Quantity (volume) of mortar needed to build a wall with a certain area and open space.
5. A process plan for laying bricks (i.e., where to start and where to end). This is done by sorting data in the database file.

4.2 Computer-Generated Results

Fig. 4-2 presents a snapshot of the “dbase III Plus” menu and a 3D CAD drawing of a masonry panel. The menu offers the end-user the ability to view and print reports listing either the coordinates of all the bricks in the masonry panel, only the full bricks, or only the half bricks. In addition, the end-user can produce a count of either all the bricks in the panel, only the full bricks, or only the half bricks. The 3D CAD drawing shows an opening that the end-user selected to represent a window slot in the masonry wall.

![Database Menu](image1.png) ![3D CAD Drawing](image2.png)

Fig. 4-2 Database Menu and 3D CAD Masonry Wall Drawing

4.3 Summary

An integrated information system was designed for this research with the ability to produce user-designed 3D CAD drawings of masonry wall panels, in addition to quantity takeoff sheets that detail the coordinates and the total quantity of the bricks in the panel. The output of this system can then be used to direct an automated brick panel fabrication system to build masonry panels based on the user design. Design automation is a critical
success factor since it provides a robotic masonry system with initial information to be used throughout the panel fabrication process. It offers a dynamic interface at the end-user level to achieve a realistic representation of the final product.
5.0 ENABLING TECHNOLOGY FOR MASONRY DEHACKING

In order to automate the delivery of bricks to a panel fabrication unit, individual bricks have to be removed from a brick cube — the common manner in which bricks are stored and delivered after their manufacture. Dehacking is the process of unstacking the brick cube into individual bricks. Achieving this process without human intervention is needed in order to automate brick panel fabrication.

5.1 Experimental Setup

A dehacking work cell will unstack the bricks and deliver them to a panel fabrication work cell. Fig. 5-1 shows a schematic of the dehacking work cell.

![Fig. 5-1 Schematic of the Dehacking Work Cell](image)

The dehacking work cell is composed of the following hardware: 1) a brick manipulator, 2) a pneumatic brick gripper, 3) an A-Tech 30/100 force-torque (F/T) sensor which measures forces and torques in three axis, and 4) a linear robot tray. The brick manipulator is affixed to this tray in order to linearly move the system in parallel to the face of the bricks. One of the many problems that had to be solved was to find a way to pick up the brick without having two parallel sides available for gripping. The pneumatic brick gripper was specially designed and fabricated to accommodate the needs of picking
up and placing bricks. It is operated by a pneumatic air cylinder that expands and contracts conical gripper pads that provide a firm grasp. Air is supplied into this cylinder through air hoses. This represents a case where a machine had to be redesigned to substitute a human motor skill. The gripper was redesigned in order to substitute the human method of picking up a brick from a brick cube. This gripper is mounted on a force-torque sensor on the robot arm. Fig. 5-2 presents a photograph of the dehacking work cell in front of a brick cube.

![Photograph of the Dehacking Work Cell](image)

Fig. 5-2 Photograph of the Dehacking Work Cell

In order to pick up a brick with the pneumatic brick gripper, the tip of the gripper must be inserted into one of the brick holes. At first, the robot arm is *approximately* situated so that the tip of the gripper is in front of the brick hole. This is done by moving both the linear robot tray and the robot itself to that position. Thereafter, the robot attempts to locate the hole in order to begin the gripping action. Once the gripper starts its approach to the brick hole, the (F/T) sensor is activated to sense any obstacle in the gripper's path. The need for this control module comes from the fact that bricks are not evenly spaced when stacked in a brick cube and the beginning of the pathway through the
brick hole can be filled with extra chips (flashes) that are a result of the kiln firing process.

5.2 Data Collection and Evaluation

As shown in Fig. 5-1, the (F/T) sensor is situated between the robot arm and the pneumatic brick gripper. It measures three forces (Fx, Fy, and Fz) and three torques (Tx, Ty, and Tz). Forces and torques greatly affected when picking up a brick are Fz, Tx, and Ty. Fig. 5-3 illustrates torques (Tx and Ty) vs. position number for one attempt to locate a brick hole. Several experiments were conducted with comparable results.

![Fig. 5-3 Torque vs. Position Diagram for Attempt to Locate a Brick Hole](image)

The torque in any of these two directions tends to be almost equal to zero unless confronted by an obstacle. As shown in Fig. 5-3, the fluctuation of the data points around position #10 indicates the beginning of the entry in the brick hole. This adaptive control enables the robot to avoid such obstacles the next time around by turning to the opposite direction. For example, if Tx is larger than a certain value, it means that the robot has hit
an obstacle in the x-direction; therefore, the robot's next position number would be in the opposite direction from where the obstacle came from. This avoidance technique continues until the gripper is inside the hole where chips do not exist. This occurred at position #22. After that, the gripper enters into the brick hole a distance of 50 mm (2 in.) - each position number is equivalent to 1 mm (5/128 in.). The other minor fluctuations are a result of small movements from the weight of the robot. Fig. 5-4 presents Fz vs. position number for the same attempt.

![Fig. 5-4 Fz vs. Position for Brick Gripping Test](image)

Fz also tends to be equal to zero except when hitting an obstacle. At that time, Fz takes a negative value as illustrated in Fig. 5-4 (notice the direction of the z-axis in Fig. 5-1). This relationship is important since it determines the time when the pneumatic gripper should activate and pick up the brick. According to the computer program controlling the robot, this occurs when Fz = -2.6 N (-0.58 lb.) and the position number is greater than 45. The value of this force was reached after a series of trial and error experiments.
Due to the way bricks are aligned in a brick cube without having two parallel sides available for gripping, this obstacle avoidance control method of picking up bricks through the brick holes was proven the most efficient in that it required no movement of the brick itself prior to picking it up. Another method that was investigated was to pick up the brick using a clamping gripper which required extra steps to nudge the brick out of position. The results from this method were inconsistent.

5.3 Summary

Several experiments were conducted using the dehacking work cell to unstack a brick cube using a specially designed pneumatic brick gripper fitted with a force-torque sensor. Integrated with these tools, a robotic arm was able to adaptively approach and pick up a brick without human intervention. Using the readings of the force-torque sensor, the robotic arm was programmed to determine the correct approach to insert the brick gripper into the brick hole, in addition to specifying the exact point where gripping should occur. Dehacking is a critical success factor since it provides an automated solution to unstacking bricks and delivering them to a panel fabrication unit without human input.
6.0 QUALITY CONTROL OF MASONRY BRICKS

Bricks have different colors, surface textures, and thicknesses. In order to reject defective bricks to be excluded from panel fabrication, measurement of brick thickness, color, and texture is needed. Color distribution throughout any masonry structure is an important aesthetic factor. Any irregular color distribution on a masonry job could be aesthetically unacceptable and may lead to demolition. Masons are asked to distribute bricks randomly in the masonry structure. In addition, cracks and chips in a brick surface may not be acceptable. Furthermore, since thickness varies from brick to brick, the mortar thickness has to be varied in order to build a horizontally leveled brick wall. Rihani and Bernold (1994) showed a significant variance in thickness reaching a maximum of 0.6 cm (0.25 in.) for one brick cube of 528 bricks. In order to automate brick masonry, measurement of individual brick characteristics such as color, surface texture, and thickness is essential.

6.1 Experimental Setup

In order to quantify brick color, texture, and thickness, an integrated sensory work station was developed. This was composed of one photoelectric sensor and two proximity sensors as illustrated in Fig. 6-1. The manufacturer of the photoelectric sensor used (OMRON - Model E3SA) recommends its use in the detection of position, size and surface characteristics, as well as color changes. The output reading of this sensor describes such features as distance, color and surface texture. If the distance from the sensor to the brick and the brick texture are kept constant, measurement of brick color can be achieved. The two proximity sensors used (Scientific Technologies Incorporated - Model 306) are sensitive only to changes in distance (7.6 cm [3 in.] range) and not to color. The robot arm grips the brick and moves it in front of the work station while the sensors collect data.
6.2 Data Collection and Evaluation of Brick Color

Using the quality control work station, a series of experiments were conducted in order to measure brick color. Fig. 6-2 shows a representative data set that was collected from one brick. The vertical axis indicates the “Combined Bits” reading which is the output measured by a data acquisition board connected to the series of sensors used in the quality control work station. The horizontal axis represents the “Reading Step Number” signifying the number of readings taken while the brick was moved a linear distance of 6.7 cm (2 5/8 in.).

The curve labeled “PHOTOELECTRIC” represents the unmodified output from the photoelectric sensor measuring brick color and texture, while the curve labeled “PROXIMITY” represents the unmodified output from proximity sensor #1 measuring only distance to the brick. The curve “FITTED PROXIMITY” is obtained by dividing the data from the “PROXIMITY” curve by 2.8. The number 2.8 was established after conducting a sequence of tests aiming at finding a constant color curve. By subtracting
the data points of curve “FITTED PROXIMITY” from curve “PHOTOELECTRIC,” the result is a constant curve, i.e., “COLOR (ONLY),” representing the color of the brick ([color + texture] - [texture] = [color]). Several experiments were conducted with comparable results.

![Fig. 6-2 Determination of Color Sensory Data](image)

Three bricks were selected with significantly different color ranges (dark, medium, and light red clay) and measured using the method described above. The sensory output for these three bricks is presented in Fig. 6-3 with three different values for “Combined Bits”. This shows a distinction between the three bricks. The dark brick (brick #1) had the least reading value, followed by the medium colored brick (brick #2) with a medium range reading, and then the light red clay brick (brick #3) with the highest reading value.
6.3 Data Collection and Evaluation of Brick Texture

Using the quality control work station, a series of experiments were conducted in order to measure brick texture. Three bricks were selected with different texture ranges and measured using output from proximity sensor #1. The sensory output for these three bricks is presented in Fig. 6-4 with three different values for “Combined Bits”. Here also, the bricks were moved linearly a distance of 6.7 cm (2 5/8 in.). The data shows that brick #1 is exceptionally smooth; while both brick #2 and brick #3 were not. This fact was easily confirmed by visual inspection. Several experiments were conducted with comparable results.
6.4 Data Collection and Evaluation of Brick Thickness

Using the quality control work station, a series of experiments were conducted in order to measure brick thickness. Three bricks were selected with different thickness ranges and measured using output from proximity sensor #2. Here also, the bricks were moved linearly a distance of 6.7 cm (2 5/8 in.). The brick thickness was calculated by subtracting the sensor output reading (representing the distance from the sensor to the top of the brick) from the distance between the sensor and the surface of the work station where the brick was placed. The sensory output for these three bricks is presented in Fig. 6-5 with three different values for “Brick Thickness” which was converted from “Combined Bits” by calibration. Several experiments were conducted with comparable results.
A modification to this setup may include using two proximity sensors at opposite ends of the brick to measure the thickness more accurately. The data shown in Fig. 6-5 represents a surface-scan profile of the brick and must be averaged in order to produce a single brick thickness value. Future experimentation is needed to correlate these readings to a single thickness value and determine its accuracy. Although the brick color and texture data collected by the work station did correlate to visual inspections of the bricks, future experimentation is needed in order to determine the ranges for this data and how it may correlate to accuracy requirements for such a system.

6.5 Summary

Several experiments were conducted using the brick quality control work station to numerically measure brick color, texture, and thickness. Using a photoelectric sensor and two proximity sensors, several tests were conducted simultaneously to differentiate these brick properties. Brick quality control was a critical success factor since it provided the ability to discard any bricks that do not meet architectural and material quality
specifications relating to color, texture, and thickness. Based on interest from local masonry contractors, this developed work station presents a potentially promising and marketable tool to assist in detecting and measuring brick properties.
7.0 CONTROL MODULE FOR ROBOTIC BRICK PLACEMENT

7.1 Background

During manual bricklaying, a mason compensates for the different brick thicknesses by pushing and tapping each brick differently. Excess mortar either falls on the ground or is collected and returned to the mortar batch. For robotic brick placement, different thickness mortar layers will be pumped on the existing leveled brick course, depending on the thickness of the bricks being placed. A major reason for this approach is to minimize the amount of mortar wasted. Fig. 7-1 presents a schematic of an example mortar layer before and after brick placement.

As shown in Fig. 7-1, bricks with larger thicknesses are placed onto mortar layers with smaller thicknesses and vice versa. Fig. 7-1 also illustrates that an additional thickness (x) is added to each mortar layer before brick placement. The mortar in this
extra layer is squeezed out to the edge of each brick and into the brick holes as depicted in Fig. 7-2.

\[
\begin{align*}
\text{Mortar Layer} & \quad \text{Brick Hole} \\
\text{Before Placement} & \quad \text{After Placement}
\end{align*}
\]

**Fig. 7-2 Mortar Distribution Before and After Brick Placement**

Fig. 7-2 represents a cross section of a brick couplet before and after placement. Special emphasis is given to the mortar distribution in each case. A comparison of the two cases will be based on the cross-sectional area of the mortar joint. The mortar joint cross-sectional area \(a_{mj}\) before brick placement is represented in Equation 7.1:

\[
a_{mj} = w_i \times (t_d + x)
\]  

(7.1)

where: 
\(a_{mj}\) = mortar joint cross-sectional area, \((\text{in}^2)\) 
\(w_i\) = initial width of mortar layer, \((\text{in})\) 
\(t_d\) = desired thickness of mortar layer, \((\text{in})\) 
\(x\) = thickness of added mortar layer, \((\text{in})\)
The mortar joint cross-sectional area \( (a_{mj}) \) after brick placement is represented as follows in Equation 7.2:

\[ a_{mj} = (w_b \times t_d) + a_h \]  \hspace{1cm} (7.2)

where: \( a_{mj} = \) mortar joint cross-sectional area, \((\text{in}^2)\)

\( w_b = \) final width of mortar layer, \((\text{in})\)

\( t_d = \) desired thickness of mortar layer, \((\text{in})\)

\( a_h = \) cross-sectional area of mortar in the brick holes, \((\text{in}^2)\)

In order to eliminate mortar waste, the mortar volume before placement is equal to that after placement. Since the mortar joint cross-sectional area \( (a_{mj}) \) before placement must be equal to that after placement, Equation 7.1 and Equation 7.2 must be equal, or:

\[ [w_i \times (t_d + x)] = [(w_b \times t_d) + a_h] \]  \hspace{1cm} (7.3)

In Equation 7.3, \( w_i \) is constant and equals the width of the pump nozzle extruding mortar, \( w_b \) is constant for each brick, and \( t_d \) is determined according to the thickness of the brick above it. In order to determine the correct value of \( (x) \), a value for \( a_h \) is assumed at first. The corresponding \( (x) \) value is tested by placing a brick over a mortar layer of a certain thickness plus \( (x) \). The correct \( (x) \) is when the final width of the mortar layer will be equal to that of the brick (i.e., \( w_b \)).

When a brick is to be placed onto a mortar bed to a certain depth, the mortar resists the placement force exerted on the brick, and can inhibit reaching a specified brick position unless other measures are taken, such as an increase in the placement force. In order to determine the placement force to reach a given position, the force vs. position relationship for that particular operation has to be established. For real time applications such as in the automation of brick placement, a robust control model is needed. One such model is based on the concept of impedance.
One of the three basic force-and-motion dependent control structures is impedance control. It is defined as “a general approach in which the robot behaves as a mass-spring-dashpot system whose parameters (inertia-damping-stiffness) can be specified arbitrarily. The objective of impedance control is to regulate the force of interaction which may vary due to uncertainty in the location of the point of contact and the environment's structural properties” (Liu and Goldenburg 1991). A major distinction between impedance control and other approaches to manipulator control is that, in the former, the controller attempts to implement dynamic relationships between manipulator variables such as end-point position and force, rather than just control these variables alone (Hogan 1985). Using the mass-spring-dashpot model, two issues can be addressed: 1) can a brick position be determined if the placement force and the mortar mixture type are known? and 2) can the mixture viscosity be specified if the placement force and the brick position are known?

Fig. 7-3 presents the physical and the dynamic models of a developed mechanical brick placement work cell that includes a robot arm and a previously laid brick with mortar. As can be seen from the physical model (Fig. 7-3a), the developed brick placement station is composed of a flexible brick manipulator (Mitsubishi Model RM-501), an A-Tech 75/250 force-torque sensor, and a photoelectric sensor that is able to monitor the actual position of the gripper while the (F/T) sensor monitors force data. Force and position data are saved while brick (A) is lowered robotically, step by step, and pressed into mortar bed (A-B). The dynamic model of the brick placement station is illustrated in Fig. 7-3b. The robot arm constitutes the impedance, and mortar bed (A-B) the admittance.
In order to determine if it is possible to predict the position of a placed brick when only the type of mortar mixture and the brick placement force are known, the position vs. force diagram was developed. Rihani and Bernold (1994) plotted this relationship for a 17mm (43/64 in.) mortar bed and showed that a mortar mixture could actually be related to the placement force increase. In order to determine the number of tests to conduct in this research, data from that study was used to determine the predicted value of the placement force ($d$). With 95% confidence and a standard deviation ($\sigma$) of 0.50 lb, Equation 7.4 determines the value of ($d$):

$$d = \pm t(0.975, \infty)(\sigma)\sqrt{\frac{1}{n}}$$

$$= \pm (1.96)(0.50)\sqrt{\frac{1}{n}}$$

$$= \pm 0.98\sqrt{\frac{1}{n}}$$

(7.4)
Table 7-1 presents the variability of the predicted value of the placement force \((d)\) as related to the number of tests \((n)\). According to below calculations, five tests will be conducted. With 95\% confidence, the predicted value of the required placement force will be \(\pm0.44\) lb. This was selected since it was the highest number of test with a predicted value closest to the standard deviation from Rihani and Bernold (1994).

<table>
<thead>
<tr>
<th>(N)</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>10</th>
<th>15</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d) (lb.)</td>
<td>(\pm0.98)</td>
<td>(\pm0.57)</td>
<td>(\pm0.44)</td>
<td>(\pm0.37)</td>
<td>(\pm0.31)</td>
<td>(\pm0.25)</td>
<td>(\pm0.18)</td>
</tr>
</tbody>
</table>

7.2 Experimental Setup

Fig. 7-4 shows the experimental setup used. A force-torque (F/T) sensor connected to the robotic arm monitored and recorded force data. The data was acquired for every position of the robotic arm, holding the top brick, as it was lowered and pressed into an existing mortar bed. Five tests were conducted for each mortar thickness.

![Experimental Setup Image]

Fig. 7-4 Photograph of Experimental Setup used to Develop the Position vs. Force Relationship
7.3 Data Collection

Rihani and Bernold (1994) determined that, for a sampled 528 brick cube, the maximum range in brick thickness was found to equal ¼ in. Given that the required mortar thickness for facing brick is 3/8 in., the maximum range in mortar thickness applied for these experiments would be from \(3/8 \text{ in.} - (1/4 \text{ in.})/2 = 1/8 \text{ in.}\) to \(3/8 \text{ in.} + (1/4 \text{ in.})/2 = 1/2 \text{ in.}\). Extending the range \(\pm 1/8 \text{ in.}\) and separating it into 1/16 in. intervals to obtain more data points for mortar thickness values, the set of mortar thicknesses, in inches, that could be pumped is: \(1/8, 3/16, 1/4, 5/16, 3/8, 7/16, 1/2, 9/16, 5/8\).

Five sets of force-step relationships (FSR) were collected for each of these nine mortar thicknesses. In order to calculate the average slope, data from each set of curves was sampled by selecting the range of data points where the linearity was most evident, and by only including those tests where such linearity existed. A regression analysis was then used to calculate the slope of each curve. All the original collected curves are listed in Appendix 14.1. The force-step relationship for the modified 3/8 in. mortar thickness is discussed in the next section. All the other modified curves are listed in Appendix 14.2.

The mortar used for these experiments was a Type S mortar with volume proportions of fly ash : lime : sand equal to 1 : ½ : 4 ½. The mortar was mixed in several batches, and the experiments were conducted over a period of days. No mortar properties were measured or recorded.

7.4 Data Evaluation

Fig. 7-5 shows the modified FSR for the 3/8 in. mortar thickness. The y-axis represents the “Placement Force” (measured in lbf) collected by the force-torque (F/T) sensor. The x-axis represents the “Step Number” which denotes the number of steps the robot has taken. This is different from the actual robot position since a deflection in the robot arm occurs during placement due to mortar resistance. That is, the step number the robot goes to could be different than the actual robot position. Each step number is equal
to 0.1mm (1/256 in.). This is a variable programmed into the robot movement control.

Fig. 7-5 shows that only tests #1, 2, 4, and 5 were used to calculate the average slope. The data from test #3 was excluded from this calculation since they varied from the remaining four. This was probably due to a closed brick hole that prevented the mortar from entering the brick. The slopes for the four tests were computed starting from Step #30 to Step #80; representing the most linear range of the slopes. The four slopes were equal to -0.32, -0.31, -0.31, and -0.33 respectively. The average slope was equal to -0.32.

Table 7-2 presents a summary of the modified test slope values and the computed average slope for all the nine mortar thicknesses. The ascending order of average slopes, in inches, in Table 7-2 is as follows: [7/16, 5/8, 3/16, 1/2, 1/4, 5/16, 3/8, and 9/16]. The slopes of the FSRs for the 1/8 in. mortar thickness varied distinctly and were excluded from this analysis (see Appendix 14.1). This phenomenon could be explained through visual observation; the 1/8 in. mortar bed, being too thin, was falling into the bottom

![Graph showing linear range and step number with placement force values for tests #1 to #5](image.png)

Fig. 7-5 Modified FSRs for the 3/8 in. Mortar Thickness
brick holes. Also excluded were the slopes of the tests where no linear range was found. Such was the case for test #3 for the 3/8 in. mortar thickness discussed above.

For the remaining eight mortar thicknesses, no correlation or direct link could be found between the values of the mortar thickness and the average slope values. The average slope values fell into a range that were minutely incremental and could be grouped into one category. The complexity in modeling the mortar-brick interface behavior during brick placement prevents a logical explanation of these average slope values as they relate to their corresponding mortar thickness. This stems from the fact that factors affecting this behavior are hard to model and their effect unknown.

Table 7-2 Summary of FSR Slope Values

<table>
<thead>
<tr>
<th>Mortar Thickness (in.)</th>
<th>Slopes for Modified Tests</th>
<th>Average Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test #1</td>
<td>Test #2</td>
</tr>
<tr>
<td>1/8</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>3/16</td>
<td>-0.13</td>
<td>---</td>
</tr>
<tr>
<td>1/4</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>5/16</td>
<td>---</td>
<td>-0.17</td>
</tr>
<tr>
<td>3/8</td>
<td>-0.32</td>
<td>-0.31</td>
</tr>
<tr>
<td>7/16</td>
<td>---</td>
<td>-0.05</td>
</tr>
<tr>
<td>1/2</td>
<td>-0.13</td>
<td>---</td>
</tr>
<tr>
<td>9/16</td>
<td>-0.32</td>
<td>-0.45</td>
</tr>
<tr>
<td>5/8</td>
<td>-0.08</td>
<td>---</td>
</tr>
</tbody>
</table>

Whether it is beneficial to model these factors is an issue to be discussed in future research of this subject. In addition, measuring and recording the properties of the mortar used in these experiments would have assisted in explaining these results. The model depicted in Fig. 7-3b is a simple depiction of a complex non-linear relationship. Such
factors that affect this behavior could include: 1) mortar consistency, 2) size of brick holes, 3) “flashes” at brick holes, 4) mortar thickness, and 5) brick thickness.

7.5 Summary

A brick placement work cell was designed to investigate the material interaction between brick and mortar during placement. Using this work cell, five sets of force and position data were each collected for nine different mortar thicknesses. The data was plotted and the individual slopes determined. The resulting force-step relationships (FSRs) failed to show any correlation between the mortar thickness and the average slope values. It was hoped that a relationship could be developed that would help in determining the correct brick position for different mortar thicknesses. A more comprehensive model and more experimental testing, based on the quantitative results from this research, are required to better understand this relationship. In addition to the mortar and brick thicknesses, the size of the brick holes and the “flashes” at their entrances may have contributed to the irregular data results. Robotic brick placement is a critical success factor since it contributes to a better understanding of the brick-mortar interface during placement.

One option to better control the positioning of the brick would be to introduce lasers to the experimental setup. One such example is by Kahane and Rosenfeld (2004) where they integrated laser positioning technologies in their tile placement robot. The proposed system consisted of a suction gripper, a CCD camera, and five laser line projectors. The overall tile setting cycle starts with a swift long-distance movement of the arm towards the target, followed by a series of fine, short-distance, iterative, "sense-and-act" cycles.
8.0 CHALLENGES WITH AUTOMATED MORTAR APPLICATION

In order to pump mortar with various thicknesses, automated mortar application processes need to be understood. Achieving this is key for bond strength development and accurate brick positioning.

8.1 Background

In order to understand and document the problems inherent in placing bricks with robotic machines, 528 bricks were analyzed to determine the variability in brick thicknesses. The brick stack analysis showed a significant variance in both thicknesses and lengths, reaching a maximum of 0.25 in. and 0.35 in. respectively (Rihani and Bernold 1994). In order to achieve a horizontally leveled brick course, mortar thickness has to be changed to offset the variance in brick thickness. Another need for the adaptive change of mortar thickness is to prevent excess mortar from “oozing” out. In the case that there was less variability in the manufacture of bricks, the changes made to mortar thicknesses for bed and head joints will decrease.

A preliminary experimental test device was developed in order to study the feasibility and the accuracy of using a computer-controlled pump for the application of mortar. A progressive cavity pump and a conveyor belt were integrated to simulate the mortar application of a bed joint. A RM-501 microrobot which held a brick head joint next to the pump nozzle plate was used to investigate the mortar application of a head joint. Fig. 8-1 is a photograph of the progressive cavity pump used. It shows the metallic hopper attached to the pump body, in addition to the stepper motor and gear used to run the pump. A nozzle plate with a rectangular opening is attached to the front end of the pump. Mortar is extruded through this nozzle onto the bricks.
An example of a bed joint application test is shown in Fig. 8-2, where an evenly smooth bed joint was pumped on a piece of plywood placed on a conveyor belt. At the time of this experiment, the ability was not present in the laboratory to move the pump across the pumpable surface. Using the piece of plywood served the purpose of demonstrating the ability to vary the mortar thickness.
Fig. 8-3 shows the two nozzle plates that were used in this study. At the beginning, nozzle plate A [2.36 in. x 0.39 in. opening] was fabricated as a first trial design. When nozzle plate A was used in the tests, the lower limit of the required mortar thickness range for bed joints could not be attained. One solution was to fabricate a plate with a smaller opening width than nozzle plate A. Nozzle plate B [2.36 in. x 0.28 in. opening] was fabricated with a width less than that of nozzle plate A.

An important factor relating to the production rate of the brick panel fabrication system was to operate a conveyor belt at the maximum constant speed possible while applying a “smooth” strip of mortar. For bed joints during this study, the following parameters were kept constant: 1) belt speed at 1550 steps/sec for bed joint mortar applications, 2) robot arm speed at SLOW (1/10) for head joint mortar applications, and 3) distance between brick and pump nozzle at 1 in. and 0.55 in. for bed joint and head joint mortar applications respectively.

Fig. 8-4 summarizes the test results of the experiments related to the mortar application of bed and head joints where data from both experiments have been combined. The x-axis represents the pump speed or the speed of the stepper motor in steps/sec, and the y-axis represents the mortar thickness in centimeters. The mortar
thickness for the bed joint increases linearly from 6,000 steps/sec at 0.3 in. mortar thickness to 15,000 steps/sec at 0.75 in. mortar thickness.

Fig. 8-4 Results of Mortar Application Tests

Fig. 8-4 also shows the data for the head joint experiment was split into two related segments. The separator between the two linear interpolations (head joint 1 and head joint 2) is approximately at a thickness of 0.52 in. This phenomenon seems to be related to the distance between the brick and pump nozzle that had been set at 0.55 in. When the pump reaches a pump speed of 8,000 steps/sec, the nozzle serves as a screeding mechanism resulting in more mortar being dispersed sideways. These experiments showed that mortar thickness can be changed by changing the speed of the mortar pump.

8.2 Pulsation-Less Pumping Technologies

Since a continuous mortar joint is needed, the choice was limited to pulsation-less pumps, as opposed to piston or diaphragm pumps that do not produce smooth mortar joints. One pulsation-less pumping technology is the auger pump. Fig. 8-5 shows a
mason from the Swiss company Keller AG using an auger pump to apply a bed joint. The auger at the bottom of the hopper pushes mortar through a hose held by the mason.

![Auger Pump Used for Mortar Application](image1)

**Fig. 8-5 Auger Pump Used for Mortar Application**

Another pulsation-less pumping technology is the progressive cavity pump such as the one used in this study. This pump is a Robbins & Myers Moyno Pump - Model #2J3-CDR. These pumps have a wide hopper (open-throat) that permits full flow into the pump’s housing. An auger feed then carries the material to the rotor-stator pumping elements. Fig. 8-6 presents a cross-section of the pump showing the hopper and the auger feed.

![Wide Hopper with Auger Feed](image2)

**Fig. 8-6 Wide Hopper with Auger Feed**
(Source: Robbins & Myers 1991)
A cross-section of the rotor-stator pumping elements is shown in Fig. 8-7. The continuous pushing action of the rotor provides uniform discharge without pulsation, turbulence, or agitation.

![Rotor-Stator Pumping Elements](image)

**Fig. 8-7 Rotor-Stator Pumping Elements**  
(Source: Robbins & Myers 1991)

The key components of a progressive cavity pump are the rotor and the stator. As shown in Fig. 8-8, the rotor is a single external helix with a round cross-section, precision machined from high strength steel. The stator is a double internal helix molded of a tough, abrasion resistant elastomer, permanently bonded within an alloy steel tube. This elastomer provides a compression fit between the rotor and stator much like an “O” ring seal. As the rotor turns within the stator, sealed cavities are formed which progress from the suction end (hopper) to the discharge end of the pump. The continuous seal between the rotor and the stator helices keeps the fluid moving steadily at a fixed flow rate proportional to the rotational speed of the pump. As one cavity diminishes, the opposing cavity is increasing at exactly the same rate. The result is a pulsation-less positive displacement flow.

The displacement, in addition to being a function of the speed, is directly proportional to three design constants: the cross sectional diameter of the rotor; its eccentricity, or radius of the helix; and the pitch of the helix. Pressure capabilities are a function of the number of times the progressing seal lines are repeated.
8.3 Experimental Evaluation of Pumping Technologies

This section describes the experiments conducted to evaluate the two different pumping technologies, progressive cavity and auger.

8.3.1 Progressive Cavity Pump

a) Factory Setup Design:

The pump was tested a number of times using a Type S mortar with volume proportions of fly ash : lime : sand equal to 1 : ½ : 4 ½. The quality of the mortar output was unsatisfactory in producing consistently smooth mortar joints. The mortar joints produced had inconsistent thickness, were rough in texture, and patchy at some points. The main recurring problem was that the mortar was not consistently entering the rotor-stator assembly from the pump housing. The pump did not have enough power to push the mortar into and through the rotor-stator assembly. Saturated mortar was apparently pumped first. As the pressure continued, rapid water loss occurred. It was also noticed that the stepper motor used to run the pump would occasionally stall, indicating that it did not have enough torque to run the pump. This stepper motor was replaced with a hydraulic motor controlled by a valve connected to the central oil pressure supply in the Civil Engineering building. The hydraulic motor installed was much more efficient and did not stall at any point. This, however, did not solve the problem; the mortar joints were still uneven under various testing speeds for the hydraulic motor.
Both the rotor and stator have dimensional tolerances that have to be met to maintain a continuous seal between them. After inspection and consultation with the pump manufacturer, it was found that the rotor met the tolerance levels while the rubber inside the stator had deteriorated. A new stator was purchased and installed, and several tests were conducted, but with no better results than before.

b) Enhanced Progressive Cavity Pump System I:

At this point, the objective was to force the mortar into and through the rotor-stator assembly. It was noticed that the mortar would actually circulate in the pump housing while the pump was running. A setup was designed to assist mortar to enter the rotor-stator assembly. Fig. 8-9 shows a photograph and a dimensions schematic of a pressure wedge cap setup made of plexiglass.

![Fig. 8-9 Photograph and Schematic of Pressure Wedge Cap](image)

The pressure wedge cap was first placed inside the pump hopper with its large end at the bottom as depicted in Fig. 8-10. After filling the hopper with mortar with the wedge inside it and running the pump, the wedge was lifted by the mortar, an action corrected by placing a weight on the setup. At this point, mortar was being forced behind
the setup between it and the hopper wall. The mortar was not being consistently pushed into the rotor-stator assembly, and the resulting mortar joints were still uneven.

Fig. 8-10 Pressure Wedge Cap in Pump Hopper (Large End at Bottom)

c) Enhanced Progressive Cavity Pump System II:

The pressure wedge cap was then placed inside the pump hopper with its small end at the bottom as shown in Fig. 8-11. The same problem occurred. The mortar was not consistently forced into the rotor-stator assembly. Again, the mortar joints produced were uneven.

Fig. 8-11 Pressure Wedge Cap in Pump Hopper (Small End at Bottom)
d) Enhanced Progressive Cavity Pump System III:

A plate made of sheet metal was designed in order to place it in the pump hopper and force the mortar, by its own weight, into the rotor-stator assembly. Fig. 8-12 shows a photograph and dimensions schematic of the inclined plate setup.

![Fig. 8-12 Photograph and Schematic of Incline Plate](image)

The incline plate was placed inside the pump hopper as illustrated in Fig. 8-13. After filling the hopper with mortar with the plate inside it and running the pump, mortar was still found to be circulating in the pump housing. The mortar was not consistently forced into the rotor-stator assembly. The resulting mortar joints were again uneven.

![Fig. 8-13 Incline Plate in Pump Hopper](image)
Several experiments were conducted to evaluate the feasibility of using a progressive cavity pump. Starting with the factory setup of the pump, and then modifying it by adding wedges or metal plates in its hopper, did not improve the pumpability of the mortar mixture. The resulting mortar joints were uneven and non-continuous.

8.3.2 Auger Pump
  a) Enhanced Auger Pump System I:

In an attempt to improve the performance of the pump, the rotor-stator assembly was removed and replaced with a continuous auger feed. The rubber inside the old stator was removed, and an auger feed was connected to the drive train of the pump. It extended from the bottom of the pump housing and into and through the stator. Fig. 8-14 shows a photograph of the new auger feed installed in the pump instead of the rotor-stator pumping elements.

![Auger Feed Installed in the Pump](image)

Fig. 8-14 Photograph on Auger Feed Installed in the Pump

Using the auger feed pushed the mortar into and through the stator, but did not apply enough pressure to move the mortar through the pipes and the two 90° elbows, so the mortar did not reach the nozzle plate. After visual inspection, it was determined that the mortar flow stopped approximately halfway in the second section of the pipe
assembly between the two elbow joints. Further visual inspection of the mortar in the pump housing showed that the auger was rotating through the body of the mortar without pushing it. The pump hydraulic motor was operated at different speeds, but still the mortar was not being pumped.

b) Enhanced Auger Pump System II:

To assist the auger in pumping the mortar, a commercial hand sander was attached to the outside of the pump hopper to add a vibration effect as shown in Fig. 8-15. Test concluded that external vibration did not result in moving the mortar through the pipes. The pressure generated by the continuous auger feed was not enough to pump the mortar.

Fig. 8-15 Photograph of Vibrator Attached to Pump Hopper

In summary, this section described several experiments with the mortar application work cell. None of the different pump setups produced a constant pulsation-less mortar joint. As expected, handling a Non-Newtonian fluid proved to be a difficult issue. The following section presents two conceptual models to help demonstrate why the progressive cavity and auger pump setups failed to produce quality mortar joints.

8.4 Conceptual Pump Pressure Models

For mortar to be pumped, enough pressure should be generated to push the mortar from the pump housing, through the entire pipe assembly, and out through the nozzle plate. This pressure must be sufficient to offset all the friction losses created by the pipe
inner surface, the pressure drops due to the two 90° elbows, and the pressure drop due to the 90° nozzle plate pneumatic actuator. Various experiments described in Section 8.3 failed to produce a quality mortar joint. Fig. 8-16 presents conceptual (not to scale) pressure models for the progressive cavity and auger setups. The intent of these models is to demonstrate the difficulties faced in producing a pulsation-less mortar joint.

Fig. 8-16 Conceptual Pressure Models for Progressive Cavity and Auger Pumps
Fig. 8-16 presents two schematics of the progressive cavity and auger pumps that show their different components, such as the pump housing (hopper), the auger and rotor-stator assembly, in addition to the pipe assembly with the two 90° elbows and the nozzle plate. Below them, in shaded polygons, are two conceptual pressure models aligned, through vertical dotted lines, with the schematics along the major component transition points. The transition points are highlighted on the polygons with a “⊗” symbol, and labeled with “pc” for the progressive cavity pump setup, or “a” for the auger pump setup.

For the progressive cavity pump setup, pressure is assumed to start at zero at point pc1 and to increase in the pump housing while being pushed by the auger to the entrance of the rotor-stator assembly at point pc2. According to the manufacturer’s documentation, pressure remains constant in the rotor-stator assembly only losing value due to friction losses in the assembly ending at point pc3. Thereafter, mortar is pushed through the first section of the pipe assembly to the first 90° elbow at point pc4, where it experiences a pressure drop due to the 90° elbow at point pc5. The mortar continues to be pushed through the second pipe-assembly section to the second 90° elbow at point pc6, again experiencing another pressure drop due to the 90° elbow at point pc7. The mortar is then pushed through the third section of the pipe assembly to the 90° nozzle actuator at point pc8, experiencing yet again a pressure drop because of the 90° actuator at point pc9. All throughout the pipe assembly, there are friction losses due to the inner pipe surface – hence the slope of the pressure model between points pc3 to pc4, pc5 to pc6, and pc7 to pc8. The resultant pressure remaining from all the friction losses and pressure drops pushes the mortar out of the nozzle plate and onto the brick.

As for the auger pump setup, pressure is assumed to start at zero at point a1 and to increase in the pump and stator housing ending at point a2. Thereafter, mortar is pushed through the first section of the pipe assembly to the first 90° elbow at point a3, where it experiences a pressure drop due to the 90° elbow at point a4. The mortar continues to be pushed through the second pipe-assembly section stopping halfway at approximately point a5, as was visually observed when that section of the pipe was removed for
inspection. All throughout the traveled pipe assembly, there are friction losses due to the inner pipe surface – hence the slope of the pressure model between points a2 to a3, and a4 to a5. As was noticed during the experiments described in Section 8.3, the mortar did not reach the nozzle plate, and eventually stopped midway in the second section of the pipe assembly between the two elbow joints.

Documentation obtained from the manufacturer’s web site (http://www.moyno.com/) stated that the open-throat progressive cavity pump setup should be able to pump mixtures such as mortar (Literature from Moyno 2002). A case study was described where a similar pump setup was partially effective in pumping filter cake (an oil drilling residue, Non-Newtonian fluid). It was found that, with a build up in the hopper above the auger, the overfeed would turn the relatively dry and brittle filter cake into gummy putty-like fluid that would build a shroud over the auger flight, thus cutting off flow into the auger and stopping pump flow. Various devices were used in an attempt to eliminate this problem. Vibrating the pump was of no value, it was found to be actually a detriment. Similarly, enclosing a portion of the auger in an attempt to force the filter cake into the elements was a failure. It was found that any attempt to force a material that tends to dewater or compact into a positive displacement pump separates the solids from the liquid. The liquid is pumped and the solids remain to foul the suction port. Devices to force the filter cake into the auger also proved unsuccessful. Eventually, it was found that the most effective means was to use a series of fingers rotating above the auger to break up any bridge forming that might shut off the flow. Since power requirements for such a device were minimal, a separate drive was not necessary. It was driven by a gear assembly attached to the main pump drive shaft.

To reinforce the manufacturer’s case study, an article in the November 1991 issue of Concrete Construction Magazine stated that, if spaces or voids between aggregates are not filled with mortar, or if the mortar is too thin and watery, pump pressure will cause segregation, forcing water through the mixture. When this happens, the lubricating layer
is lost, coarse particles interlock, friction increases, and the mortar stops moving (Concrete Construction Magazine 1991).

8.5 Summary

Several experiments were conducted to evaluate the feasibility of using pulsation-less pumping technologies. A mortar application work cell comprised of a Robbins & Myers Moyno pump (Model # 3J6-CDR) and a three-section pipe assembly was retrofitted and modified several times in attempts to produce consistently smooth pulsation-less mortar joints. Although all options failed to produce a continuous mortar joint, better results were achieved by using the progressive cavity pump setup as opposed to the auger option. Conceptual pressure models helped to demonstrate why the work cell did not generate sufficient pressure to produce quality mortar joints.

The current pump model was unsatisfactory. In order to pump Non-Newtonian fluids such as mortar, the pump manufacturer recommended using another pump model with a larger rotor-stator opening and longer pumping elements (such as the Robbins & Myers Moyno Pump - Model #3J6-CDR), in addition to installing a series of fingers rotating above the auger to break up any bridge forming that might shut off the flow. Another possible pump model is the “Putzmeister P11” worm pump. Goodier and Austin (2002) used this model for low-volume wet-process sprayed mortar. In this process, the constituents (cement, aggregate, admixtures, and water) were batched and mixed together before being fed into the pump. The mixture was then conveyed under pressure to the nozzle, where compressed air was injected to project the mixture into place. This produced a continuous and pulsation-free mortar supply to the nozzle. The wet process has become dominant for large-scale tunnel construction, often involving robot-controlled spraying. Lack of funding for this project prevented the researchers from purchasing another mortar pump.

Installing fluid sensors to measure viscosity in addition to pumping pressure could contribute valuable information in understanding the mortar behavior. This feedback
would direct certain actions such as adding more water to the mixture or increasing the pumping pressure. Moreover, using another type of pipe material with less friction properties could assist in decreasing the friction losses. In addition, another mixing method and location, for example, a mixing module attached to the pump hopper, might have a positive effect on pumping the mortar. Mortar application is a critical success factor since it provides an automated approach to pumping mortar joints. Experiments provided a clearer understanding of the requirements needed to produce a pulsation-less mortar joint with varying thicknesses, both necessary for strong bond development and accurate brick positioning.
9.0 AN INVESTIGATION OF BRICK-MORTAR BOND STRENGTH

In order to understand the brick-mortar bond strength and how it is affected, a quantitative analysis of manual vs. robotic bond strength was conducted. This will assist in demonstrating the ability of mechanical capabilities to replace human skills.

Several factors can affect the bond strength of brick masonry units including initial rate of absorption (IRA) of water for bricks, brick porosity, brick texture, type of mortar, type of sand, mixture proportions, mortar water content, mortar workability, mortar viscosity, time between the application of mortar and placement of the brick, and the placement method (Mehrotra 1986). This section presents the research conducted to compare the bond strength of robotically and manually placed brick prisms using the Bond Wrench Test Apparatus described in ASTM C1072.

9.1 Experimental Setup

The apparatus used to determine the bond strength values was the Bond Wrench Test as described in ASTM C1072 (see Fig. 1-5). The Bond Wrench Test machine was borrowed from Dr. W. Mark McGinley at North Carolina A&T State University in Greensboro, NC. Fig. 9-1 shows a two-brick masonry prism placed in the support frame of the Bond Wrench Test apparatus.

![Fig. 9-1 Clamping Mechanism for a Masonry Prism](image)
Once the prism was placed vertically on the metal frame, it was clamped firmly into a locked position using the lower clamping bracket. The prism was oriented so that the face of the joint, intended to be subject to flexural tension, was on the same side of the specimen as the clamping screws. The prism was positioned at the required elevation resulting in a single brick projecting above the lower clamping bracket. A piece of polystyrene, a soft bearing material, was placed between the bottom of the prism and the adjustable prism base support. The upper clamping bracket was then attached to the top brick. Each clamping bolt was tightened using a torque of 50 lbf-in (5.7 N·m). The load was applied at a uniform rate so that the total load was applied in a time frame between 1 and 3 minutes. An electronic load cell measured the load. Fig. 9-2 shows the electronic load cell as part of the Bond Wrench Test machine.

![Electronic Load Cell](image)

**Fig. 9-2 Electronic Load Cell used in the Bond Wrench Test Apparatus**

The electronic load cell shown in Fig. 9-2 is manufactured by StrainSert (Model TLN-2). It has a maximum load capacity of 2000 lbs. The loads were determined by connecting the load cell to an analog-input data acquisition board that was connected to a desktop computer. The load cell was calibrated such that a 24mV output reading corresponded to a 2000 lb. load.
9.2 Data Collection

According to ASTM C1072, the net area of brick determines the equation used to calculate the bond strength value. The bricks used in the bond wrench experiments have the following dimensions (Rihani and Bernold 1994):

- Average Width = 3.39 in.
- Average Length = 7.62 in.
- Average Diameter of Hole #1 = 1.41 in.
- Average Diameter of Hole #2 = 1.24 in.
- Average Diameter of Hole #3 = 1.41 in.

Using these values, the following parameters can be determined:

- Total Surface Area = 3.39" × 7.62" = 25.83 in^2
- Total Hole Area = \( \pi \left[ \left( \frac{1.41}{2} \right)^2 + \left( \frac{1.24}{2} \right)^2 + \left( \frac{1.41}{2} \right)^2 \right] \) = 4.33 in^2
- Net Brick Area = 25.83 in^2 – 4.33 in^2 = 21.50 in^2
- % Net Brick Area = (21.50 in^2 / 25.83 in^2) x 100 = 83.24%

Since the value of % Net Brick Area (83.24%) is greater than 75%, the masonry units are considered solid rather than hollow. Therefore, Equation 9.1 was used to calculate the bond strength, or the gross area flexural tensile strength:

\[
F_g = \left[ \frac{6(PL + P_1L_1)}{bd^2} \right] - \left[ \frac{(P + P_1)}{bd} \right] \quad (9.1)
\]

where: 
- \( F_g \) = gross area flexural tensile strength, (psi)
- \( P \) = maximum applied load, (lbf)
- \( P_1 \) = weight of loading arm, (lbf)
- \( L \) = distance from center of prism to loading point, (in.)
\[ L_1 = \text{distance from center of prism to centroid of loading arm, (in.)} \]
\[ b = \text{average width of cross section of failure surface, (in.)} \]
\[ d = \text{average thickness of cross section of failure surface, (in.)} \]

For this experimental setup, a number of terms in Equation 9.1 have constant values:

\[ P_1 = 40.5 \text{ lbf} \]
\[ L = 13-3/16 \text{ in.} \]
\[ L_1 = 3/16 \text{ in.} \]
\[ b = 7.6185 \text{ in. for manual brick placement} \]
\[ = 7 \text{ in. for robotic brick placement} \]
\[ d = 3/8 \text{ in. for manual and robotic brick placement} \]

Although ASTM C1072 states that a minimum of five tests should be conducted, it was decided to look at previous research on this apparatus to determine if more tests may be required. A study conducted by McGinley (1993) found an average bond strength of 673 kPa (97.7 psi) with a coefficient of variation (cov) of 0.182. The standard deviation (\( \sigma \)) of the data would equal to \((0.182) \times 97.7 \) = 17.8 psi. Therefore, the variability of the predicted value of the bond strength \( (F_g) \) with 95% confidence is given in Equation 9.2:

\[
F_g = \pm t(0.975, \infty)(\sigma)\sqrt{\frac{1}{n}}
\]

\[
= \pm (1.96)(17.8)\sqrt{\frac{1}{n}}
\]

\[
= \pm 34.85\sqrt{\frac{1}{n}} \quad (9.2)
\]

Table 9-1 presents the variability of the predicted value of the bond strength \( (F_g) \) as related to the number of tests \( (n) \).
Table 9-1 Variability of the Predicted Value of the Bond Strength as related to the Number of Tests

<table>
<thead>
<tr>
<th>n</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>10</th>
<th>15</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>(F_g) (psi)</td>
<td>±34.85</td>
<td>±20.12</td>
<td>±15.59</td>
<td>±13.17</td>
<td>±11.02</td>
<td>±9.00</td>
<td>±6.36</td>
</tr>
</tbody>
</table>

According to the calculations in Table 9-1, ten tests would provide, with 95% confidence, a predicted value of bond strength equal to ±11.02 psi. Therefore, ten experiments were conducted with the robot arm and another ten experiments with a qualified mason placing bricks using his normal style. In all twenty experiments, the brick-mortar bond strength was measured. Fig. 9-3 shows the randomly selected bricks used in the experiments.

![Fig. 9-3 Bricks Selected for the Bond Strength Experiments](image_url)

For the manual brick placement experiments, the services of a qualified mason were utilized. Mr. Jason Janet, an Electrical Engineering graduate student at NCSU, has 15 years of experience in brick and block masonry and has worked on more than 1,000 masonry jobs since 1980.
For the first robotic brick placement experiments, a mold was used to create the mortar bed joint. Since the mortar pump did not produce quality results, it was decided to manually place the mortar inside the mold. The top brick was placed robotically. Fig. 9-4 shows a photograph and dimensions schematic of the mold.

![Photograph and Schematic of First Robotic Placement Mortar Mold](image)

The 2-7/8 in. wide - 1/2 in. thick mold was fabricated from stainless steel. The length of the mold was 7 in. so as to fit the length of the brick. ASTM C1072 requires the mortar joint to be 3/8 in. thick. An additional 1/4 in. was added to the mold thickness so as to allow for the compression of the mortar joint during brick placement. Prior to robotic placement, the mold was placed on the bottom brick then filled with mortar using a trowel. The mold was then removed before the top brick was robotically placed on the bed joint.
Ten prisms were built manually and another ten were built robotically. According to ASTM C1072, all prisms were cured for seven days, then tested using the Bond Wrench Test apparatus. During the 7-day curing period, all prisms were placed inside white plastic bags as shown in Fig. 9-5 in order to maintain closer control on temperature and humidity as permitted by ASTM C1072.

Table 9-2 presents the bond strength measurements for both manual and robotic brick placement. It shows that the average value of the manual placement bond strength was 5210 psi compared to 1442 psi for robotic placement. As for the variance values, it was 23.59E+05 for the manual placement measurements as opposed to 47.31E+05 for the robotic placement measurements. The standard deviation of the manual prisms was 1536 psi and 2175 psi for robotic placement. Per ASTM C1072, the individual, average, and standard deviation bond strength values are reported to the nearest psi.
Table 9-2 Bond Strength Measurements for Manual and Robotic Placement

<table>
<thead>
<tr>
<th>Prism #</th>
<th>Bond Strength Measurements (psi)</th>
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<td>Manual Placement</td>
<td>Robotic Placement</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5839</td>
<td>31</td>
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<tr>
<td>Standard Deviation:</td>
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<td>2175</td>
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<tr>
<td>Variance:</td>
<td>23.59E+05</td>
<td>47.31E+05</td>
<td></td>
</tr>
</tbody>
</table>

Clearly, the bond strength measurements using manual placement are higher and more consistent than those using robotic placement. After close observation of both kinds of prisms, it seemed that the lack of performance of the robotically placed prisms was due to the flat bed joint placed using the mold shown in Fig. 9-4. In fact, some of the robotic prisms fell apart prior to testing. During manual placement, the mason applied an uneven bed joint with a considerably larger thickness than 1/2 in. Once the top brick was placed and the bed joint compacted to a thickness of 3/8 in., mortar entered into the holes of the top brick. This was clearly noticed on the tested manual prisms, and was definitely lacking in the robotic prisms since the molded bed joint was flat. Accordingly, a second mold was fabricated.
Fig. 9-6 shows a photograph and dimensions schematic of the second mold. The second mold includes a bump in the middle of the section that would be aligned with the holes of the top brick in order to allow mortar to enter them. Ten prisms were built using this mold. After a curing period of seven days, the prisms were tested using the bond wrench test apparatus.

Table 9-3 presents the bond strength measurements for the robotic brick placement prisms using the second mold. It shows that the average value of the robotic placement bond strength using the second mold was equal to 3026 psi with a variance of 24.28E+05 and a standard deviation of 1558 psi. Per ASTM C1072, the individual,
average, and standard deviation bond strength values are reported to the nearest psi. Comparing the second robotic bond strength measurements to the first values reveals that the average bond strength value was nearly twice that of the first mold, while the variance in the second measurements was nearly cut in half. This significant improvement can be credited to the second mold allowing mortar to enter the holes of the top brick and create a stronger bond.

Table 9-3 Bond Strength Measurements for Robotic Placement using the Second Mold

<table>
<thead>
<tr>
<th>Prism #</th>
<th>Bond Strength Measurements (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1650</td>
</tr>
<tr>
<td>2</td>
<td>3045</td>
</tr>
<tr>
<td>3</td>
<td>2242</td>
</tr>
<tr>
<td>4</td>
<td>832</td>
</tr>
<tr>
<td>5</td>
<td>1569</td>
</tr>
<tr>
<td>6</td>
<td>2783</td>
</tr>
<tr>
<td>7</td>
<td>4864</td>
</tr>
<tr>
<td>8</td>
<td>5682</td>
</tr>
<tr>
<td>9</td>
<td>4400</td>
</tr>
<tr>
<td>10</td>
<td>3196</td>
</tr>
<tr>
<td>Average:</td>
<td>3026</td>
</tr>
</tbody>
</table>
| Standard Deviation:| 1558 |}

Bond Wrench Test reports for the robotically placed prisms using the second mold and the manually placed prisms are presented in Appendix 14.3. Each report includes all the brick, mortar, and prism properties, in addition to a description of the failure. A photograph of the prism showing the two bricks and the mortar joint after failure is also included. These are presented in accordance with Section 9 of ASTM C1072.
9.3 Data Evaluation

The averages, variances, and standard deviations of the bond strength measurements for the different placement methods can now be compared. Fig. 9-7 presents a bar chart illustrating the average bond strength values for the different placement methods. The average bond strength for manual placement was the highest, followed by the second robotic, then by the first robotic.

Fig. 9-7 Average Values of $F_g$ for Different Placement Methods

Fig. 9-8 presents a bar chart showing the variance in the bond strength values for different placement methods. The variance in the bond strength for the first robotic placement was the highest followed by the second robotic and the manual. The variance in bond strength measurements was almost equal for the manual and the second robotic placement methods.
Fig. 9-8 Variance in $F_g$ Values for Different Placement Methods

Fig. 9-9 presents a bar chart showing the standard deviation in the bond strength values for different placement methods. The standard deviation in the bond strength for the first robotic placement was the highest followed by the second robotic and the manual. The standard deviation in bond strength measurements was almost equal for the manual and the second robotic placement methods.

Fig. 9-9 Standard Deviation in $F_g$ Values for Different Placement Methods
Hypothesis testing was conducted on the second robotic and manual bond strength data to compare the means ($\mu_R$ and $\mu_M$) and the variances ($\sigma_R^2$ and $\sigma_M^2$) of the two samples respectively. The two hypothesis for the mean to be tested were ($H_0$: $\mu_R > \mu_M$) and ($H_1$: $\mu_R < \mu_M$). For the variance, the two hypothesis were ($H_0$: $\sigma_R^2 < \sigma_M^2$) and ($H_1$: $\sigma_R^2 > \sigma_M^2$). Table 9-4 presents the results of the hypothesis analysis. The first column shows the ten bond strength measurements for robotic placement using the second mold, while the second column displays the measurements using manual placement. $\alpha$ is the probability of committing a Type I error (i.e., concluding $H_1$ when the true state of nature is $H_0$). $\alpha$ is set at a minimum level, usually 0.05, 0.01, or 0.001, depending on the degree of criticality of such an error (i.e., in academia and social sciences $\alpha$ is usually 0.05; whereas, in hospital tests or other critical areas of testing, $\alpha$ is either 0.01 or 0.001).

Table 9-4 Hypothesis Analysis of Bond Strength Data

<table>
<thead>
<tr>
<th></th>
<th>Robotic</th>
<th>Manual</th>
<th>Two-Sample Hypothesis Test for the Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>3045.26</td>
<td>6306.44</td>
<td>3026.46</td>
</tr>
<tr>
<td>Variance</td>
<td>2242.06</td>
<td>6361.57</td>
<td>2427950.68</td>
</tr>
<tr>
<td>Observations</td>
<td>832.46</td>
<td>6218.97</td>
<td>10</td>
</tr>
<tr>
<td>df</td>
<td>1569.26</td>
<td>7547.94</td>
<td>18</td>
</tr>
<tr>
<td>alpha</td>
<td>2782.86</td>
<td>3179.52</td>
<td>0.01</td>
</tr>
<tr>
<td>$t$</td>
<td>4864.46</td>
<td>4843.68</td>
<td>-3.16</td>
</tr>
<tr>
<td>$P(T&lt;=t)$ one-tail</td>
<td>5682.06</td>
<td>5267.07</td>
<td>0.003</td>
</tr>
<tr>
<td>4399.66</td>
<td>3156.00</td>
<td>4.4864</td>
<td>4.4864</td>
</tr>
<tr>
<td>3196.46</td>
<td>3380.93</td>
<td>4.4864</td>
<td>4.4864</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Robotic</th>
<th>Manual</th>
<th>Two-Sample Hypothesis Test for the Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>3026.46</td>
<td>5210.11</td>
<td>3026.46</td>
</tr>
<tr>
<td>Variance</td>
<td>2427950.68</td>
<td>2359170.87</td>
<td>2359170.87</td>
</tr>
<tr>
<td>Observations</td>
<td>832.46</td>
<td>6218.97</td>
<td>10</td>
</tr>
<tr>
<td>df</td>
<td>1569.26</td>
<td>7547.94</td>
<td>18</td>
</tr>
<tr>
<td>alpha</td>
<td>2782.86</td>
<td>3179.52</td>
<td>0.01</td>
</tr>
<tr>
<td>$F$</td>
<td>4864.46</td>
<td>4843.68</td>
<td>0.01</td>
</tr>
<tr>
<td>$P(F&lt;=f)$ one-tail</td>
<td>5682.06</td>
<td>5267.07</td>
<td>0.483</td>
</tr>
</tbody>
</table>
The analysis for the two-sample hypothesis test for the mean indicates (with
99.7\% confidence) that robotically placed bond strength measurement is less than those
of the manually placed. The fact that the bond strength values for the second robotic
prisms were nearly twice that of the first robotic prisms is in itself a significant change.
Areas for future research could concentrate on finding an optimal shape and size of this
mold, and to test robotic placement method enhancements such as vibrating the brick into
place.

In the two-sample hypothesis test for the variance, it was found that P is greater
than \alpha. Therefore, \( H_0 (\sigma^2_R < \sigma^2_M) \) cannot be rejected. But since P=48.3\%,

it could be
said that the variance for the robotically placed bond strength measurements is not
statistically different from those of the manually placed. This represents an important in
showing that bond strength values are almost equally consistent when prisms are placed
either robotically or manually.

9.4 The Bond-Enhancing Orifice (BEO)
Since the robotic prisms built with the second robotic placement mortar mold had
higher and more consistent bond strength values than those built with the first mold, a
new nozzle plate was fabricated with the same cross-section as that of the second mold to
be used in the panel fabrication tests (see Fig. 9-6). This implied redesigning the nozzle
to include a bump on the bed joint in order to allow mortar into the brick holes; an
important factor in developing bond strength. This represents a case where a machine
part had to be redesigned to substitute a human motor skill. The nozzle plate was
redesigned in order to substitute the human method of placing mortar bed joints. Fig. 9-
10 shows a photograph and dimensions schematic of the bond-enhancing orifice (BEO).
Further study is needed to determine the optimal shape of the nozzle plate that would
produce the best bond strength.
9.5 Summary

Experiments were conducted using the ASTM C1072 Bond Wrench Test Apparatus to compare the bond strengths of ten manually vs. ten robotically placed masonry prisms. Initial results using a flat rectangular metallic mold produced robotically placed prisms with bond strengths significantly lower and less consistent than those manually placed. Analysis of the data showed that the lack of performance of the robotically placed prisms was due to the flat bed joint. During manual placement, the mason applied an uneven bed joint that enabled mortar to enter into the holes of the brick. This was clearly noticed on the tested manual prisms and was lacking in the robotic prisms.

A second mold was fabricated with a bump in the middle of its section that would be aligned with the holes of the top brick. Ten additional robotic prisms were built using
this mold, and analyzed using the test apparatus. Results showed that the bond strength of prisms constructed using the second mold were nearly double that of the first mold, while the variance in the second measurements was nearly cut in half. The variance in bond strength measurements was essentially equal for the manual and the second robotic placement methods. This significant improvement can be credited to the second mold that allowed mortar to enter the holes of the top brick and create a stronger and more consistent bond.

Based on the design of the second robotic mold, a new nozzle plate was fabricated with the same cross-section as the mold to be used in the panel fabrication tests. This brick-enhancing orifice (BEO) represents a case where a machine part had to be redesigned to substitute a human skill. Brick-mortar bond strength is a critical success factor since it affects the structural stability of the brick panel. The results offered a quantitative analysis that served in assessing how mechanical capabilities can possibly replace human skills.
10.0 A PROPOSED CONTROL FRAMEWORK FOR ROBOTIC MASONRY

This chapter proposes a control framework for brick panel fabrication. It presents a model for the control structure that shows the flow of data and materials within its components. Also presented are the results of a pilot test for a “pathfinder” system used to evaluate the fabrication of a masonry panel.

10.1 Proposed Control Framework

Fig. 10-1 presents a proposed model of the data and material (brick and mortar) flow that embodies the work cells described in Chapters 4 to 9. The process starts with design automation and the brick panel design. After the end-user enters the masonry bond type, wall dimensions, and space dimension and location; the design automation work cell generates data that are shared with the production planning and control unit. This unit is responsible for sharing and transferring data between the work cells. Brick classification and the number of bricks are then shared with the dehacker. The quality control work cell generates brick thickness, color, and texture data, and sends it back to the production planning and control unit. Brick position and the process plan data are then sent to the brick panel fabricator work cell, in addition to brick thickness data being sent to the mortar application work cell.

Material flow includes brick dehacking at the work cell where they are unstacked from the brick cube, after which they are measured for thickness, color, and texture at the quality control work cell. A conveyor then transports the bricks to the brick panel fabricator work cell. Mortar is pumped from the mortar application work cell to the brick panel fabricator work cell onto the panel bricks.
The method of integration in this proposed model is based on the concept of the hierarchical control structure which is equivalent to the line or tree structure found in conventional manufacturing systems. This structure is "constructed using the philosophy of levels of control. Superior/subordinate relationships are created between levels with command data flowing downward in the hierarchy toward machines and processing stations at the lowest levels, and sensory data flowing upward in the hierarchy toward the manufacturing level" (Bernold et al. 1989).

Fig. 10-2 illustrates a simplified example of the hierarchical control model between the Production Planning and Control unit and the Brick Panel Fabricator unit, and how these units would communicate. The arrows represent the “READ-COMPUTE-WRITE” cycle typical of hierarchical control structures. For example, the robot arm would receive position commands from the Panel Fabricator control unit and would submit back to the control unit its status once it has reached the desired position. Concurrently, the Brick Fabricator unit would inform the Production Planning and
Control unit of this status so that it may send any dependant commands to other control units in the system. Albus (1985) states that at every level in the hierarchy, three components function cooperatively: 1) a command module that receives data from higher levels and takes appropriate action through task decomposition to accomplish them, 2) a sensory feedback processing module that receives status information from lower levels and aids in control decisions at every level of task decomposition, and 3) a world model that interacts with the other two modules to enable them to carry out their duties.

Fig. 10-2 Partial Model of Hierarchical Control Structure

It must be stated again that this model is offered here as a proposal and was not tested as part of this research. The software integrating the robotic placement and mortar application modules that was used in data collection in Chapters 7 and 8 did incorporate logic to control components such as the robotic arm, the pneumatic brick gripper, and the mortar pump. This software control integration was demonstrated when the brick masonry panel fabrication experiments were conducted as discussed in the following section.
10.2 Pilot Test of a Pathfinder System

Boles (et al. 1995) define a “pathfinder” system as a laboratory test platform where candidate technologies can be compared. This is where technology options are investigated for incorporation into a prototype. The pathfinder system is important because the word “prototype” implies a fully functional device that is easily field-demonstrable. The author uses the term “pathfinder” as referring to a partially functional laboratory device used for experimentation.

This section introduces such a pathfinder system that was constructed to produce and evaluate the fabrication of masonry panels. The problem this research addressed was to determine the critical success factors for robotic masonry. This pathfinder system is presented here as an initial step for future work in this area, and does not directly address the objectives of this research.

Combining some of the work cells identified in the control model proposed in Fig. 10-1, an experiment to fabricate a brick masonry panel was conducted. The gantry frame shown in Fig. 10-3 covers an area 180 in. (4.6m) wide and 120 in. (3.1m) high. The gantry platform carries a brick placement arm with a pneumatic brick gripper and force-torque sensor similar to those in the dehacking work cell. The platform can travel in this area via horizontal and vertical movement thread screws that are attached to stepper motors. The brick placement arm is used for placement of bricks supplied by a conveyor. A progressive cavity pump is used to apply the mortar for bed and head joints.
These components are shown in Fig. 10-4. Mortar is pumped through a series of pipes to the nozzle. A 90° pneumatic actuator attached to the nozzle controls the position for bed and head joint application. A motor attached to the drive gear operates the pump. The control units for the robotic arm, stepper motors, the pneumatic valves for the gripper and nozzle, and for the hydraulic valve are attached at the top of the gantry platform as shown in Fig. 10-3.
Several tests were conducted to fabricate a three-course brick masonry panel with a running masonry bond. The resulting fabricated panel had generally horizontal brick layers with minimum mortar oozing. Closer inspection of the panel revealed that not enough mortar was pumped on the bricks and that there were apparent gaps in the mortar bed and head joints. Moreover, the bricks did not seem to be placed with sufficient force to bond with the mortar. This was noticed after some bricks removed from the panel indicated that mortar did not enter the brick holes. Tests such as the one described produced uneven bed and head joints because the pump had difficulties in producing a pulsation-less mortar joint. It was noticed that the mortar was not consistently being drawn from the suction housing into and through the rotor-stator pumping elements throughout these experiments. Conducting this test has confirmed that mortar application is one of the most critical success factors affecting robotic masonry. Although this pathfinder system proved that the integrated system failed at producing quality masonry panels, one benefit incurred was to demonstrate the integration of the brick placement, mortar application, and gantry positioning modules.
11.0 ANALYSIS OF CRITICAL SUCCESS FACTORS

This chapter reviews the Critical Success Factors identified using the Cause-Effect Diagram in Chapter 3, and highlights those that have been identified as the most critical.

11.1 Revised Cause-Effect Diagram

Given the investigations of the predicted critical success factors presented in Chapters 4 to 9 and the experiments conducted with the pathfinder system discussed in Chapter 10, Fig. 11-1 below highlights the most important Critical Success Factors.

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Fig. 11-1 Revised Cause-Effect Diagram

Fig. 11-1 emphasizes, in shaded frames, the CSFs that would play a major factor in delivering a “successful robotic masonry system”. Added to these are sub-factors that
were shown to be major effects. These critical factors and sub-factors are:

1. Brick Placement:
   a. Brick Thickness
   b. Mortar Thickness
   c. Placement Force

2. Mortar Application:
   a. Pumping Method
   b. Pumping Pressure

3. Brick-Mortar Bond Strength:
   a. Profile of Mortar Joint
   b. Depth of Mortar Penetration in Brick Holes

For brick placement, the thickness of the brick and mortar joint and the force applied were major sub-factors. The force-step relationships (FSRs) plotted for different mortar thickness failed to show any correlation between the mortar thickness and the average slope values. It was hoped that a model could be developed that would help determine the correct brick position for different mortar thicknesses. Having such a model would assist in fabricating a horizontally-leveled brick wall by varying the placement force and mortar thickness for each different brick thickness value.

For mortar application, the pumping method and pressure were major sub-factors. Conceptual pressure models helped to demonstrate why the work cell did not generate sufficient pressure to produce quality mortar joints. They showed that the resultant pressure at the end of the work cell assembly was insufficient in producing acceptable mortar joints.

For the Brick-Mortar Bond Strength, the profile of the mortar joint and the depth of mortar penetration in the brick holes were major sub-factors. Initial results using a flat rectangular metallic mold produced robotically placed prisms with bond strengths significantly lower and less consistent than those manually placed. Analysis of the data
showed that the lack of performance of the robotically placed prisms was due to the lack of mortar penetration in the brick holes. A second mold was fabricated with a bump in the middle of its section that would be aligned with the holes of the top brick. Results showed that the bond strength of prisms constructed using the second mold were nearly double that of the first mold, while the variance in the second measurements was nearly cut in half.

11.2 Relevance to Future Research

The Critical Success Factor analysis has identified three factors considered most critical (see Fig. 11-1). These factors are inter-related in that they represent the basic process of building a masonry panel. The relationship between these factors is critical in achieving a “successful” system. The factors identified were 1) Brick Placement, 2) Mortar Application, and 3) Brick-Mortar Bond Strength. While mortar application proved to be the most challenging; its integration with brick placement is the root cause in achieving a strong bond strength. The research has shown that the depth of mortar penetration in the brick holes plays a major factor in achieving the desired bond strength.

Although the results proven by the pathfinder system are considered preliminary at best; they serve as a guide to future researchers attempting to develop automated systems that involve complicated material handling requirements. Future research in automating construction processes involving material handling must pay close attention to material positioning and delivery requirements.
12.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

12.1 Summary

Automation and robotics technologies have found many valuable applications in places where laborers are engaged in hazardous or repetitive work. The construction industry does not offer opportunities to apply advanced systems not only because most of the work takes place outside a closed factory environment, but the work tasks themselves tend to be complex and involve the handling of specialized tools to join, pour, mix, nail, or attach a variety of materials. The intention of the presented research was to study the efficiency of automating brick laying operations executed in a pre-fabrication mode. While mechanization of the operation had been attempted before, its mission to meet the quality standards established for masons created many difficult challenges.

After an extensive review of the literature, the Critical Success Factors (CSF) method was utilized as a top-down planning process to define the most relevant problem areas that had to be solved in order to create a successful robotic masonry system. Critical Success Factors are “the limited number of areas in which results, if they are satisfactory, will ensure successful competitive performance of an operation.” Using this approach, the following six topics were identified: 1) design automation, 2) dehacking, 3) brick quality control, 4) brick placement quality, 5) mortar application quality, and 6) brick-mortar bond-strength.

In investigating Design Automation, Chapter 4 presented an integrated information system with the ability to produce user-designed 3D CAD drawings of masonry wall panels, in addition to quantity takeoff sheets that detail the coordinates and the total quantity of the bricks in the panel. The coordinate points of each brick, generated by the system, would be passed to the robotic control software. Brick would then be cut, if need be, and placed on a conveyor belt for delivery to a panel fabrication station. Design automation was a critical success factor since it provided a robotic masonry system with initial information to be used throughout the panel fabrication
process. It offered a dynamic interface at the end-user level to achieve a realistic representation of the final product.

Chapter 5 presented the work done to solve the Dehacking problem. Dehacking was a critical success factor since it not only included the unstacking of bricks from the cubes coming from the brick plant, but had to find a way to transport it to the location where the placement arm could reach them. The main problem was solved by designing and testing an innovative adaptive pneumatic brick gripper, fitted with a force-torque sensor, able to insert a wedge-type instrument into the brick holes. Integrated with this tool, a robotic arm was successfully able to pick up bricks.

In investigating Brick Quality Control, Chapter 6 discussed the experiments conducted using the brick quality control work station to numerically measure brick color, texture, and thickness. Using a photoelectric sensor and two proximity sensors, several tests were conducted to present a visual representation and a clear differentiation of these brick properties. This work cell can be used to discard any bricks that do not meet architectural and material quality specifications relating to color, texture, and thickness. Brick quality control was a critical success factor since it provided accurate and consistent results for quantifying these brick properties. Based on interest from local masonry contractors, this developed work station presented a potentially promising and marketable tool to assist in detecting and measuring brick properties.

Chapter 7 studied the Brick Placement Quality issue. A brick placement work cell was designed to investigate the material interaction between brick and mortar during placement. Using this work cell, five sets of force and position data were collected for each of the nine different mortar thickness possibilities. The data was plotted in order to compute the individual slopes. The resulting force-step relationships (FSRs) failed to show any correlation between the mortar thickness and the average slope values. It was hoped that a relationship could be developed that would help in determining the correct brick position for different mortar thicknesses. A more comprehensive model and more
experimental testing are required to better understand this relationship. In addition to the mortar and brick thicknesses, the size of the brick holes and the “flashes” at their entrances seemed to contribute to the irregular data results. Robotic brick placement was a critical success factor since it contributed to a better understanding of the brick-mortar interface during placement. The results offered a quantitative analysis of the material behaviors and the factors affecting them.

In investigating **Mortar Application Quality**, Chapter 8 presented several experiments to evaluate the feasibility of using pulsation-less pumping technologies. A mortar application work cell comprised of a Robbins & Myers Moyno pump (Model # 3J6-CDR) and a three-section pipe assembly was retrofitted and modified several times in attempts to produce consistently smooth pulsation-less mortar joints. The progressive cavity pump setup produced better mortar joints than the auger option. Conceptual pressure models helped to demonstrate why the work cell did not generate sufficient pressure to produce quality mortar joints. They showed that the resultant pressure at the end of the work cell assembly was what remained after all the friction losses and pressure drops, and that this pressure was insufficient in producing acceptable mortar joints. Tests conducted to fabricate a masonry panel produced unsatisfactory results. The fabricated panel had generally horizontal brick layers with minimum mortar oozing, but closer inspection of the panel revealed that not enough mortar was pumped on the bricks and that there were apparent gaps in the mortar bed and head joints. Mortar application was a critical success factor since it provided an automated approach to pumping mortar joints. Experiments provided a clearer understanding of the requirements needed to produce a pulsation-less mortar joint with varying thicknesses, both necessary for strong bond development and accurate brick positioning.

Chapter 9 examined the **Brick-Mortar Bond Strength** problem. Experiments were conducted using the ASTM C1072 Bond Wrench Test Apparatus to compare the bond strengths of ten manually vs. ten robotically placed masonry prisms. Initial results using a flat rectangular mold produced robotically placed prisms with bond strengths
significantly lower and less consistent than those manually placed. Analysis of the data showed that the lack of performance of the robotically placed prisms was due to the flat bed joint. During manual placement, the mason applied an uneven bed joint that enabled mortar to enter into the holes of the brick. This was clearly noticed on the tested manual prisms, and was lacking in the robotic prisms. A second mold was fabricated with a bump in the middle of its section that would be aligned with the holes of the top brick. Ten additional robotic prisms were built using this mold, and analyzed using the test apparatus. Results showed that the bond strength of prisms constructed using the second mold were nearly double that of the first mold, while the variance in the second measurements was nearly cut in half. In fact, the variance in bond strength measurements was almost equal for the manual and the second robotic placement methods. This significant improvement can be credited to the second mold that allowed mortar to enter the holes of the top brick and create a stronger and more consistent bond. Based on the design of the second robotic mold, a new nozzle plate was fabricated with the same cross-section as the mold. This brick-enhancing orifice (BEO) represents a case where a machine part had to be redesigned to substitute a human skill. Brick-mortar bond strength was a critical success factor since it affected the structural stability of the brick panel.

Looking back at the research objectives stated in this dissertation, the contributions of this research are summarized below:

1. The Critical Success Factors analysis, applied to identify key problem areas, was useful in providing a focused list of topics to be studied and solved.
2. Controlling the amount of mortar applied and designing an efficient nozzle are crucial for achieving high bond strength.
3. The changing pressures inside a progressive cavity pump used to apply the mortar require further study. The complexity of the problem is the result of a series of factors: a) the speed of the pump motor drive, b) the size of the rotor-stator opening, c) the length of the rotor-stator assembly, and d) the consistency/viscosity of the mortar
4. The size of the brick holes and the “flashes” at their entrances affect the brick-mortar interface during brick placement.

5. The experiments confirmed that bond strength is created primarily by mortar entering the brick holes.

6. The consistency of bond strength values of masonry prisms placed robotically matched that of prisms placed manually.

7. Substituting human skills with mechanical capabilities is an essential component of robotics. This research presented three examples of “economic” means that showed how machines have to be redesigned to substitute motor and sensory human skills:

   a. For the design of the dehacking work cell, one problem that had to be solved was to find a way to pick up the brick without having two parallel sides available for gripping. The gripper was redesigned in order to substitute the human skill of picking up bricks from a brick cube.

   b. For the design of the brick quality control work cell, one problem that had to be resolved was to find a way to only collect and quantify brick color data from the photoelectric sensor. The data collected from this sensor was manipulated in order to substitute the human skill of detecting different colors.

   c. A bond-enhancing orifice (BEO) was fabricated with the same cross-section as that of a manually placed mortar joint. The nozzle plate was redesigned in order to substitute the human skill of placing mortar bed joints where they are most effective in producing a better bond strength.

To achieve the substitution of human skills with mechanical capabilities, the following guidelines are offered:

1. Avoid replicating complicated human motions: The design of the pneumatic brick gripper allowed picking up the brick without a complicated tilt movement.
2. Understand material-material interaction: Comprehending brick-mortar interaction properties is vital to the development of the Force-Step Relationships and analyzing the brick-mortar bond strength.

3. Understand complex material behavior: Interpreting mortar as a Non-Newtonian fluid assisted in comprehending its behavior and in the attempts to pump it.

4. Use quantitative methods to assess trade-off: Hypothesis testing of robotically vs. manually placed brick prisms provided a quantitative analysis of this critical success factor.

5. Take advantage of special mechanical and electronic methods: The development of a special pneumatic brick gripper in addition to the use of electronic sensors was essential in developing the dehacking and brick quality control work cells.

12.2 Conclusions

This research work concluded the following:

1. Brick placement is a critical success factor for robotic masonry.
2. Mortar application is a critical success factor for robotic masonry.
3. Brick-mortar bond strength is a critical success factor for robotic masonry.
4. Factors affecting brick placement are: brick thickness, mortar thickness, and placement force.
5. Factors affecting mortar application are: pumping method and pumping pressure.
6. Factors affecting brick-mortar bond strength are: profile of mortar joint and the depth of mortar penetration in the brick holes.
7. Consistency in bond strength measurements for prisms placed robotically matched that for manually placed prisms.
12.3 Recommendations for Future Research

After conducting this research effort, the following recommendations/new questions are offered for future research endeavors on robotic masonry:

1. Continue the development of the brick panel fabrication system to produce better quality brick masonry panels.
2. Conduct more tests using the brick quality workstation to correlate the brick thickness sensor readings to a single thickness value. Determine how the measured brick color, texture, and thickness readings correlate to specified accuracy requirements.
3. Conduct more tests to better understand the force-step relationships of the different mortar thicknesses. Record the properties of the mortar used in the force-step relationship experiments to determine its effect.
4. Investigate how to best model the brick mortar interaction during brick placement.
5. Study the effect of using laser positioning on brick placement quality and how it may improve the data gathered from the force-step relationship experiments.
6. Investigate whether panel fabrication should be performed in both directions of the gantry motion instead of the current one direction. This would increase panel production rate.
7. Examine the effect of using two nozzles, each with a different plate – one for bed joint application and one for head joint application. This could be more pertinent than using the same plate for both joints, since the head joint needs to be flat while the bed joint has to have a bump similar to the second robotic placement mortar mold.
8. Investigate the effect of using the proposed Robbins & Myers Moyno pump (Model # 3J6-CDR) on the quality of the pumped mortar joint.
9. Determine whether the feedback provided by fluid sensors measuring viscosity and water content in addition to pumping pressure, contribute valuable information in understanding the mortar behavior.
10. Investigate whether using another type of pipe material in the mortar pump assembly with less friction properties would assist in decreasing the friction losses and improve mortar pumping.

11. Study whether pumping more mortar, using a larger nozzle plate opening, would place enough mortar on the bed joint.

12. Investigate the effect of adopting another mixing method and location (e.g., a mixing module attached to the pump hopper) on mortar pumping.

13. Determine the optimal shape and size of a mold that would create a sufficiently stronger bond for the robotic placement method. This would also apply to the shape of the nozzle plate.

14. Determine whether changing the placement method (e.g., vibrating the brick into place) would have a positive effect for creating a better bond.

15. Investigate the validity of the proposed hierarchical control structure.
13.0 LIST OF REFERENCES


Literature from L. C. Pardue Inc. Masonry Panels.


Robinson, G. C. (1986). “Influence of the Type of Mortar in Air Content on Bond Strength.” Research Report, Ceramic Engineering Department, Clemson University, Clemson, SC.


14.0 APPENDICES
The appendices below pertain to the following topics:

14.1 Collected Force-Step Relationships (FSRs):
This appendix presents the original Force-Step Relationships collected using the experimental setup described in Chapter 7.

14.2 Modified Force-Step Relationships (FSRs):
This appendix presents the modified Force-Step Relationships used to obtain the slope values listed in Table 7-2. These relationships were modified from the original curves listed in Appendix 14.1.

14.3 ASTM C1072 Bond Wrench Test Reports:
This appendix presents the test reports for the bond wrench experiments described in Chapter 9.
14.1 Collected Force-Step Relationships (FSRs)

Listed here are the unmodified Force-Step Relationships collected using the experimental setup described in Chapter 7. Figures 14-1 through 14-9 present the collected FSRs for the following mortar thickness values, in inches, respectively: [1/8, 3/16, ¼, 5/16, 3/8, 7/16, ½, 9/16, 5/8]. Refer to section 7.4 for an explanation regarding the graph details.

![Graph of collected FSRs for different mortar thicknesses](image)

Fig. 14-1 Collected FSRs for the 1/8 in. Mortar Thickness
Fig. 14-2 Collected FSRs for the 3/16 in. Mortar Thickness

Fig. 14-3 Collected FSRs for the ¼ in. Mortar Thickness
Fig. 14-4 Collected FSRs for the 5/16 in. Mortar Thickness

Fig. 14-5 Collected FSRs for the 3/8 in. Mortar Thickness
Fig. 14-6 Collected FSRs for the 7/16 in. Mortar Thickness

Fig. 14-7 Collected FSRs for the ½ in. Mortar Thickness
Fig. 14-8 Collected FSRs for the 9/16 in. Mortar Thickness

Fig. 14-9 Collected FSRs for the 5/8 in. Mortar Thickness
14.2 Modified Force-Step Relationships (FSRs)

Listed here are the modified Force-Step Relationships used to obtain the slope values listed in Table 7-2. These relationships were modified from the original curves listed in Appendix 14.1. Refer to section 7.4 for an explanation regarding the graph details. The 1/8 in. collected FSRs (see Fig. 14-1) were not modified since the five slopes varied distinctly. The 3/8 in. collected FSRs are presented and discussed in section 7.4.

Fig. 14-10 shows the modified FSRs for the 3/16 in. mortar thickness. It shows that only tests #1, 4, and 5 were used to calculate the average slope. The slopes for the three tests were computed starting from Step #50 to Step #100. The three slopes were equal to -0.13, -0.16, and -0.16 respectively with an average of -0.15.

![Fig. 14-10 Modified FSRs for the 3/16 in. Mortar Thickness](image-url)
Fig. 14-11 shows the modified FSRs for the ¼ in. mortar thickness. It shows that only tests #3, 4, and 5 were used to calculate the average slope. The slopes for the three tests were computed starting from Step #40 to Step #100. The three slopes were equal to -0.19, -0.15, and -0.17 respectively with an average of -0.17.

Fig. 14-11 Modified FSRs for the ¼ in. Mortar Thickness
Fig. 14-12 shows the modified FSRs for the 5/16 in. mortar thickness. It shows that only tests #2, 3, and 4 were used to calculate the average slope. The slopes for the three tests were computed starting from Step #20 to Step #40. The three slopes were equal to -0.17, -0.17, and -0.20 respectively with an average of -0.18.
Fig. 14-13 shows the modified FSRs for the 7/16 in. mortar thickness. It shows that only tests #2, 3, and 4 were used to calculate the average slope. The slopes for the three tests were computed starting from Step #15 to Step #50. The three slopes were equal to -0.05, -0.05, and -0.04 respectively with an average of -0.05.

![Graph showing modified FSRs](image)

**Fig. 14-13 Modified FSRs for the 7/16 in. Mortar Thickness**
Fig. 14-14 shows the modified FSRs for the ½ in. mortar thickness. It shows that only tests #1, 4, and 5 were used to calculate the average slope. The slopes for the three tests were computed starting from Step #0 to Step #20. The three slopes were equal to -0.13, -0.17, and -0.17 respectively with an average of -0.15.
Fig. 14-15 shows the modified FSRs for the 9/16 in. mortar thickness. It shows that only tests #1 and 2 were used to calculate the average slope. The slopes for the two tests were computed starting from Step #10 to Step #20. The two slopes were equal to -0.32 and -0.45 respectively with an average of -0.39.

![Graph showing modified FSRs for the 9/16 in. mortar thickness.](image)

**Linear Range**

Fig. 14-15 Modified FSRs for the 9/16 in. Mortar Thickness
Fig. 14-16 shows the modified FSRs for the 5/8 in. mortar thickness. It shows that only tests #1, 4, and 5 were used to calculate the average slope. The slopes for the three tests were computed starting from Step #20 to Step #60. The three slopes were equal to -0.08, -0.09, and -0.10 respectively with an average of -0.09.

Fig. 14-16 Modified FSRs for the 5/8 in. Mortar Thickness
14.3 ASTM C1072 Bond Wrench Test Reports

In accordance with Section 9 of ASTM C1072, this appendix presents the Bond Wrench Test Reports for the ten manually placed prisms and the ten robotically placed prisms (using the second mold shown in Fig. 9-6). Manual prisms are designated with an “M” in the “PRISM ID#” section, while robotic prisms are designated with an “R”. Each report contains information on the following:

1. Physical properties of both bricks used in the prism such as: width, depth, height, weight, and initial rate of absorption (IRA).

2. Prism properties such as:
   \[ F_g = \text{gross area flexural tensile strength}, \text{ (psi)} \]
   \[ P = \text{maximum applied load}, \text{ (lbf)} \]
   \[ P_1 = \text{weight of loading arm}, \text{ (lbf)} \]
   \[ L = \text{distance from center of prism to loading point}, \text{ (in.)} \]
   \[ L_1 = \text{distance from center of prism to centroid of loading arm}, \text{ (in.)} \]
   \[ b = \text{average width of cross section of failure surface}, \text{ (in.)} \]
   \[ d = \text{average thickness of cross section of failure surface}, \text{ (in.)} \]

3. Mortar properties such as type and mixture proportions.

4. Description of failure location (i.e., top of mortar joint, bottom of mortar joint, or both).

5. Test description in regard to joint tooling, curing history, and mortar joint thickness.

6. Photograph of the prism post failure.
# Bond Wrench Test Report

**PRISM ID#: 1M**

<table>
<thead>
<tr>
<th>Brick Properties</th>
<th>Mortar Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bottom Brick</strong></td>
<td><strong>Mortar Type:</strong> S</td>
</tr>
<tr>
<td>width (in.) = 7.80</td>
<td>Mix Proportions (by volume):</td>
</tr>
<tr>
<td>depth (in.) = 3.58</td>
<td>C \  L \  S \  W</td>
</tr>
<tr>
<td>height (in.) = 2.28</td>
<td>1 \ 1/2 \ 4-1/2 \ 1-1/2</td>
</tr>
<tr>
<td>weight (lb.) = 3.79</td>
<td></td>
</tr>
<tr>
<td>IRA (gm/min/30in²) = 31.63</td>
<td></td>
</tr>
<tr>
<td><strong>Top Brick</strong></td>
<td></td>
</tr>
<tr>
<td>width (in.) = 7.83</td>
<td></td>
</tr>
<tr>
<td>depth (in.) = 3.54</td>
<td></td>
</tr>
<tr>
<td>height (in.) = 2.24</td>
<td></td>
</tr>
<tr>
<td>weight (lb.) = 3.74</td>
<td></td>
</tr>
<tr>
<td>IRA (gm/min/30in²) = 33.49</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Prism Properties</th>
<th>Description of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (lb.) = 79.05</td>
<td>Failure occurred at:</td>
</tr>
<tr>
<td>P₁ (lb.) = 40.5</td>
<td>top of mortar joint ☑</td>
</tr>
<tr>
<td>L (in.) = 13-3/16</td>
<td>bottom of mortar joint ☐</td>
</tr>
<tr>
<td>L₁ (in.) = 3/16</td>
<td>both ☐</td>
</tr>
<tr>
<td>b (in.) = 7.62</td>
<td></td>
</tr>
<tr>
<td>d (in.) = 3/8</td>
<td></td>
</tr>
<tr>
<td>F₉ (psi) = 5839</td>
<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>Prism Photo:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Tooling:</td>
<td></td>
</tr>
<tr>
<td>Curing History:</td>
<td></td>
</tr>
<tr>
<td>Joint Thickness (in.) = 3/8</td>
<td></td>
</tr>
</tbody>
</table>
### BOND WRENCH TEST REPORT

**PRISM ID#: 2M**

<table>
<thead>
<tr>
<th>• BRICK PROPERTIES:</th>
<th>• MORTAR PROPERTIES:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom Brick</td>
<td>Mortar Type: S</td>
</tr>
<tr>
<td>width (in.) = 7.80</td>
<td>Mix Proportions (by volume):</td>
</tr>
<tr>
<td>depth (in.) = 3.54</td>
<td>C 1/2 4-1/2 1-1/2</td>
</tr>
<tr>
<td>height (in.) = 2.24</td>
<td></td>
</tr>
<tr>
<td>weight (lb.) = 3.78</td>
<td></td>
</tr>
<tr>
<td>IRA (gm/min/30in²) = 32.76</td>
<td></td>
</tr>
<tr>
<td>Top Brick</td>
<td></td>
</tr>
<tr>
<td>width (in.) = 7.80</td>
<td></td>
</tr>
<tr>
<td>depth (in.) = 3.54</td>
<td></td>
</tr>
<tr>
<td>height (in.) = 2.28</td>
<td></td>
</tr>
<tr>
<td>weight (lb.) = 3.75</td>
<td></td>
</tr>
<tr>
<td>IRA (gm/min/30in²) = 31.45</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>• PRISM PROPERTIES:</th>
<th>• DESCRIPTION OF FAILURE:</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (lb.) = 85.41</td>
<td>Failure occurred at:</td>
</tr>
<tr>
<td>P₁ (lb.) = 40.5</td>
<td>top of mortar joint □</td>
</tr>
<tr>
<td>L (in.) = 13-3/16</td>
<td>bottom of mortar joint √</td>
</tr>
<tr>
<td>L₁ (in.) = 3/16</td>
<td>both □</td>
</tr>
<tr>
<td>b (in.) = 7.62</td>
<td></td>
</tr>
<tr>
<td>d (in.) = 3/8</td>
<td></td>
</tr>
<tr>
<td>F₉ (psi) = 6306</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>• DESCRIPTIONS:</th>
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</thead>
<tbody>
<tr>
<td>Joint Tooling: None</td>
</tr>
<tr>
<td>Curing History: 7 days</td>
</tr>
</tbody>
</table>

| • PRISM PHOTO: | |
|----------------|
## BOND WRENCH TEST REPORT

**PRISM ID#: 3M**

### BRICK PROPERTIES:

<table>
<thead>
<tr>
<th>Brick</th>
<th>Width (in.)</th>
<th>Depth (in.)</th>
<th>Height (in.)</th>
<th>Weight (lb.)</th>
<th>IRA (gm/min/30in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom Brick</td>
<td>7.76</td>
<td>3.54</td>
<td>2.24</td>
<td>3.76</td>
<td>20.86</td>
</tr>
<tr>
<td>Top Brick</td>
<td>7.72</td>
<td>3.62</td>
<td>2.20</td>
<td>3.79</td>
<td>25.28</td>
</tr>
</tbody>
</table>

### MORTAR PROPERTIES:

- **Mortar Type:** S
- Mix Proportions (by volume):
  - C
  - L
  - S
  - W
  - 1
  - 1/2
  - 4-1/2
  - 1-1/2

### PRISM PROPERTIES:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>P (lb.)</td>
<td>86.16</td>
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<tr>
<td>P₁ (lb.)</td>
<td>40.5</td>
</tr>
<tr>
<td>L (in.)</td>
<td>13-3/16</td>
</tr>
<tr>
<td>L₁ (in.)</td>
<td>3/16</td>
</tr>
<tr>
<td>b (in.)</td>
<td>7.62</td>
</tr>
<tr>
<td>d (in.)</td>
<td>3/8</td>
</tr>
<tr>
<td>Fg (psi)</td>
<td>6362</td>
</tr>
</tbody>
</table>

### DESCRIPTION OF FAILURE:

- Failure occurred at:
  - top of mortar joint **✓**
  - bottom of mortar joint **☐**
  - both **☐**

### DESCRIPTIONS:

- Joint Tooling: None
- Curing History: 7 days
- Joint Thickness (in.) = 3/8

---

**PRISM PHOTO:**

![Prism Image](image-url)
**BOND WRENCH TEST REPORT**

### BRICK PROPERTIES:

<table>
<thead>
<tr>
<th></th>
<th>Bottom Brick</th>
<th>Top Brick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width (in.)</td>
<td>7.76</td>
<td>7.76</td>
</tr>
<tr>
<td>Depth (in.)</td>
<td>3.62</td>
<td>3.74</td>
</tr>
<tr>
<td>Height (in.)</td>
<td>2.24</td>
<td>2.28</td>
</tr>
<tr>
<td>Weight (lb.)</td>
<td>3.75</td>
<td>3.76</td>
</tr>
<tr>
<td>IRA (gm/min/30in²)</td>
<td>20.55</td>
<td>31.47</td>
</tr>
</tbody>
</table>

### MORTAR PROPERTIES:

- **Mortar Type:** S
- **Mix Proportions (by volume):**
  - C
  - L
  - S
  - W

### PRISM PROPERTIES:

- **P (lb.):** 84.22
- **P₁ (lb.):** 40.5
- **L (in.):** 13-3/16
- **L₁ (in.):** 3/16
- **b (in.):** 7.62
- **d (in.):** 3/8
- **Fg (psi):** 6219

### DESCRIPTIONS:

- **Joint Tooling:** None
- **Curing History:** 7 days
- **Joint Thickness (in.):** 3/8

### PRISM PHOTO:

![Prism Photograph](image)
## BOND WRENCH TEST REPORT

**PRISM ID#: 5M**

### • BRICK PROPERTIES:

<table>
<thead>
<tr>
<th>Bottom Brick</th>
<th>width (in.) = 7.76</th>
<th>depth (in.) = 3.54</th>
<th>height (in.) = 2.24</th>
<th>weight (lb.) = 3.71</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IRA (gm/min/30in²) = 29.99</td>
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</table>

<table>
<thead>
<tr>
<th>Top Brick</th>
<th>width (in.) = 7.80</th>
<th>depth (in.) = 3.62</th>
<th>height (in.) = 2.24</th>
<th>weight (lb.) = 3.74</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IRA (gm/min/30in²) = 31.56</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### • MORTAR PROPERTIES:

| Mortar Type: S |
| Mix Proportions (by volume): |
| C L S W |
| 1 1/2 4-1/2 1-1/2 |

### • PRISM PROPERTIES:

| P (lb.) = 102.30 |
| P1 (lb.) = 40.5 |
| L (in.) = 13-3/16 |
| L1 (in.) = 3/16 |
| b (in.) = 7.62 |
| d (in.) = 3/8 |
| Fg (psi) = 7548 |

### • DESCRIPTION OF FAILURE:

- Failure occurred at:
  - top of mortar joint ✓
  - bottom of mortar joint □
  - both □

### • DESCRIPTIONS:

- Joint Tooling: None
- Curing History: 7 days
- Joint Thickness (in.) = 3/8

### • PRISM PHOTO:
### BOND WRENCH TEST REPORT

**PRISM ID#: 6M**

<table>
<thead>
<tr>
<th>BRICK PROPERTIES:</th>
<th>MORTAR PROPERTIES:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom Brick</td>
<td>Mortar Type: S</td>
</tr>
<tr>
<td>width (in.) = 7.80</td>
<td>Mix Proportions (by volume):</td>
</tr>
<tr>
<td>depth (in.) = 3.62</td>
<td>C  L  S  W</td>
</tr>
<tr>
<td>height (in.) = 2.24</td>
<td>1  1/2  4-1/2  1-1/2</td>
</tr>
<tr>
<td>weight (lb.) = 3.73</td>
<td>IRA (gm/min/30in²) = 34.09</td>
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<tr>
<td>IRA (gm/min/30in²) = 34.09</td>
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</tr>
<tr>
<td>Top Brick</td>
<td></td>
</tr>
<tr>
<td>width (in.) = 7.80</td>
<td></td>
</tr>
<tr>
<td>depth (in.) = 3.62</td>
<td></td>
</tr>
<tr>
<td>height (in.) = 2.24</td>
<td></td>
</tr>
<tr>
<td>weight (lb.) = 3.76</td>
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</tr>
<tr>
<td>IRA (gm/min/30in²) = 31.91</td>
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<th>DESCRIPTION OF FAILURE:</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (lb.) = 42.87</td>
<td>Failure occurred at:</td>
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<td>P₁ (lb.) = 40.5</td>
<td>top of mortar joint □</td>
</tr>
<tr>
<td>L (in.) = 13-3/16</td>
<td>bottom of mortar joint ✔</td>
</tr>
<tr>
<td>L₁ (in.) = 3/16</td>
<td>both □</td>
</tr>
<tr>
<td>b (in.) = 7.62</td>
<td></td>
</tr>
<tr>
<td>d (in.) = 3/8</td>
<td></td>
</tr>
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<td>F₉ (psi) = 3180</td>
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<td>Joint Tooling: None</td>
<td></td>
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<tr>
<td>Curing History: 7 days</td>
<td></td>
</tr>
<tr>
<td>Joint Thickness (in.) = 3/8</td>
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</table>
### BOND WRENCH TEST REPORT

**PRISM ID#: 7M**

#### BRICK PROPERTIES:

<table>
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<tr>
<th>Bottom Brick</th>
<th>width (in.)</th>
<th>7.87</th>
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<td></td>
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<td>height (in.)</td>
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<td>weight (lb.)</td>
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</tr>
<tr>
<td></td>
<td>IRA (gm/min/30in²)</td>
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<table>
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<th>7.76</th>
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</thead>
<tbody>
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<td></td>
<td>depth (in.)</td>
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<tr>
<td></td>
<td>height (in.)</td>
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<tr>
<td></td>
<td>weight (lb.)</td>
<td>3.73</td>
</tr>
<tr>
<td></td>
<td>IRA (gm/min/30in²)</td>
<td>36.03</td>
</tr>
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#### MORTAR PROPERTIES:

- Mortar Type: S
- Mix Proportions (by volume):
  - C 1
  - L 1/2
  - S 4-1/2
  - W 1-1/2

#### PRISM PROPERTIES:

- P (lb.) = 65.51
- P₁ (lb.) = 40.5
- L (in.) = 13-3/16
- L₁ (in.) = 3/16
- b (in.) = 7.62
- d (in.) = 3/8
- F₉ (psi) = 4844

#### DESCRIPTION OF FAILURE:

Failure occurred at:
- top of mortar joint  □
- bottom of mortar joint  ✓
- both  □

#### DESCRIPTIONS:

- Joint Tooling: None
- Curing History: 7 days
- Joint Thickness (in.) = 3/8

#### PRISM PHOTO:
# BOND WRENCH TEST REPORT

## BRICK PROPERTIES:

<table>
<thead>
<tr>
<th>Bottom Brick</th>
<th>Top Brick</th>
</tr>
</thead>
<tbody>
<tr>
<td>width (in.)</td>
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<td>depth (in.)</td>
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<tr>
<td>weight (lb.)</td>
<td>3.75</td>
</tr>
<tr>
<td>IRA (gm/min/30in²)</td>
<td>37.05</td>
</tr>
</tbody>
</table>

## MORTAR PROPERTIES:

- Mortar Type: S
- Mix Proportions (by volume):
  - C: 1
  - L: 1/2
  - S: 4-1/2
  - W: 1-1/2

## PRISM PROPERTIES:

<table>
<thead>
<tr>
<th>P (lb.)</th>
<th>71.27</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₁ (lb.)</td>
<td>40.5</td>
</tr>
<tr>
<td>L (in.)</td>
<td>13-3/16</td>
</tr>
<tr>
<td>L₁ (in.)</td>
<td>3/16</td>
</tr>
<tr>
<td>b (in.)</td>
<td>7.62</td>
</tr>
<tr>
<td>d (in.)</td>
<td>3/8</td>
</tr>
<tr>
<td>F₉ (psi)</td>
<td>5267</td>
</tr>
</tbody>
</table>

## DESCRIPTION OF FAILURE:

- Failure occurred at:
  - top of mortar joint: ☑
  - bottom of mortar joint: ☐
  - both: ☐

## DESCRIPTIONS:

- Joint Tooling: None
- Curing History: 7 days
- Joint Thickness (in.): 3/8
## BOND WRENCH TEST REPORT

**PRISM ID#: 9M**

<table>
<thead>
<tr>
<th>• BRICK PROPERTIES:</th>
<th>• MORTAR PROPERTIES:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom Brick</td>
<td></td>
</tr>
<tr>
<td>width (in.) = 7.87</td>
<td>Mortar Type: S</td>
</tr>
<tr>
<td>depth (in.) = 3.54</td>
<td>Mix Proportions (by volume):</td>
</tr>
<tr>
<td>height (in.) = 2.28</td>
<td>C  L  S  W</td>
</tr>
<tr>
<td>weight (lb.) = 3.77</td>
<td>1  1/2  4-1/2  1-1/2</td>
</tr>
<tr>
<td>IRA (gm/min/30in²) = 37.13</td>
<td></td>
</tr>
<tr>
<td>Top Brick</td>
<td></td>
</tr>
<tr>
<td>width (in.) = 7.72</td>
<td></td>
</tr>
<tr>
<td>depth (in.) = 3.50</td>
<td></td>
</tr>
<tr>
<td>height (in.) = 2.24</td>
<td></td>
</tr>
<tr>
<td>weight (lb.) = 3.76</td>
<td></td>
</tr>
<tr>
<td>IRA (gm/min/30in²) = 11.96</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>• PRISM PROPERTIES:</th>
<th>• DESCRIPTION OF FAILURE:</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (lb.) = 42.55</td>
<td>Failure occurred at:</td>
</tr>
<tr>
<td>P₁ (lb.) = 40.5</td>
<td>top of mortar joint ☑</td>
</tr>
<tr>
<td>L (in.) = 13-3/16</td>
<td>bottom of mortar joint □</td>
</tr>
<tr>
<td>L₁ (in.) = 3/16</td>
<td>both □</td>
</tr>
<tr>
<td>b (in.) = 7.62</td>
<td></td>
</tr>
<tr>
<td>d (in.) = 3/8</td>
<td></td>
</tr>
<tr>
<td>F_g (psi) = 3156</td>
<td></td>
</tr>
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</table>

**• DESCRIPTIONS:**
- Joint Tooling: None
- Curing History: 7 days
- Joint Thickness (in.) = 3/8

**• PRISM PHOTO:**

![Image of brick and mortar joint]
### BOND WRENCH TEST REPORT

**PRISM ID#: 10M**

**• BRICK PROPERTIES:**

- **Bottom Brick**
  - width (in.) = 7.87
  - depth (in.) = 3.54
  - height (in.) = 2.24
  - weight (lb.) = 3.74
  - IRA (gm/min/30in²) = 35.85

- **Top Brick**
  - width (in.) = 7.87
  - depth (in.) = 3.54
  - height (in.) = 2.24
  - weight (lb.) = 3.76
  - IRA (gm/min/30in²) = 33.29

**• MORTAR PROPERTIES:**

- Mortar Type: S
- Mix Proportions (by volume):
  
<table>
<thead>
<tr>
<th>C</th>
<th>L</th>
<th>S</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1/2</td>
<td>4-1/2</td>
<td>1-1/2</td>
</tr>
</tbody>
</table>

**• PRISM PROPERTIES:**

- P (lb.) = 45.61
- P₁ (lb.) = 40.5
- L (in.) = 13-3/16
- L₁ (in.) = 3/16
- b (in.) = 7.62
- d (in.) = 3/8
- F₉ (psi) = 3381

**• DESCRIPTION OF FAILURE:**

- Failure occurred at:
  - top of mortar joint  □
  - bottom of mortar joint  ☑
  - both  □

**• DESCRIPTIONS:**

- Joint Tooling: None
- Curing History: 7 days
- Joint Thickness (in.) = 3/8

**• PRISM PHOTO:**

![Prism photo](image-url)
### BOND WRENCH TEST REPORT

**PRISM ID#: 1R**

<table>
<thead>
<tr>
<th>• BRICK PROPERTIES:</th>
<th>• MORTAR PROPERTIES:</th>
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</thead>
<tbody>
<tr>
<td>Bottom Brick</td>
<td>Mortar Type: S</td>
</tr>
<tr>
<td>width (in.) = 7.68</td>
<td>Mix Proportions (by volume):</td>
</tr>
<tr>
<td>depth (in.) = 3.54</td>
<td>C</td>
</tr>
<tr>
<td>height (in.) = 2.28</td>
<td>L</td>
</tr>
<tr>
<td>weight (lb.) = 3.74</td>
<td>S</td>
</tr>
<tr>
<td>IRA (gm/min/30in²) = 23.76</td>
<td>W</td>
</tr>
<tr>
<td>Top Brick</td>
<td></td>
</tr>
<tr>
<td>width (in.) = 7.76</td>
<td></td>
</tr>
<tr>
<td>depth (in.) = 3.50</td>
<td></td>
</tr>
<tr>
<td>height (in.) = 2.24</td>
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</tr>
<tr>
<td>weight (lb.) = 3.71</td>
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<tr>
<td>IRA (gm/min/30in²) = 27.05</td>
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<table>
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<tr>
<th>• PRISM PROPERTIES:</th>
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<tbody>
<tr>
<td>P (lb.) = 20.24</td>
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<tr>
<td>P₁ (lb.) = 40.5</td>
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<tr>
<td>L (in.) = 13-3/16</td>
</tr>
<tr>
<td>L₁ (in.) = 3/16</td>
</tr>
<tr>
<td>b (in.) = 7</td>
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<tr>
<td>d (in.) = 3/8</td>
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<tr>
<td>F_g (psi) = 1650</td>
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<table>
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<tr>
<th>• DESCRIPTION OF FAILURE:</th>
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<tbody>
<tr>
<td>Failure occurred at:</td>
</tr>
<tr>
<td>top of mortar joint ✓</td>
</tr>
<tr>
<td>bottom of mortar joint □</td>
</tr>
<tr>
<td>both □</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>• DESCRIPTIONS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint Tooling:</td>
</tr>
<tr>
<td>None</td>
</tr>
<tr>
<td>Curing History:</td>
</tr>
<tr>
<td>7 days</td>
</tr>
</tbody>
</table>

| Joint Thickness (in.) = 3/8 |

---

**PRISM PHOTO:**

![Prism Test Photo]
### BOND WRENCH TEST REPORT

<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td><strong>BRICK PROPERTIES:</strong></td>
<td><strong>MORTAR PROPERTIES:</strong></td>
<td></td>
</tr>
<tr>
<td>Bottom Brick</td>
<td>width (in.) = 7.83</td>
<td>Mortar Type: S</td>
</tr>
<tr>
<td></td>
<td>depth (in.) = 3.62</td>
<td>Mix Proportions (by volume):</td>
</tr>
<tr>
<td></td>
<td>height (in.) = 2.28</td>
<td>C 1/2 4-1/2 1-1/2</td>
</tr>
<tr>
<td></td>
<td>weight (lb.) = 3.77</td>
<td>IRA (gm/min/30in²) = 33.76</td>
</tr>
<tr>
<td></td>
<td>IRA (gm/min/30in²) = 33.76</td>
<td></td>
</tr>
<tr>
<td>Top Brick</td>
<td>width (in.) = 7.83</td>
<td></td>
</tr>
<tr>
<td></td>
<td>depth (in.) = 3.58</td>
<td></td>
</tr>
<tr>
<td></td>
<td>height (in.) = 2.28</td>
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</tr>
<tr>
<td></td>
<td>weight (lb.) = 3.81</td>
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<tr>
<td></td>
<td>IRA (gm/min/30in²) = 32.14</td>
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<td><strong>DESCRIPTION OF FAILURE:</strong></td>
<td></td>
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<tr>
<td></td>
<td>P (lb.) = 37.68</td>
<td>Failure occurred at:</td>
</tr>
<tr>
<td></td>
<td>P₁ (lb.) = 40.5</td>
<td>top of mortar joint  □</td>
</tr>
<tr>
<td></td>
<td>L (in.) = 13-3/16</td>
<td>bottom of mortar joint ☑</td>
</tr>
<tr>
<td></td>
<td>L₁ (in.) = 3/16</td>
<td>both  □</td>
</tr>
<tr>
<td></td>
<td>b (in.) = 7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d (in.) = 3/8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fg (psi) = 3045</td>
<td>Joint Tooling: None</td>
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<tr>
<td><strong>DESCRIPTIONS:</strong></td>
<td>Curing History: 7 days</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Joint Thickness (in.) = 3/8</td>
<td></td>
</tr>
<tr>
<td><strong>PRISM PHOTO:</strong></td>
<td></td>
<td><img src="image_url" alt="Image" /></td>
</tr>
</tbody>
</table>
# Bond Wrench Test Report

**Prism ID#: 3R**

## Brick Properties:
- **Bottom Brick**
  - Width (in.): 7.80
  - Depth (in.): 3.58
  - Height (in.): 2.24
  - Weight (lb.): 3.78
  - IRA (gm/min/30in²): 32.71

- **Top Brick**
  - Width (in.): 7.83
  - Depth (in.): 3.70
  - Height (in.): 2.28
  - Weight (lb.): 3.74
  - IRA (gm/min/30in²): 22.02

## Mortar Properties:
- **Mortar Type:** S
- **Mix Proportions (by volume):**
  - C: 1
  - L: 1/2
  - S: 4-1/2
  - W: 1-1/2

## Prism Properties:
- **P (lb.):** 27.64
- **P₁ (lb.):** 40.5
- **L (in.):** 13-3/16
- **L₁ (in.):** 3/16
- **b (in.):** 7
- **d (in.):** 3/8
- **F₉ (psi):** 2242

## Description of Failure:
- Failure occurred at:
  - Top of mortar joint: ✅
  - Bottom of mortar joint: ⬜
  - Both: ⬜

## Descriptions:
- **Joint Tooling:** None
- **Curing History:** 7 days
- **Joint Thickness (in.):** 3/8

## Prism Photo:
![Prism Photo](image-url)
### BOND WRENCH TEST REPORT

<table>
<thead>
<tr>
<th>BRICK PROPERTIES:</th>
<th>MORTAR PROPERTIES:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom Brick</td>
<td></td>
</tr>
<tr>
<td>width (in.)</td>
<td>7.76</td>
</tr>
<tr>
<td>depth (in.)</td>
<td>3.62</td>
</tr>
<tr>
<td>height (in.)</td>
<td>2.24</td>
</tr>
<tr>
<td>weight (lb.)</td>
<td>3.74</td>
</tr>
<tr>
<td>IRA (gm/min/30in²)</td>
<td>28.25</td>
</tr>
</tbody>
</table>

| Top Brick         |                   |
| width (in.)       | 7.76              |
| depth (in.)       | 3.58              |
| height (in.)      | 2.28              |
| weight (lb.)      | 3.75              |
| IRA (gm/min/30in²)| 30.88             |

<table>
<thead>
<tr>
<th>PRISM PROPERTIES:</th>
<th>DESCRIPTION OF FAILURE:</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (lb.)</td>
<td>Failure occurred at:</td>
</tr>
<tr>
<td></td>
<td>top of mortar joint</td>
</tr>
<tr>
<td>P₁ (lb.)</td>
<td>bottom of mortar joint</td>
</tr>
<tr>
<td>L (in.)</td>
<td>both</td>
</tr>
<tr>
<td>L₁ (in.)</td>
<td></td>
</tr>
<tr>
<td>b (in.)</td>
<td>7</td>
</tr>
<tr>
<td>d (in.)</td>
<td>3/8</td>
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<tr>
<td>F₉ (psi)</td>
<td>832</td>
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</table>

<table>
<thead>
<tr>
<th>MORTAR PROPERTIES:</th>
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</thead>
<tbody>
<tr>
<td>Mortar Type: S</td>
</tr>
<tr>
<td>Mix Proportions (by volume):</td>
</tr>
<tr>
<td>C L S W</td>
</tr>
<tr>
<td>1 1/2 4-1/2 1-1/2</td>
</tr>
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<table>
<thead>
<tr>
<th>DESCRIPTIONS:</th>
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</thead>
<tbody>
<tr>
<td>Joint Tooling: None</td>
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<tr>
<td>Curing History: 7 days</td>
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</table>

<table>
<thead>
<tr>
<th>PRISM PHOTO:</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Prism Image]</td>
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</tbody>
</table>
## BOND WRENCH TEST REPORT

- **PRISM ID#: 5R**

### BRICK PROPERTIES:

<table>
<thead>
<tr>
<th>Bottom Brick</th>
<th></th>
<th>Top Brick</th>
</tr>
</thead>
<tbody>
<tr>
<td>width (in.)</td>
<td>7.76</td>
<td>7.87</td>
</tr>
<tr>
<td>depth (in.)</td>
<td>3.50</td>
<td>3.54</td>
</tr>
<tr>
<td>height (in.)</td>
<td>2.24</td>
<td>2.28</td>
</tr>
<tr>
<td>weight (lb.)</td>
<td>3.63</td>
<td>3.75</td>
</tr>
<tr>
<td>IRA (gm/min/30in²)</td>
<td>27.05</td>
<td>36.25</td>
</tr>
</tbody>
</table>

### MORTAR PROPERTIES:

- Mortar Type: S
- Mix Proportions (by volume):
  - C 1
  - L 1/2
  - S 4-1/2
  - W 1-1/2

### PRISM PROPERTIES:

- **P (lb.)** = 19.23
- **P₁ (lb.)** = 40.5
- **L (in.)** = 13-3/16
- **L₁ (in.)** = 3/16
- **b (in.)** = 7
- **d (in.)** = 3/8
- **F₉ (psi)** = 1569

### DESCRIPTION OF FAILURE:

- Failure occurred at:
  - top of mortar joint ✓
  - bottom of mortar joint □
  - both □

### DESCRIPTIONS:

- Joint Tooling: None
- Curing History: 7 days
- Joint Thickness (in.) = 3/8

### PRISM PHOTO:
# BOND WRENCH TEST REPORT

**PRISM ID#: 6R**

## BRICK PROPERTIES:
- **Bottom Brick**
  - width (in.) = 7.95
  - depth (in.) = 3.50
  - height (in.) = 2.28
  - weight (lb.) = 3.68
  - IRA (gm/min/30in²) = 39.36

- **Top Brick**
  - width (in.) = 7.80
  - depth (in.) = 3.54
  - height (in.) = 2.28
  - weight (lb.) = 3.75
  - IRA (gm/min/30in²) = 30.50

## MORTAR PROPERTIES:
- **Mortar Type**: S
- **Mix Proportions (by volume)**:
  - C: 1
  - L: 1/2
  - S: 4-1/2
  - W: 1-1/2

## PRISM PROPERTIES:
- **P (lb.)** = 34.40
- **P₁ (lb.)** = 40.5
- **L (in.)** = 13-3/16
- **L₁ (in.)** = 3/16
- **b (in.)** = 7
- **d (in.)** = 3/8
- **Fₐ (psi)** = 2783

## DESCRIPTION OF FAILURE:
- Failure occurred at:
  - top of mortar joint: □
  - bottom of mortar joint: ☑
  - both: □

## DESCRIPTIONS:
- **Joint Tooling**: None
- **Curing History**: 7 days
- **Joint Thickness (in.)** = 3/8
**BOND WRENCH TEST REPORT**

**PRISM ID#: 7R**

<table>
<thead>
<tr>
<th><strong>• BRICK PROPERTIES:</strong></th>
<th><strong>• MORTAR PROPERTIES:</strong></th>
</tr>
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<tbody>
<tr>
<td><strong>Bottom Brick</strong></td>
<td></td>
</tr>
<tr>
<td>width (in.) = 7.83</td>
<td>Mortar Type: S</td>
</tr>
<tr>
<td>depth (in.) = 3.54</td>
<td>Mix Proportions (by volume):</td>
</tr>
<tr>
<td>height (in.) = 2.24</td>
<td>C  L  S  W</td>
</tr>
<tr>
<td>weight (lb.) = 3.73</td>
<td>1  1/2  4-1/2  1-1/2</td>
</tr>
<tr>
<td>IRA (gm/min/30in²) = 31.26</td>
<td></td>
</tr>
</tbody>
</table>

| **Top Brick**          |                          |
| width (in.) = 7.76     |                          |
| depth (in.) = 3.58     |                          |
| height (in.) = 2.24    |                          |
| weight (lb.) = 3.74    |                          |
| IRA (gm/min/30in²) = 17.11 |

<table>
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<tr>
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<th><strong>• DESCRIPTION OF FAILURE:</strong></th>
<th><strong>• DESCRIPTIONS:</strong></th>
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<tbody>
<tr>
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<td>Failure occurred at:</td>
<td>Joint Tooling:</td>
</tr>
<tr>
<td>P₁ (lb.) = 40.5</td>
<td>top of mortar joint  ✓</td>
<td>None</td>
</tr>
<tr>
<td>L (in.) = 13-3/16</td>
<td>bottom of mortar joint  ☐</td>
<td>Curing History:</td>
</tr>
<tr>
<td>L₁ (in.) = 3/16</td>
<td>both  ☐</td>
<td>7 days</td>
</tr>
<tr>
<td>b (in.) = 7</td>
<td></td>
<td>Joint Thickness (in.) = 3/8</td>
</tr>
<tr>
<td>d (in.) = 3/8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F₉ (psi) = 4864</td>
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</table>

| **• PRISM PHOTO:**     |                          |                    |
**BOND WRENCH TEST REPORT**

<table>
<thead>
<tr>
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<th>PRISM ID#: 8R</th>
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</thead>
<tbody>
<tr>
<td>Bottom Brick</td>
<td></td>
</tr>
<tr>
<td>width (in.) = 7.72</td>
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<tr>
<td>depth (in.) = 3.50</td>
<td></td>
</tr>
<tr>
<td>height (in.) = 2.24</td>
<td></td>
</tr>
<tr>
<td>weight (lb.) = 3.73</td>
<td></td>
</tr>
<tr>
<td>IRA (gm/min/30in²) = 14.97</td>
<td></td>
</tr>
</tbody>
</table>

| Top Brick                              |               |
| width (in.) = 7.76                     |               |
| depth (in.) = 3.54                     |               |
| height (in.) = 2.24                    |               |
| weight (lb.) = 3.75                    |               |
| IRA (gm/min/30in²) = 16.01             |               |

| MORTAR PROPERTIES:                     |               |
| Mortar Type: S                        |               |
| Mix Proportions (by volume):           |               |
| C L S W                                |               |
| 1 1/2 4-1/2 1-1/2                     |               |

| PRISM PROPERTIES:                      |               |
| P (lb.) = 70.64                        |               |
| P₁ (lb.) = 40.5                        |               |
| L (in.) = 13-3/16                      |               |
| L₁ (in.) = 3/16                        |               |
| b (in.) = 7                            |               |
| d (in.) = 3/8                          |               |
| Fₙ (psi) = 5682                        |               |

| DESCRIPTION OF FAILURE:                |               |
| Failure occurred at:                   |               |
| top of mortar joint ☑                  |               |
| bottom of mortar joint                 |               |
| both □                                 |               |

| DESCRIPTIONS:                          |               |
| Joint Tooling: None                    |               |
| Curing History: 7 days                 |               |
| Joint Thickness (in.) = 3/8            |               |

**PRISM PHOTO:**

![PRISM PHOTO](image-url)
# BOND WRENCH TEST REPORT

<table>
<thead>
<tr>
<th>PRISM ID#: 9R</th>
</tr>
</thead>
</table>

## BRICK PROPERTIES:

<table>
<thead>
<tr>
<th>Bottom Brick</th>
<th>Top Brick</th>
</tr>
</thead>
<tbody>
<tr>
<td>width (in.) = 7.87</td>
<td>width (in.) = 7.83</td>
</tr>
<tr>
<td>depth (in.) = 3.54</td>
<td>depth (in.) = 3.54</td>
</tr>
<tr>
<td>height (in.) = 2.28</td>
<td>height (in.) = 2.28</td>
</tr>
<tr>
<td>weight (lb.) = 3.76</td>
<td>weight (lb.) = 3.73</td>
</tr>
<tr>
<td>IRA (gm/min/30in²) = 34.96</td>
<td>IRA (gm/min/30in²) = 31.26</td>
</tr>
</tbody>
</table>

## MORTAR PROPERTIES:

<table>
<thead>
<tr>
<th>Mortar Type: S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix Proportions (by volume):</td>
</tr>
<tr>
<td>C L S W</td>
</tr>
<tr>
<td>1 1/2 4-1/2 1-1/2</td>
</tr>
</tbody>
</table>

## PRISM PROPERTIES:

<table>
<thead>
<tr>
<th>P (lb.) = 54.61</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_l (lb.) = 40.5</td>
</tr>
<tr>
<td>L (in.) = 13-3/16</td>
</tr>
<tr>
<td>L_l (in.) = 3/16</td>
</tr>
<tr>
<td>b (in.) = 7</td>
</tr>
<tr>
<td>d (in.) = 3/8</td>
</tr>
<tr>
<td>F_g (psi) = 4400</td>
</tr>
</tbody>
</table>

## DESCRIPTION OF FAILURE:

Failure occurred at:
- top of mortar joint
- bottom of mortar joint
- both

## DESCRIPTIONS:

- Joint Tooling: None
- Curing History: 7 days
- Joint Thickness (in.) = 3/8

## PRISM PHOTO:
<table>
<thead>
<tr>
<th>BRICK PROPERTIES:</th>
<th>MORTAR PROPERTIES:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bottom Brick</strong></td>
<td><strong>Mortar Type:</strong> S</td>
</tr>
<tr>
<td>width (in.) = 7.87</td>
<td>Mix Proportions (by volume):</td>
</tr>
<tr>
<td>depth (in.) = 3.58</td>
<td>C 1/2 4-1/2 1-1/2</td>
</tr>
<tr>
<td>height (in.) = 2.28</td>
<td></td>
</tr>
<tr>
<td>weight (lb.) = 3.76</td>
<td></td>
</tr>
<tr>
<td>IRA (gm/min/30in²) = 33.60</td>
<td></td>
</tr>
</tbody>
</table>

| **Top Brick**           |                           |
| width (in.) = 7.87       |                           |
| depth (in.) = 3.54       |                           |
| height (in.) = 2.28      |                           |
| weight (lb.) = 3.75      |                           |
| IRA (gm/min/30in²) = 34.06 |                         |

<table>
<thead>
<tr>
<th>PRISM PROPERTIES:</th>
<th>DESCRIPTION OF FAILURE:</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (lb.) = 39.57</td>
<td>Failure occurred at:</td>
</tr>
<tr>
<td>P₁ (lb.) = 40.5</td>
<td>top of mortar joint □</td>
</tr>
<tr>
<td>L (in.) = 13-3/16</td>
<td>bottom of mortar joint ✓</td>
</tr>
<tr>
<td>L₁ (in.) = 3/16</td>
<td>both □</td>
</tr>
<tr>
<td>b (in.) = 7</td>
<td></td>
</tr>
<tr>
<td>d (in.) = 3/8</td>
<td></td>
</tr>
<tr>
<td>Fₑ (psi) = 3196</td>
<td></td>
</tr>
</tbody>
</table>

| DESCRIPTIONS:           |                              |
| Joint Tooling: None     |                              |
| Curing History: 7 days  |                              |
| Joint Thickness (in.) = 3/8 |                          |