BOND STRENGTH MEASUREMENTS FROM A TAMU UNBALANCED BOND WRENCH IN COMPARISON TO BRICK PRISM ASTM E518 BEAM TEST

A Thesis

by

ANKIT KATIYAR

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	John M. Nichols
Committee Members,	Edelmiro Escamilla Kevin T. Glowacki
Head of Department,	Joseph P. Horlen

August 2015

Major Subject: Construction Management

ABSTRACT

The bond strength of the masonry unit is an important characteristic affecting its performance under different loading conditions, including shear and flexural loading. Bond strength of brick masonry is confirmed experimentally using a variety of techniques, including the bond wrench. Four bond wrenches have been built at TAMU over the last five years. In 2010 a lightweight unbalanced and a balanced bond wrench was developed. An Australian Standard Bond Wrench was manufactured in 2011 and in 2012 an ASTM C 1072 Bond Wrench was developed.

Numerous researchers have conducted experiments to study the bias between different bond wrenches. These studies illustrated that no unacceptable bias existed in the flexural strength values calculated using the TAMU balanced and unbalanced wrench. However there existed a bias between American Bond Wrench and Australian Bond wrenches according to research. This thesis aims at understanding the bias between Unbalanced Bond Wrench developed at Texas A&M University and Standard ASTM E518 beam test method.

This experimental research uses Portland cement and a total of 50 prisms was built in two sets. Each prism comprised of six bricks with five joints, and all the bricks used were Texan bricks. The mortar used here was 1:1:6. The samples were cured for a period of 28 days, and all the experiments were carried out under same weather conditions. TAMU Unbalanced Bond Wrench was used to test the first set of prisms and second set of prisms were tested using standard ASTM E518 beam method.

A t-Test analysis was run between the flexural strength values of the TAMU unbalanced wrench and ASTM E518 method. From the plots, it can be inferred that the mean value of the American standard was low when compared with the mean values of the Unbalanced Bond Wrench. The plots of ASTM E518 method and TAMU unbalanced were quite dissimilar.

Further research is recommended using the Texas red brick.

ACKNOWLEDGEMENTS

I would like to express my sincere thanks and respect to my Chair Dr. John M. Nichols and my committee members Dr. Kevin Glowacki and Dr. Edelmiro Escamilla for their guidance and support they have given me to conduct this research successfully.

I would like to thank my colleagues, Rishav Choudhary, Rajath Kengeri, Navaneeeth Gowda, Sai Anirudh Challa and Rushabh Khinvasara for helping me out in casting. Also, the testing would not have been completed without the help of Nikhil Ranka, Saumya Thakur, Vaarun Chajjed, Nishant Gupta, Adnan Ali and Karan Chugh.

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CHAPTER I

INTRODUCTION

Background

This research provides a direct comparison of the flexural test results for the ASTM E518 Beam Test and the TAMU Unbalanced Bond Wrench test. Flexural bond strength results are reported for many different types of bricks and mortar combinations from studies taken all over the world, including Australia (S. J. Lawrence, 1994; Nichols, 2000; Page, 1983; Sugo, 2000), Italy (Baronio, Binda, Tedeschi, & Tiraboschi, 2003; L. Binda, 2008; L. Binda, Saisi, & Tiraboschi, 2000), Canada (Sise, Shrive, & Jessop, 1988) and the USA. The central question is whether two bond wrenches yield the same results for a sample of bricks of consistent properties.

Masonry systems are an essential part of a structure & several masonry units and masonry mortars join to form masonry systems. These masonry systems influence both structural integrity and weather resistance for a structure. The important factor in the performance of a masonry system is the Bond strength between mortar and masonry unit (Coombs, 2007). This research provides a direct comparison of the flexural test results for the ASTM E518 Beam Test “Standard Test Method for Flexural Bond Strength of Masonry” and the TAMU Unbalanced Bond Wrench test.

This research builds on the bias research work by Chaudhari (2010) who studied the flexural test results for a balanced wrench and an unbalanced wrench, and Nichols (2013), McHargue (2013) & Suresh (2014) who studied the bias results for flexural strength from four different bond wrenches on a consistent masonry unit. Students at Texas A&M University had previously built a lightweight TAMU balanced and Unbalanced Bond Wrench to measure the bond strength of masonry systems. The purpose of this research is to take the previous researches to the next level and compare the bias and accuracy between ASTM E518 method and TAMU Unbalanced Bond Wrench to measure the bond strength for a masonry unit.

Problem statement

The purpose of this research is to determine if a statistical difference exists between the mean flexural strength results for the ASTM E518 beam test and the TAMU Unbalanced Bond Wrench test.

Hypothesis

The following hypothesis will be tested for the study:

No statistical difference exists between the flexural strength test results for ASTM E518 beam test and the TAMU Unbalanced Bond Wrench for a same type of masonry.

Limitations

The challenge is the comparison of bond wrench results within a country and between countries; the bias between wrenches has not been fully satisfied. This research is in continuation of the researches done previously to understand the bias between different bond wrenches and other tests available to measure the bond strength. It is also important to compare these values with the standard methods for measuring the flexural bond strength recommended by different countries. Due to usage of these methods by a limited number of groups, the bond wrench has not reached any kind of acceptable standardization level.

Some of the significant issues that arise while developing internationally recognized standards as listed by Nichols (2013) are:

1. Developing a testing method that includes moisture limits on the bricks and the exact mixture requirement for the mortar and testing schedule.
2. Higher coefficient of deviation in results due to pre-damaging of joints from the usage of clamping mechanism for the tests.
3. Designing a simple clamping mechanism.
4. Constructible in a small workshop with limited tools.

Study limitations are:

1. The first population sample consists of 25 prisms which has 125 joints to be tested for failure, using TAMU Unbalanced Bond Wrench.
2. The second population sample consists of 25 prisms to be tested for failure using standard ASTM E518 beam test.
3. The cement used is Portland Cement
4. Composition of mortar is 1:1:6 (lime: cement: aggregate) by volume.

CHAPTER II

LITERATURE REVIEW

Introduction

This literature review provides a review of masonry properties, bond issues, early research work, bond characteristics and other information related to flexural and tensile strength testing of masonry assemblages. The variability in the flexural strength of the masonry is visible even with a small samples of masonry constructed by the same mason, using the same mortar and in the same working conditions. The purpose of this research is to minimize such variations due to the random issues linked with the experiments, except for a systematized modification in the type of testing methods used for the experimental measurements.

Masonry properties

The different characteristics of a masonry system are workability, durability and the ability to support compressive loads as well as bond strength to resist flexural tensile stresses (Portland Cement Association, 1994b). Workability can be increased by adding materials such as, fire clay and dishwashing detergent but it comes only at the expense of durability of masonry systems (J. M. Nichols, 1990, 1991). The most important thing is to maintain a consistent quality in the construction of test prisms (Sugo et al., 2000). The bond strength dictates the maximum tensile stress a masonry system can withstand, thus it is a controlling factor in the design. The bond between the unit and mortar is responsible for the serviceability and stability of the masonry, this is why it is very essential to understand this complex property which is critical to masonry design. The purpose of this research is to explore different methods of experimentally determining the flexural bond strength between masonry units and mortar.

Bond issues

To understand the term “Bond”, there are two different and important reference to mortar brick interface. The first is the strength of the area of contact between the mortar and masonry unit and the second is the stress (flexural, shear, or direct tension) required to break the mortar (A. Sise, N. G. Shrive, & E. L. Jessop, 1988). The flexural strength of each prism couplet is the lower of these two values. (Baker, 1914) studied this problem broadly and tested the tensile strength of mortar which was followed by (Sugo et al., 2000) who carried forward this experimental work on masonry cylinders.

In the unreinforced masonry, which is generally designed using the working stress analysis, the resistance of flexural stresses due to eccentric axial loads, out of plane loads, or both, depends on adhesion of mortar to units (Portland Cement Association, 1994b). To resist environmental loads such as wind and earthquake, masonry elements require Tensile Flexural capacity. The typically accepted value for a minimum accepted flexural strength of average masonry is 0.1 MPa (Page, 1983, 1991). According to (J. Nichols, 2000) by pre-wetting a pressed brick, the measured flexural strength is affected and it also introduces a consistent bias in the strength.

Initial works

There have been different research groups who have created different testing apparatus and setups to measure the bond strength of mortar and masonry. The earliest work by Baker(1914) tested the tensile strengths of cement mortar which was followed by various other tests, like the bond wrench test, the bench test, bridge pier test, crossed couplet test, test on wallets (small walls) and the direct tensile test. According to (Kamph, L., 1963) all these tests have their own disadvantages and complications. The tests mentioned above are briefly described below:

Crossed brick couplet test method

The crossed brick couplet test method measures a direct tensile strength of the bond between the mortar and the masonry joint. The specimen used for the test is crossed couplet specimen and the failure is induced without pulling the specimen. A testing jig is used to convert a conventional compression-testing machine's downward force into a direct tensional force. The tensile stresses over the joint are not uniform as higher stresses become concentrated at the corners of the composite interface. These areas of high stress are subjected to variation under construction and shrinkage stresses resulting in a wide scatter of results (Portland Cement Association, 1994a). *Figure 1* gives the setup of the instrument and *Figure 2* shows the elevation and top view of the apparatus.

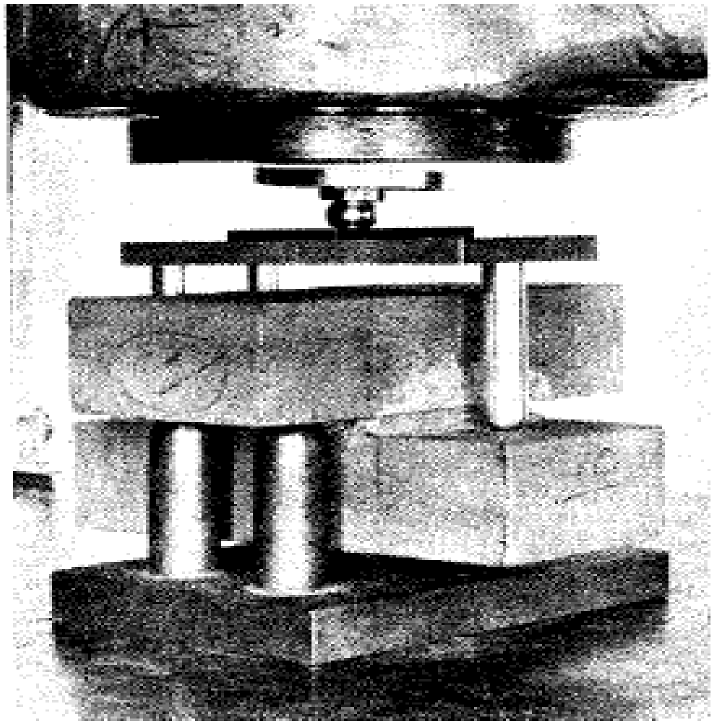


Figure 1: Crossed brick couplet test method

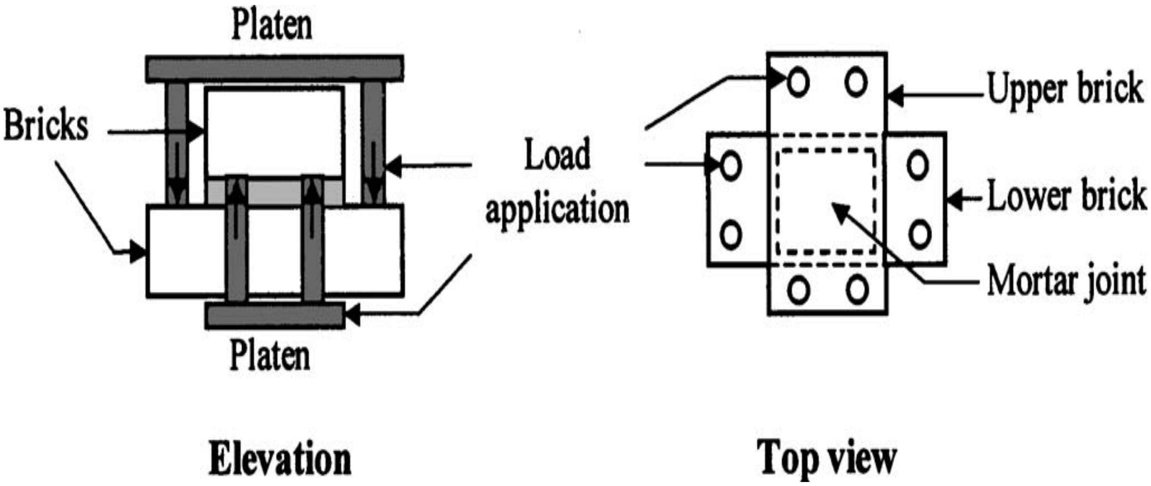


Figure 2: Elevation and top view of the corresponding setup

Couplet brick test through holes

This test utilizes a regular couplet as bolt-holes which run between a steel plate and through the middle of masonry units to apply opposing forces of tension. (Riddington & Jukes, 1994) used this test to determine and compare the results of bond strengths. The results of this test were quick, consistent and could be administered easily. This test is shown in *Figure 3*.

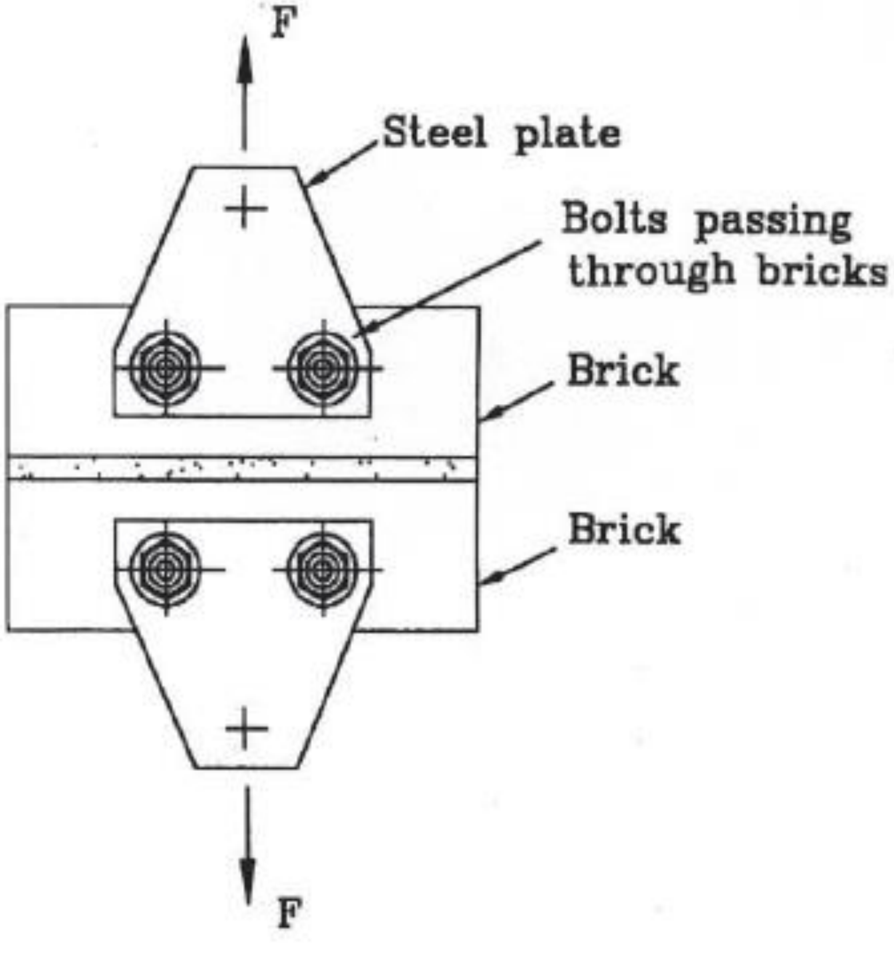


Figure 3: Direct tensile strength as executed by (Riddington & Jukes, 1994)

Test on wallettes

A popular and a well-known standard for this test is the BS 5628 (British Standards Institution, 1992). It uses a four point loading to determine the flexural bond strength and is performed on small bricks/block wall specimens (wallettes). The figure 4 shows the Wallette test arrangement for planes of failure parallel and normal to the bed joint.

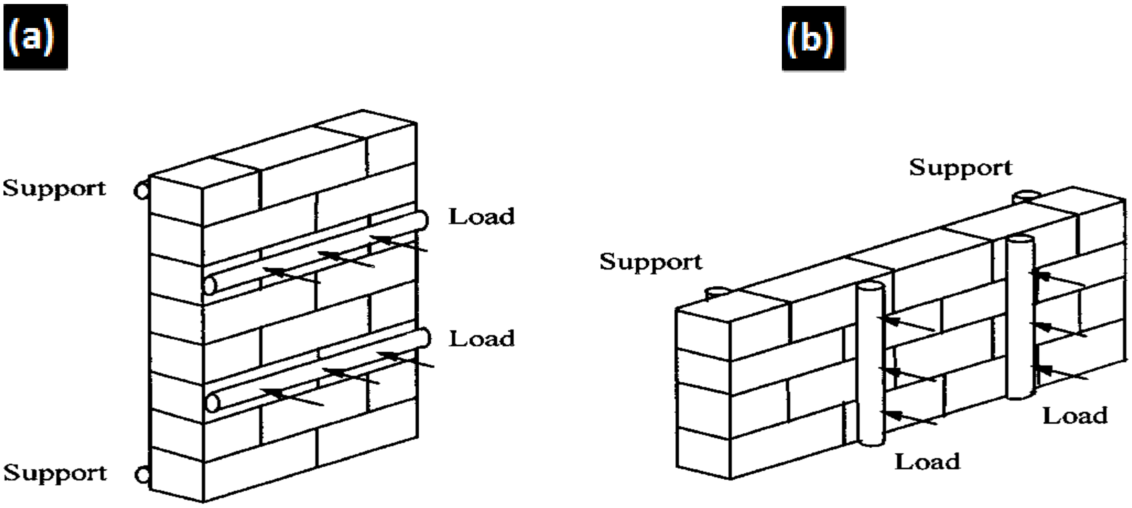


Figure 4: Testing arrangement of wallettes (small walls), BS 5628
(a) Plane of failure parallel to bed joint (b) Plane of failure normal to bed joint

The main difficulty with the BS 5628 test is that it requires a large specimen and setup makes this form of experiment and the whole process to be time consuming and difficult to execute (Khalaf, 2005). The researchers have compared the results from the several crossed couplet tests with the tests performed on wallettes in accordance with BS 5628. The results obtained from wallettes were higher than those from the couplet tests as shown in the *Figure 5*.

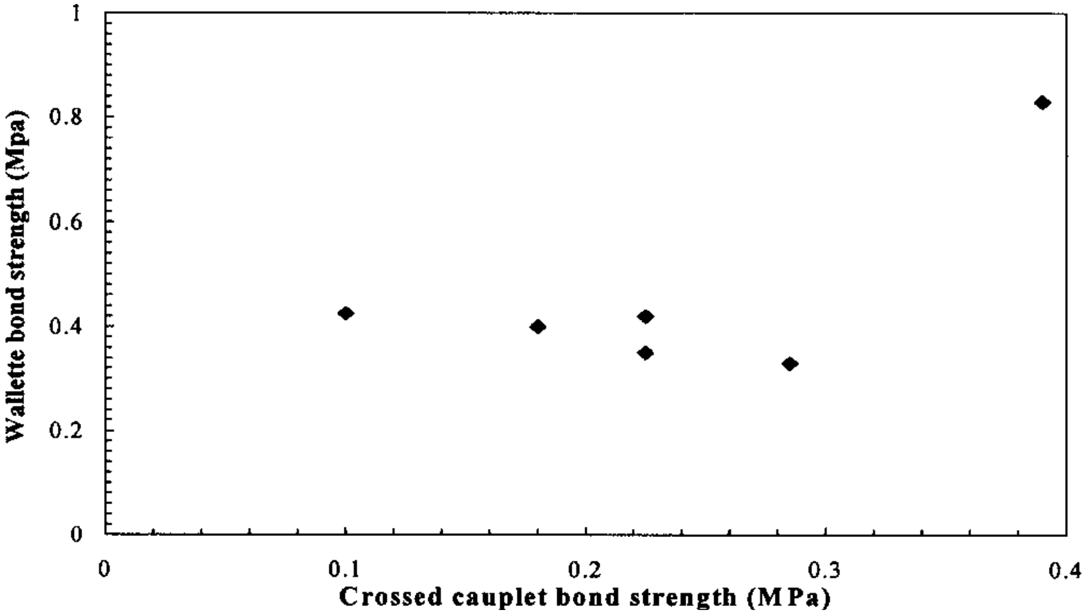


Figure 5: Comparison of bond strengths from crossed couplet bond strength and test on wallettes

Bridge pier test

This test is commonly known as ASTM E518, adopted in 1974 and is the standard test method for measuring flexural bond strength. It was recently reapproved in 2010 (ASTM International, 2010). This test is used for measurement of flexural bond strength developed with different types of masonry units and mortar or for purpose of checking the quality of the job (materials and workmanship). Riddington et al., (1998) did a finite element analysis using ANSYS to model this test and found out that the experiment is uneconomical in terms of the quantity of materials used and the effort that is put to produce the specimen and conducting the experiment. Only one test result is obtained from each test specimen. *Figure 6* shows the two of the test methods from ASTM E518.

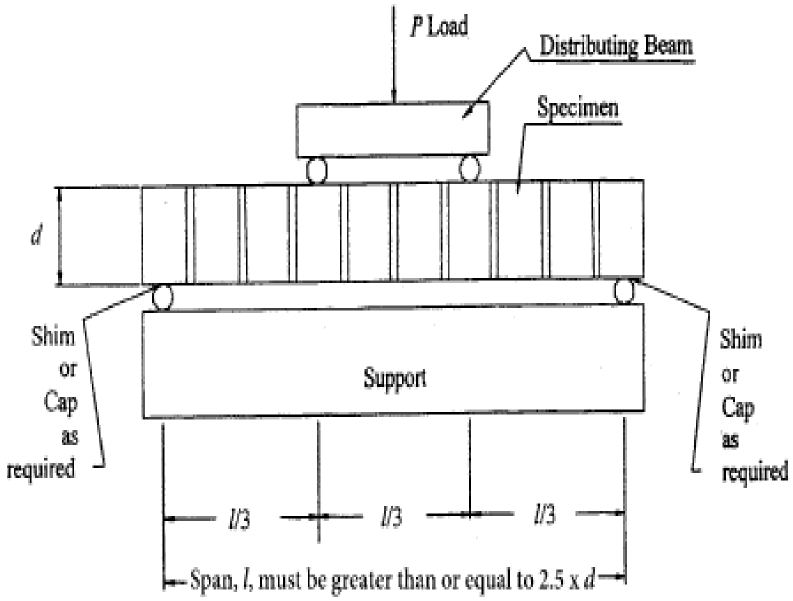


FIG. 1 The Third-Point Loading Method (Test Method A)

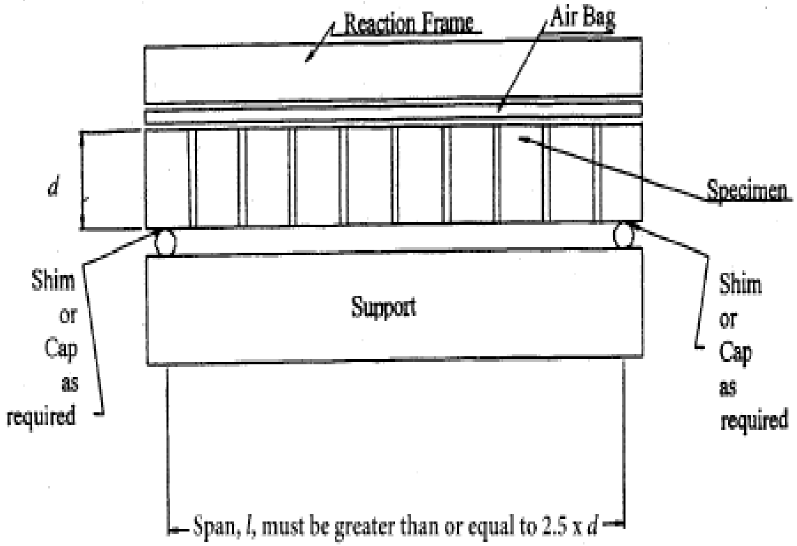


FIG. 2 The Uniform Loading Method (Test Method B)

Figure 6: ASTM E518 Test methods A & B (ASTM International, 2010)

Bond wrench types

The initial bond wrench was developed by (Hughes, Zsembery, & Brick, 1980) as shown in *Figure 7*. The test is a simple variation of the bond beam test. *Figure 8* shows the distinct step taken by Hughes and Zsembery in the development of the second stage of the bond wrench.

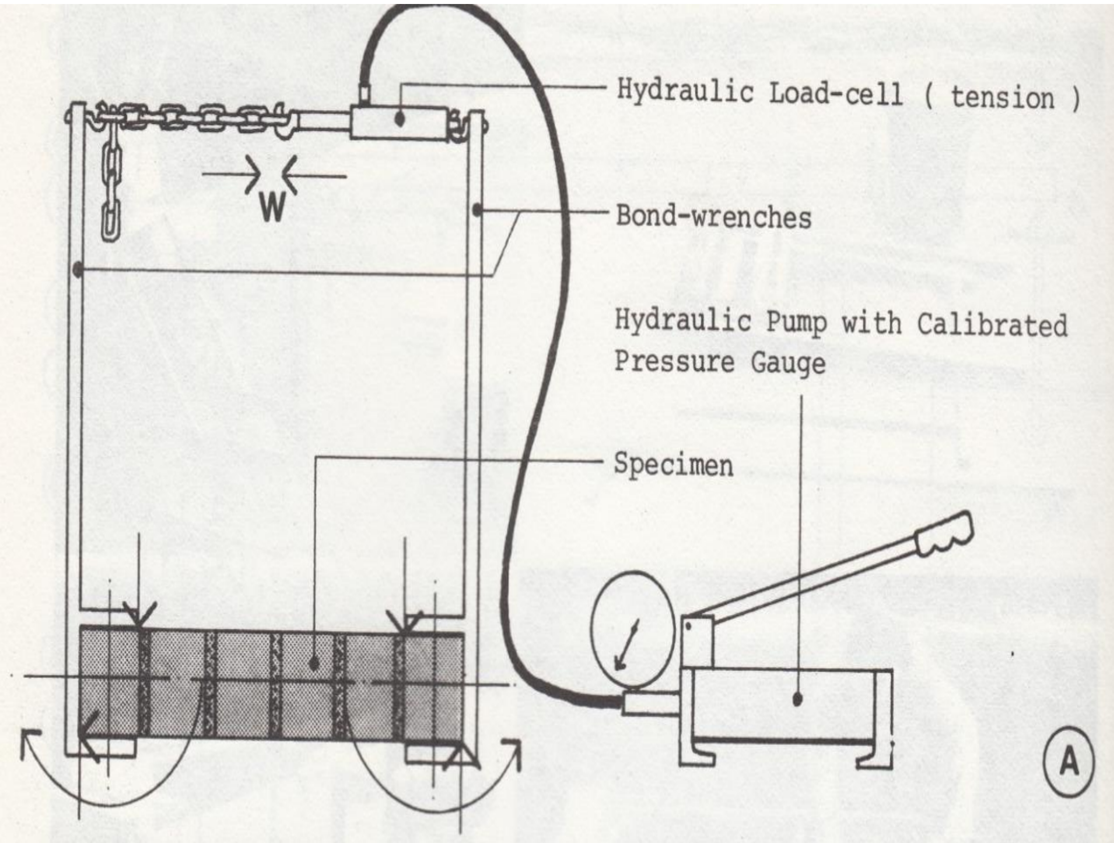


Figure 7: Bond wrench stage I (Hughes et al., 1980)

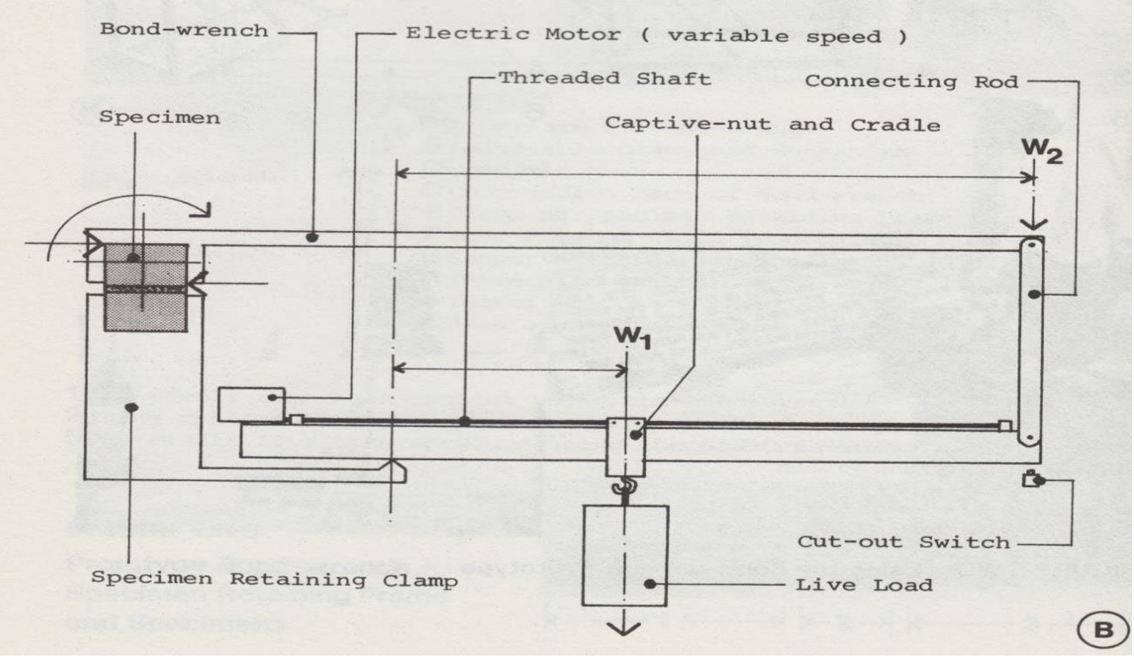


Figure 8: Bond wrench stage II (Hughes et al., 1980)

A number of different bond wrenches have been developed in the past after the first wrench without modifying the basic structural form of the original structure. A bond wrench consists of two parts, the lower part of the bond wrench have a base mechanism to clamp the prism to the base, and the upper part is the wrench that applies the moment to the uppermost brick. (Rao, Reddy, & Jagadish, 1996) did a widespread research on the flexural bond strength of a masonry using a bond wrench test setup and came to a conclusion that irrespective of the type of masonry unit, the flexural bond strength increases with an increase in mortar strength for cement mortar. They also concluded that the moisture content of the brick at the time of casting and laying had a significant effect on flexural bond strength, however the brick strength did not have any significant effect on flexural bond strength. *Figure 9* shows a typical setup of the Bond wrench.

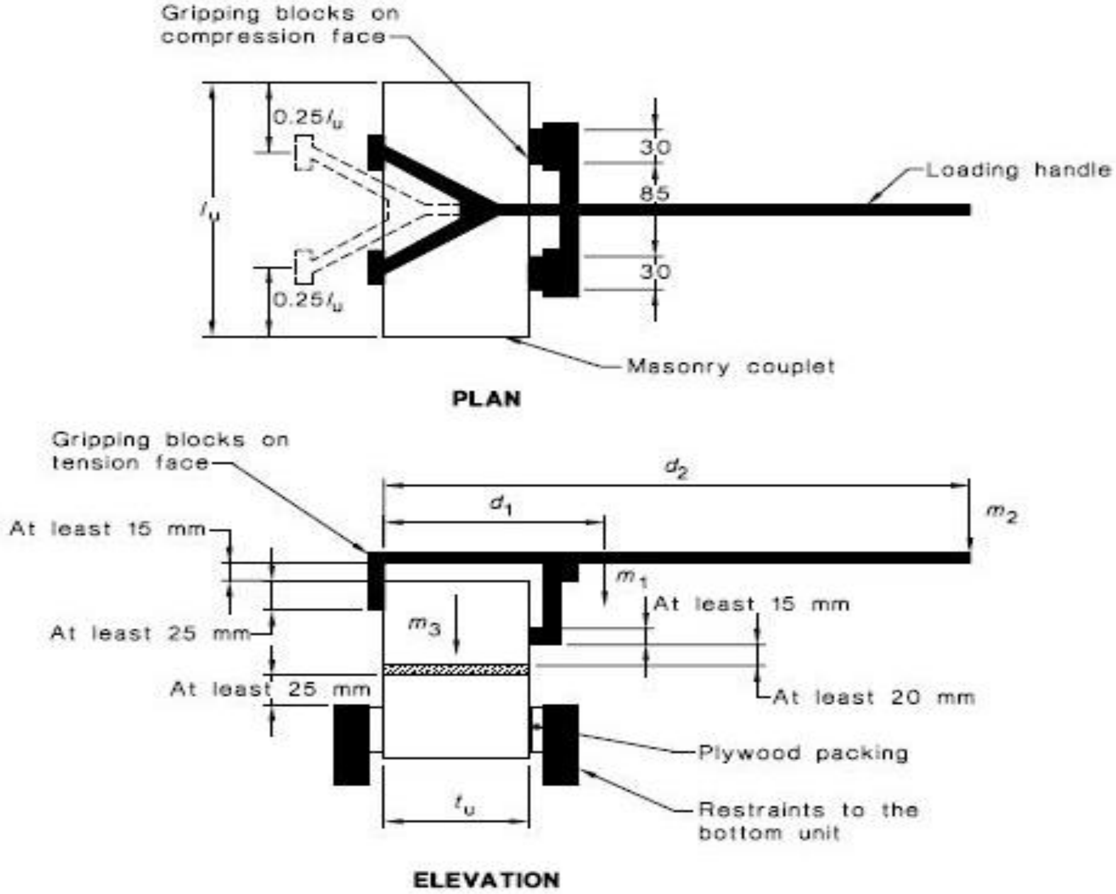


Figure 9: Bond wrench setup

Over the years four different wrenches have been made at TAMU namely Australian bond wrench AS 3700, ASTM C1072, TAMU Balanced and Unbalanced Bond Wrenches.

Previous researches to check for the bias between different test methods has been conducted by Chaudhari (2010) and McHargue (2013) and the results have shown that there exists a bias for the specimen prepared using masonry cement.

Bond wrench designs

McGinley (1996) found out that for the ASTM Standard Bond Wrench there is a difference in the linear stress distribution assumed by flexural theory and the existing stress distributions determined using LVDT system.

The bond wrench test must be capable of generating a simple bending-theory stress distribution, while doing the analysis of masonry bond tests (Riddington & Jukes 1994). However, attention has to be given to ensure that due to the clamping mechanisms or by the wrench not being of the full length of the specimen being tested, the stress distribution is not affected adversely.

It has been noted by Radcliffe, Bennett and Bryja (2004) that when bond wrenches are used it causes an unbalanced stress distribution across the masonry prism cross section. This stress distribution has a couple of components, uniform axial compressive stress distribution and a linear flexural stress distribution. The flexural stress distribution is inversely proportional to length of loading arm due to the impact of the compressive load Therefore, a longer loading arm results in lower impact or influence on the total stress distribution, due to the additional compression and flexural stresses.

Modified bond wrench

Figure 11 shows the pure couple bond wrench created by (Radcliffe et al., 2004) using the ASTM C 1072. The purpose of this design was to negate the downward testing load by the upward load and hence the design of wrench enables the weight of the clamping mechanism to be the only compressive load. This confirms that the sum of forces in the vertical directions in the pure couple bond wrench is zero. The arrangement of ASTM C1072 bond wrench is illustrated in the *Figure 10*.

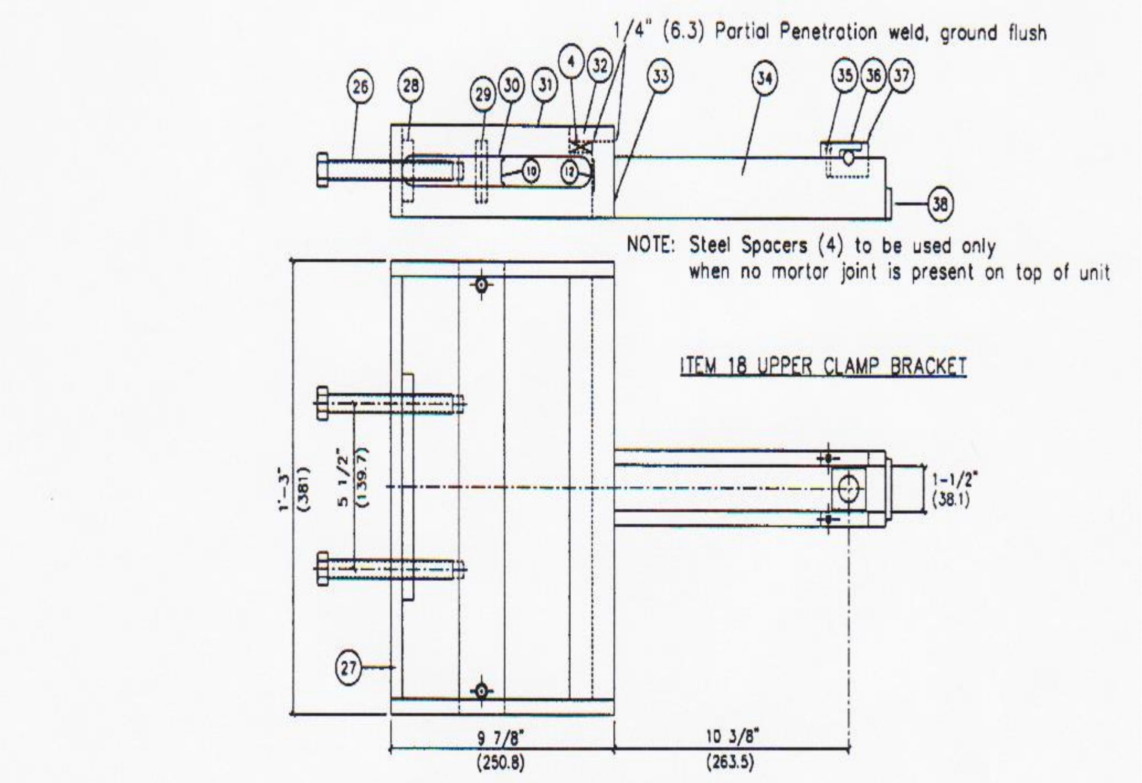


Figure 10: ASTM C1072 Bond wrench clamp bracket ASTM International (2013)

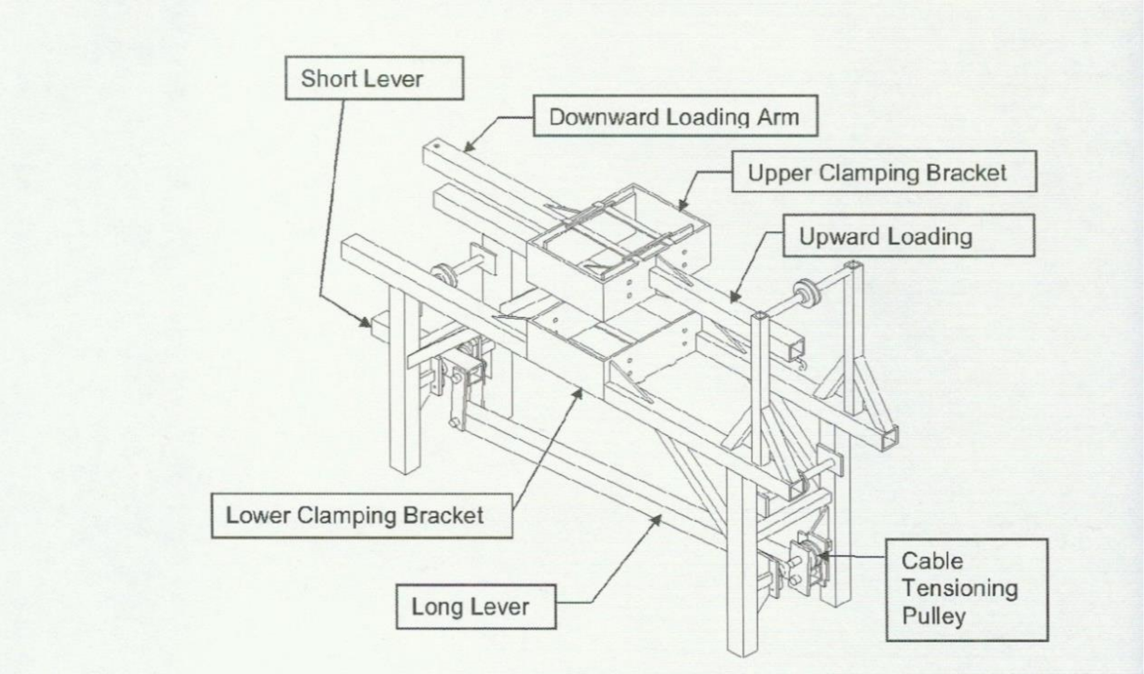


Figure 11: Pure couple bond wrench by (Radcliffe et al., 2004)

There is a negative attribute in the American bond wrench as compared to the Australian bond wrench as it creates a moment before the external load was applied Nichols (2013). The induced moment depends on the mass of the bond wrench and the center of gravity of the wrench. An Italian group conducted their research on soft mortars, and found out the concept of balanced bond wrench which was in lines with the conceptual idea put forth by (Radcliffe et al., 2004).

Chaudhari (2010) developed a TAMU balanced bond wrench by adding a counter balance extension in the opposite direction to the apparatus's loading arm. This imparted zero moment at the start of the test to the top of the prism used in testing. *Figure 12* shows the TAMU balanced bond wrench developed by Chaudhari.

Figure 12: TAMU balanced bond wrench by Chaudhari (2010)

Figure 13: TAMU Unbalanced Bond Wrench by Chaudhari (2010)

Chaudhari developed the balanced wrench and his fellow student developed TAMU Unbalanced Bond Wrench. The unbalanced stress generated, due to the self-weight of the wrench and its center of gravity, is cancelled by counter balance extension in the opposite direction of the apparatus's loading arm. Following table (see *Table 1*) shows the test results that illustrates the difference that existed in the flexural results between the two wrenches. ACME brick was used in the research and the mortar mix used was 1:1:6.

Table 1: Balanced to unbalanced test results (John M Nichols & Holland, 2011)

Flexural Strength (MPa)	Unbalanced Bond Wrench		Balanced Bond Wrench	
	Researcher I	Researcher II	Researcher I	Researcher II
	0.762	0.813	0.472	0.661
	0.773	0.533	0.579	0.701
	0.645	0.813	0.740	0.472
	0.533	0.690	0.691	0.759
	0.706	0.730	0.759	0.691
	0.645	0.794	0.722	0.661
	0.813	0.794	0.661	0.722
	0.832	0.533	0.638	0.759
	0.773	0.832	0.661	0.606
	0.705	0.730	0.691	0.472
Mean (μ)	0.72	0.73	0.66	0.65
Standard Deviation(σ)	0.09	0.11	0.08	0.10
COV	0.13	0.15	0.13	0.16

The results from the balanced and the balanced bond wrench were analyzed, using statistical Student's t Test, with a 5% acceptance level and it showed that the bond wrenches yield statistically different results. The flexural strength ranged from 0.65MPa to 0.73 MPa.

Later Nichols (2013) tested Chaudhari (2010) bond wrench with Australian bond wrench model, ASTM C 1072, and an equivalent unbalanced wrench. There were total eleven prisms utilized in the experiment. The summary of the flexural test results of the four wrenches has been shown in *Table 2*. The American wrench results were on average fifty percent higher in comparison to the other three tests. The mean was distinct and dissimilar from the other three sets. Also, the student's t test results using five percent acceptance level illustrated that the results from unbalanced, balanced and Australian bond wrenches were statistically indistinguishable.

Table 2: Test results – failure load and peak stress (MPa) Nichols (2013)

Prism/Brick	Test Wrench	Failure L (kg)	Stress (MPa)
1-1	Australian	9.97	0.55
1-2	American	34.53	1.14
2-1	Unbalanced	25.36	0.81
2-2	Failed in setup	0	0
2-3	Failed in setup	0	0
2-4	Balanced	17.45	0.58
3-1	Australian	10.72	0.59
4-1	American	26.42	0.96
4-2	Unbalanced	51.28	1.63
4-3	Balanced	30.73	1.02
5-1	American	52.25	1.53
5-2	Australian	17.09	0.90
5-3	Balanced	17.07	0.57
5-4	Unbalanced	21.00	0.63
6-1	American	57.87	1.65
6-2	Australian	28.65	1.46
6-3	Unbalanced (smooth bond failure)	10.80	0.38
7-1	Balanced	12.58	0.42
7-2	American	75.35	2.03
7-3	Australian	23.12	1.19
8-1	Unbalanced	9.43	0.30
8-2	Balanced	40.71	1.35
8-3	Failed in American Setup	0	0
9-1	American	28.28	1.00
9-2	Australian	21.42	1.11
10-1	Unbalanced	29.25	0.94
10-2	Balanced	31.65	1.05
11-1	American	16.09	0.74
11-2	Australian	6.64	0.39
11-3	Unbalanced	39.14	1.21
11-4	American	41.73	1.30

Kinds of flexural failures

Sarangapani, Reddy, & Jagadish, (2005) conducted different tests utilizing different flexural tests, various mortars and a modified ASTM C1027 bond wrench pertaining to masonry bond and compressive strengths. The flexural prism failures fell into one of the three categories that have been mentioned below.

Type 1: Failure at the brick-mortar interface indicating the bond failure (*Figure 14*).

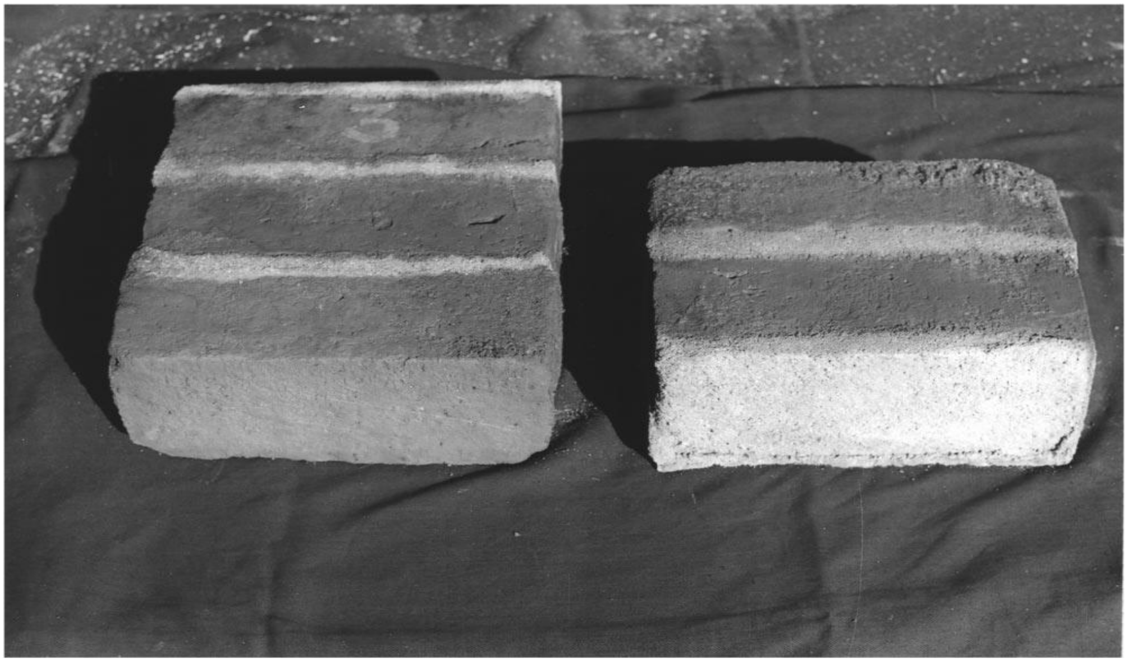


Figure 14: Bond failure at brick-mortar interface (Sarangapani et al., 2005)

Type 2: Failure of brick in flexure with brick-mortar interface intact, refer to *Figure 15*

Figure 15: Bond failure when the mortar is still intact (Sarangapani et al., 2005)

Type 3, which is a combination of Type 1 and Type 2 Failure as shown in *Figure 16*

Figure 16: Type 1 and Type 2 failure (Sarangapani et al., 2005)

Water retention, initial flow, air content and workmanship are some of the properties due to which the bond strength is influenced (Boynton & Gutschick, 1964; Edgell, 1987). A good bond is affected by various properties not limited to workability alone (Kampf, 1963).

Different mortars which differed in the cementitious materials appeared to have some kind of relationship that exists between the flexural strength values of tested walls and the compressive strength of the mortar (Fishburn, 1961). Masonry cement was used by Chaudhari (2010) and McHargue (2013) in their research, but this research uses Portland cement.

(Palmer, & Parsons, 1934) conclusion about the factors affecting bond strength:

- The maximum bond-strength results from fifteen different mortars increased with the compressive strength of mortars provided that the extent of bond formation was good.
- Bricks with low rates of absorption and porous bricks made practically non-absorptive by wetting acquired their highest bond strength with mortars of highest strength, when the extent of bond was good.

The timeliness of brick setting has a major effect on the bond strength as the bond strength reduces when there is a late setting of brick onto the mortar bed (Boynton & Gutschick, 1964; Ritchie & Davison, 1962). The maximum bond strength reduction is for high suction brick and lowest for low suction bricks according to (Kampf, 1963). If the bricks are realigned after the brick mortar begins to stiffen, the bond gets destroyed (Boynton & Gutschick, 1964). The window of opportunity for realigning of a brick without damaging is greatest for low-suction brick and high water-retention mortar, as shown in *Figure 17* & *Figure 18*.

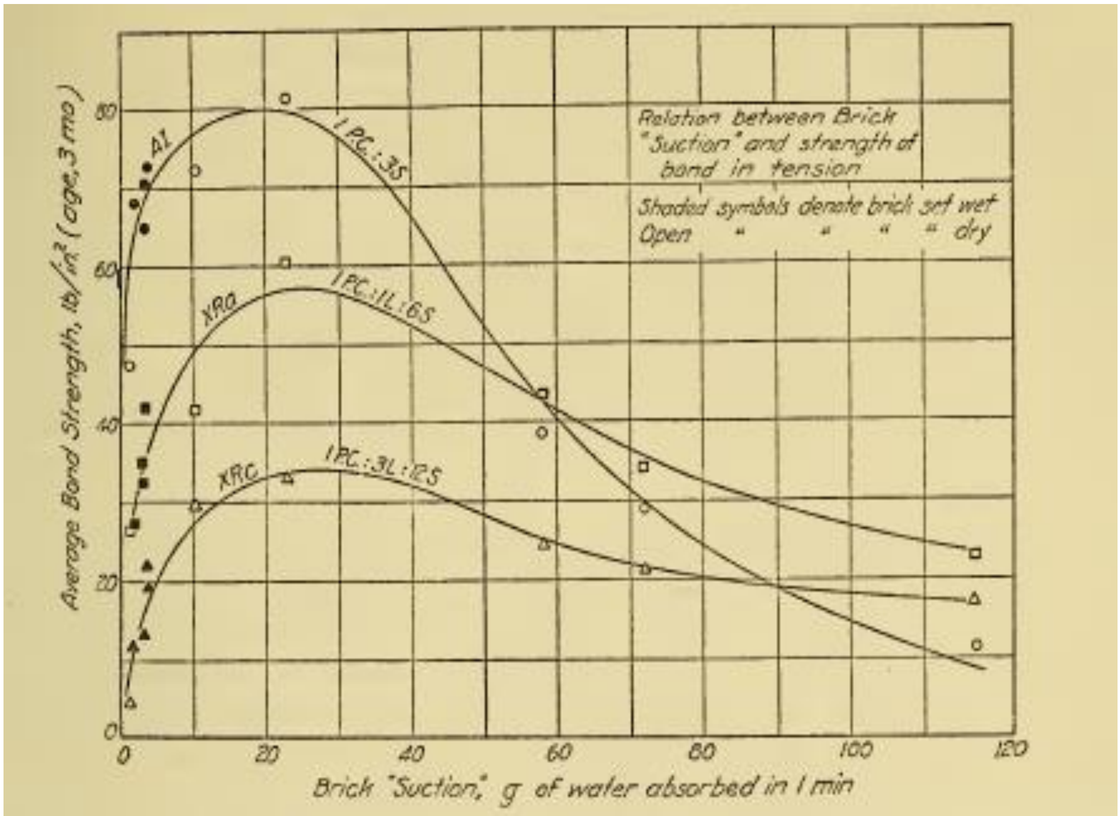


Figure 17: Bond strength results across a range of brick suction values (Boynton & Gutschick, 1964)

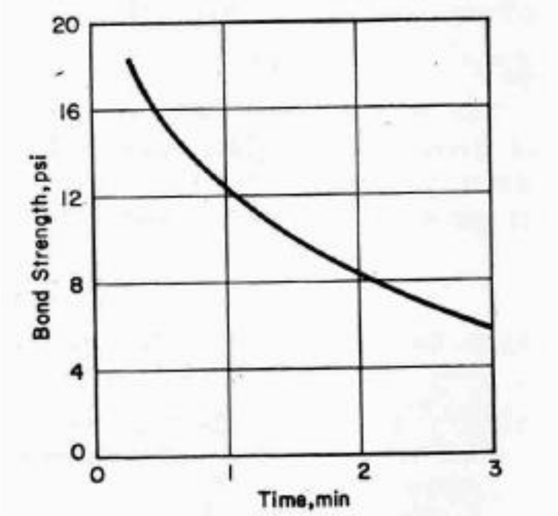


Figure 18: Bond strength plotted against time to placement (Kampf, 1963)

On a continuous basis, many experiments and researches have been done and results have been published for different wrench designs. Chaudhari (2010) & Suresh (2014) conducted tests at Texas A&M University and compared bond strength results between different bond wrenches. Their results have showed that the unbalanced wrench yielded ten percent higher results than the balanced wrench. Different results were obtained when the four bond wrenches were tested under similar conditions at TAMU (Nichols 2013). The results obtained by American bond wrench ASTM C 1072 were fifty percent higher than the Australian bond wrench & no statistical difference was observed between the other three wrenches, although it was a limited test set. As the testing proceeded for both bricks which could have been due to perfections in building of prisms or the way the tests have been carried out there exists a statistically significant increase in the test strength.

CHAPTER III

METHODOLOGY

Introduction

This research work covers the manufacturing of 50 prisms using Portland cement mix and the testing is done using the TAMU Unbalanced Bond Wrench and ASTM E518 beam testing. Methodology covers the experimental procedure, the material used, brief descriptions about the equipment, experimental measurement issues, different bond wrench procedures and the data analysis methods.

Experimental procedure

The basic purpose of this research is to identify if any bias exists between bond strength values obtained from TAMU Unbalanced Bond Wrench and ASTM E518 beam method. The standard procedures outlined in the ASTM E518/E518-10 will be followed for this experiment.

Figure 19 shows the mixer used in the experiments. *Figure 20* shows the typical brick used for this experimental work.

Figure 19: Concrete mixer, cement and sand

Figure 20: Typical brick used in the experiment

Brick prisms were built by laying 6 bricks vertically with mortar. Only one proportion of mortar was used 1:1:6 (cement: lime: sand). The mortar was made in concrete mixer using Portland cement.

Figure 21 shows the samples and *Figure 22* the materials.

Figure 21: Bricks laid for the experiment

Figure 22: Sand and lime

A total of fifty prisms (250 joints) have been casted as two separate sets of twenty five prisms each. The first set of prisms would be tested with the TAMU Unbalanced Bond Wrench and the second set by ASTM E518 beam setup.

Figure 23 shows the loading table being fixed inside the main frame to carry on the experiment, *Figure 24* shows the hydraulic jack that has been used for the experiment.

Figure 23: Steel frame for the bond wrench experiment

Choudhary will be assisting in the present research, as his research focuses on comparing the results between the TAMU Balanced bond wrench and ASTM E518 beam method. The main frame was manufactured by Chaudhari (2010) and it had the following dimensions, Height: 36 inches, Width: 22 inches, Breadth: 34 inches.

Figure 24: Hydraulic Jack to lift the specimen

Figure 25: Setup of the frame and hydraulic table for placing bricks to be tested

The prism is placed over the loading table, a bucket is used to apply the sand load to the end of the bond wrench moment arm. *Figure 26* shows the sand method underway.

Figure 26: A bucket used to apply sand load to end of bond wrench moment arm

Experimental set up for Unbalanced Bond Wrench

Step 1

Preparation of the Specimen:

1. Six hollow Texas clay bricks stacked vertically shall be used to build brick prisms.
2. The mortar joint used will be on 10 mm.
3. The mortar cement, lime, and sand will be gathered.
4. A concrete mixer shall be used for the preparation of mortar. Enough water will be used to create adequate workability.

Step 2

Setup for the equipment:

- The equipment used are the hydraulic jacks, main frame, ropes to hold the bond wrench, hooks for holding the buckets etc.
- Uses a hydraulic table, as shown in *Figure 25* , which has been positioned in the center of main frame, to place bricks for testing.
- A lever is present to lift the table vertically upward to sit in the location within the lower hydraulic clamping bracket.
- Uses the hydraulic jack to apply pressure to lower clamping bracket to hold the masonry specimen tightly in place when testing is being done (see *Figure 25*).
- Clamp the bond wrench to the top of masonry unit of the specimen in the manner in which the arm is horizontal for the test.
- Place the bucket on one side of loading arm as shown in *Figure 26* to the upper clamping bracket.

- Add sand as the counter weight, until the failure occurs in the joint, as shown in figure.
- The weight of bucket is then measured to get the value of failure load.

Analysis

Figure 27 shows the schematic setup and the variables used in the analysis.

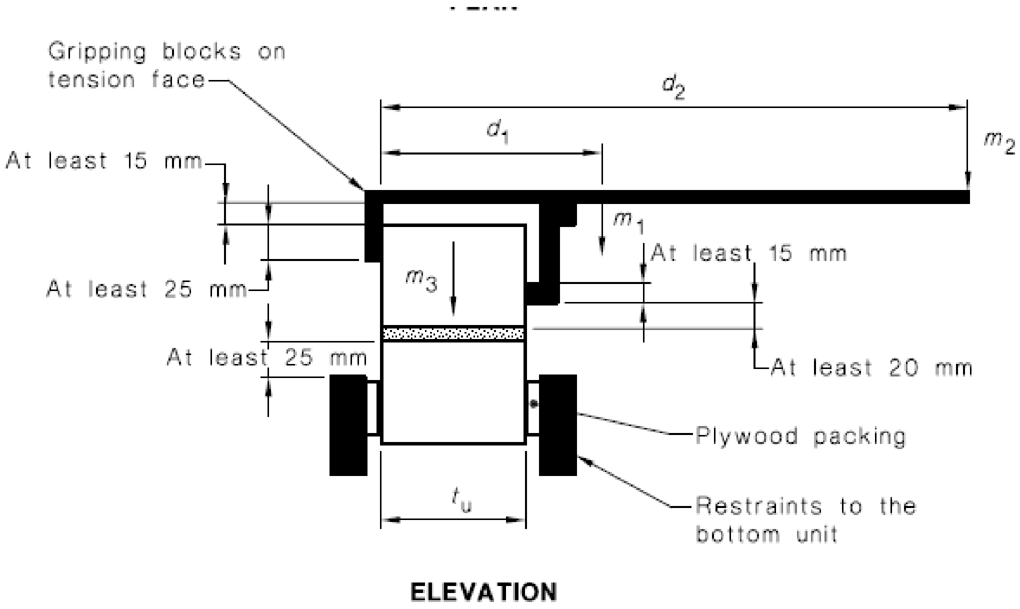


Figure 27: Schematic diagram of bond wrench set up

The flexural strength of each test joint of the specimen shall be determined using eqn. (1)

$$f_{sp} = (M_{sp} / Z_d) - (F_{sp} / A_d) \qquad (1)$$

Where,

f_{sp} = the flexural strength of the specimen, in Mega Pascal’s

M_{sp} = the bending moment about the centroid of the bedded area of the test joint at failure, in Newton millimeters

$= 9.81m_2 (d_2 - t_u / 2) + 9.81m_1 (d_1 - t_u / 2)$

Z_d = the section modulus of the design cross-sectional area, (A_d) of a member

F_{sp} = the total compressive force on the bedded area of the tested joint, in N

$= 9.81 (m_1 + m_2 + m_3)$

A_d = the design cross-sectional area of a member

m_1, m_2, m_3 = the masses of components used in flexural strength testing, in kilograms

d_1 = the distance from the inside edge of the tension gripping block to the center of gravity, in millimeters

d_2 = the distance from the inside edge of the tension gripping block to the loading handle, in millimeters

t_u = the width of the masonry unit.

Experimental set up for ASTM E518 beam test

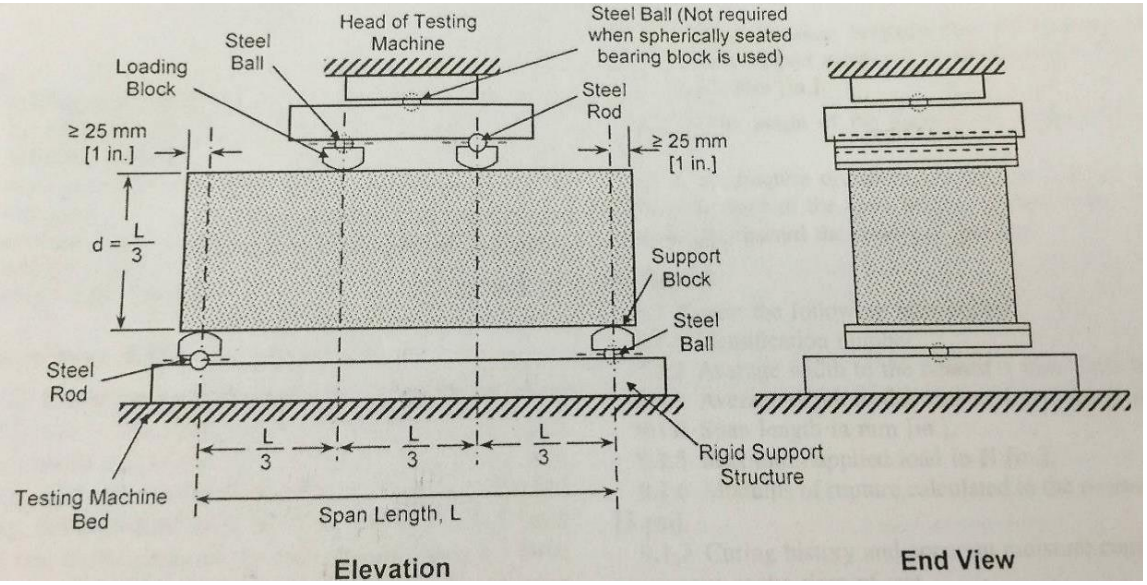


Figure 28: ASTM E518 experimental setup (ASTM International, 2010)

The experimental procedure is as follows:

1. The prism is turned on its side with respect to its position as moulded and centre it on the support blocks. The wooden planks with depth = 75mm are used as the support blocks.

2. Steel rods of diameter = 12mm are placed on the wooden planks to cover the entire length. The wooden support is placed at a distance of 300mm centre to centre so that distance between supports is greater than 2.5 times the depth of specimen.

3. The prism is kept over the steel rods such that it’s simply supported on the rods and has an overhang of more than 25mm on both sides.

4. Further two steel rods with diameter = 12mm is placed in contact with the surface of the specimen at the third points. So it is 100mm from the centre of steel rods placed on the wooden support.

5. Another wooden plank of length = 350mm, width = 220mm and depth = 40mm is placed over the rods to distribute the load on the specimen.

6. The prism is loaded continuously and without shock. The load is applied at a constant rate to the breaking point. Bricks are used to load the specimen.

7. The number of bricks are calculated at the failure point and failure weight is calculated

The flexural strength of each of the specimen is calculated by:

$F = PL/ (bd^2)$

Where,

F = flexural strength, MPa

P = maximum applied load at the failure

L = span length

b = average width of specimen, mm

d = average depth of specimen, mm

Figure 29: Equivalent ASTM E518 arrangement

Figure 30: Loading the specimen

CHAPTER IV

RESULTS

Introduction

This chapter gives a summary of the results of the experimental works carried out for this research. The chapter outlines the flexural strengths and the results. *Table 3* shows the brick measurements.

Table 3: Brick measurements

Length	Width	Area
192.00	55.10	10579.2
192.10	55.05	10575.11
192.25	55.05	10583.36
192.05	54.95	10553.15
191.83	54.95	10541.06
191.94	55.08	10572.06
192.00	55.00	10560.00
192.25	54.95	10564.14
191.90	55.00	10554.50
191.85	55.07	10565.18

Note: All dimensions in mm

The average length of the brick is noted as 192.017 mm, width is 55.02 mm and an area of 10564.77mm^2.

Flexural strength

To calculate the flexural strength we need to have the self-weight of the wrench (m_1), self -weight of the brick (m_3) and the failure load (m_2), the distance from inside edge of tension gripping block to the center of gravity (d_1) in mm, the distance from the edge of the tension gripping block to the loading handle, in mm (d_2), the width of the masonry unit (t_u). The mass (m_3) of the brick is 1.57 kg's. *Table 4* shows the measurements of the bond wrenches for the analysis.

Table 4: Measurements of the bond wrench

Variable	TAMU Unbalanced
d_1	196.00
d_2	698.50
m_1	4.19

Note: Lengths in millimeter and Weight in kilograms

The design analysis is:

Design Cross-sectional area of a member (A_d) in mm^2 = 10564.77 mm^2

Section modulus of the fractured section of the beam = 80003.73 mm^3

(Z_d) = ($bh^2/6$), in cubic millimeters

Total compressive force on the bedded area of the tested joint (Fsp), in Newton = 9.81 ($m_1 + m_2 + m_3$)

Bending moment about the centroid of the bedded area of the test joint at failure (M_{sp}), in Newton millimeters = $9.81m_2\,(d_2 - t_u/2) + 9.81m_1(d_1 - t_u/2)$

Flexural Strength of the bond wrench (f_{sp}), in MPa = $(M_{sp} / Z_d) - (F_{sp} / A_d)$

Table 5, *Table 6*, *Table7*, *Table 8*, *Table 9*, *Table10* and *Table 11* shows the stress values of the samples tested by TAMU Unbalanced Bond Wrench. *Table 12* shows the results for samples tested using ASTM E518 beam test method.

Table 5: Flexural strength of samples 1-1 to 4-5: TAMU Unbalanced Bond Wrench

No	m_2	F_{sp}	M_{sp}	f_{sp}
1-1	24.95	301.27	171156.77	2.11
1-2	19.35	246.33	134295.27	1.66
1-3	29.54	346.29	201370.04	2.48
1-4	35.86	408.29	242970.89	3.00
1-5	29.84	349.24	203344.77	2.51
2-1	33.50	385.14	227436.39	2.81
2-2	22.50	277.23	155029.86	1.91
2-3	Failed	-	-	-
2-4	27.86	329.81	190311.59	2.35
2-5	22.48	277.03	154898.22	1.91
3-1	27.86	329.81	190311.59	2.35
3-2	32.48	375.13	220722.33	2.72
3-3	33.58	385.93	227962.99	2.81
3-4	34.89	398.78	236585.95	2.92
3-5	33.65	386.61	228423.76	2.82
4-1	Failed	-	-	-
4-2	33.56	385.73	227831.34	2.81
4-3	36.52	414.77	247315.28	3.05
4-4	35.54	405.15	240864.52	2.97
4-5	34.15	391.52	231714.96	2.86

Table 6: Flexural strength of samples 5-1 to 8-3: TAMU Unbalanced Bond Wrench

No	m_2	F_{sp}	M_{sp}	f_{sp}
5-1	Failed	-	-	-
5-2	29.86	349.43	203476.42	2.51
5-3	33.85	388.57	229740.24	2.83
5-4	25.86	310.19	177146.77	2.18
5-5	33.58	385.93	227962.99	2.81
6-1	34.58	395.74	234545.40	2.89
6-2	27.89	330.11	190509.06	2.35
6-3	Failed	-	-	-
6-4	28.67	337.76	195643.35	2.41
6-5	29.65	347.37	202094.11	2.49
7-1	Failed	-	-	-
7-2	24.20	293.91	166219.96	2.05
7-3	18.45	237.50	128371.10	1.58
7-4	27.25	323.83	186296.32	2.30
7-5	20.14	254.08	139495.37	1.72
8-1	25.85	310.09	177080.94	2.18
8-2	22.21	274.39	153120.96	1.89
8-3	19.85	251.23	137586.47	1.70

Table 7: Flexural strength of samples 8-4 to 12-3: TAMU Unbalanced Bond Wrench

S No	m_2	F_{sp}	M_{sp}	f_{sp}
8-4	27.28	324.12	186493.79	2.30
8-5	23.56	287.63	162007.22	2.00
9-1	22.81	280.27	157070.41	1.94
9-2	Failed	-	-	-
9-3	24.97	301.46	171288.42	2.11
9-4	28.89	339.92	197091.48	2.43
9-5	27.68	328.05	189126.76	2.33
10-1	17.85	231.61	124421.65	1.53
10-2	29.58	346.69	201633.34	2.49
10-3	26.54	316.86	181622.81	2.24
10-4	Failed	-	-	-
10-5	Failed	-	-	-
11-1	27.58	327.07	188468.52	2.32
11-2	24.52	297.05	168326.34	2.08
11-3	23.65	288.51	162599.64	2.01
11-4	28.75	338.54	196169.94	2.42
11-5	31.25	363.07	212625.97	2.62
12-1	27.56	326.87	188336.87	2.32
12-2	Failed	-	-	-
12-3	22.16	273.90	152791.84	1.88

Table 8: Flexural strength of samples 12-4 to 16-1: TAMU Unbalanced Bond Wrench

S No	m_2	F_{sp}	M_{sp}	f_{sp}
12-4	19.85	251.23	137586.47	1.70
12-5	14.23	196.10	100593.32	1.24
13-1	20.37	256.34	141009.33	1.74
13-2	Failed	-	-	-
13-3	24.73	299.11	169708.64	2.09
13-4	17.25	225.73	120472.20	1.48
13-5	19.87	251.43	137718.12	1.70
14-1	26.54	316.86	181622.81	2.24
14-2	26.18	313.33	179253.14	2.21
14-3	23.34	285.47	160559.09	1.98
14-4	26.69	318.33	182610.17	2.25
14-5	28.64	337.46	195445.87	2.41
15-1	Failed	-	-	-
15-2	15.72	210.72	110401.11	1.36
15-3	Failed	-	-	-
15-4	23.54	287.43	161875.57	2.00
15-5	22.49	277.13	154964.04	1.91
16-1	25.48	306.46	174645.45	2.15

Table 9: Flexural strength of samples 16-2 to 20-3: TAMU Unbalanced Bond Wrench

S No	m_2	Fsp	Msp	f_{sp}
16-2	27.29	324.22	186559.62	2.30
16-3	22.27	274.97	153515.91	1.89
16-4	23.89	290.87	164179.42	2.02
16-5	28.24	333.54	192812.91	2.38
17-1	Failed	-	-	-
17-2	18.54	238.38	128963.51	1.59
17-3	Failed	-	-	-
17-4	17.98	232.89	125277.36	1.54
17-5	21.73	269.68	149961.41	1.85
18-1	26.57	317.16	181820.28	2.24
18-2	29.87	349.53	203542.24	2.51
18-3	28.35	334.62	193536.97	2.39
18-4	31.59	366.40	214863.99	2.65
18-5	29.15	342.47	198802.90	2.45
19-1	Failed	-	-	-
19-2	17.95	232.60	125079.89	1.54
19-3	19.67	249.47	136401.64	1.68
19-4	22.38	276.05	154239.97	1.90
19-5	24.69	298.71	169445.35	2.09
20-1	Failed	-	-	-
20-2	28.24	333.54	192812.91	2.38
20-3	31.54	365.91	214534.87	2.65

Table 10: Flexural strength of samples 20-4 to 24-5: TAMU Unbalanced Bond Wrench

S No	m_2	Fsp	Msp	f_{sp}
20-4	33.25	382.69	225790.79	2.79
20-5	29.57	346.59	201567.52	2.49
21-1	Failed	-	-	-
21-2	24.68	298.62	169379.52	2.09
21-3	28.59	336.97	195116.75	2.41
21-4	28.00	331.19	191233.13	2.36
21-5	24.95	301.27	171156.77	2.11
22-1	20.50	257.61	141865.04	1.75
22-2	23.67	288.71	162731.29	2.01
22-3	22.43	276.54	154569.10	1.91
22-4	23.61	288.12	162336.34	2.00
22-5	Failed	-	-	-
23-1	27.32	324.51	186757.09	2.30
23-2	25.12	302.93	172275.78	2.12
23-3	29.38	344.72	200316.86	2.47
23-4	30.17	352.47	205516.96	2.54
23-5	24.39	295.77	167470.62	2.07
24-1	Failed	-	-	-
24-2	33.27	382.88	225922.44	2.79
24-3	28.61	337.17	195248.40	2.41
24-4	29.53	346.19	201304.22	2.48
24-5	27.82	329.42	190048.30	2.34

Table 11: Flexural strength of samples 25-1 to 25-5: TAMU Unbalanced Bond Wrench

S No	m_2	F_{sp}	M_{sp}	f_{sp}
25-1	26.84	319.81	183597.53	2.26
25-2	24.17	293.61	166022.49	2.05
25-3	Failed	-	-	-
25-4	28.24	333.54	192812.91	2.38
25-5	27.19	323.24	185901.38	2.29

Table 12: Flexural strength of samples 1-25 using ASTM E518 beam test

S No	Load	Stress
1	55.24	1.18062
2	47.29	1.010708
3	28.75	0.614461
4	26.69	0.570433
5	50.38	1.076749
6	48.67	1.040202
7	20.15	0.430657
8	36.27	0.775182
9	23.91	0.511018
10	15.24	0.325718
11	11.65	0.24899
12	23.65	0.505461
13	38.54	0.823698
14	42.96	0.918165
15	47.63	1.017975
16	26.87	0.57428
17	18.25	0.390049
18	12.68	0.271004
19	11.87	0.253692
20	21.98	0.469769
21	43.65	0.932912
22	50.27	1.074398
23	25.35	0.541794
24	9.78	0.209024
25	18.69	0.399453

Table 13: Initial rate of absorption for bricks (10 samples)

S No	Water absorbed(grams)	IRA(kg/m^2/min)
1	16.72	0.79
2	15.04	0.71
3	19.16	0.90
4	19.70	0.93
5	14.79	0.7
6	19.85	0.93
7	16.44	0.77
8	12.83	0.60
9	15.18	0.71
10	17.07	0.80

The Initial rate of absorption was calculated for the bricks used in the experiment as shown in *Table 13*. The average rate of absorption was 0.78 kg/m^2/min. The value lies between the acceptable limits of 0.5 to 1.5 kg/m^2/min according to ASTM C67 standards.

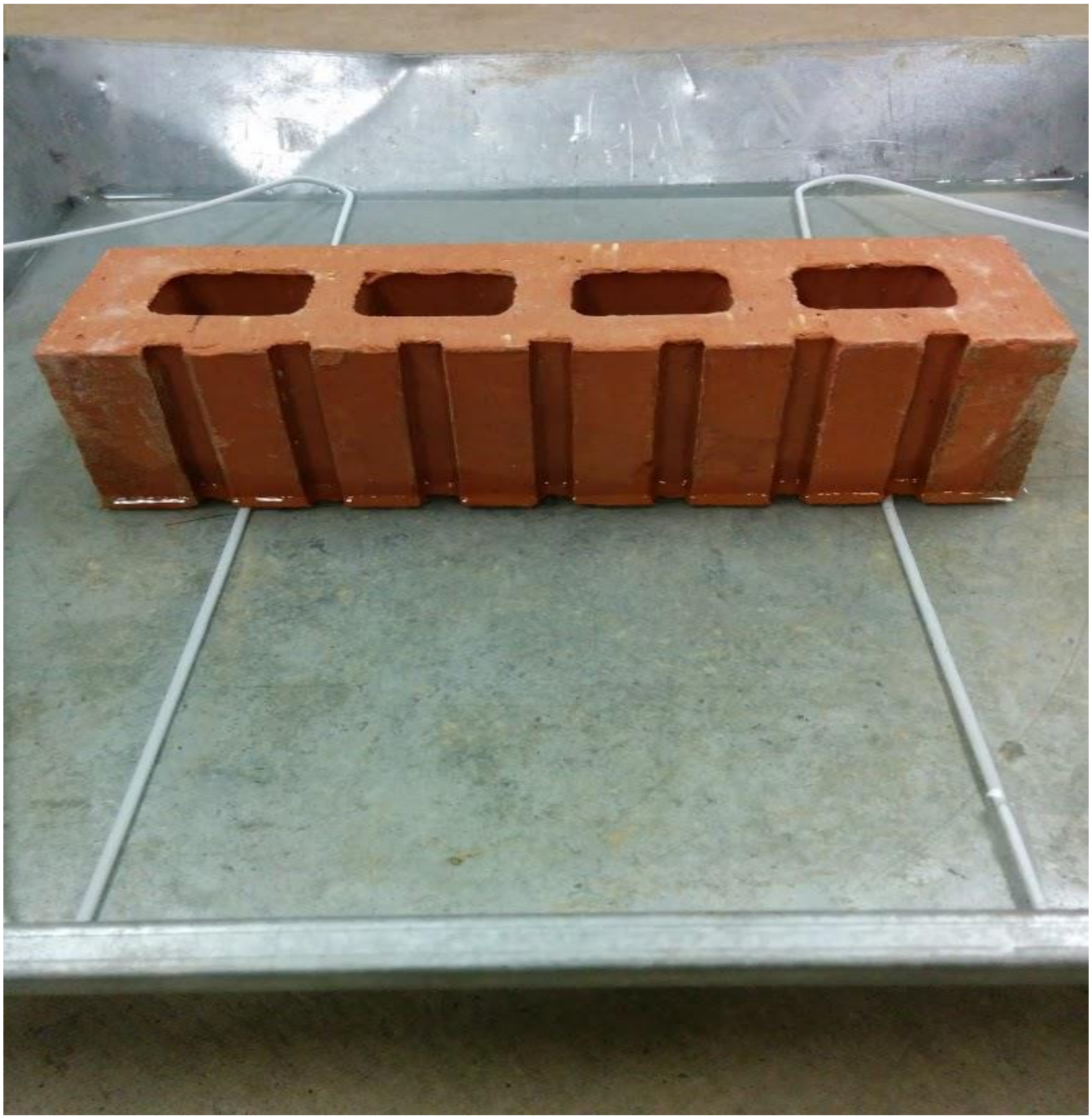


Figure 31: Absorption test on sample brick

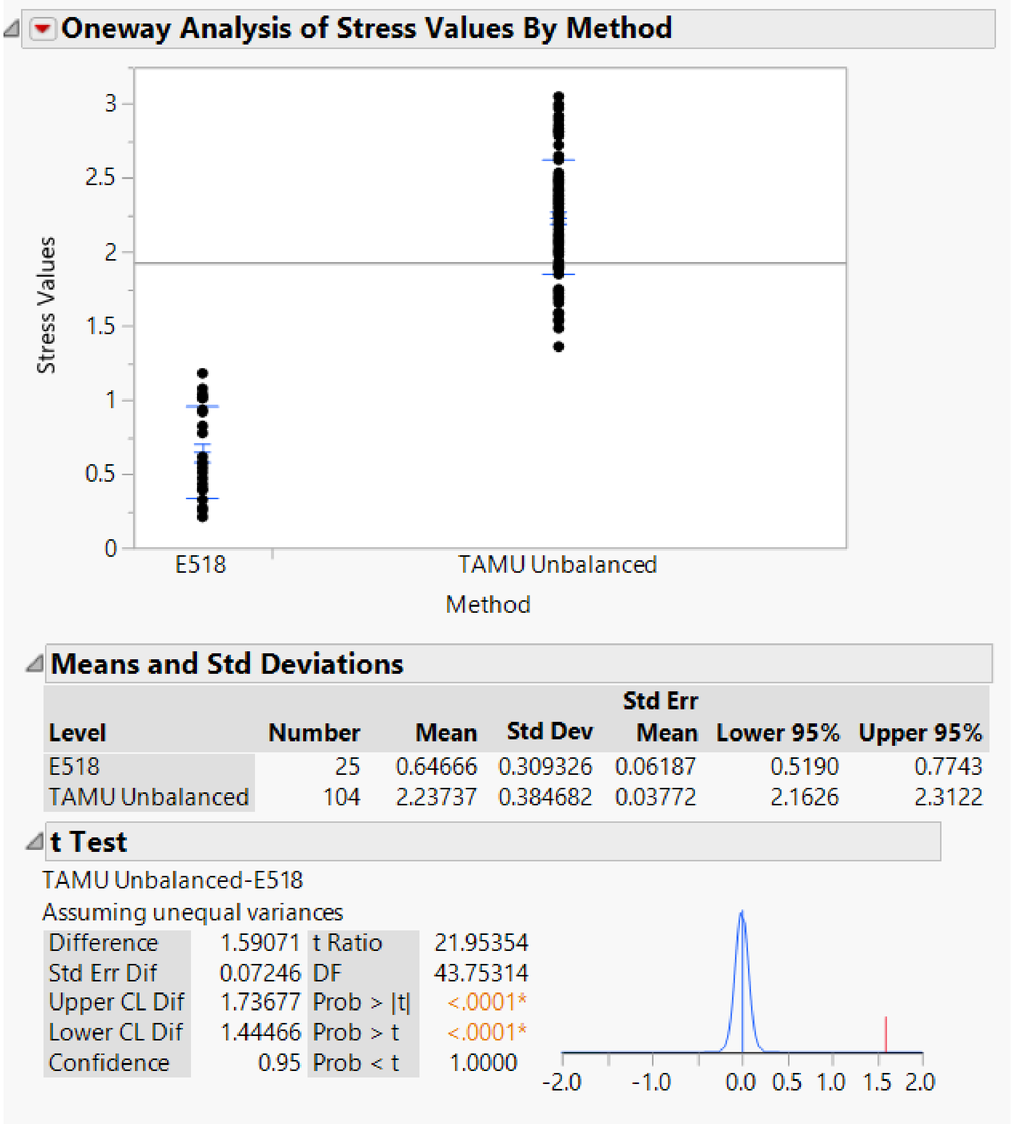
A Student t Test analysis has been carried out between TAMU Unbalanced Bond Wrench and ASTM E518 beam test, *Table 14* shows the method for interpreting Student's t Test carried out on two samples.

Table 14: Interpretation of student T-test

If	Then
Test statistic > critical value (i.e. $t > t_{crit}$)	Reject the null hypothesis
test statistic < critical value (i.e. $t < t_{crit}$)	Accept the null hypothesis
p value < α	Reject the null hypothesis
p value > α	Accept the null hypothesis

The null hypothesis is that there exists no bias between the flexural strength values from the TAMU Unbalanced Bond Wrench and ASTM E518 beam test. The present test is a two sided test, and hence two tail values were used for the analysis.

If the (t statistic < t critical) and (p value > α) in all the t Test comparisons between the sample sets, we can accept the null hypothesis that the means are the same. *Figure 32* show the results of the statistical analysis comparison.



Oneway Analysis of Stress Values By Method

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
E518	25	0.64666	0.309326	0.06187	0.5190	0.7743
TAMU Unbalanced	104	2.23737	0.384682	0.03772	2.1626	2.3122

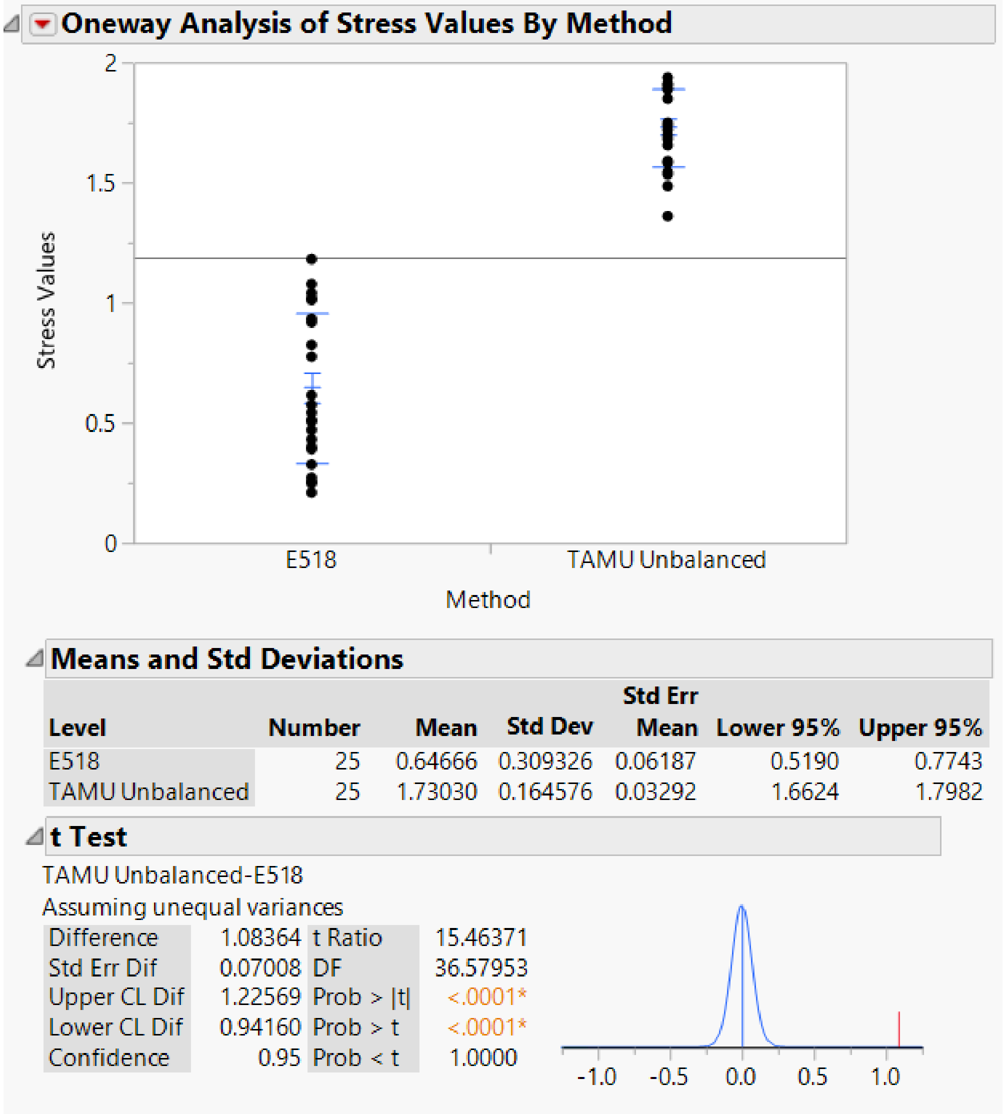
t Test

TAMU Unbalanced-E518

Assuming unequal variances

Difference	1.59071	t Ratio	21.95354
Std Err Dif	0.07246	DF	43.75314
Upper CL Dif	1.73677	Prob > |t|	<.0001*
Lower CL Dif	1.44466	Prob > t	<.0001*
Confidence	0.95	Prob < t	1.0000

Figure 32: Student t test- TAMU Unbalanced Bond Wrench – ASTM E518 beam test comparison



Oneway Analysis of Stress Values By Method

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
E518	25	0.64666	0.309326	0.06187	0.5190	0.7743
TAMU Unbalanced	25	1.73030	0.164576	0.03292	1.6624	1.7982

t Test

TAMU Unbalanced-E518

Assuming unequal variances

Difference	1.08364	t Ratio	15.46371
Std Err Dif	0.07008	DF	36.57953
Upper CL Dif	1.22569	Prob > |t|	<.0001*
Lower CL Dif	0.94160	Prob > t	<.0001*
Confidence	0.95	Prob < t	1.0000

Figure 33: Student t test- Comparison of weakest joint of TAMU Unbalanced Bond Wrench & ASTM E518 beam test

Summary of Results

- From the above t test analysis
    - The mean of the values from TAMU Unbalanced Bond Wrench is 2.23 MPa
    - The mean of the values from ASTM E518 beam test is 0.646MPa
- From the above t test analysis (see *Figure 32*), it can be found that the mean values of the TAMU Unbalanced Bond Wrench and ASTM E518 beam test are found to be dissimilar.
- The stress values for joints which failed during the bond wrench test were not considered for the statistical analysis. The values were zero and hence were outliers for the given data sample.
- The initial rate of absorption for brick samples was calculated and the average value was 0.78 kg/m^2/min which is under acceptable limits according to ASTM C67.
- The distribution for both the data set obtained from bond wrench experiment and ASTM E518 beam test were normal and t-test was valid.
- The values obtained from ASTM E518 method gives stress values for the joint which is weakest and hence the mean is lower (0.646 MPa) than the values obtained from TAMU Unbalanced Bond Wrench. The bond wrench measures the strength for each joint and hence the mean value is on the higher side (2.23 MPa)

- The null hypothesis is rejected because the probability of alternative being true is 100% at 95% confidence interval, which generates evidence that there exists a bias between TAMU Unbalanced Bond Wrench and ASTM E518 beam test.
- The results of student t-test (see *Figure 33*) conducted between the lowest stress values obtained from TAMU Unbalanced Bond Wrench and ASTM E518 beam method shows that null is to be rejected and hence there is a bias when the stress values of weakest joints (tested by Unbalanced Bond Wrench) are compared with ASTM E518 beam test.

CHAPTER V

CONCLUSIONS

The performance of a joint under various loading conditions is significantly affected by the bond strength and hence it is one of the important factors in a masonry joint. The flexural bond strength of a joint can be measured using a bond wrench. The first of the bond wrenches was developed in 1980s in an Australian laboratory. In the past few years a variety of bond wrenches with different designs have been manufactured.

Two graduate students developed the TAMU unbalanced and balanced bond wrench. An Australian bond wrench was manufactured in 2011 and subsequently in 2012 an ASTM C 1072 Bond Wrench was developed. The Australian and the American wrenches are unbalanced imparting a torque to the prism upon placement. Among the TAMU wrenches, one wrench is balanced and the other is unbalanced. The TAMU balanced and the unbalanced wrenches vary only with respect to the upper clamping buckets.

A number of studies have been conducted before at TAMU to study the bias between the different wrenches for the mean flexural strength obtained using a set of masonry prisms. Previous researchers have found out that no unacceptable bias existed in the flexural strength values forecasted using the TAMU balanced and unbalanced wrench. The results have also shown that there exists a bias between American Bond Wrench and Australian Bond wrenches. Hence it was suggested that the tests be carried out by replacing the cement with Portland cement.

This experimental research uses Portland cement and aims to make a comparison of bond strength values forecasted by the TAMU balanced wrenches and ASTM E518 the standard method to measure the values check the bias among them.

For the experimental purposes, a total of 50 prisms were built. Each prism comprised of 6 bricks with 5 joints, and all the bricks used were Texan bricks. The mortar used here was 1:1:6, and Portland cement was used. All the experiments were carried out under the same weather conditions. The first set of 25 prisms was tested using TAMU Unbalanced Bond Wrench. The second set of 25 prims was tested using ASTM E518 method.

It can be concluded that the values forecasted using ASTM E518 were low due to failure of the weakest joint in the prism. The TAMU Unbalanced Bond Wrench on the other end measures each joint and gives stress values according to the strength of that joint. The ease of setup of apparatus and experiment and weight of the instrument also makes it favorable to use the bond strength for flexural analysis of joints.

Further research is recommended using the Texas red brick. Also other bond wrenches and methods for measuring bond strength can be compared with ASTM E518 to check any bias between them.

REFERENCES

American Society for Testing and Materials International. (2010). *E518/E518M-10 Standard Test Methods for Flexural Bond Strength of Masonry* (Vol. 04.05). W. Conshohocken PA.: ASTM International.

American Society for Testing and Materials International. (2013). *C1072-13 Standard Test Method for Measurement of Masonry Flexural Bond Strength* (Vol. 04.05). W. Conshohocken, PA.: ASTM International.

Baker, I. O. (1914). *A treatise on masonry construction(10th ed.).* J. Wiley & sons.

Binda, L. (2008). *Learning from failure: long-term behaviour of heavy masonry structures* (Vol. 23): WIT press.

Binda, L., Baronio, G., Tiraboschi, C., & Tedeschi, C. (2003). Experimental research for the choice of adequate materials for the reconstruction of the Cathedral of Noto. *Construction and Building Materials, 17*(8), 629-639.

Binda, L., Saisi, A., & Tiraboschi, C. (2000). Investigation procedures for the diagnosis of historic masonries. *Construction and Building Materials, 14*(4), 199-233.

Boynton, R. S., & Gutschick, K. A. (1964). *Bond of Mortar to Masonry Units Factors Influencing Strength, Extent, and Durability of Bond*. Washington, DC: National Lime Association.

Chaudhari, S. (2010). *Comparitive Analysis between a balanced and unbalanced bond wrench.* Professional Paper, Texas A&M University, TAMU.

Coombs, J. M. (2007). *Enhancement of masonry curriculums through virtual laboratory experiments*: Master's Thesis, University of Wyoming.

Edgell, G. (1987). Factors affecting the flexural strength of brick masonry. *Masonry Int., 1*(1), 16.

Fishburn, C. C. (1961). *Effect of mortar properties on strength of masonry* (Vol. NBS Monograph 36). Washington: U.S. Dept. of Commerce, National Bureau of Standards.

Hughes, D. M., & Zsembery, S. (1980). *A Method of Determining the Flexural Bond Strength of Brickwork at Right Angles to the Bed Joint.* Paper presented at the Proceedings of the 2nd Canadian Masonry Symposium, Ottawa. pg. (105-115)

Institution, B. S. (1992). BS 5628: Part 1:1992. *Code of practice for the use of masonry-Part 1: Structural use of unreinforced masonry*. British Standards Institution, London.

Kampf, L. (1963). *Factors affecting bond of mortar to brick.* Paper presented at the Symposium on Masonry Testing NY. ASTM: American Society for Testing and Materials: ASTM Special Technical Publication No. 320 pg. (127 - 142)

Khalaf, F. M. (2005). New test for determination of masonry tensile bond strength. *Journal of materials in civil engineering, 17*(6), 725-732.

Lawrence, S., Page, A. W., & Scientific, C. (1994). *Bond studies in masonry*: CSIRO. Division of Building, Construction and Engineering.

McGinley, W. M. (1996). *An Evaluation of Bond Wrench Testing Apparatus* (Vol. SEDL / STP / STP1246-EB / STP18207S). W. Conshocken, PA: ASTM.

McHargue, E (2013). *Bond strength measurements from an Australian standard bond wrench in comparison to the unbalanced ASTM C 1072 bond wrench.* Master of Science (Construction Management) Professional Paper, Texas A&M University, College Station, Texas.

Nichols, J. M. (1990, 15-17 Feb 1990). *Behaviour of Structures - Churches.* Paper presented at the Conference on the Newcastle Earthquake, Newcastle. Institution of Engineers, (Australia), Barton ACT: pg. (35-38)

Nichols, J. M. (1991). *Site control of masonry - A case study.* Paper presented at the National Masonry Seminar, Newcastle, Australia.

Nichols, J. M. (2000). *A Study of the Progressive Degradation of Masonry Shear Walls Subjected to Harmonic Loading.* Thesis (Ph.D.) No: 2148, University of Newcastle, Newcastle.

Nichols, J. M. (2013). *Comparative study of four bond wrenches with recommendations on changes to ASTM C 1072.* Paper presented at the 12th Canadian Masonry Symposium, Vancouver.

Nichols, J. M., & Holland, N. L. (2011). *A Comparative Study of Balanced Bond Wrench Testing and Unbalanced Bond Wrench Testing.* Paper presented at the Eleventh North American Masonry Conference, Minneapolis.

Page, A. (1983). The strength of brick masonry under biaxial compression-tension. *International Journal of Masonry Construction, 3*(1), 26-31

Page, A. (1991). Newcastle earthquake- behaviour of masonry structures. *Masonry International, 5*(1), 11-18.

Palmer, L. A., & Parsons, D. A. (1934). A study of the properties of mortars and bricks and their relation to bond. *Bureau of Standards Journal of Research, 12*, 609-644

Portland Cement Association. (1994a). *Bond Strength Testing of Masonry* (Vol. Informational Set 277). Skokie, IL: Portland Cement Association.

Portland Cement Association. (1994b). *Factors affecting Bond Strength Masonry* (Vol. Information Set 278). Skokie, IL: Portland Cement Association.

Radcliffe, M. R., Bennett, R. M., & Bryja, J. (2004). *Highly Cored Extruded Clay Units: Testing and Design Procedures.* Paper presented at the Structures 2004: Building on the Past, Securing the Future Nashville, TN. ASCE: pg. (1-8)

Rao, K. V. M., Reddy, B. V., & Jagadish, K. (1996). Flexural bond strength of masonry using various blocks and mortars. *Materials and structures, 29*(2), 119-124.

Riddington, J., & Jukes, P. (1994). A masonry joint shear strength test method. *Proceedings of the ICE-Structures and Buildings, 104*(3), 267-274.

Ritchie, T., & Davison, J. (1962). Factors affecting resistance to moisture penetration and strength of bond of brick masonry. *ASTM Special Technical Publication*(320) pg. (16-30).

Sarangapani, G., Venkatarama Reddy, B., & Jagadish, K. (2005). Brick-mortar bond and masonry compressive strength. *Journal of materials in civil engineering, 17*(2), 229-237.

Sise, A., Shrive, N. G., & Jessop, E. L. (1988). Flexural Bond Strength of Masonry Stack Prisms. *Proceedings, British Masonry Society, 2*, 103-108.

Sugo, H., Page, A., & Lawrence, S. (2000). *Study of bond strength and mortar microstructure developed using masonry cement.* Paper presented at the 12th International brick/block masonry conference.

Suresh, S. V. C. G. (2014). *Bond strength measurements from an Australian standard bond wrench in comparison to the unbalanced ASTM C 1072 bond wrench to the balanced and unbalanced wrenches*. (Unpublished master's thesis), Master of Science (Construction Management) Texas A&M University, College Station, Texas.