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

A Thesis

by

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ABSTRACT

The brick to mortar bond strength affects the performance of the joints in brick masonry when subjected to various loading conditions. The flexural bond strength of masonry units can be measured using a bond wrench or a standard test like ASTM E518 beam test. The early bond wrenches were developed in the 1980s in Australian laboratories. In 2011, an Australian bond wrench was manufactured and consequently an ASTM C1072 Bond Wrench was developed in 2012. Further research was done in the field and two more lightweight bond wrenches, i.e. balanced and unbalanced, were built by Indian students at Texas A&M University.

Several researchers have performed experiments to study the bias between different bond wrenches. These researches illustrated that no unacceptable bias existed in the flexural strength values calculated using the Indian 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 balanced bond wrench developed at Texas A&M University and Standard ASTM E518 beam test method. Also, Indian balanced and unbalanced bond wrench would be referred as TAMU (Texas A&M University) balanced and unbalanced bond wrench in this report.

A total of 50 prisms using Portland cement and Texan bricks were built for this experimental research. The prisms were built in two sets and each prism comprised of six bricks with five joints. The mortar used here was 1:1:6 (cement: lime: sand). The

samples were cured for a period of 07 days, and all the experiments were carried out under same weather conditions. TAMU balanced 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 Student's t-Test analysis was run between the flexural strength values of the TAMU balanced 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 balanced bond wrench. The plots of ASTM E518 method and TAMU balanced were quite dissimilar.

Further research is recommended using the Texas red brick.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

Background

Masonry systems are an integral 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. Bond strength between mortar and masonry unit is a significant factor in the performance of a masonry system (Coombs, 2007). The calculation of bond strength between masonry units and mortar has been of significant interest to researchers for some time (Khalaf, 2005). 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 balanced bond wrench test.

Researchers from all over the world have studied flexural bond strength for many different types of bricks and mortar combinations including Australia (Lawrence, Page, & Scientific, 1994), (J. Nichols, 2000), (Page, 1983), (Sugo, Page, & Lawrence, 2000), Italy (L Binda, Baronio, Tiraboschi, & Tedeschi, 2003), (L Binda, Saisi, & Tiraboschi, 2000), (Luigia Binda, 2008), Canada (A. Sise, N. Shrive, & E. Jessop, 1988) and the USA (McGinley, 1996).

Chaudhari (2010) studied the flexural test results for a balanced wrench and an unbalanced wrench, and Nichols (2013), McHargue (2013) & Suresh (2014) studied the bias results for flexural strength from four different bond wrenches on a consistent masonry unit. Former Texas A&M University students had built a lightweight TAMU balanced and unbalanced bond wrench to measure the bond strength of masonry systems. This research is aimed at taking these researches further and compares the bias and precision between ASTM E518 method and TAMU balanced bond wrench to measure the bond strength for a masonry unit. ASTM E 518 test is also known as the "Standard Test Method for Flexural Bond Strength of Masonry".

Problem Statement

The purpose of this study is to determine if a statistically significant difference exists in the mean strength results for common brick and mortar masonry prisms using ASTM E518 beam test and TAMU balanced bond wrench.

Hypothesis

The following hypothesis will be tested for the study:

No statistical difference exists between the flexural test results for ASTM E518 beam test and the TAMU balanced bond wrench for a consistent type of masonry.

Limitations

This research is an extension of the studies done so far to understand, the bias between different bond wrenches and other tests available to measure the bond strength. The comparison of test results from different bond wrenches across the world is still under research. It is also important to compare these values with the standard methods for measuring the flexural bond strength recommended by different countries. Due to the limited usage of the bond wrenches for tests, the level of standardization is still far from acceptable.

Nichols (2013) listed some of the significant issues that arise while developing internationally recognized standards. They are:

1. Developing a testing method which checks for the moisture content and exact mixture ratios and limits it according to the requirement for the mortar and testing schedules.
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 comprising of 25 prisms has 125 joints tested to failure, using TAMU balanced bond wrench.
2. The second population sample again comprises 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 highlights the importance of flexural bond strength in a masonry system and various other factors like masonry properties, bond issues, bond characteristics and other information which affects the flexural and tensile strength testing of masonry assemblages. The deformation characteristics of the brick and mortar can be independent from the interaction between brick and mortar, however bond is very often influenced by factors such as the surface characteristics of the brick, which may not have any bearing on the deformation of the brick or mortar (Sarangapani, Venkatarama Reddy, & Jagadish, 2005). However, the objective of this experimental work is minimizing such variations due to the random factors associated with the experiments, except for an organized change in the type of testing apparatus used for the experimental measurements.

Masonry properties

Workability, durability, ability to support compressive loads as well as bond strength to resist flexural tensile stresses are different aspects of a masonry system (Portland Cement Association, 1994b). Addition of unsuitable materials, including fire clay and dishwashing detergent can result in additional workability but only at the expense of durability of masonry systems (J. M. Nichols, 1990, 1991). It is important to maintain a consistent quality in the manufacture of test prisms (Sugo et al., 2000). The maximum tensile stress a masonry system can sustain is dictated by bond strength and thus it controls the design. The water integrity of the wall is related to the bond strength and thus serviceability and durability of the masonry is affected by bond between the unit and mortar. This is why it is very important to understand this complex property which is crucial to masonry design. The purpose of this laboratory study is to explore different methods of experimentally determining the flexural bond strength between masonry units and mortar while also observing the effect of mortar type on bond strength.

Bond issues

There are two important concepts to understand the term "Bond" in reference to mortar brick interface. The strength of the area of contact between the mortar and masonry unit is the first important factor while the other 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 determined by lower of these two values. (Baker, 1914) studied extensively and tested the tensile strength of mortar which was followed by (Sugo et al., 2000) who continued this experimental work on masonry cylinders.

The resistance of flexural stresses resulting from eccentric axial loads, out of plane loads, or both, for unreinforced masonry rely on adhesion of mortar to units , in case they are designed using working stress analysis (Portland Cement Association, 1994b). Masonry elements require Tensile Flexural capacity to resist environmental loads, such as wind and earthquake. 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) the measured flexural strength is affected by pre-wetting a pressed brick and it also introduces a consistent bias in the strength.

Initial works

The flexural bond strengths have been investigated by many researchers and research groups through different set ups. (Baker, 1914) tested the tensile strengths of cement mortar initially followed by 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 (Kampf, 1963) all these tests have their own disadvantages and complications. The tests mentioned above are briefly described below:

Crossed brick couplet test method

The bond strength is established by measuring 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. The downward force generated by the testing machine's compression is converted into a direct tension force using a test jig. The non-uniformity of tensile stresses over the joints results in concentration of higher stresses in the corners of the composite interfaces. The test results shows inconsistency in stress values especially at areas subjected to shrinkage stresses (Portland Cement Association, 1994a). *Figure 1* gives the plan and section view of the set up.

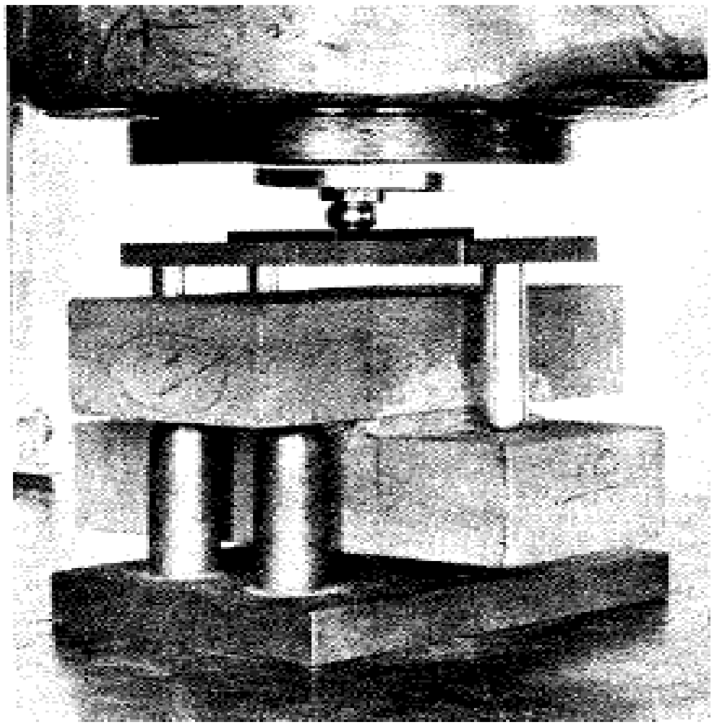


Figure 1: Crossed brick couplet test method (Adams, 1994)

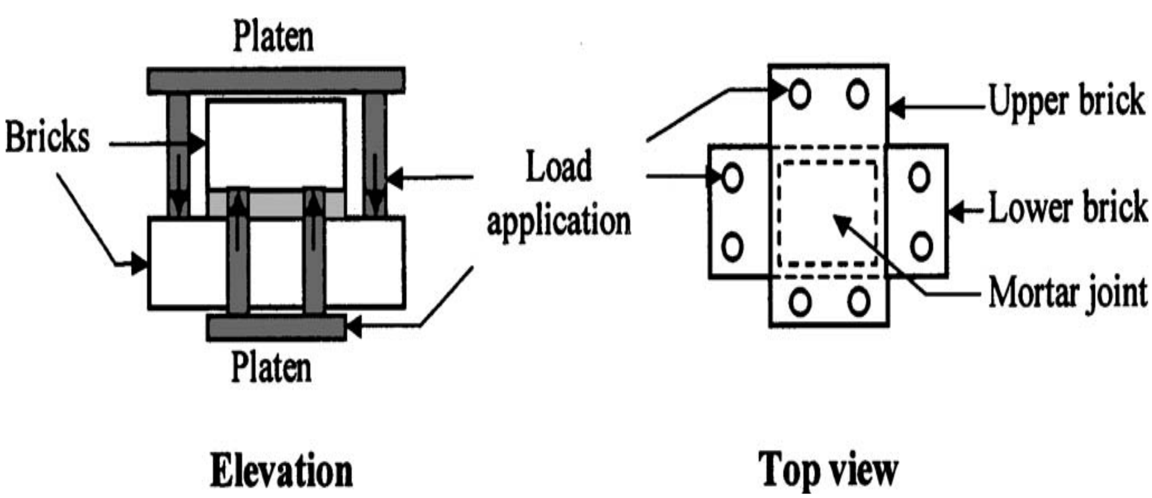


Figure 2: Elevation and top view of the corresponding setup (Adams, 1994)

Couplet brick test through holes

The regular couplet as bolt-holes (see *Figure 3*) is used for this test 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.

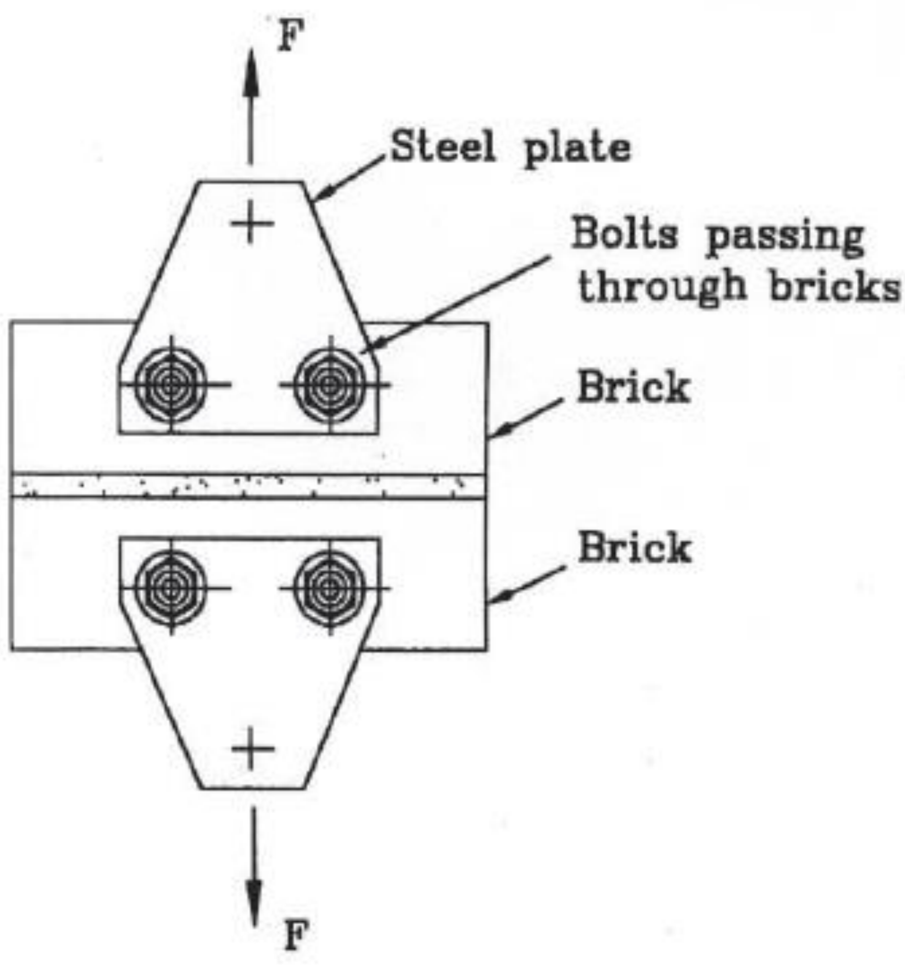


Figure 3: Direct tensile strength as executed by (Riddington & Jukes, 1994)

Test on wallettes

A well-known and standard test according to the British Standards BS 5628 (INSTITUITION, 1992) is performed on small bricks/block wall specimens (wallettes) under four-point loading to determine the flexural bond strength of masonry bed joints. The undermentioned figure shows the wallette test arrangement for planes of failure parallel and normal to the bed joint.

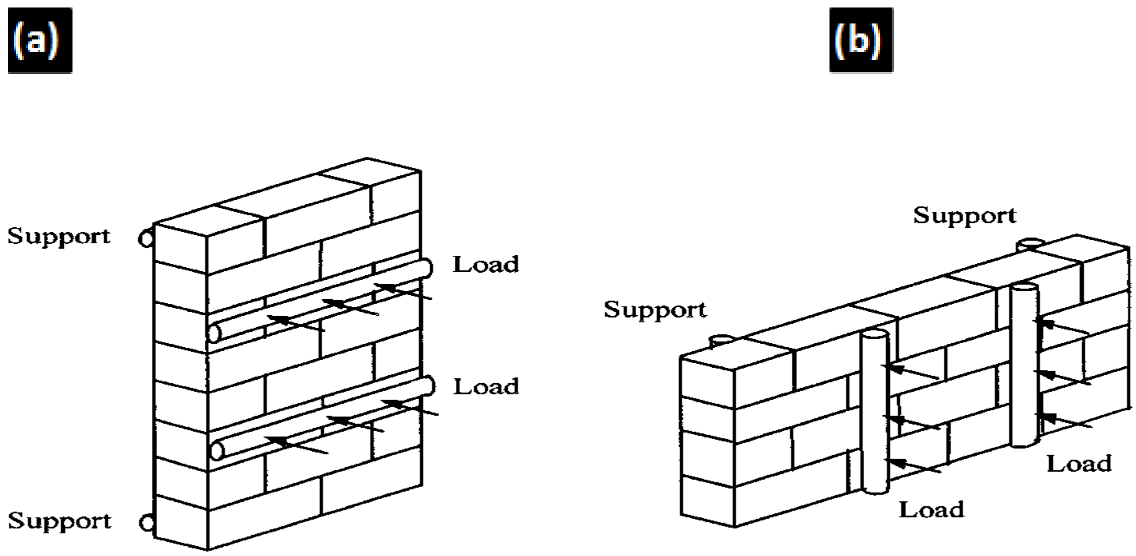


Figure 4: Testing arrangement of wallettes (small walls), BS 5628 (INSTITUITION, 1992) (a) Plane of failure parallel to bed joint (b) Plane of failure normal to bed joint

The requirement of large specimen and setup makes this form of experiment and the whole process to be time consuming and difficult to execute. The bond strength values from several crossed couplet tests were compared with tests performed on wallettes in accordance with BS 5628 (INSTITUITION, 1992) by (Adams, 1994) and

(De Vekey et al. 1990). The results obtained from wallettes were higher than those from the couplet tests as shown in the *Figure 5.*

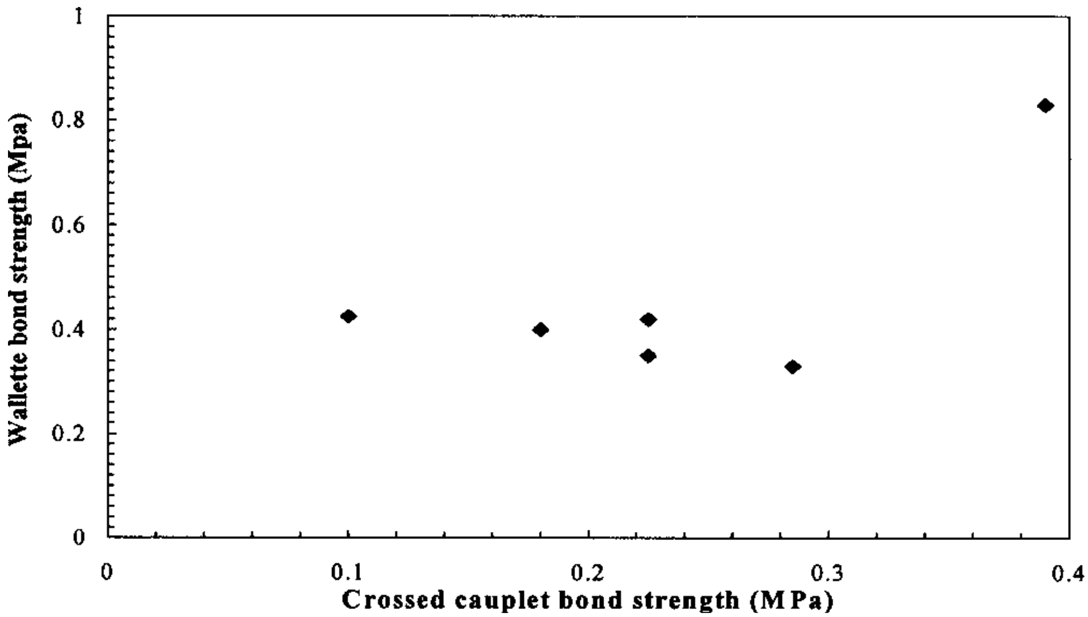


Figure 5: Comparison of bond strengths from crossed couplet bond strength and test on wallettes after (Adams, 1994) and De Vekey et al. (1990)

Bridge pier test

ASTM E518 is the standard test method for measuring flexural bond strength and was adopted in 1974 and most recently reapproved in 2010 (ASTM International, 2010). The 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) can be achieved using these test methods which are intended to provide simplified means for gathering research data (Park, 2013). The method uses a stacked bond masonry prism tested as a simple beam in third point loading or uniform loading.

The ease to prepare the specimen for and perform the testing of both these tests, led to their widespread use in the field and laboratory.

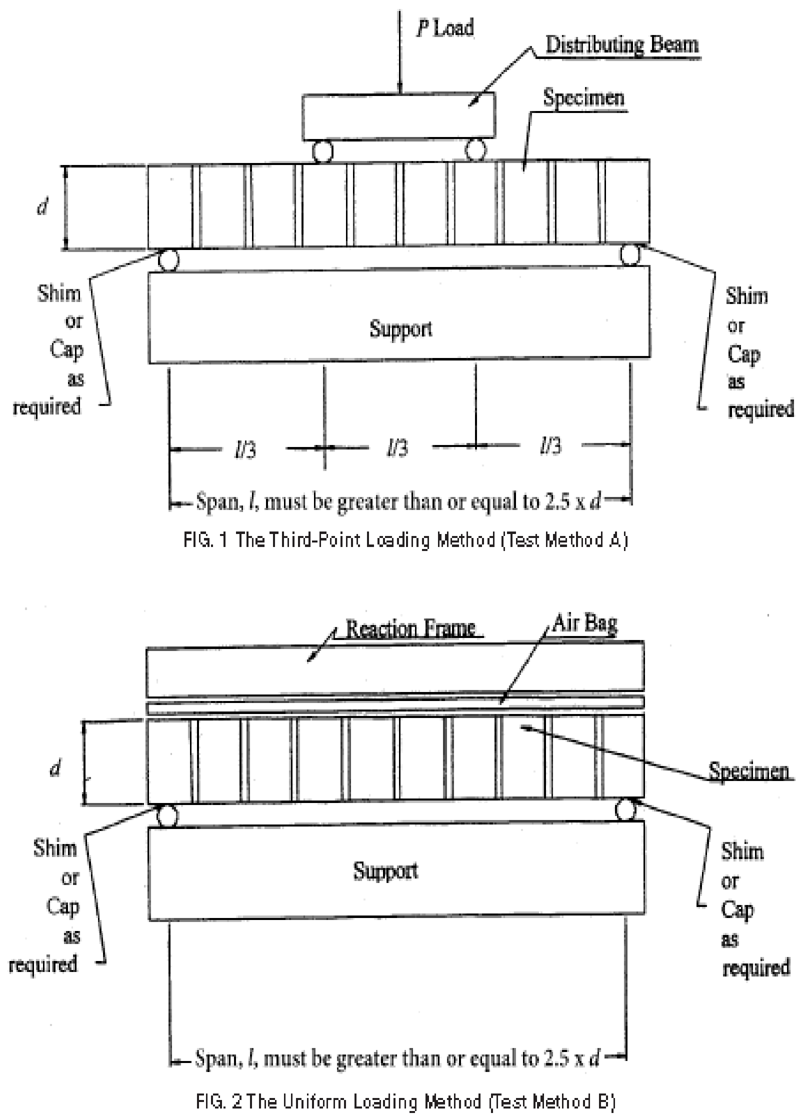


Figure 6: ASTM E518 Test methods A & B (ASTM International, 2010)

ASTM C1072 is also the standard test method for measurement of masonry flexural strength and was adopted in 1986 and reapproved in 2011. The method evaluates flexural bond strength normal to the bed joints. Its uses a bond wrench for the test and can be used for laboratory and field prepared specimens along with prisms removed from the existing masonry. EN 1052-5 is the "European standards method of test for masonry" used to evaluate the bond strength through bond wrench method.

Bond wrench types

The first bond wrench was created by (Hughes, Zsembery, & Brick, 1980) as shown in *Figure 7*. The test is a variant of the bond beam test. *Figure 8* shows the distinct step, second stage of the set-up of the bond wrench.

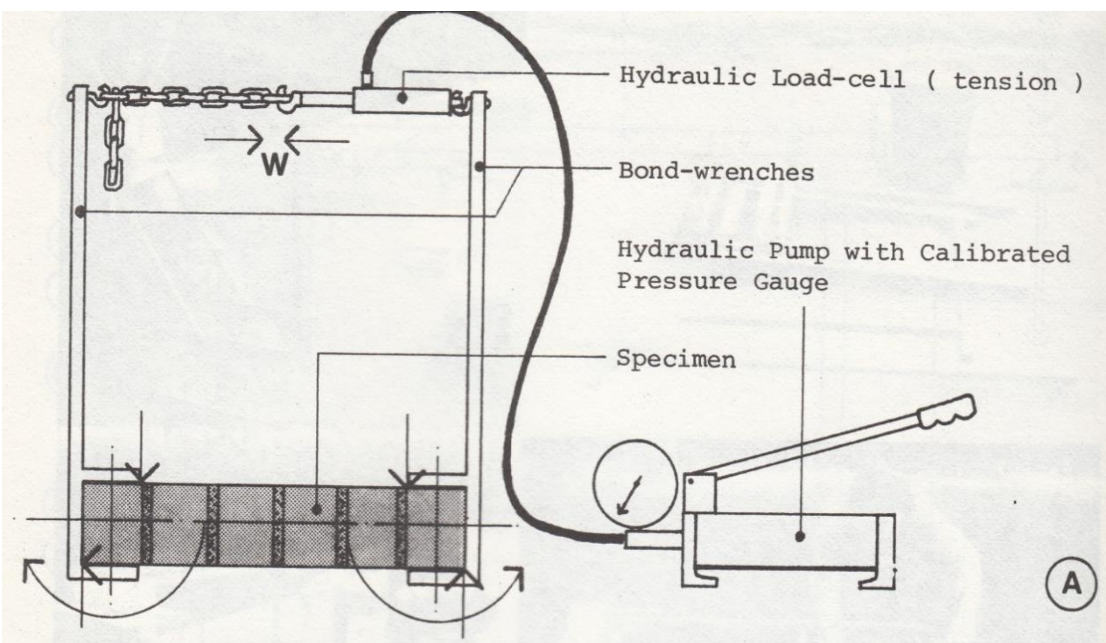


Figure 7: Bond wrench stage I (Hughes et al., 1980)

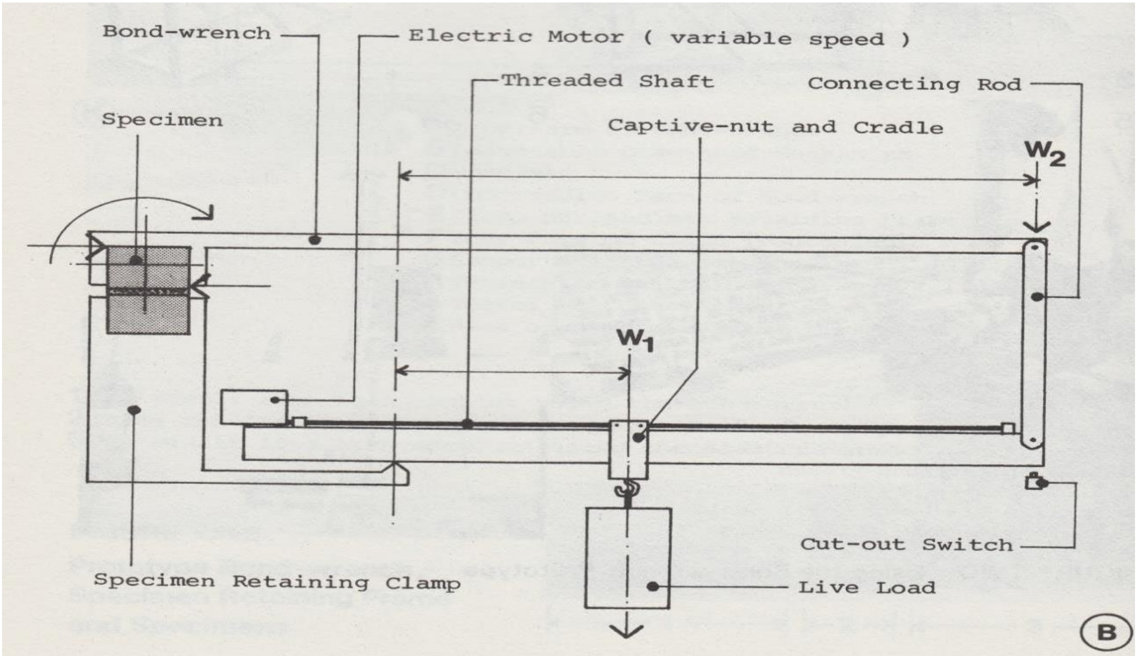


Figure 8: Bond wrench stage II (Hughes et al., 1980)

Different bond wrenches have been developed in the past without modifying the basic structural form of the original structure shown in *Figure 9*. 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) also carried out extensive research on the flexural bond strength of a masonry using a bond wrench test setup and concluded that flexural bond strength increases with an increase in mortar strength for cement mortar irrespective of the type of masonry unit. Also the brick strength didn't have any significant effect on the flexural bond strength. The moisture content at the time of casting had a significant effect, where the optimum moisture content led to the maximum bond strength.

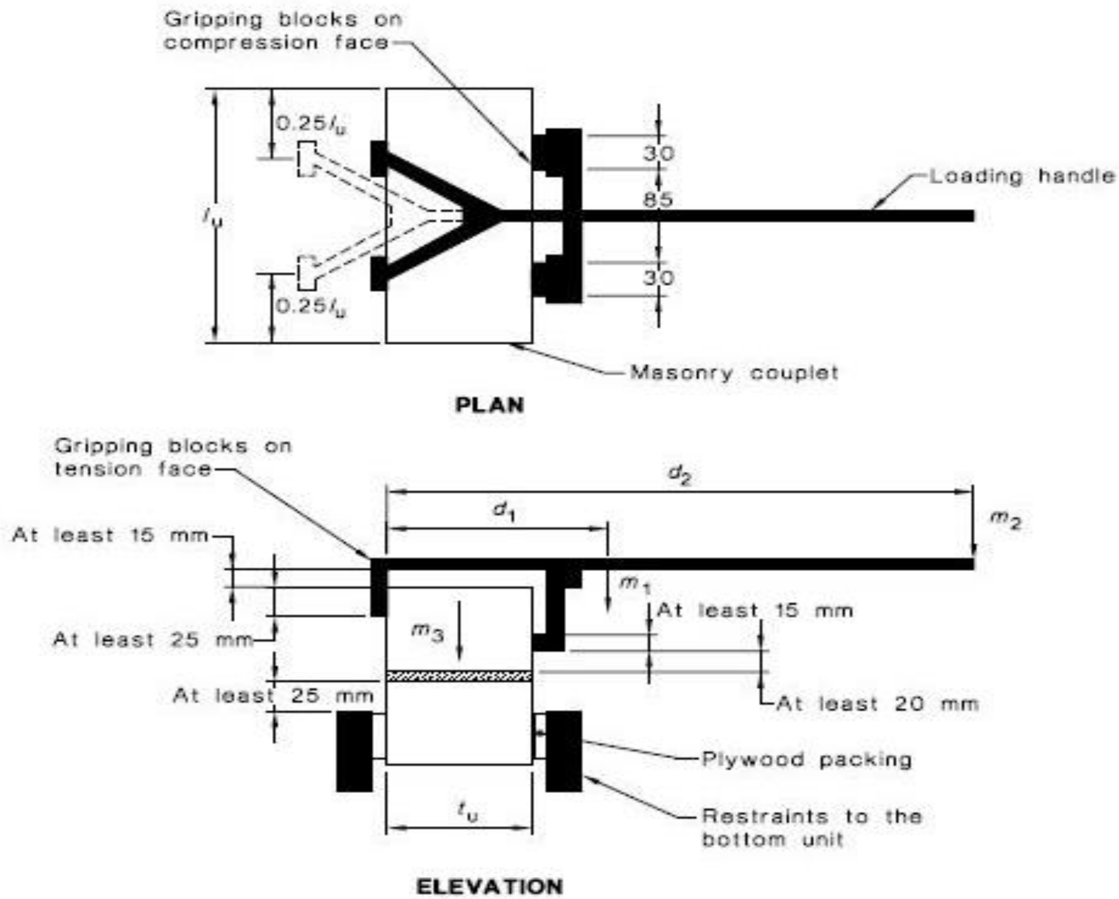


FIGURE D1 SCHEMATIC DIAGRAM OF THE BOND WRENCH SET UP

Figure 9: Australian bond wrench setup, AS 3700 (2001)

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

Bond wrench designs

The linear stress distribution assumed by flexural theory does not hold well for ASTM Standard bond wrench according to (McGinley, 1996), and the existing stress distributions are a result of measurements determined using LVDT system.

The bond wrench test must be proficient of producing a simple bending-theory stress distribution, while doing the analysis of masonry bond tests (Riddington, Jukes & Morrell, 1998), however stress distribution can get affected by the clamping mechanisms or wrench not being the full length of the specimen being tested and hence care needs to be taken to prevent it.

Unbalanced stress distribution happens across a masonry prism cross section when bond wrenches are used & this particular stress distribution has a couple of components, uniform axial compressive stress distribution and a linear flexural stress distribution (Radcliffe, Bennett, & Bryja, 2004). The compressive stress load impacts the flexural stress distribution and hence it is inversely proportional to length of loading arm. This results in lower impact or influence on the total stress distribution, due to compression and flexural stresses depicted by the Australian Bond Wrench, AS 3700 which has a longer moment arm and lower mass than the American Bond Wrench.

Modified bond wrench

The pure couple bond wrench (see *Figure 11*) was created by (Radcliffe et al., 2004) using the ASTM C 1072. The download testing load is negated by the upward load and hence the design of wrench enables the weight of the clamping mechanism to be the only compressive load. This ensures 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*.

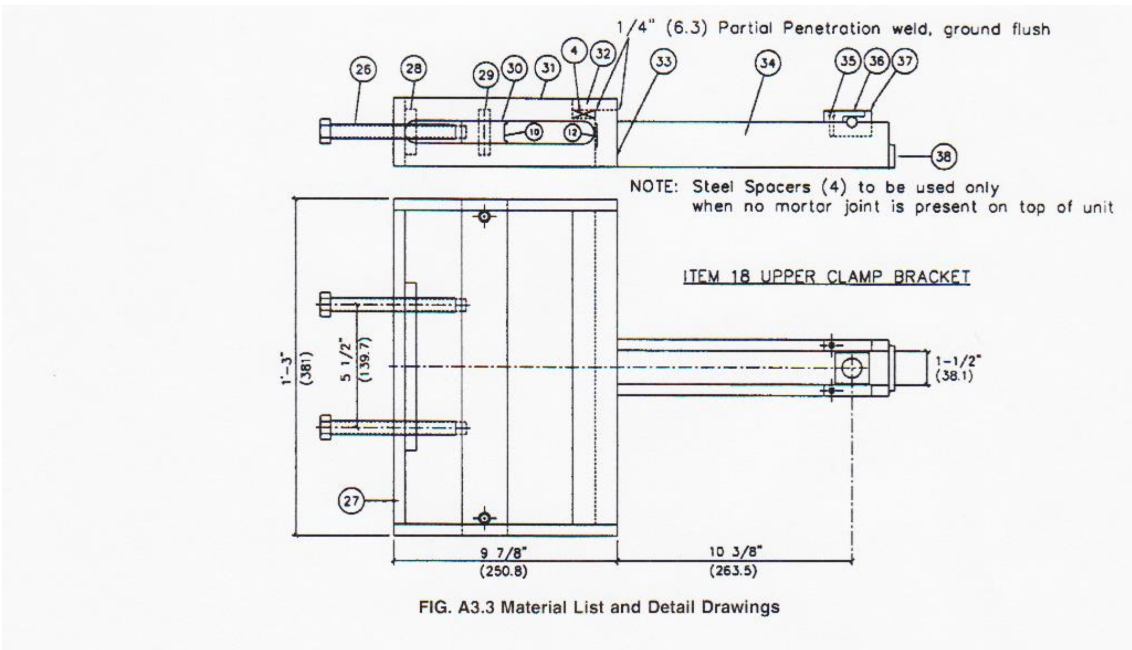


Figure 10: ASTM C1072 Bond wrench clamp bracket ASTM International (2013c)

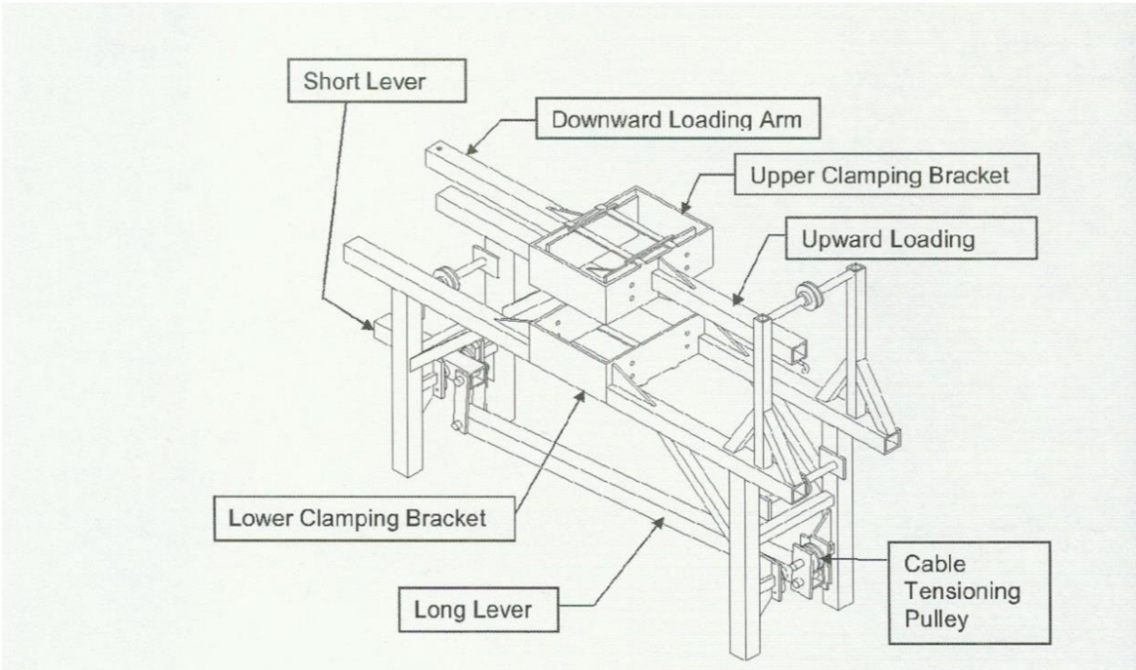


Figure 11: Pure couple bond wrench by (Radcliffe et al., 2004)

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

The TAMU balanced wrench developed by Chaudhari (2010), designed to impart zero moment at the start of the test to the top of prism used in testing is shown in *Figure 12*.

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

Figure 13: TAMU unbalanced bond wrench by Chaudhari (2010)

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	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 flexural values ranged from 0.65 MPa – 0.73 MPa when stress values obtained from unbalanced test and the balanced wrench were analyzed, using statistical Student's t Test, with a 5% acceptance level.

Further Nichols (2013) tested Chaudhari (2010) bond wrench with Australian bond wrench model, ASTM C 1072, an equivalent unbalanced wrench. The experiment was conducted using a total of eleven prisms. The summary of the results of the four wrenches has been depicted below in *Table 2* In comparison to other three tests the American wrench results were on average fifty percent higher. The mean was discrete 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

Research pertaining to masonry bond and compressive strengths was conducted by (Sarangapani et al., 2005) that utilized different flexural tests, various mortars and a modified ASTM C1027 bond wrench. 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*).

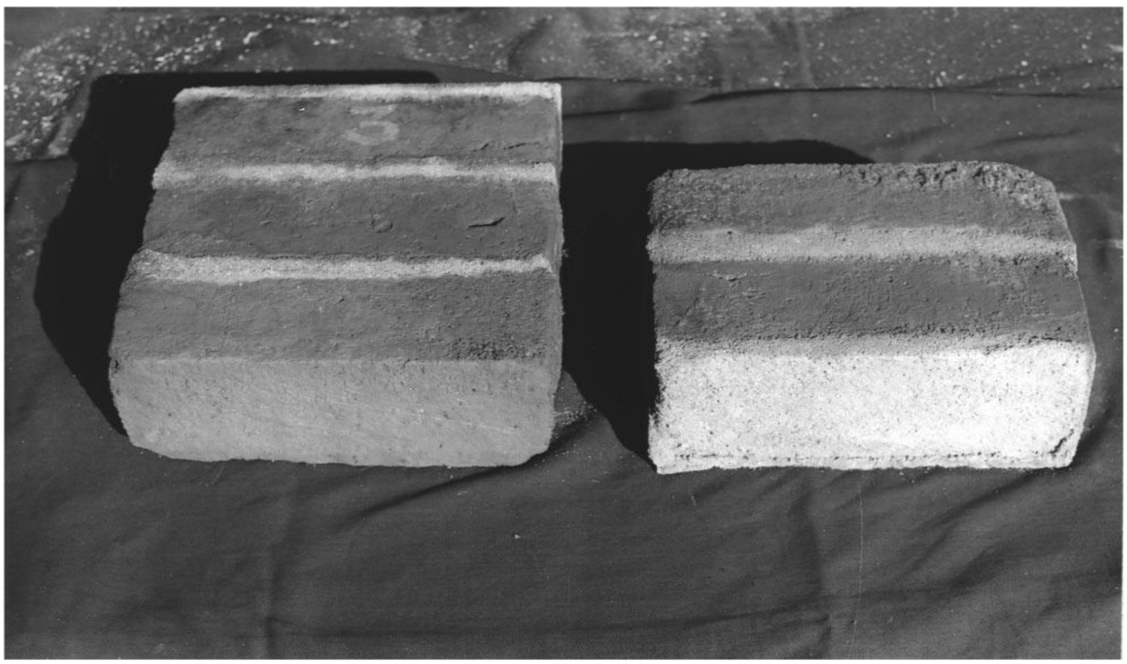


Figure 14: Bond failure at brick-mortar interface (Sarangapani et al., 2005)

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*

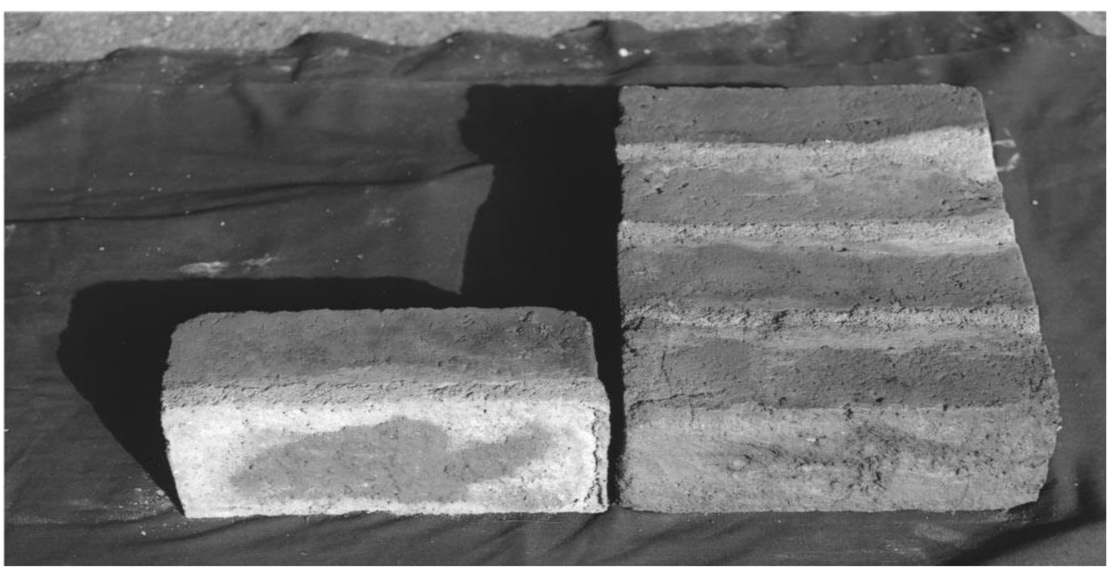


Figure 16: Type 1 and Type 2 failure (Sarangapani et al., 2005)

Bond strength is influenced by some of the familiar properties of mortar like water retention, initial flow, air content and workmanship (Boynton & Gutschick, 1964; Edgell, 1987). Previous works by (Kampf, 1963) showed that workability is not a single property, but a mixture of many factors and is the most significant property that affects a good bond.

Studies conducted by (Fishburn, 1961) showed that different mortars which differed in the cementitious materials appeared to have some kind of connection that affected the flexural strength values of tested walls due to the compressive strength of the mortar. Masonry cement was used by Chaudhari (2010) and McHargue (2013) in their research, but this research paper uses Portland cement.

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

- The maximum bond-strength results from fifteen different mortars improved with the compressive strength of mortars if the extent of bond formation was good.
- The maximum bond strength with mortars of high strength was obtained with bricks which were porous and had a low rate of absorption if the extent of bond was good.

The bond strength reduces when there is a late setting of brick onto the mortar bed indicating that timeliness of brick setting has a major effect on the bond strength (Boynton & Gutschick, 1964; Ritchie & Davison, 1962). The bond strength reduction is the maximum for high suction brick and lowest for low suction bricks according to (Kampf, 1963). The bonds get destroyed if the bricks are realigned after the brick mortar begins to stiffen (Boynton & Gutschick, 1964), which suggests that the chances for realigning of brick without getting damaged is greatest for low –suction brick and high water- retention mortar, refer to *Figure 17* & *Figure 18*.

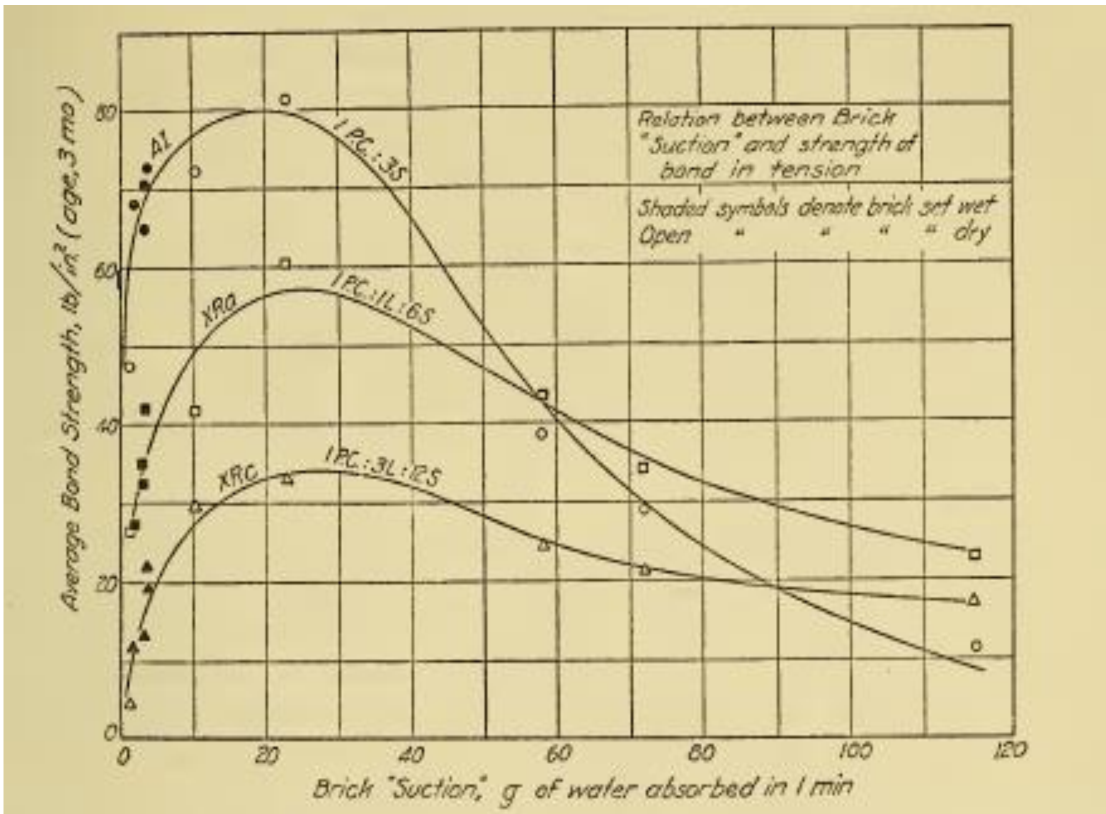


Figure 17: Bond strength results across a range of brick suction values (Boynton & Gutschick, 1964)

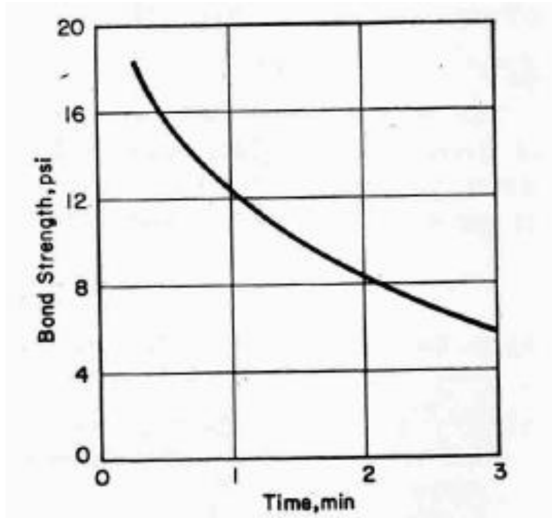


Figure 18: Bond strength plotted against time to placement (Kampf, 1963)

Several experiments and research have been done results have been published for different wrench designs on a continuous basis. Chaudhari (2010) & Suresh (2014) conducted tests at Texas A&M University to compare bond strength results between difference bond wrenches. The results showed that the unbalanced wrench yielded ten percent higher results than the balanced wrench. The four bond wrenches yield different results when tested under similar conditions at TAMU according to Nichols (2013). The American bond wrench ASTM C 1072, gave results so far that are 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. There was a statistically significant, increase in the test strength 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.

CHAPTER III

METHODOLOGY

Introduction

The test program includes manufacturing of 50 prisms using Portland cement mix and the testing is done using the TAMU balanced bond wrench and ASTM E518 setup. It also includes experimentally observing the water absorption qualities of the bricks. 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 principle objective of this research is to understand any kind of bias if any between bond strength values obtained from TAMU balanced 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 balanced bond wrench and the second set by ASTM E518 beam setup.

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

Figure 23: Steel frame for the bond wrench experiment

Katiyar will be supporting in the present paper, as his paper concentrates on comparing the results between the TAMU unbalanced bond wrench and ASTM E518 beam method. The main frame was manufactured by Chaudhari (2010) and it had the following dimensions, Height: 91.44 cm, Width: 55.88 cm, Breadth: 86.36 cm.

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 balanced 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:

- Uses the same base equipment for all the experimental works. The equipment used are the hydraulic jacks, main frame, ropes to hold the American 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.

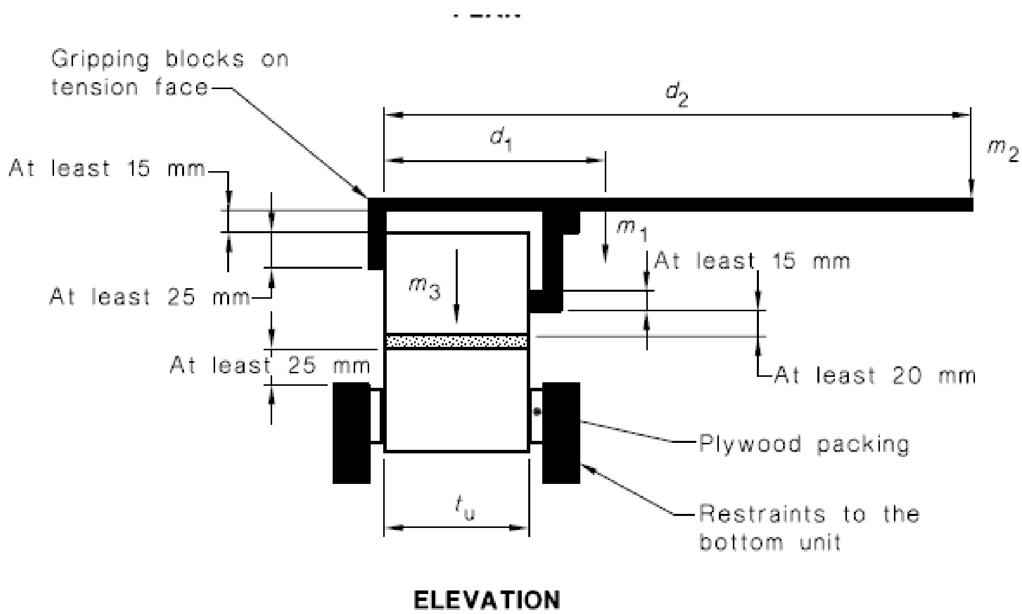


Figure 27: Schematic diagram of bond wrench set up

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

$$f_{sp} = (M_{sp} / Z_d) – (F_{sp} / A_d) \tag{1}$$

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

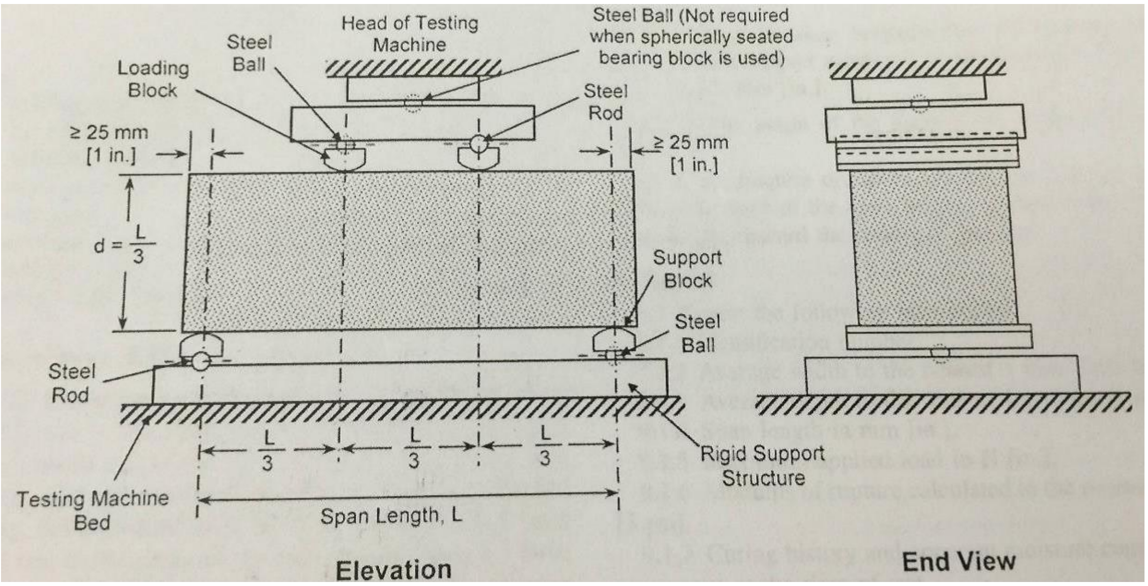


Figure 28: ASTM experimental setup (ASTM International, 2010)

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 13

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* shows the brick measurements

Table 3: Brick measurements

Length	Width	Area
192.10	55.05	10575.11
192.00	55.10	10579.20
192.00	55.03	10565.76
192.05	54.95	10553.15
191.93	54.95	10546.55
191.97	55.08	10573.71
192.00	55.00	10560.00
192.03	54.95	10552.05
191.96	55.00	10557.80
191.98	55.07	10572.34

Note: All dimensions in mm

The average length of the brick is noted as 192.002 mm, width is 55.018 mm and an area of 10563.57mm^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 balanced
d_1	115.8
d_2	711.2
m_1	5.75

Note: Lengths in millimeter and Weight in kilograms

The design analysis is:

Design Cross-sectional area of a member (A_d) in mm^2 = 10563.57 mm^2

Section modulus of the fractured section of the beam = 80000.83 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 shows the results for the first twenty samples. *Table 6* shows the results for another eighteen samples for the balanced bond wrench. *Table 7*, *Table 8*, *Table 9*, *Table 10* & *Table 11* shows the stress values for the rest of samples tested by TAMU balanced bond wrench. *Table 12* shows the results for specimens tested using ASTM E518 beam test method.

Table 5: Flexural strength of samples 1-1 to 4-5 using TAMU Balanced Bond wrench

S. No	m_2	F_{sp}	M_{sp}	f_{sp}
1-1	3.55	106.63	28790.98	0.3497
1-2	13.67	205.91	96666.8	1.1888
1-3	10.58	175.60	75941.87	0.9326
1-4	4.55	116.44	35498.07	0.4326
1-5	5.89	129.59	44485.58	0.5438
2-1	3.89	109.97	31071.39	0.3779
2-2	7.22	142.64	53406.02	0.6541
2-3	6.45	135.08	48241.56	0.5902
2-4	8.98	159.90	65210.51	0.7999
2-5	7.41	144.50	54680.37	0.6698
3-1	3.98	110.85	31675.03	0.3854
3-2	10.58	175.60	75941.87	0.3926
3-3	12.5	194.43	88819.49	1.0918
3-4	13.88	207.97	98075.29	1.2062
3-5	14.56	214.64	102636.1	1.2626
4-1	4.59	116.84	35766.36	0.4360
4-2	4.57	116.64	35632.22	0.4343
4-3	4.96	120.47	38247.98	0.4667
4-4	6.44	134.99	48174.49	0.5893
4-5	5.78	128.51	43747.8	0.5347

Table 6: Flexural strength of samples 5-1 to 8-3 using TAMU balanced bond wrench

S. No	m_2	F_{sp}	M_{sp}	f_{sp}
5-1	16.5	233.67	115647.9	1.4234
5-2	8.78	157.94	63869.09	0.7834
5-3	10.23	172.16	73594.38	0.9036
5-4	15.45	223.37	108605.4	1.3364
5-5	12.36	193.06	87880.5	1.0802
6-1	5.89	129.59	44485.58	0.5437
6-2	3.96	110.65	31540.89	0.3838
6-3	10.24	172.36	73661.46	0.9044
6-4	7.01	140.57	51997.53	0.6366
6-5	9.85	168.43	71045.69	0.8721
7-1	5.78	128.51	43747.80	0.5346
7-2	4.78	118.70	37040.71	0.4517
7-3	6.45	135.08	48241.56	0.5902
7-4	7.59	146.26	55887.65	0.6847
7-5	3.24	103.59	26711.78	0.3241
8-1	15.45	223.37	108605.4	1.3364
8-2	5.78	128.51	43747.8	0.5347
8-3	12.34	192.86	87746.36	1.0785

Table 7: Flexural strength of samples 8-4 to 12-3 using TAMU balanced bond wrench

S. No	m_2	F_{sp}	M_{sp}	f_{sp}
8-4	11.47	184.32	81911.18	1.0064
8-5	16.45	233.18	115312.5	1.4193
9-1	4.76	118.50	36906.56	0.4501
9-2	6.28	133.42	47101.35	0.5761
9-3	7.45	144.89	54948.65	0.6731
9-4	8.88	158.92	64539.8	0.7916
9-5	4.54	116.34	35431.0	0.4318
10-1	5.87	129.39	44351.44	0.5421
10-2	8.47	154.90	61789.89	0.7577
10-3	8.33	153.53	60850.90	0.7461
10-4	7.89	149.21	57899.78	0.7096
10-5	3.58	106.92	28992.19	0.3522
11-1	3.88	109.87	31004.32	0.3771
11-2	4.78	118.07	37040.71	0.4517
11-3	10.45	174.32	75069.95	0.9218
11-4	13.48	204.05	95392.45	1.1730
11-5	7.48	145.18	55149.87	0.6756
12-1	14.45	213.56	101898.3	1.2535
12-2	15.14	220.33	106526.2	1.3107
12-3	5.48	125.57	41735.67	0.5098

Table 8: Flexural strength of the samples 12-4 to 16-1 using TAMU balanced bond wrench

S. No	m_2	F_{sp}	M_{sp}	f_{sp}
12-4	4.86	119.48	37577.27	0.4584
12-5	6.57	136.26	49046.41	0.6001
13-1	12.15	191.00	86472.01	1.0628
13-2	13.48	204.05	95392.45	1.1730
13-3	6.32	133.81	47369.64	0.5794
13-4	Failed	0	0	0
13-5	14.63	215.33	103105.6	1.2684
14-1	5.21	122.92	39924.76	0.4874
14-2	4.25	113.50	33485.94	0.4078
14-3	8.78	157.94	63869.09	0.7834
14-4	3.89	109.97	31071.39	0.3779
14-5	6.48	135.38	48442.77	0.5927
15-1	5.65	127.24	42875.88	0.5238
15-2	5.45	125.27	41534.46	0.5073
15-3	Failed	0	0	0
15-4	4.77	118.60	36973.63	0.4509
15-5	15.98	228.57	112160.3	1.3803
16-1	14.45	213.56	101898.3	1.2534

Table 9: Flexural strength of samples 16-2 to 20-3 using TAMU balanced bond wrench

S. No	m_2	F_{sp}	M_{sp}	f_{sp}
16-2	3.44	105.56	28053.2	0.3406
16-3	Failed	0	0	0
16-4	5.21	122.91	33924.76	0.4874
16-5	5.48	125.57	41735.67	0.5098
17-1	6.53	135.87	48778.13	0.5968
17-2	Failed	0	0	0
17-3	17.48	243.29	122220.8	1.5047
17-4	8.47	154.90	61789.89	0.7577
17-5	12.45	193.94	88484.14	1.0876
18-1	12.36	193.06	87880.5	1.080
18-2	Failed	0	0	0
18-3	14.15	210.62	99886.2	1.228
18-4	7.11	141.55	52668.24	0.6449
18-5	8.46	154.80	61722.82	0.7568
19-1	9.96	169.51	71783.47	0.8812
19-2	9.48	164.80	68564.06	0.8414
19-3	17.45	242.99	122019.6	1.5022
19-4	Failed	0	0	0
19-5	5.45	125.27	41534.46	0.5073
20-1	8.45	154.70	61655.75	0.7560
20-2	15.45	223.37	108605.4	1.3364
20-3	5.77	128.41	43680.73	0.5338

Table 10: Flexural strength of samples 20-4 to 24-5 using TAMU balanced bond wrench

S. No	m_2	F_{sp}	M_{sp}	f_{sp}
20-4	6.73	137.83	50119.55	0.6134
20-5	6.59	136.45	49180.55	0.6018
21-1	11.45	184.13	81777.04	1.0047
21-2	16.22	230.92	113769.9	1.400
21-3	17.21	240.63	120409.9	1.4823
21-4	Failed	0	0	0
21-5	Failed	0	0	0
22-1	11.45	184.13	81777.04	1.0047
22-2	11.56	185.21	82514.82	1.0138
22-3	5.45	125.27	41534.46	0.5073
22-4	6.45	135.08	48241.56	0.5902
22-5	7.48	145.18	55149.87	0.6756
23-1	Failed	0	0	0
23-2	10.56	175.4028	75807.73	0.9309
23-3	4.23	113.30	33351.8	0.4061
23-4	18.4	252.31	128391.4	1.5809
23-5	7.56	145.97	55686.44	0.6822
24-1	4.58	138.52	35699.29	0.4351
24-2	13.59	205.12	96130.23	1.1821
24-3	15.45	223.37	108605.4	1.3364
24-4	9.85	168.43	71045.69	0.8721
24-5	Failed	0	0	0

Table 11: Flexural strength of samples 25-1 to 25-5 using TAMU balanced bond wrench

S. No	m_2	F_{sp}	M_{sp}	f_{sp}
25-1	10.56	175.40	75807.73	0.9309
25-2	10.25	172.36	73728.53	0.9052
25-3	3.45	105.65	28120.27	0.3414
25-4	Failed	0	0	0
25-5	8.65	156.66	62997.17	0.7726

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

S. No	Load	Stress Value
1	50.24	1.073
2	45.53	0.9731
3	23.55	0.5031
4	14.13	0.3019
5	9.42	0.2013
6	9.42	0.2013
7	25.12	0.5368
8	54.95	1.1744
9	36.11	0.7717
10	26.69	0.5704
11	23.55	0.5033
12	18.84	0.4026
13	20.41	0.4362

Table 12 continued

S. No	Load	Stress Value
14	17.27	0.3691
15	20.41	0.4362
16	21.98	0.4697
17	26.69	0.5704
18	28.26	0.6040
19	29.83	0.6375
20	48.67	1.0402
21	48.67	1.0402
22	34.54	0.7382
23	12.56	0.2684
24	14.13	0.3019
25	9.42	0.2013

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

Table 13 continued

S. No	Water absorbed(grams)	IRA($kg/m^2/min$)
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.

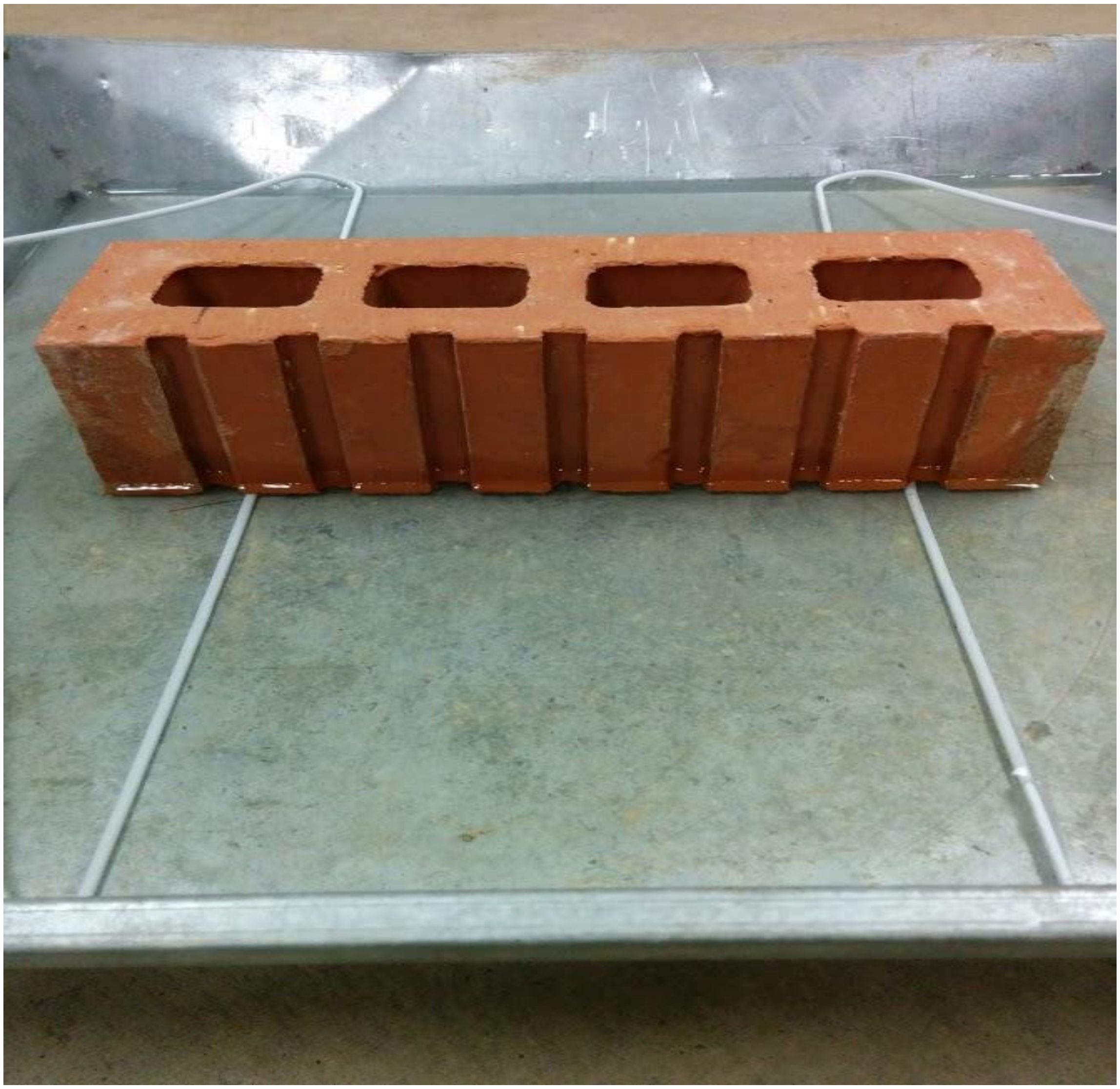


Figure 31: Absorption test on sample brick

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

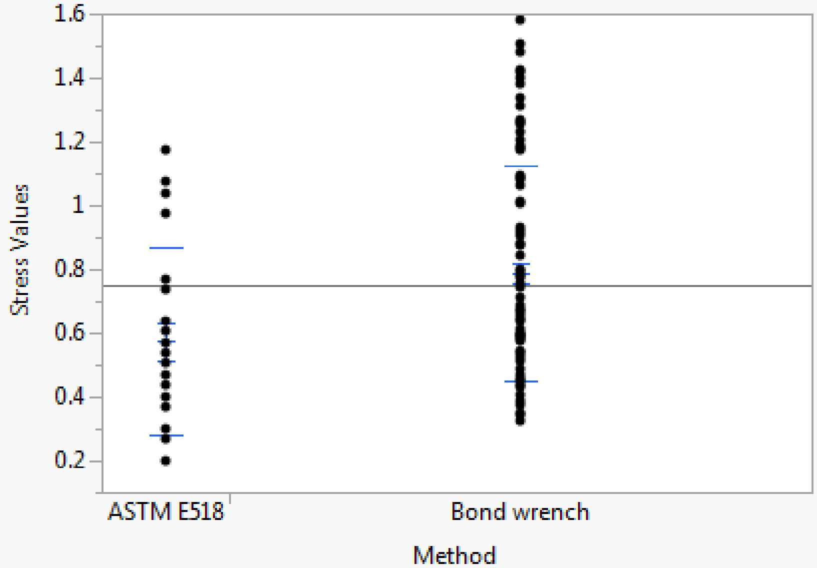
Table 14: Interpretation of student T-test

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 balanced 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%
ASTM E518	25	0.573118	0.293313	0.05866	0.45204	0.69419
Bond wrench	114	0.788997	0.338382	0.03169	0.72621	0.85178

t Test

Bond wrench-ASTM E518

Assuming unequal variances

Difference	0.215879	t Ratio	3.237726
Std Err Dif	0.066676	DF	39.34233
Upper CL Dif	0.350707	Prob > |t|	0.0024*
Lower CL Dif	0.081051	Prob > t	0.0012*
Confidence	0.95	Prob < t	0.9988

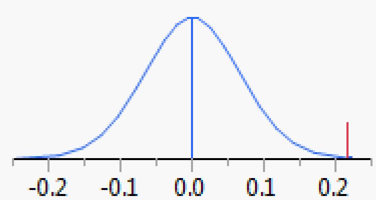
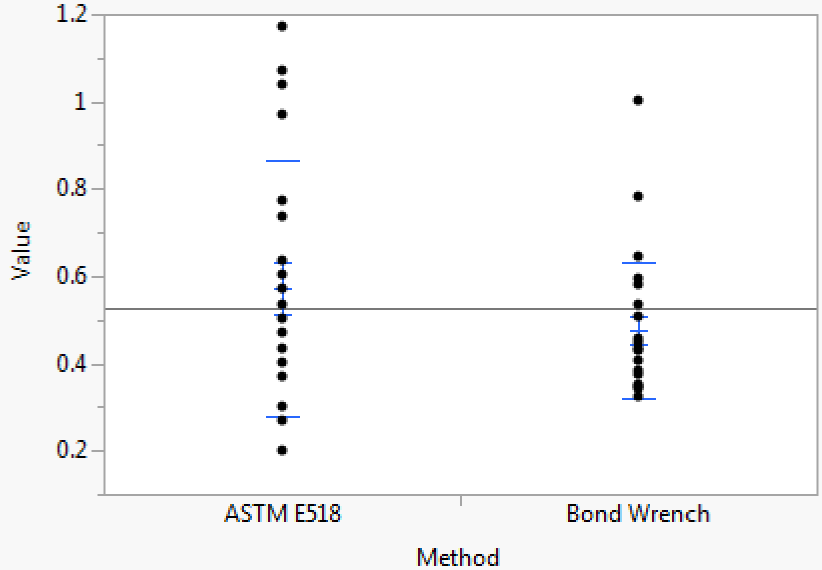


Figure 32: Student t test- TAMU balanced bond wrench – ASTM E518 beam test comparison

Oneway Analysis of Value By Method



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 90%	Upper 90%
ASTM E518	25	0.573118	0.293313	0.05866	0.47275	0.67348
Bond Wrench	25	0.476240	0.155969	0.03119	0.42287	0.52961

t Test

Bond Wrench-ASTM E518

Assuming unequal variances

Difference	-0.09688	t Ratio	-1.45811
Std Err Dif	0.06644	DF	36.56758
Upper CL Dif	0.01525	Prob > |t|	0.1533
Lower CL Dif	-0.20900	Prob > t	0.9233
Confidence	0.9	Prob < t	0.0767

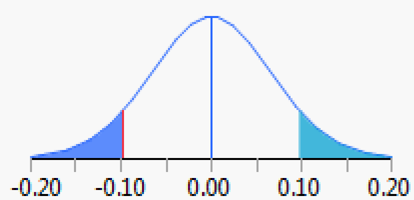


Figure 33: Student t test- Comparison of weakest joint of balanced bond wrench & ASTM E518 beam test

Summary of results

- From the above t test analysis
  - The mean of the values from TAMU balanced bond wrench is 0.788 MPa
  - The mean of the values from ASTM E518 beam test is 0.573MPa
- From the above t test analysis (see *Figure 32*), it can be found that the mean values of the TAMU balanced 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 (0.573 MPa) than the values obtained from TAMU balanced bond wrench. The bond wrench measures the strength for each joint and hence the mean value is on the higher side (0.788 MPa)

- The null hypothesis is rejected because the probability of alternative being true is 99.76% at 95% confidence interval, which generates evidence that there exists a bias between Indian balanced 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 balanced bond wrench and ASTM E518 beam method shows that null can't be rejected and hence there is no bias when the stress values of weakest joints (tested by balanced 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 Indian 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 Indian 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 balanced bond wrench. The second set of 25 prims was tested using ASTM E518 method.

A Student's t Test analysis was run between the flexural strength values of the four wrenches. From the plots, it can be inferred that the mean value of the American testing standard was low when compared with the mean values of the balanced bond wrench. The plots were quite dissimilar.

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 balanced 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.

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