American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)

ISSN (Print) 2313-4410, ISSN (Online) 2313-4402

http://asrjetsjournal.org/

Effects of Plastering and Ferrocement on the Shear Properties of Masonry Triplets

Abdullah Al Hashib[a]*, Md Sayeed Faisal[b], Md. Aminur Rashid[c], Sayin Tamhid[d]

[a,b,c,d]Ahsanullah University of Science and Technology, Tejgaon Industrial Area, Dhaka 1208, Bangladesh

[a]Email: abdullahal.hashib@jacks.sdstate.edu

[b]Email: mdsayeedfaisal@gmail.com

[c]Email: rashid6306@gmail.com

[d]Email: sayinfaisal@gmail.com

Abstract

Masonry triplet is formed by three and half bricks keeping the same type of bond exhibited in a brick wall. The triplet has been investigated by researchers as an indicator of lateral loading capacity of masonry wall. Although strength is an important parameter in determining the property of triplet, displacement capacity is significant specially for the cases of lateral loads such as wind load or earthquake load. Experimental investigations carried out to determine the effect of plastering and ferrocement in masonry triplets in terms of both shear strength and strain at maximum stress. The study identified several parameters that affect these properties e.g. mortar strength, mortar thickness, compressive strength of brick, plastering layer thickness, diameter of the wire mesh, and amount of wire mesh. Equations have been proposed to determine the shear strength and strain at maximum stress of the triplet based on these factors. Bond strength was found to be the key factor for the failure of the triplets. It can be inferred that the construction in Bangladesh lack the bond strength in the horizontal bed surface, decreasing both the load and displacement capacity of the brick wall. Ferrocement can be used as a retrofitting technique as it has been found from the tests that laminating the triplet surface with ferrocement prevents sudden collapse and confines the triplet so that the shear strength and strain at maximum stress increase.

Keywords: Triplet; Shear strength; Strain at maximum stress; Ferrocement.

1. Introduction

Brick masonry is one of the significant and most common construction works in buildings and roads in Bangladesh. Brick is widely used for the construction of partition walls, boundary walls, retaining wall, brick soling, pavement of roads for heavy traffic, light traffic and pedestrian etc.

----

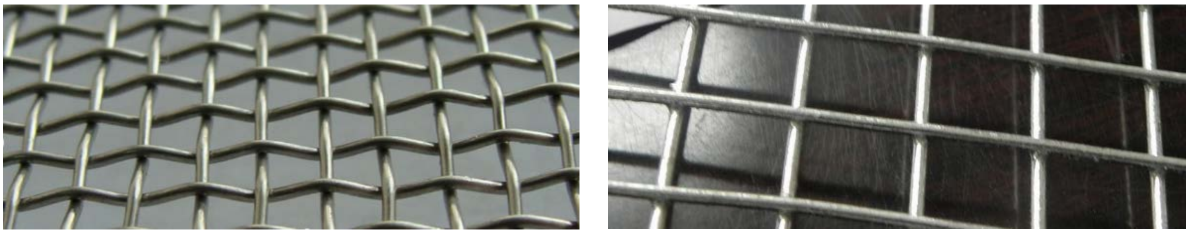
* Corresponding author.

Many research works have been carried out on bricks as a wall element since long before. Brick wall can be used in load bearing as well as non-load-bearing structure. Bricks used in wall are usually ignored in strength or deflection capacity calculation of the non-load-bearing structure. But experimental research conducted by [1], [2] etc. show that brick increases the strength of the non-load-bearing structure too. Thus, it has been a concern for researchers to determine the strength of brick walls. There are different types of bricks manufactured in Bangladesh. Of them, burnt clay bricks are the widely used one. Clay bricks are fired either by coal or by wood. Other types are – ceramic bricks, green bricks (non-fired bricks) etc. Ceramic bricks are made by some limited industries. They are not usually available and widely used bricks. They are used for special purposes. Green brick is a compressed stabilized earth block made from soil and cement. These eco-friendly bricks save a large amount of greenhouse gas emission as there is no use of top soil, coal and firewood in its manufacturing. Besides, some hollow bricks and blocks are used now-a-days to reduce the weight of the overall structure. Although there are various types of bricks used in Bangladesh, the conventional solid burnt clay bricks are still the mostly used one in Bangladesh. Thus, this study only focuses on this type of ordinary brick.

The grades of the traditional bricks in Bangladesh depend on the quality of the raw materials used, evenness of firing and damages like cracks or breaks. The bricks are divided in three grades. Compressive strength decreases from grade I to grade III. Water absorption increases from grade I to grade III. Uniformity or regularity in shape decreases from grade I to grade III. Grade I can be made both manually and automatic machine. These bricks are the best one among the three grades and suitable to use for any purpose. Grade II is the intermediate grade. Plastering is preferred for using these bricks. Grade III bricks are used for unimportant constructions. In this study, both machine-made and hand-made grade I bricks were used because of their wide range of acceptability in any type of masonry construction.

Another concern for researchers is to experimentally investigate the suitability of ferrocement for retrofitting structural elements e.g. slabs, beams, columns, joints etc. Definition of ferrocement is discussed by the Concrete Society, UK [3], and ACI Concrete Terminology [4]. Application of ferrocement is more popular in developing country like Bangladesh as construction of ferrocement requires intensive labor which is cheap in developing countries. Ferrocement is also used to retrofit non-structural element such as wall or roof. The studies on ferrocement retrofitted masonry wall were accomplished by [5,6,7,8] etc. Reference [5] investigated the hysteretic behavior of ferrocement-retrofitted clay tile walls which is not typical for masonry construction in Bangladesh. Reference [6] tested masonry specimens under diagonal tension which is comparatively difficult to apply in laboratory. Reference [7,8] tested ferrocement wall panels under axial load only. Reference [9] showed that addition of slight reinforcement in masonry infilled wall strengthen the bare frame.

Wire mesh of the ferrocement can be of different types. Such as – woven wire mesh, welded wire mesh etc. Different types of wire mesh are shown in Fig. 1. Woven wire mesh is made as a cloth with wire threads woven together to form a pattern. On the other hand, welded wire mesh is a metal wire screen in which the grids of parallel longitudinal wires are welded to cross wires at a specific require spacing. Wire mesh can consist of square or hexagonal openings. Woven wire mesh with square opening was used in the present study as it is the most common of all the types of wire mesh available in Bangladesh.



(a) Woven wire mesh (b) Welded wire mesh

Figure 1: Difference of different types of wire Mesh [10]

There are different types of wire mesh available in Bangladesh. Such as – galvanized steel, stainless steel, mild steel etc. Stainless steel is costlier for using in masonry construction. Practically used wire mesh for retrofitting masonry wall in Bangladesh is the galvanized steel wire mesh. Thus, the scope of this study was limited to galvanized steel wire mesh. Diameter of wires found in Bangladesh are ranges from 0.02 in (0.5 mm) to 0.06 in (1.5 mm). The ones used in wall are generally in the lower range such as 0.02 in (0.5 mm) to 0.03 in (0.75 mm). Present study used two different sizes (diameter of wire) – 0.02 in (0.5 mm) and 0.025 in (0.63 mm). Spacing of the wires varies from 0.2 in (5 mm) to 1 in (25.4 mm). Strength of ferrocement increases with decreasing spacing of the wire mesh. Present study used spacing of 0.2 in (5 mm).

It is well understandable that behavior of a wall is more justifiable than testing a single brick. But testing a wall is costly and requires special instrumental setup. Both compression and tensile behavior of masonry units are provided in ASTM. But there is no standard method available for testing sliding resistance or shear resistance of masonry [16]. Masonry prisms are mainly tested to measure the compressive characteristics of bricks. But shearing of the masonry triplet can also be one of the major failure criterias in masonry construction. Shear strength of masonry wall is a relevant parameter for the evaluation of seismic behavior of masonry wall in load bearing or non-load bearing structure. Testing of brick triplet indicates the shear strength of the wall as well as the shear bond strength of the mortar used in the horizontal bed joints. Triplet test also measures cohesion, and coefficient of friction. It has been found from the experimental test that the strength of masonry triplet is related to the strength of unreinforced masonry wall. Shear strength of triplet mostly depends on the bond strength in the horizontal bed surfaces. But in Bangladesh, construction is not properly maintained or monitored to ensure quality bond strength. Masons or labors in Bangladesh work based on the ratio of cement, sand, and water. Thus, other effective solution is needed to substitute for increasing the bond strength. Ferrocement was sought for this substitution. Triplet is a comparatively easy testing method conducted by several researchers previously also [11,12,13,14,15,16,17,18] etc. None of them attached ferrocement on the triplet for the tests. Besides, the lateral loads such as seismic loads or wind loads affect the wall in the form of small triplets. Therefore, the triplets are the most representative and simple arrangement of a conventional brick wall under lateral load. Thus, loads were applied on the triplet in the direction of lateral loading on the brick wall.

The main objective of the present study is to investigate the shear effect of the masonry triplet in different conditions. This shear effect also changes the overall structural behavior of the system. Adding ferrocement affects the lateral capacity of any load-bearing or non-load-bearing structure. Thus, determining the effect of the ferrocement on the wall and potentiality of using it as a retrofitting material was also the objective of this study. This study contains investigation carried out on triplets to determine the capacity in terms of both strength and deflection. The results of this study can be used for the masonry wall of both load bearing or non-load bearing structures in Bangladesh. Few relationships were evaluated based on the results of the tests.

2. Methodology

There are various testing standards throughout the world. American Society for Testing and Materials (ASTM) and Canadian Standards Association (CSA), Indian Standard (IS) are few of them. All of them were not in the scope of this study. Only ASTM standards were followed in this study. ASTM code provides certain guidelines for testing bricks and mortars. Standard brick testing methods includes [18]. There are many tests for determining brick properties according to this standard which includes modulus of rupture, compressive strength, absorption, saturation co-efficient, effect of freezing and thawing, efflorescence, initial rate of absorption, and determination of weight, size, warpage, length change, and void areas [18]. Additional tests pertinent to ceramic glazes according to this standard are imperviousness, chemical resistance, opacity, and resistance to crazing [18].

Bricks are used for different purposes in civil engineering sectors. Bricks are manufactured for different uses – building brick, facing brick, hollow brick, pedestrian and light traffic brick, heavy vehicular paving brick, sewer and manhole brick, industrial floor brick etc [19]. Standard specification also differs based on these different types of bricks. Building brick [20] is used in all types of purposes in the construction of buildings, roads etc. in Bangladesh. This study is only limited to the building brick, mostly used type of brick in Bangladesh. Building brick is intended to be used in both structural and nonstructural masonry regardless of the external appearance [20]. Bricks are manufactured from clay, shale, or similar naturally occurring earthy substances by subjecting to a heat treatment at elevated temperatures e.g. firing [20]. The heat treatment must develop sufficient fired bond between the particulate constituents to provide the strength and durability requirements of this specification [20]. These bricks are solid. These bricks are also known as fired masonry unit or burnt clay bricks.

Reference [21] provides guideline to determine physical and mechanical properties, allowable stress, design criteria, and testing of ferrocement. Reference [22] provides construction and application of ferrocement. ACI code also discussed the repairing technique through ferrocement. The tests were conducted complying with all these standards.

Tests conducted can be discussed in three parts – Preparation and testing of bricks, Preparation and testing of mortars and Preparation and testing of triplets.

2.1. Preparation and Testing of Bricks

According to ASTM, there are several standard tests to measure the properties of bricks. Of them, compressive strength test, modulus of rupture test, and initial rate of absorption (IRA) are important tests. For compressive strength test, five half-bricks were tested according to the ASTM. Three specimens were tested for determining modulus of rupture and IRA.

Compressive strength test is the most important test in terms of strength of brick. As this study deals with the strength of the brick masonry, this test was conducted. Five samples were tested according to the [18]. The samples were sawed into half-brick and tested flatwise in the Concrete Laboratory of Ahsanullah University of Science and Technology (AUST). The moisture content can affect the compressive strength. Therefore, the specimens were dried in oven for 24 hours. Specimens were placed on the center of the loading. Figure 2 shows the compressive strength test in the compression testing machine. As there is no specific loading rate in [18], a moderate rate of loading was applied at a uniform rate. The pace of the loading (the speed of the test) was 1.12 kips /sec (5000 N/sec).

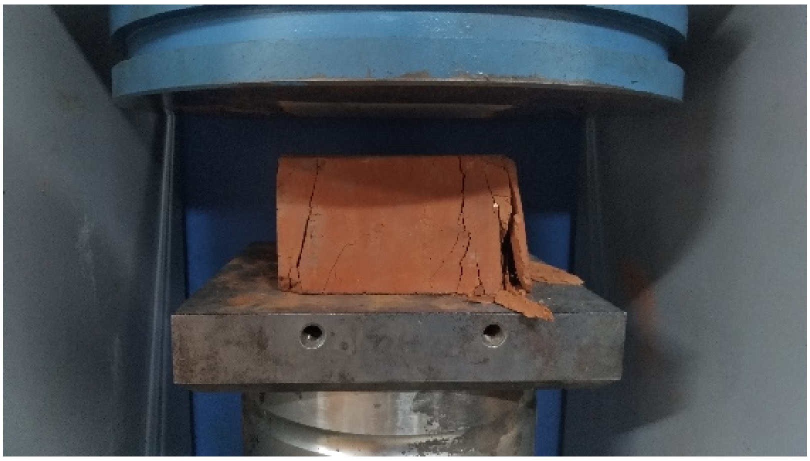


Figure 2: Test Setup for Determining Compressive Strength of Bricks

Two types of bricks were used in this study – machine-made and hand-made 1st class bricks. Hand-made brick was not used for ferrocement laminated triplets. They were only used to form control triplets. The arithmetic average compressive strength of the of the machine-made bricks and hand-made bricks are 3.68 ksi (25.37 MPa) and 2.72 ksi (18.75 MPa) respectively. Six half-bricks and three half-bricks were tested for machine-made and hand-made bricks respectively for determining the compressive strength of brick.

Modulus of rupture (flexure test) indicates the tensile stress capacity in the bottom fiber of the brick which is not as significant as the compressive strength of brick. For the flexural test or modulus of rupture, load was applied in the direction of the depth of the unit using the Universal Testing Machine (UTM) of Strength of Materials Laboratory of Ahsanullah University of Science and Technology (AUST). The rate of the loading was 0.02 in / min (0.5 mm / min). Figure 3 shows the specimens before loading and after loading. Three bricks were undergone through this test. Average modulus of rupture is 2.86 kips (12702.63 N) for machine-made bricks and 1.49 kips (6635.97 N).

Initial rate of absorption (IRA) is another important test of bricks. IRA is a measure of how quickly the brick will remove water from mortar. IRA is not a qualifying property of condition of brick in the ASTM specifications [19]. If the IRA of brick exceeds an acceptable upper limit, problems with excessive shrinkage of mortar and poor bond tend to occur [23]. But if enough curing can be done, this problem can be avoided. Three bricks were used for this test. Average IRA is 15.87%.

(a) Before loading

(b) After loading

(c) Specimens after failure

Figure 3: Modulus of Rupture Test of Bricks

2.2. Preparation and Testing of Mortar Cube

According to [24], the primary purpose of mortar in masonry triplet is to bond masonry units into an assemblage which acts as an integral element having desired functional performance characteristics [24]. Mortar is usually placed between absorbent masonry units, and as soon as contact is made the mortar loses water to the units [24]. Six mortar specimens were made according to [24]. Then the mortars are placed in the center of the loading in the compression testing machine as mentioned in [24].

There are three ways mortar can be made according to [24]. Such as – cement-lime, mortar cement and masonry cement. As specification for mortar cement such as lower air contents and flexural bond strength requirement was not ensured, the mortar in this study can be termed as masonry cement. Masonry cement can be different types – M, S, N or O. Average compressive strength of mortar of M, S, N, O are 2500 psi (17.2 MPa), 1800 psi (12.4 MPa), 750 psi (5.2 MPa), and 350 psi (2.4 MPa). The established proportion of cement to sand in this project was set out to be 1 to 3, the most practicing ratio for masonry wall construction in Bangladesh. Potable water was used as it is acceptable according to [24]. Materials were measured by volume, sand was measured in damp, loose conditions. No change was made except the quantity of mixing water. The amount of water removal and its consequences affect the strength of the mortar and thus the strength, as well as other properties of the masonry assemblage [24]. The suction exerted by the masonry unit is a very important external factor which affects the fresh mortar and initiates the development of bond. According to [24], mortar for use in the field must be mixed with the sufficient amount of water, consistent with workability, in order to provide sufficient water to satisfy the initial rate of absorption (suction) of the masonry units. Greater water content was required in this study too. The water-cement ratio for mortar came out to be 0.7. Figure 4 shows the preparation of mortar. Compressive strength of mortar increases with an increase in cement content and decreases with an increase in lime, sand, water or air content. The amount of the reduction of mortar compressive strength increases with water addition and time between mixing and retempering. It is frequently desirable to sacrifice some compressive strength of the mortar in favor of improved bond, consequently retempering within reasonable time limits is recommended to improve bond [24]. To obtain good mixing results, about ¾ of the required water, ½ of the sand, and all of the cementitious materials were briefly mixed together. The balance of the sand is then charged and the remaining water added. Bond is probably the most important single property of a conventional mortar. Many variables can affect bond [24]. It is suggested to obtain optimum bond using a mortar with properties that are compatible with the masonry units to be used. But as the masonry work in Bangladesh are constructed by illiterate and inefficient labors, it is difficult to ensure optimum bond strength of mortar. Furthermore, the aim of this study was to investigate the local masonry construction. Thus, using some basic proportioning of mortar (cement : sand = 1:3, water : cement = 0.7), mortar was made, used and cured for 28 days.

Figure 4: Preparation of Mortar

The compressive strength of mortar is sometimes used as a principal criterion for selecting mortar type, since compressive strength is relatively easy to measure, and it commonly relates to some other properties, such as tensile strength and absorption of the mortar. The compressive strength of mortar depends largely upon the cement content and the water-cement ratio. Often overlooked is the size/shape of mortar joints in that the ultimate compressive load carrying capacity of a typical 3/8 in (9.5 mm) bed joint will probably be well over twice the value obtained when the mortar is tested as a 2 in (50.8 mm) cube. But to maintain consistency of all tests performed by researchers, the accepted laboratory means for measuring compressive strength is to test 2 in. (50.8 mm) cubes of mortar. Because the referenced test in this specification is relatively simple, and because it gives consistent, reproducible results, compressive strength is considered a basis for assessing the compatibility of mortar ingredients [24]. After the mortars are made in 2" by 2" cube, the mortar was kept in a moist room so the upper surface is kept open. Specimens were removed from the molds after 48 hours and cured for 28 days until tested.

Reference [24] states that masonry mortars have two distinct, important sets of properties, those of plastic mortars and those of hardened mortars. Plastic properties determine a mortar's construction suitability, which in turn relate to the properties of the hardened mortar and, hence, of finished structural elements [24]. Properties of the finished masonry include bond, durability, elasticity, and compressive strength [24]. As many of these properties are quantitatively undefinable because of a lack of measurement standards, compressive strength of mortar was used in relating to the strength of masonry triplets since compressive strength of mortar is quantifiable, comparatively easy to determine, and reproducible. According to [24], there is some discernible relationship between bond and compressive strength of mortar. Thus, compressive strength of mortar was considered to be the most significant factor in affecting the shear strength of the masonry triplet.

There are several test methods in ASTM for testing bond strength of mortar to masonry units, normal or perpendicular to the mortar joints. These include C952, C1072-13e1, C1717-18, C1357, E518 / E518-15, and E72. But there is no test method developed for testing bond strength of mortar to masonry, parallel to mortar joints. The tensile and compressive strength of mortar far exceeds the bond strength between the mortar and the masonry unit. Mortar joints, therefore, are subject to bond failures at lower tensile or shear stress levels. Complete and intimate contact between mortar and masonry unit is essential for good bond. This can best be achieved through use of mortar having proper composition, good workability, and being properly placed [24]. Compressive strength of mortar was measured according to ASTM test method C109. Pace rate of the loading was 0.2 kips/sec (0.9 kN/sec). Arithmetic average of the compressive stress of mortar is 2.84 ksi (19.58 MPa) for machine-made bricks and 3.94 ksi (27.17 MPa). Loading arrangement and failed specimens are shown in Fig. 5.

(a) Loading arrangment for compressive strength test of mortar

(b) Failed mortars

Figure 5: Compressive Strength Test of Mortars

2.3. Preparation and Testing of Triplets

The triplet consists of 3 and half bricks. In total, 14 triplets were made and tested. 12 triplets were machine-made bricks and 2 control triplets were hand-made bricks.

Of machine-made triplets, 4 were control specimens and 8 were ferrocement laminated specimens. Two of the control specimens were made as bare triplet (without any plastering on any side), and the other two were made as plastering on all sides. Diameter of the wire mesh for the 4 out of 8 ferrocement laminated specimens was 0.5 mm and 0.63 mm for the rest 4 ferrocement laminated specimens. Ferrocement was applied on two sides and four sides for each diameter of wire mesh. Name of the specimens are tabulated in Table 1.

Woven wire mesh is abbreviated by WV. S indicates the number of sides ferrocement is laminated on the triplet. N indicates the number of the specimen. For example, WV 0.63mm 4S N1 indicates 1st specimen of 0.63 mm diameter woven wire mesh laminated on 4 sides of the triplet.

CTRL 1 to CTRL 4 were formed by machine-made bricks and CTRL 5 and CTRL 6 were formed by hand-made bricks.

Table 1: Name of the Specimens

Number of Specimens	Name of the Specimens	Remarks
1	CTRL 1	Without plastering and ferrocement (machine-made brick)
2	CTRL 2	Without plastering and ferrocement (machine-made brick)
3	CTRL 3	Plastering without ferrocement (machine-made brick)
4	CTRL 4	Plastering without ferrocement (machine-made brick)
5	WV 0.5mm 2S N1	0.5 mm wire mesh on two sides (machine-made brick)
6	WV 0.5mm 2S N2	0.5 mm wire mesh on two sides (machine-made brick)
7	WV 0.5mm 4S N1	0.5 mm wire mesh on four sides (machine-made brick)
8	WV 0.5mm 4S N2	0.5 mm wire mesh on four sides (machine-made brick)
9	WV 0.63mm 2S N1	0.63 mm wire mesh on two sides (machine-made brick)
10	WV 0.63mm 2S N2	0.63 mm wire mesh on two sides (machine-made brick)
11	WV 0.63mm 4S N1	0.63 mm wire mesh on four sides (machine-made brick)
12	WV 0.63mm 4S N2	0.63 mm wire mesh on four sides (machine-made brick)
13	CTRL 5	Without plastering and ferrocement (hand-made brick)
14	CTRL 6	Without plastering and ferrocement (hand-made brick)

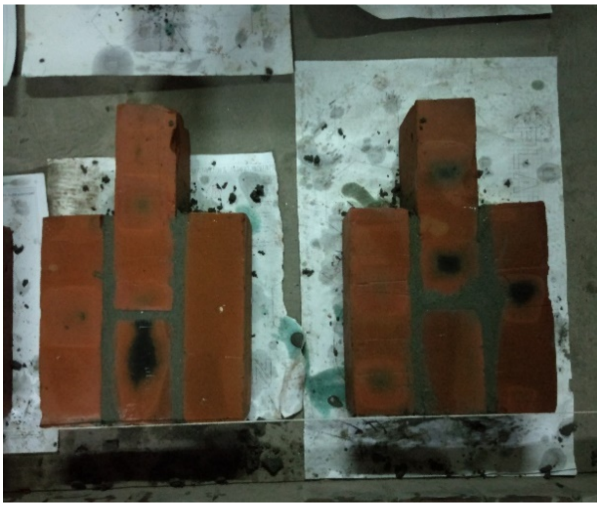
Thickness of the plastering for the 4 control specimens is 0.3 in (7.5 mm). For the 8 ferrocement laminated specimens, one layer of plastering was given of 0.3 in (7.5 mm) firstly, then ferrocement was attached by nails, lastly additional 0.3 in (7.5 mm) plastering was given to make the total plastering of 0.6 in (15 mm). As the mortar was stiffening, it was retempered by adding water as frequently as needed to restore the required consistency. Triplet was made within 2 hours of mortar mixing. Figure 6 shows the preparation of triplet.

(a) Making half-brick

(b) Arrangement of bricks before casting

(c) Maintaining 10 mm mortar thickness

(d) Appearance of triplet just after casting



(e) Cured Triplets

(f) All completed specimens

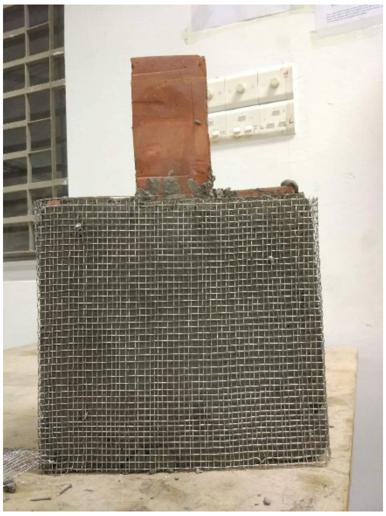
(g) Elevation view of wire mesh cage

(h) Plan view of wire mesh cage

(i) After 1st layer of plastering

(j) Nailing to fix the wire mesh cage with the 1st layer of plastering

(k) Wire mesh on two sides



(l) Wire mesh on four sides

Figure 6: Preparation of Triplet

Fourteen triplets were tested in the Universal Testing Machine (UTM) of Strength of Materials Laboratory of Ahsanullah University of Science and Technology (AUST). This vertical load through UTM was applied in displacement control system (constant 1 mm displacement per minute) from two sides of the specimen which is shown in Fig. 7. Load from the center of the triplet was distributed in two horizontal bed surfaces. As a result, shear strength of the specimen can be measured. Load was applied till the failure of the specimen or significant reduction of the loading capacity.

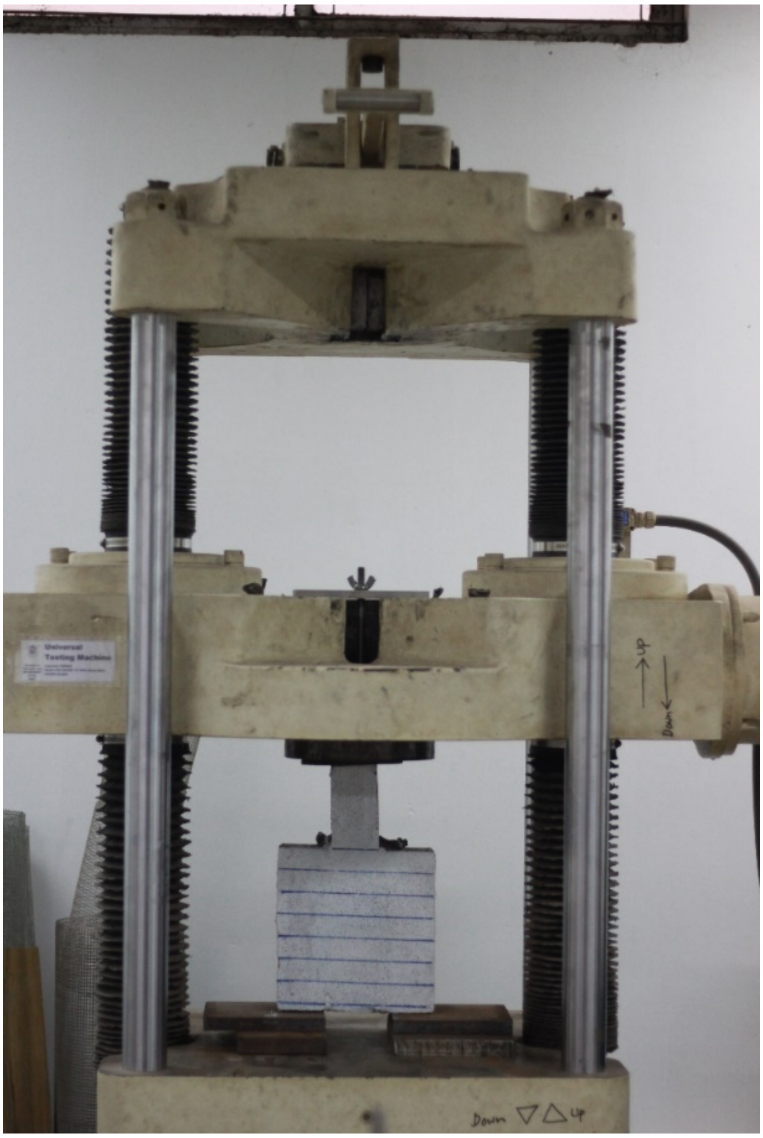
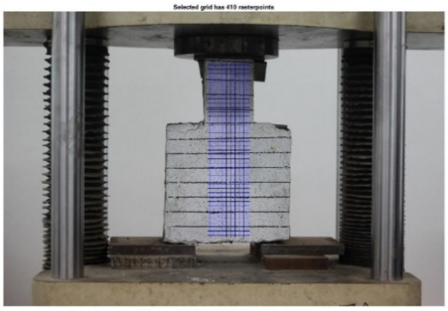


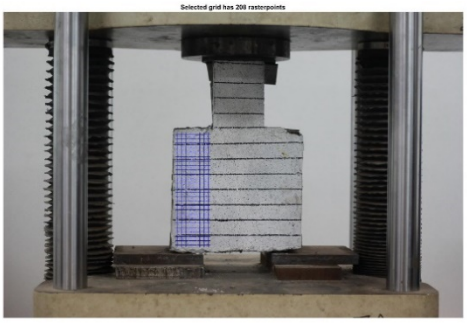
Figure 7: Test Setup in Universal Testing Machine (UTM)

Displacement was measured through UTM and digital image correlation (DIC) system. Grids are drawn at 1" spacing in the direction of the loading or displacement. White lime is painted before spraying to create scattered points in black dots on the surface of the triplet. Images were taken at regular time interval of 20 seconds with a high-resolution camera. Camera was attached with a fixed stand so that the camera does not move at all. Images were analyzed by a computer software MATLAB. Steps for measuring DIC for WV 0.63mm 4S N2 in MATLAB are shown in Fig. 8.



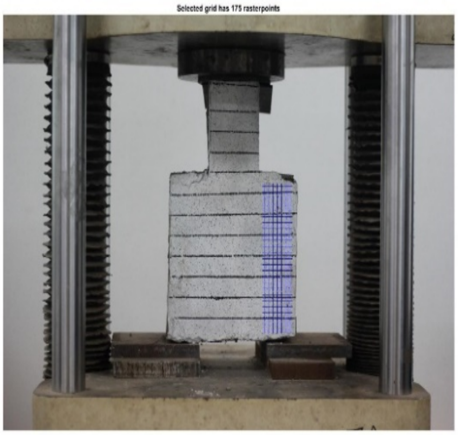
(a) Generation of grid in middle (before failure)

(b) Loading image in middle (after failure)



(c) Generation of grid at left (before failure)

(d) Loading image grid at left (after failure)

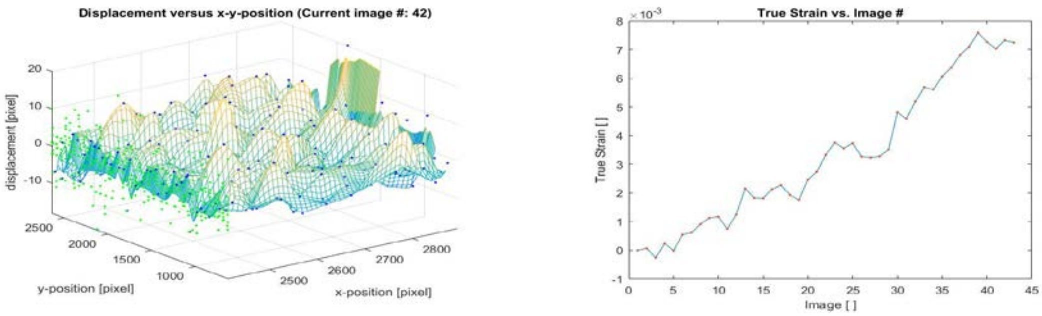


(e) Generation of grid at right (after failure)

(f) Loading image at right (after failure)

Figure 8: Digital Image Correlation (DIC) in MATLAB

True stain vs image plot was collected from the DIC analysis and checked with the UTM strain. Three-dimensional (3D) mesh plot of displacement was observed to confirm the displacement at all points of the selected regions (Fig. 9a). Data was visualized in 1D average strain measurement (Fig 9b).



(a) Three-dimensional mesh plot of displacement showing overall displacement

(b) True strain vs image to show increase of strain with time in 1D average strain measurement

Figure 9: Interpreting Displacement using DIC in MATLAB

3. Results and Discussion on the Triplet Tests

The results of the loading are discussed in three parts – data analysis, failure pattern investigation and prediction of stress-strain behavior.

3.1. Test Results of Triplets

Results of the triplet tests have notable comparison with the previous experimental data (Rahman and Ueda, 2014). Test results of this study are summarized in Table 2.

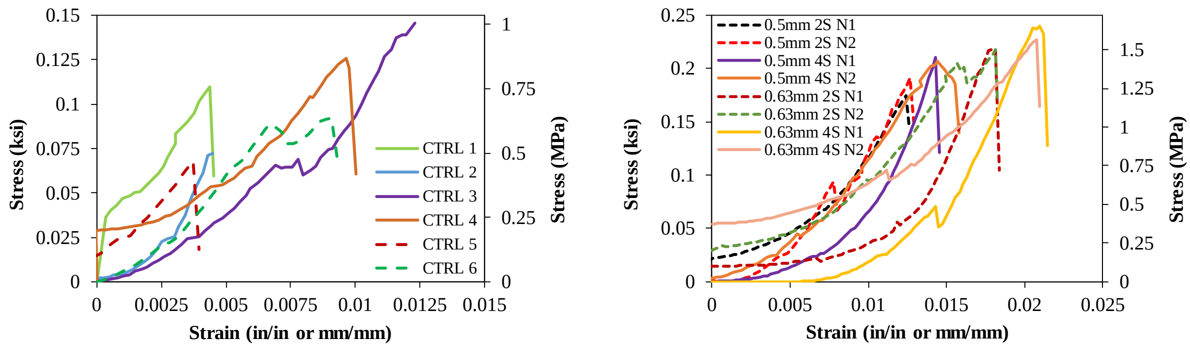
Table 2: Summary of Test Results of Triplets

No.	Name of the Specimen	Strain at Ultimate Stress	Average Strain at Ultimate Stress	Shear Strength, ksi (MPa)	Average Shear Strength, ksi (MPa)
1	CTRL 1	0.0044	0.0045	0.11 (0.76)	0.09 (0.62)
2	CTRL 2	0.0045		0.07 (0.5)	
3	CTRL 3	0.0123	0.011	0.15 (1.05)	0.14 (0.97)
4	CTRL 4	0.0096		0.13 (0.67)	
5	WV 0.5mm 2S N1	0.0124	0.0126	0.17 (1.17)	0.18 (1.24)
6	WV 0.5mm 2S N2	0.0127		0.19 (1.31)	
7	WV 0.5mm 4S N1	0.0143	0.0147	0.21 (1.45)	0.21 (1.45)
8	WV 0.5mm 4S N2	0.015		0.21 (1.45)	
9	WV 0.63mm 2S N1	0.0181	0.0181	0.22 (1.52)	0.22 (1.52)
10	WV 0.63mm 2S N2	0.0181		0.22 (1.52)	
11	WV 0.63mm 4S N1	0.0209	0.0209	0.24 (1.65)	0.24 (1.65)
12	WV 0.63mm 4S N2	0.0208		0.23 (1.59)	
13	CTRL 5	0.0037	0.0037	0.07 (0.47)	0.07 (0.47)
14	CTRL 6	0.0091	0.0091	0.09 (0.62)	0.09 (0.62)

Adding ferrocement in triplet increases the confinement and thus delays the collapse similar in manner confinement helps concrete to increase its strength and strain. In this way, ferrocement helps increase both the shear strength and the displacement capacity of the triplet. Diameter of wires and the amount of wire mesh play role in increasing the capacity displacement capacity. For example, the average shear strength (maximum shear stress) of the ferrocement laminated specimens are 0.21 ksi (1.45 MPa) which is 2.3 times more than specimen without any plastering on any side and 1.5 times more than plastering on all sides. Average strain at maximum stress of the ferrocement laminated specimens are 0.0165 which is 3.7 times more than specimen without any plastering on any side and 1.5 times more than plastering on all sides. Stress-strain behavior of CTRL triplets and WV triplets are shown in Fig. 10 (a) and Fig. 10 (b) respectively. Plastered control triplets show 1.6 times higher stress and 2.4 times higher strain than unplastered control triplets. Figure 10(a) shows the stress-strain graphs for all the tested CTRL specimens and Figure 10(b) shows the stress-strain graph for all the WV specimens.

Effect of ferrocement varies depends on the diameter of the wire mesh and location of the wire mesh. If the diameter of the wire mesh increases, the strength and displacement capacity of the triplet increases. The reason lies in the confinement capacity. The confinement capacity increases as the diameter of the wire mesh increases. Wire mesh on all four sides of the triplet is much stronger in both strength and displacement capacity than the wire mesh on the two sides.

From the stress-strain graphs of ferrocement laminated triplets it is observed that slope of the stress-strain curve is an increasing slope till the peak stress reaches.



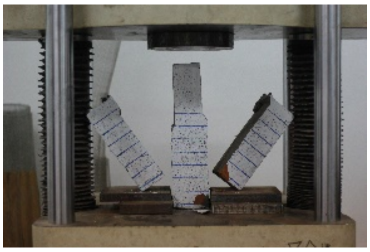
(a) Stress-strain behavior of CTRL specimens (b) Stress-strain behavior of WV specimens

Figure 10: Stress-strain behavior of Triplets

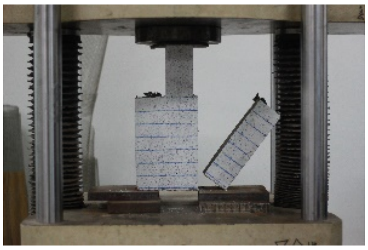
3.2. Failure Pattern

Figure 11 shows the crack pattern after failure of the specimen. All CTRL triplets failed completely detaching into two separate parts. Control triplets without plastering failed suddenly without any prior warning. Out of the 14 specimens, only CTRL 1, CTRL 2, and CTRL 5 failed suddenly. Specimens (CTRL 3, CTRL 4, and CTRL 6) plastered on all sides detached completely but showing some warning cracks before complete failure.

Laminating the triplet surface with ferrocement prevent triplet from this type of sudden failure. Thus, displacement capacity increases because of using ferrocement. Bricks in specimen no. 5 to 12 were confined because of the ferrocement so that the bond in bed surface does not detach or fail. Cracks in the plaster forms in less width.

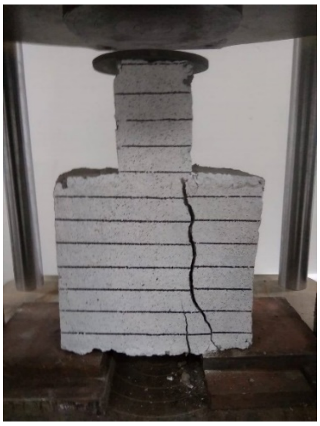


(a) CTRL 1

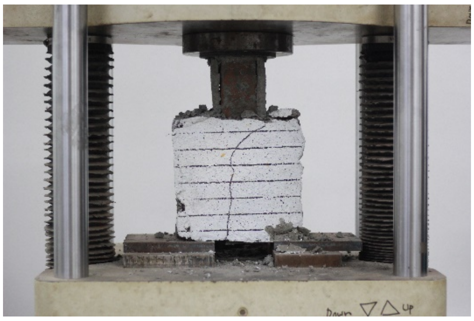


(b) CTRL 2

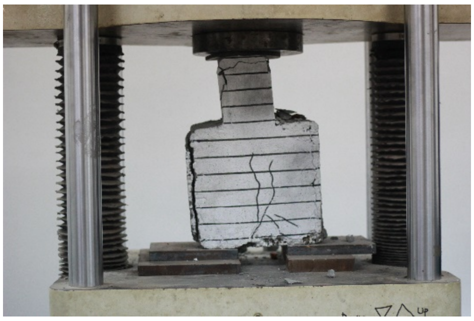
(c) CTRL 3



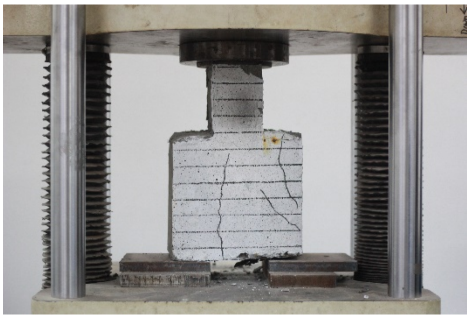
(d) CTRL 4



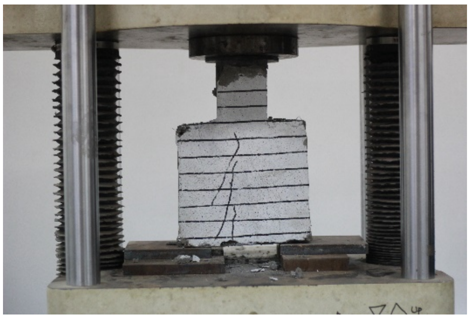
(e) WV 0.5mm 2S N1



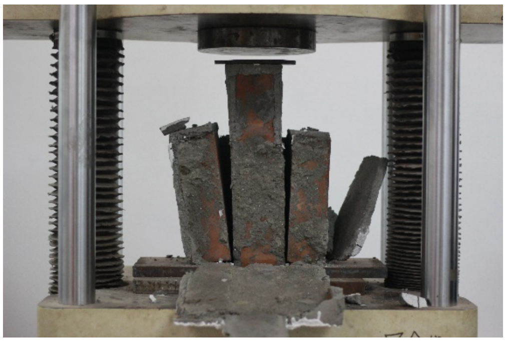
(f) WV 0.5mm 2S N2



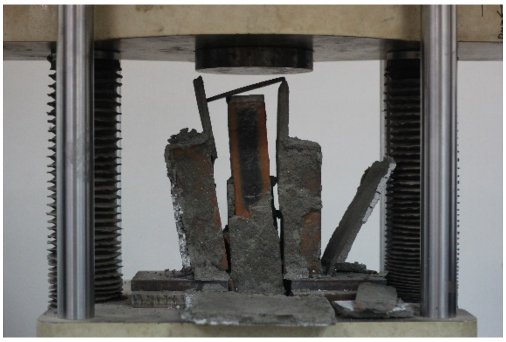
(g) WV 0.5mm 4S N1



(h) WV 0.5mm 4S N2

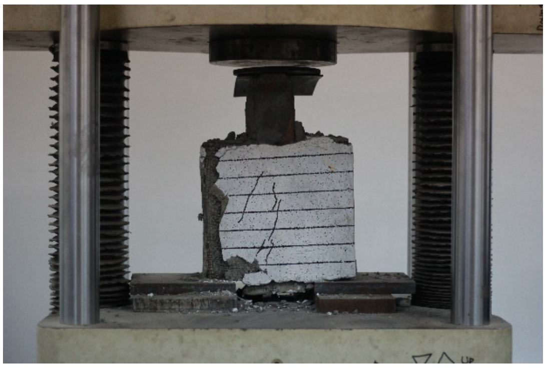


(i) WV 0.63mm 2S N1



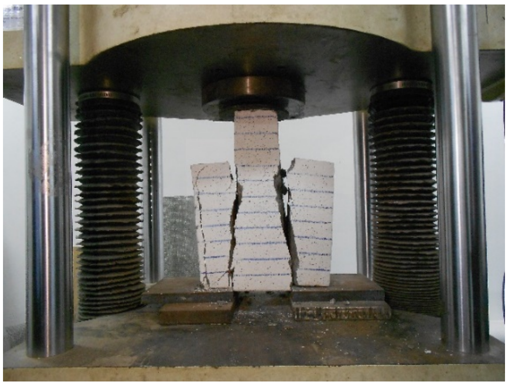
(j) WV 0.63mm 2S N2

(k) WV 0.63mm 4S N1



(l) WV 0.63mm 4S N2

(m) CTRL 5



(n) CTRL 6

Figure 11: Failure Patterns of the Triplets

The collapse of the specimens did not initiate by the crushing of the bricks, rather by exceeding the bond strength of the mortar. There was no major crack in the bricks even after failure of the triplet. Therefore, it can be concluded that mortar plays a significant role in sliding resistance or shear resistance of a brick wall. It has been observed that CTRL triplets without plastering failed by debonding the bed surface joints (Fig. 12 a). Failure pattern of CTRL triplets with plastering can be stated in 2 steps – (i) Releasing the confinement due to plaster i.e. failure of the bond between brick and plastering and (ii) debonding the bed surface joints. Failure pattern of WV triplets can be stated in 2 steps– (i) Releasing the confinement due to plaster i.e. failure of the bond between brick and plastering and (ii) debonding the bed surface joints or fracture of the wire mesh (Fig. 12 b). The specimen failed by the former one can not resist enough load before fails while the later one can generate higher strength. Failure in the later type of specimens initiated with a sharp loud noise of fracturing wires. Therefore, failure by fracturing of the wires are expected in WV specimens. Sliding is prevented due to the use of ferrocement in these specimens. Thus, total collapse of the specimens is not observed in these types of specimens.

(a) Sample of detaching bed surface for failure

(b) Fracture of wire mesh for failure

Figure 12: Sample bed surface after failure

3.3. Proposed Design Equations

Strength of triplet laminated with ferrocement depends on the diameter of wire mesh, amount of wire mesh (number of sides laminated). Bond strength, spacing of wire mesh, mortar strength, thickness of mortar, compressive strength of brick are also some other factors, but they are out of the scope of this study. Out of different test procedures for determining the brick properties, this study focuses on the tests somewhat more directly related to the strength such as modulus of rupture and compressive strength tests. These two tests are also readily conductible by compression testing machine or universal testing machine. Modulus of rupture is a flexure test of the brick where the brick fails due to the failure in tensile strain. In a flexure test, modulus of rupture in bending is the maximum fiber stress at failure. Tensile strength of brick is not a significant property of brick. This test is also slightly complicated. Thus, relationships based on the compressive strength test of unit masonry was developed. Linear, logarithmic, polynomial, power, and exponential curves were fitted to the data to find the best match. Best fitted graph depends on R^2 value. It was found that a polynomial equation represents the behavior for CTRL specimens and strain behavior of WV specimens. Logarithmic trendline best represents the shear strength of WV specimens. Approximate equations have been developed to predict shear strength (T), and strain at maximum stress ($\mathcal{E}$) of the triplet.

Proposed equation for shear strength of CTRL triplet without plastering is

$$T_{(CTRL\ w/o\ plaster)} = 0.039*x^{0.5941}\ ;\ \text{where, } x = f_{cm} * f_{cb} * t_b \quad (1)$$

$T_{(CTRL\ w/o\ plaster)}$ = Shear strength of CTRL triplet without plastering (ksi)

f_{cm} = Uniaxial compressive strength of mortar (ksi)

f_{cb} = Uniaxial compressive strength of brick (ksi)

t_b = horizontal bed joint and head joint thickness (bond thickness) (in)

Proposed equation for strain at maximum stress of CTRL triplet without plastering is

$$\mathcal{E}_{(CTRL\ w/o\ plaster)} = 0.023*x^{0.4851}\ ;\ \text{where, } x = f_{cm} * f_{cb} * t_b \quad (2)$$

$\mathcal{E}_{(CTRL\ w/o\ plaster)}$ = Strain at maximum stress of CTRL triplet without plastering

Proposed equation for shear strength of CTRL triplet with plastering is

$$T_{(CTRL\ w/\ plaster)} = 0.0699*x^{4.7393}\ ;\ \text{where, } x = f_{cm} * f_{cb} * t_b * t_p \quad (3)$$

$T_{(CTRL\ w/\ plaster)}$ = Shear strength of CTRL triplet with plastering (ksi)

t_p = Thickness of plastering

Proposed equation for strain at maximum stress of CTRL triplet with plastering is

$$\mathcal{E}_{(CTRL\ w/\ plaster)} = 0.0082*x^{1.914}\ ;\ \text{where, } x = f_{cm} * f_{cb} * t_b * t_p \quad (4)$$

$\mathcal{E}_{(CTRL\ w/\ plaster)}$ = Strain at maximum stress of CTRL triplet with plastering

Proposed equation for shear strength of WV triplet is

$$T_{(WV)} = 0.0433 \ln(x) + 0.1912\ ;\ \text{where, } x = N * t_p \quad (5)$$

$T_{(WV)}$ = Shear strength of WV triplet (ksi)

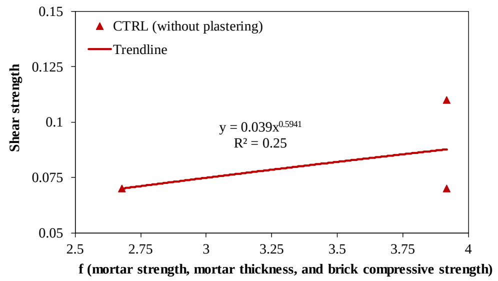
d = Diameter of the wires in ferrocement (mm), N = Number of ferrocement laminated sides (1, 2, 3 or 4)

Proposed equation for strain at maximum stress of WV triplet is

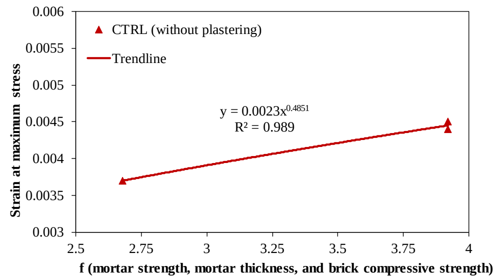
$$\mathcal{E}_{(WV)} = 0.003*x^2 - 0.0072*x + 0.0.0189\ ;\ \text{where, } x = N * t_p \quad (6)$$

$\mathcal{E}_{(WV)}$ = Strain at maximum stress of WV triplet

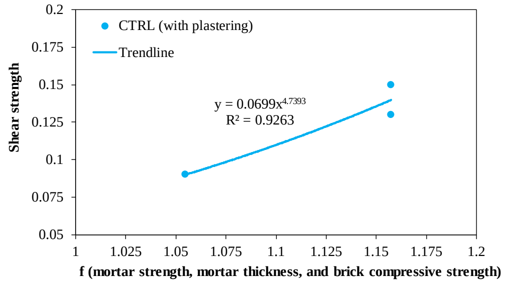
R^2 value of the trendlines are 0.25, 0.989, 0.9263, 0.4059, 0.5735, and 0.4601 respectively. R^2 values indicate a good approximation. The trendlines for proposed equations for shear strength, and strain at maximum stress for CTRL without plastering, CTRL with plastering, and WV triplets were shown in Fig. 13. It can be seen that the proposed equations estimate the stress and strain with reasonable accuracy.



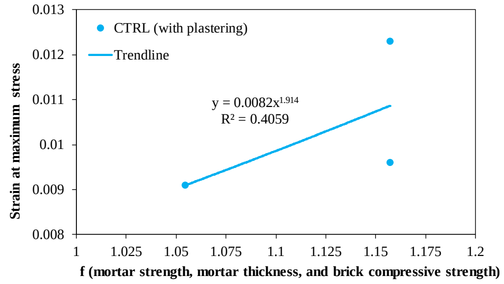
(a) Shear Strength of CTRL Triplets (without plastering)



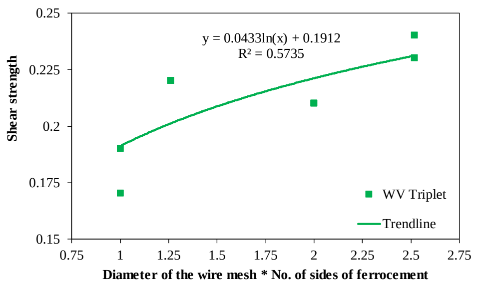
(b) Strain at Maximum Stress of CTRL Triplets (without plastering)



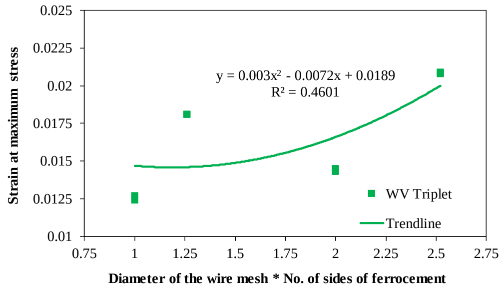
(c) Shear Strength of CTRL Triplets (with plastering)



(d) Strain at Maximum Stress of CTRL Triplets (with plastering)



(e) Shear Strength of WV Triplets



(f) Strain at Maximum Stress of WV Triplets

Figure 13: Summary of Stress-Strain of Triplets

4. Summary and Conclusions

4.1. Summary

Most of the triplet failed by debonding the horizontal bed surface joints. Application of plastering and ferrocement on the triplet prevents this earlier failure thereby increasing the strength and displacement capacity. Factors affecting the shear strength and displacement capacity of the triplet are diameter and amount of wire mesh. Shear strength and displacement capacity increase with the increase of diameter and amount of wire mesh. Equations were proposed based on the tests to measure the shear strength or strain at maximum stress for both CTRL and WV triplets based on the factors affecting them. A general trend is observed in terms of slope of the stress-strain curves of the triplets. The slope of the curve increases with the increase of the displacement.

4.2. Conclusions

Based on the test results, following conclusions can be drawn:

- As strength and displacement capacity of masonry wall increases with strength or displacement capacity of triplet, adding ferrocement will increase the strength and displacement capacity of a masonry wall. The reason is wire mesh confine the bricks of the triplets. At higher load, the bond between wire mesh and plaster breaks and wire mesh releases the confinement pressure. The discretization of this bond between mortar and wire mesh is unpredictable. Thus, it is not possible to reach a concrete conclusion just based on these tests. But the general trend is that the wire mesh confines the triplet such that it allows more deflection of the specimen and resists more shear strength.
- Only 14 samples were tested in this study. Numerous samples should be tested for more reliable results.
- The wall constructed by attaching ferrocement in load-bearing masonry panel may be significant than non-load bearing masonry panel as the effect of masonry wall in load bearing structure is more than non-load bearing structure. The masonry panel can be prefabricated or cast-in-place for installing the ferrocement.

Overall, the effect of ferrocement on masonry triplet is significant.

4.3. Recommendations

Based on this study, following recommendations can be proposed:

- The strength of a wall can be increased by increasing the bond strength of horizontal bed joints and head joints. Bond strength in typical construction work in Bangladesh is not strong enough in terms of this study as it is found that all the specimens failed in bond strength. Thus, it is recommended that the bond strength should be increased by increasing the proportion of cement or the other ways ASTM refers.
- Ferrocement can be used to increase the lateral load capacity and displacement capacity of the masonry wall.

References

[1] G. Al-Chaar, M. Issa, and S. Sweeney. “Behavior of Masonry-Infilled Nonductile Reinforced Concrete

Frames". Journal of Structural Engineering, vol. 128, No. 8, pp. 1055-1063, Aug, 2002.

[2] A.B. Mehrabi, P.B. Shing, M.P. Schuller, and J.L. Noland. "Experimental Evaluation of Masonry-Infilled RC Frames". Journal of Structural Engineering, vol. 122, No. 3, pp. 228-237, Mar, 1996.

[3] Concrete Society, "What is Ferrocement?". Internet: http://www.concrete.org.uk/fingertips-nuggets.asp?cmd=display&id=526 [May 11, 2019]

[4] ACI Concrete Terminology, American Concrete Institute. "Ferrocement." Internet: https://www.concrete.org/topicsinconcrete/topicdetail/ferrocement, [May 11, 2019]

[5] Clarke R.P., and Sharma A.K. "Hysteretic Behavior of Ferrocement-Retrofitted Clay Tile Walls.", ACI Structural Journal, Vol. 101, No. 3, pp. 387-394, May-Jun, 2004.

[6] A.M. Reinhorn, S.P. Prawel, and Z. Jia. "Experimental Study of Ferrocement as a Seismic Retrofit Material for Masonry Walls." Journal of Ferrocement. Vol. 15, No. 13, ,pp. 247-260, Jul 1985.

[7] P. Balaji, S.A. Selvan. "Performance Evaluation of Ferrocement Sandwich Wall Panels with Different Infills". International Research Journal of Engineering and Technology, Volume 5, Issue 4, pp. 1518-1524, Apr 2018.

[8] S.V. Venkatesh. "Strength characteristics of brick masonry wall before and after encasing with ferrocement." in 8th International Masonry Conference, Dresden, Jul, 2010, pp 1-8.

[9] G.M. Calvi, D. Bolognini, and A. Penna. "Seismic Performance of Masonry-Infilled R.C. Frames: Benefits of Slight Reinforcements." Seismic 2004 - 6th Portugese Congress of Seismology and Earthquake Engineering. Portugal, 2004, pp. 253-276.

[10] Hi-Top Merchandising, inc. "Stainless Steel Wiremesh (Welded & Woven". Internet: https://hitopmdsg.com/products/wire-mesh-welded-woven/, [May 11, 2019].

[11] A. Rahman, T. Ueda. "Experimental Investigation and Numerical Modeling of Peak Shear Stress of Brick Masonry Mortar Joint under Compression". Journal of Materials in Civil Engineering. vol. 26, pp. 1-13, Oct, 2014.

[12] G. Andreotti, F. Graziotti, and G. Magenes. "Detailed micro-modeling of the direct shear tests of brick masonry specimens: The role of dilatancy". Engineering Structures, vol. 168, pp. 929-949, May, 2018.

[13] S.B. Singh, and P. Munjal. "Bond strength and compressive stress-strain characteristics of brick masonry." Journal of Building Engineering. vol. 9, pp. 10-16, Nov. 2016.

[14] B. Istegun, E. Celebi. "Triplet Shear Tests on Retrofitted Brickwork Masonry Walls". International Journal of Civil, Environmental, Strutural, Construction and Architectural Engineering, Vol. 11, No. 9,

pp. 1250-1255, 2017.

[15] K.M.C. Konthesingha, C. Jayasinghe, and S.M.A. Nanayakkara. "Bond and Compressive Strength of Masonry for Locally Available Bricks". The Institution of Engineers, Sri Lanka. Vol. XXXX, No. 4, pp 7-13, 2007.

[16] J. Milosevic, A.S. Gago, M. Lopes, R. Bento. "Experimental tests on rubble masonry specimens – diagonal compression, triplet and compression tests" in 15 world conference on earthquake engineering (15 WCEE), Lisbon, 2012

[17] T. Nagarajan, S. Viswanathan, S. Ravi, V. Srinivas, P. Narayanan. "Experimental Approach to Investigate the Behaviour of Brick Masonry for Different Mortar Ratios" in International Conference on Advances in Engineering and Technology, Singapore, Mar, 2014, pp. 586-592.

[18] ASTM C67 / C67M-18, "Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile", ASTM International, West Conshohocken, PA, 2015, www.astm.org.

[19] "Specifications for and Classification of Brick". Technical Notes on Brick Construction. Brick Industry Association, Reston, Virginia, 2007.

[20] ASTM C62-17, "Standard Specification for Building Brick (Solid Masonry Units made from Clay and Shale)", ASTM International, West Conshohocken, PA, 2017, www.astm.org

[21] ACI 549.1R-18 (2018), "Design Guide for Ferrocement". ACI Committee 549, American Concrete Institute.

[22] ACI 549R-18 (2018). "Report on Ferrocement". ACI Committee 549, American Concrete Institute.

[23] "Technical Notes 39 – Testing for Engineered Brick Masonry- Brick and Mortar". Technical Notes on Brick Construction. Brick Industry Association, Reston, Virginia, Nov, 2001.

[24] ASTM C270-03b, 2003 (latest version: ASTM C270-19), "Standard Specification for Mortar for Unit Masonry", ASTM International, West Conshohocken, PA, 2019, www.astm.org.