Journal of Civil Engineering
The Institution of Engineers, Bangladesh
Vol. CE 25, No. 2, 1997

PROPERTIES OF MASONRY CONSTITUENTS

Md. Monjur Hossain[1], Sk. Sekender Ali[2] and M. Azadur Rahman[2]

ABSTRACT : This paper presents the results of non conventional experimental investigations of small burnt clay brick masonry samples. The in-situ deformation characteristics of bricks and mortar joints have been determined from 5 bricks-high stack bonded prisms. The deformation characteristics of individual brick and mortar have also been determined and found to be different from their in-situ characteristics. This is due to the composite action between brick and more softer mortar joint. The tensile bond strength has been obtained from 3 bricks high prism and shear bond strength from brickwork triplets. It has been found that the strength and deformation characteristics of masonry constituents obtained from these tests are more representative of the actual composite behaviour of masonry. The properties of brick and mortar joint determined from these tests are also found to be more appropriate for the study of non-linear behaviour of masonry structures.

KEY WORDS: Brick, Mortar, Masonry, Compressive Strength, In-situ, Deformation Characteristics.

INTRODUCTION

Brick masonry is one of the oldest building materials comparatively superior to other alternatives in terms of appearance, durability and cost. In addition to tremendous use of bricks (from unburned to engineering type) for low-cost housing in Bangladesh, its use is getting popularity both in high rise structures and in factory buildings.

The bricks are manufactured locally by burning the surface clay. The manufacturing method is labour extensive and easily adopted one, resulting a huge employment in Bangladesh. Thus brick masonry plays a significant role in the construction industries of Bangladesh where natural stones are not available and other types of building materials like concrete, MS sheets or CI sheets, timber and artificial materials are costly.

Since brick masonry structures are primarily subjected to compression, the interest of the researchers drew attention to the relevant tests which have formed the basis of brickwork strength used in

1 Deprtment of Civil Engineering, BIT, Khulna, Bangladesh
2 Deprtment of Civill Engineering, BUET, Dhaka-1000, Bangladesh

structural design. Although these empirical approach provides a basis for the structural design but are not altogether satisfactory and the standard tests used to define the strength of the component material not necessarily reproduce their in-situ state of stress in the brickwork (Hendry, 1981). Also, the recommendations are not yet fully available regarding the different kinds of structural properties which are rendered by brick unit and mortar in different types of masonry structures. In some instances the explanation of behaviour and the design criteria that are practised now, are somewhat speculative and may change as more information become available. This paper is intended to fill a part of such a need by presenting a systematic and comprehensive coverage for the basic properties of burnt clay solid brick masonry.

EXPERIMENTAL STUDY

Burnt clay brick unit and mortar are the main constituents for masonry in our country. The mortar being in general a composition of cement and sand. Standard tests, along with non-conventional tests, which are important to determine the material properties of fired clay solid brick, and cement sand mortar are discussed in the following articles. All samples of brick masonry tests were moist cured for 14 days and tested at 28 days. The joint thickness for all masonry specimens was 7 mm. Test set-up of experiments are schematically shown in Table 1.

PROPERTIES OF BRICK

Hand moulded kiln burnt half size bricks (size 123 mm x 60 mm x 36 mm) without any frog mark, were supplied by conforce Ltd., Dhaka. The same type of brick was used throughout the study. All the bricks were stored in the laboratory for the duration of the experimental program.

COMPRESSIVE STRENGTH

Compressive strength test has been performed according to Bangladesh Standard specification BDS 208 (1980).

In addition to the standard tests, compressive strength was also determined from uniaxial compression test on brick applying load in the direction parallel to bed joint orientation. Average results are given in Table 2. Details can be seen from Table A 1 in Appendix. The difference between compressive strength thus obtained and the standard test (load applied normal to bed joint) is due to the platen effect of the testing machine which apparently increases the actual compressive strength and the manufacturing process of the bricks. Page & Marshal (1985), carried out compressive tests with brush platen to reduce the platen effect (see Fig. 1). They proposed that for brick and prism having aspect ratio (Height/Least width) varying from 3 to 0.4, the actual compressive strength varies from 0.85 to 0.5 times the apparent strength obtained from so called standard test. For the bricks used in the present study aspect ratio (H/L) was 0.6. For this aspect ratio the correction factor, proposed by Page & Marshal is equal to 0.567. Applying this correction factor to the compressive strength of so called standard test, the actual compressive strength obtained was approximately equal to the value obtained when the brick is tested on end with loading parallel to bed joint. Therefore, the result obtained from brick tested on end with vertical load along the length of the brick may be taken as a rough guide for actual compressive strength of brick.

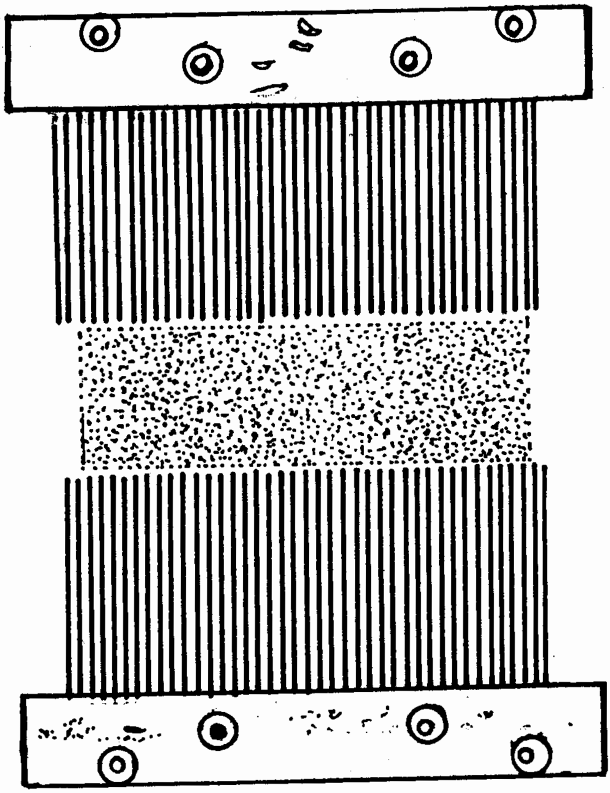


Fig 1. Brush Platen for Compressive Strength Test (Page and Marshal, 1985)

DEFORMATION CHARACTERISTICS OF BRICKS

The uniaxial compression test was done on bricks loaded parallel to bed joint and normal to bed joint (prism test). The load was applied monotonically until failure. The strains were measured by electric strain gauges attached to opposite faces of bricks at mid height level.

LOAD PARALLEL TO BED JOINT ORIENTATION

For this purpose uniaxial compression test was done on bricks loaded on end. The load at the rate of 100 kN/min was applied until failure. The strains measured in opposite faces were averaged to *eliminate bending effects. The aspect ratio (Height/Least dimension)* being 3.4 for the brick tested in this study eliminates platen effect. Bricks exhibited almost linear load deformation characteristics under uniaxial compression. Average modulus of elasticity obtained from this test (E_{bp}) is given in Table 2. Average stress-strain curve for brick obtained from this test is shown in Fig. 2 and individual curves are shown in Fig. A1 of Appendix. The variation in modulus of elasticity of individual brick and other parameters is inherent due to their material variability and manufacturing process.

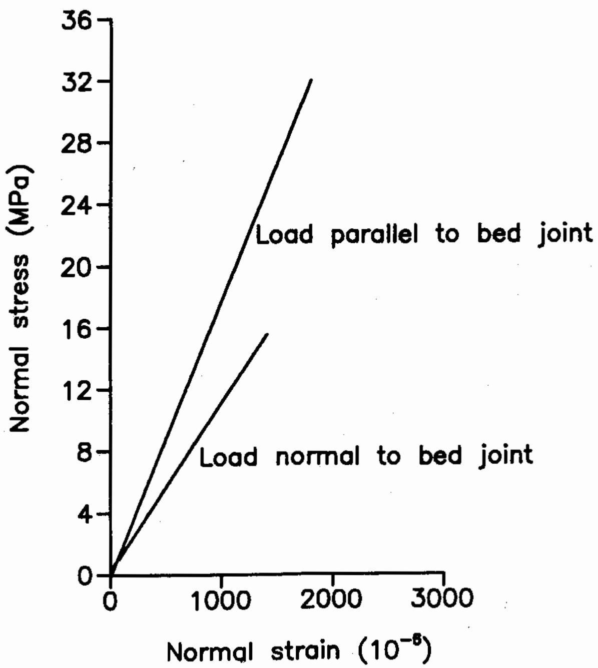


Fig 2. Average Stress-Strain Curve for Brick

LOAD NORMAL TO BED JOINT ORIENTATION

The evaluation of deformation characteristics of brick with load applied normal to the usual bed joint orientation is more difficult, since a brick loaded in this manner exhibits significant aspect ratio effect. To avoid this problem the deformation characteristics were measured on the central brick of a five bricks high stack bonded prism. The prism tests were also used to establish the in-situ properties of the mortar. The prisms were tested dry at an age of 28 days with the load being applied at a rate of 400 kN/min, producing stress level similar to those in tests with load applied parallel to the long direction of the brick. The strains were measured in horizontal and vertical directions for central brick unit of the prisms. The electrical strain gages were attached to opposite vertical faces of central brick unit as shown in Fig. 3.

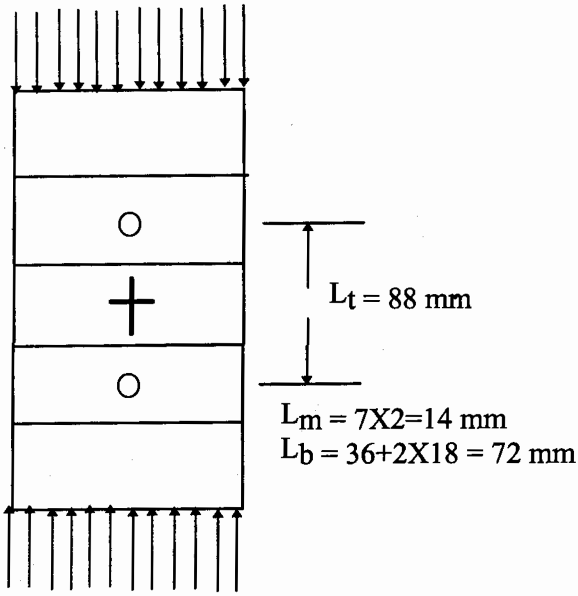


Fig 3. Stack Bonded Prism Showing Position of Electric Strain Gages and Demec Gauge

The stress-strain curve for the central brick obtained from vertical stress and corresponding vertical strains measured above gives the in-situ deformation characteristics of the brick. The modulus of elasticity thus obtained for brick is designated as modulus of elasticity of brick when load is normal to bed joint, (E_{bn}) and the average is given in Table 2. The comparison of deformation characteristics of bricks in two different directions are shown in Fig. 2. Individual stress-strain curve for brick loaded normal to bed joint are shown in Fig. A.1 of Appendix.

STRESS-STRAIN CURVE

The instantaneous axial deformation of brick under load can be described conveniently by stress-strain diagram. The average stress-strain curves for brick in both cases are almost linear as can be seen from Fig. 2. They can be represented by $\sigma = E_{bn}\varepsilon$ and $\sigma = E_{bp}\varepsilon$ where E_{bn} and E_{bp} are the initial tangent modulus having average values of 12930

MPa and 17900 MPa respectively for normal to bed joint (E_{bn}) and parallel to bed joint (E_{bp}) orientation. The detailed results can be seen from Appendix. Since the burnt clay bricks exhibit brittle behaviour both in compression and tension, the stress-strain curve in tension was assumed to be the same as the stress-strain curve in compression and can be expressed by the same formula.

Table 1. Summary of Brick Mortar and Brick-Masonry Tests.

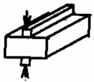
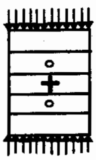
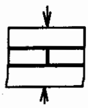
Type of Tests	Material Property Evaluated
Compression test on brick (load parallel to bed joint) 	Compressive Strength of Brick Parallel to Bed Joint. Deformation Characteristics of Brick. Initial Tangent Modulus of brick. Ultimate Strain and Secant Modulus of Brick at Ultimate Strength. Posisson's Ratio of Brick.
Split Tensile Test of Brick 	Tensile Strength of Brick from Indirect Test
Compression Test on Stack bonded brick Prism 	Deformation Characteristics and Compressive Strength of Masonry. In-situ Deformation Characteristics of Mortar Joint. In-situ Initial Modulus of elasticity of Mortar Joint. Deformation Characteristics of Brick (Load normal to be joint).
Shear Test on Brickwork Couplet 	Shear Deformation Characteristics of Mortar Joint
Splitting Test of Masonry Prism 	Tensile Bond Strength of Mortar Joint.
Compression Test on Triplet 	Shear Bond Strength of Mortar Joint.

Table 2. Summary of Brick Properties

Type of Test	$\bar{X}$	S	C. of V. %	No of Specimens
Size (mm)	122.7x59.6x 35.8	3.4, 1.2, .81	3, 2, 2	10
Weight of brick (gm)	448.7	11	2	10
Absorption (%)	13.6	4	29	10
Compressive Strength Parallel to bed Joint (MPa)	40.2	5.44	13.5	10
Compressive Strength (Standard Method) (MPa)	66.2	6.94	10.5	10
Indirect Tensile Strength (MPa)	3.2	0.44	13.6	10
E_{bn} (MPa)	12,930	3,280	25	10
E_{bp} (MPa)	17,900	2,634	14.7	10

PROPERTIES OF MORTAR

Mortar was prepared from normal Portland cement (Buffalo head brand) and local sand (FM =1.5), mixed in ratio of 1:4 by weight. For preparation of workable paste, the amount of water required was determined from flow test of mortar as proposed by ASTM Standard C109 (1980). The w/c ratio of 1.0 (by weight) was determined to prepare the mortar and was used throughout the study.

The compressive and tensile strength of mortar have been determined according to ASTM Standard C109 (1980) and C1006 (1984) respectively. The average results are given in Table 3 (for details see Table A.2 in Appendix). The deformation characteristics of the mortar is discussed in the following sections.

STRESS-STRAIN CHARACTERISTICS OF MORTAR

The load deformation characteristics of mortar joint was studied by attaching 30 mm and 10 mm electric strain gages in longitudinal and transverse direction respectively, at mid height of the cylinders used for compression test. Mean stress-strain curve obtained from cylinders is shown in Fig. 4 along with the average in-situ stress-strain curve of mortar obtained from prism tests as described below. Fig. 4 also shows that the deformation characteristics obtained from mortar cylinder tests do not reflect the true behaviour of the mortar in the joints. The horizontal mortar joints experience triaxial compressive stress due to brick mortar interaction. The average modulus of elasticity of mortar obtained from cylinder test E_{mc} is given in Table 3.

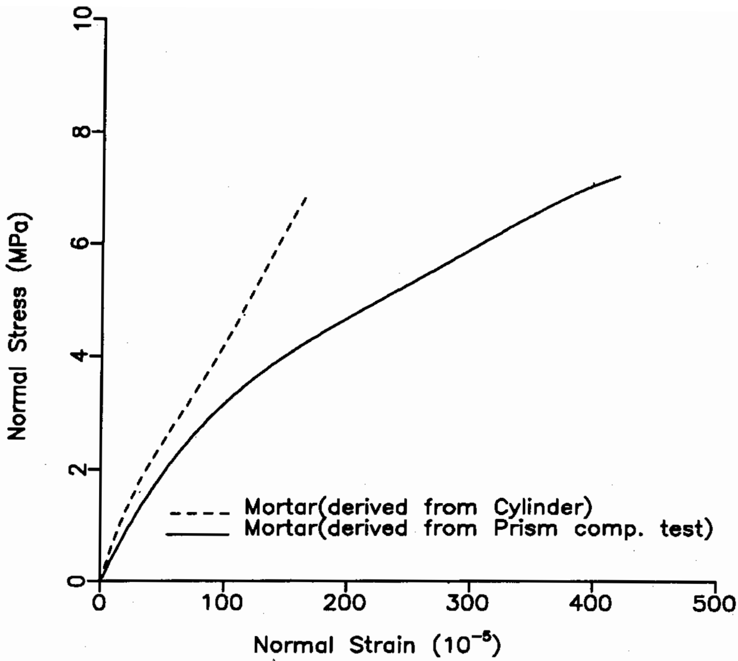


Fig 4. Average Stress-Strain Curve for Mortar (from Cylinder and Prism Test)

Table 3. Summary of Mortar Properties

Type of Test	$\bar{X}$	S	C. of V. %	No of Specimens
Compressive Strength 2 in. Cube (MPa)	12.5	0.66	5	10
Compressive Strength 3 in. X 6 in. Cylinder (MPa)	12.0	0.43	4	5
Indirect Tensile Strength (MPa)	0.97	0.04	4	10
Initial Modulus of Elasticity E_{mc} (MPa) (Cylinder test)	9590	1587	16	3
Intial Modulus of Elasticity E_{mp} (MPa) (prism test)	3270	703.4	21	9

UNIAXIAL COMPRESSION TESTS OF STACK BONDED PRISM

Five bricks high stack bonded prisms (208 mm height x 123 mm width x 60 mm thick) with plywood capping at top and bottom, were loaded in uniaxial compression to failure. Longitudinal strains were measured on a central 88 mm gauge length on both sides of the prisms using a Demec gauge. The gauge length encompassed 2 mortar joints, one full brick and two half bricks which is assumed to be a representative brickwork. Local strains were measured on the middle brick using electric strain gauges (see Fig. 3). Failure occurred by tensile splitting induced by the differing strain characteristics of the weaker mortar and stronger brick. The average prism strength was 18.16 MPa (coefficient of variation 11%). The average modulus of elasticity of the brick prisms tested was 8000 MPa (coefficient of variation 15%). The modulus of elasticity of the prisms thus obtained is 445 times the average compressive strength of the prisms. This value (445 times) lies within the range specified by previous authors (Plowman, 1965; Sahlin, 1971).

The average modulus of elasticity obtained for the prisms can be expressed by,

$$E=2.2\sigma'/\varepsilon' \quad (1)$$

where σ' is the average crushing strength of the prisms and ε' is the corresponding strain. In this study ε' was obtained by extrapolating the average stress-strain curve for brickwork. This relation resembles with that proposed by Powell and Hodgkinson, (1976).

IN-SITU DEFORMATION CHARACTERISTICS OF MORTAR JOINT

It is assumed that all the bricks encompassed by the demec gauge are in a uniform state of vertical stress and the difference between the total measured deformation and the brick deformation can be attributed to the mortar. The mortar strain corresponding to the stress level can be determined from the expression

$$\varepsilon_m = \frac{\varepsilon_t L_t - \varepsilon_b L_b}{L_m} \quad (2)$$

in which ε_t = total measured strain; ε_b = strain in the brick; L_m = total mortar thickness; L_b = total brick thickness; and L_t = total gauge length. The notations are explained in Fig 3.

Using Eq. (2) the net strain for the mortar can be derived from the average measured masonry strain and brick strains for each prism. The method was also adopted by Ali, 1987. The average stress-strain characteristics of mortar and brickwork as derived from the prism tests and for brick derived from uniaxial compression test (load parallel to bed joint) are shown in Fig 5. which shows the extent of difference of the

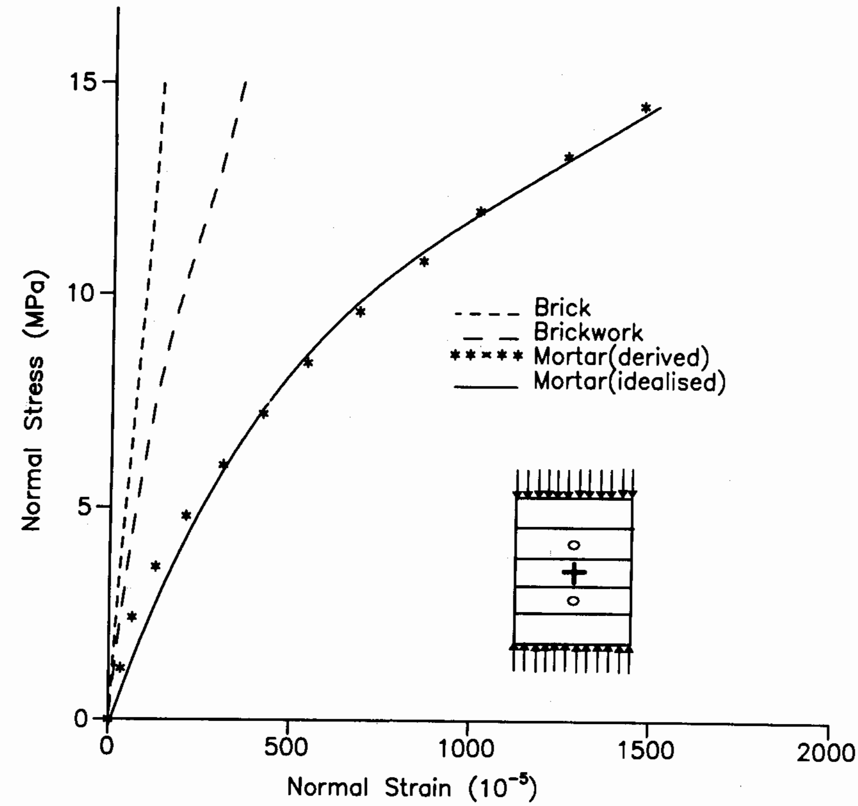


Fig 5. Average Stress-Strain Curves for Brick, Brickwork and Mortar

load deformation response of the constituents of the masonry when the composite action between them are considered. The stress-strain curve for mortar is non-linear in nature. The average initial tangent modulus of elasticity for the mortar thus obtained was 3270 MPa (coefficient of variation 21%). The higher coefficient of variation of E_{mp} in comparison to E_{mc} may be due to the poor quality control of brick specimens. The effectiveness of vertical strain gages attached to the central brick units of the prisms may also have some influence in this case. However, the high coefficient of variation of absorption of brick is entirely due to its poor quality control.

The in situ stress-strain curves for mortar can be idealised by the relation proposed by Dhanasekar (1985). The relation predicts plastic strains throughout the stress range. The total strain is the sum of elastic strain $\varepsilon^e = \sigma/E_o$ and the plastic strain (ε^p) and is given by Eqn. (3)

$$\varepsilon^t = \sigma_n / E_o + e^{a}n(e^{b}n^{\sigma}n - 1) \qquad (3)$$

where ε^t = total strain; σ_n = normal stress; E_o = initial tangent modulus and a_n and b_n are constants of stress -plastic strain equation determined from semilogarithmic plots of plastic strain against stress. The mean values of stress plastic strain constants with coefficients of variation are given in Table 4. Plastic strains vs. normal stress diagram for mortar of each prism are shown in Fig. A 2 of Appendix.

SHEAR TESTS ON BRICK MASONRY WITH SLOPING BED JOINT

Couplets with sloping bed joints as shown in Fig. 6 were tested by uniaxial loading. In the inclined joint shear and normal stresses will be induced. The steep angle (θ = 40°) will ensure significant shear deformations. For all the specimens failure was confined within the joints. Strains were measured using Demec gauge on 50 mm gauge length in two diagonal directions and on both faces of the specimen. Using the average of strains on both faces the shear strains were determined from the strain transformation equation (Eq. 4).

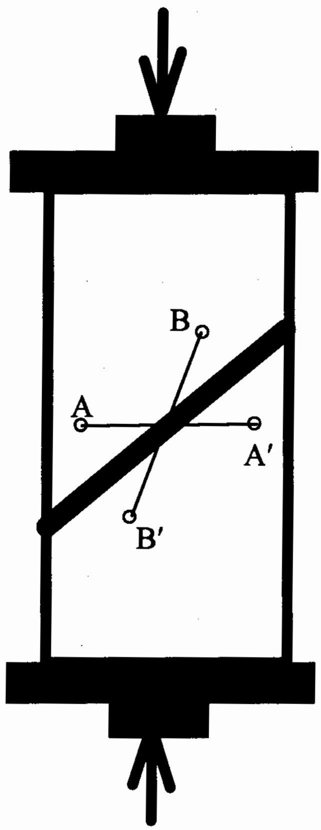


Fig 6. Uniaxial Compression Test on Shear Couplets

$$\gamma_{xy} = \frac{\varepsilon_A - \varepsilon_B}{\mathrm{Sin}2\theta} \tag{4}$$

where ε_A and ε_B are the strains in the diagonal directions (i.e.,ε_A = AA' and ε_B = BB') measured in Fig. 6. The joint shear strain was then determined at a particular shear stress level by subtracting the brick shear deformation from the total shear deformation. Thus the mortar shear strain (ε_m) at shear stress level (τ) is given by the Eq. 5.

$$\gamma_m = \frac{\gamma_t L_t - \tau . \frac{L_b}{G_b}}{L_m} \tag{5}$$

in which γ_t = total measured shear strain and G_b = shear modulus of brick. Substituting the appropriate value of L_t = 37 mm, L_b = 30 mm, L_m = 7 mm and G_b = 9126 MPa, the mortar shear strain can be expressed as

$$\gamma_m = 5.286\,\gamma_t - 0\,.0004696\tau \tag{6}$$

From Eq. 6 shear strains are calculated and the average experimental shear stress-strain curve obtained for the joint and its idealised curve are shown in Fig. 7 together with the average curves for brick and brick masonry under shear.

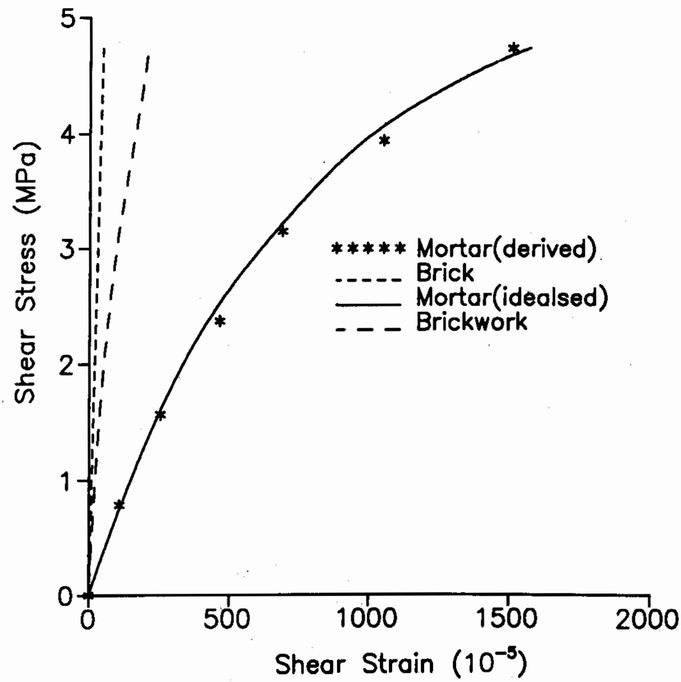


Fig 7. Shear Stress-Strain Curve of Brick, Brickwork and Mortar

The shear stress-strain curve of mortar is non-linear in nature and can be idealised by similar relation for normal stress-strain curve for the mortar and is given in Eq. 7.

$$\gamma^t = \tau/G + e^{a_s}(e^{b_s.\tau} - 1) \quad (7)$$

where a_s and b_s are constants obtained from semi-logarithmic plots of plastic shear strain against shear stress. The mean values of stress plastic shear strain constants with coefficients of variation are given in Table 4. The average initial shear modulus (G) for mortar was 1817 MPa. The details of the experimental results can be found else where (Hossain M.M., 1997).

Table 4. Constants of Stress Plastic -Strain Equations (Normal Stess and Shear Stress)

Constants	Mean	Standard Deviation	Coefficient of Variation (%)
a_n	-8.24	-0.67	8
b_n	0.27	0.05	18
a_s	-9.42	-0.95	10
b_s	.845	0.04	5

TENSILE BOND STRENGTH

An estimate of the tensile bond strength can be obtained from splitting test on a masonry prism. A compressive load is applied through narrow steel plates inducing an indirect tensile stress on the vertical mortar joint. The load is applied until failure and the corresponding tensile bond strength is calculated from the Eq. 8 with C equal to 0.67. The mean tensile bond strength calculated in this manner for 10 specimens was found to be 1.443 MPa with coefficient of variation is 10%. The details of the experimental results can be found else where (Hossain M.M., 1997).

$$\text{Tensile bond strength, } \sigma_T = \frac{CP}{DI} \quad (8)$$

where P = Splitting load at failure

I = specimen thickness

D = equivalent diameter

$$= \sqrt{\frac{h.a}{\pi/4}}$$

h, a = specimen height and width

$C = 0.67$

For many applications this type of test is more representative than direct tensile tests on joints, since it reflects the restraining influence of the surrounding bricks and joints.

SHEAR BOND STRENGTH

A total of 10 triplets were tested. The average shear stress (τ_{ab}) is obtained by dividing the ultimate load by the total sheared area. The mean shear bond stress was found to be 0.594 MPa. Details of the experimental results can be found elsewhere (Hossain M.M., 1997).

A summary of brick, mortar and brick masonry tests are given in Table 1.

CONCLUSIONS

Finite element models for masonry in which bricks and mortars are considered separately require the properties of individual constituents. If the in-situ test data are available the model can be more realistic. The strength and deformation characteristics of brickwork are also required in the numerical models where masonry is considered as homogeneous material. The results of routine tests and non-conventional tests discussed in this paper are important both for 'micro' and 'macro' modelling of masonry structures. The following conclusions can be made from this laboratory experimental study.

1. The compressive strength of brick determined by standard test overestimates the actual strength by approximately 1.65 times as observed in this particular investigation.
2. For design purposes the compressive strength of bricks determined by standard method should be corrected considering the aspect ratio effect.
3. The burnt clay bricks under investigation exhibited brittle behaviour approximately up to failure load.
4. The in-situ elastic modulus of the bricks were found to be lower than those obtained by testing the bricks individually.
5. The tensile strength of brick was found to be 5% of the compressive strength determined by standard test while it was 8% of the compressive strength determined by test when the load is parallel to bed joint orientation.
6. Mortar exhibited non-linear stress-strain characteristics with a relatively large deformation capacity under compression.
7. The in-situ elastic modulus of mortar obtained from prism tests is found to be lower than that obtained from uniaxial test on mortar cylinder.
8. The average modulus of elasticity for brick prisms can be expressed by $E = 2.2\sigma'/\varepsilon'$ where σ' is the average crushing strength of the prisms and ε' is the corresponding strain of the prism.
9. Compression tests on stack bonded prisms and prisms with sloping bed joints gives in-situ properties for brick and mortar while splitting tests on stretcher bonded prisms and compression tests on masonry triplets are aimed at establishing the basic bond parameters between bricks and joints.

10. The results from routine tests and nonconventional tests on brick, mortar and small brick masonry samples obtained in this investigations are very helpful for 'micro' modelling of masonry structures. Since these tests are easy and simple repeated tests can be done to attain the representative value.

NOTATIONS

a_n, b_n =	Constants of Plastic Strain for Mortar
C. of V. =	Coefficient of Variation
E_{bn} =	Modulus of Elasticity of Brick Perpendicular to the Bed Joint obtained from stack bonded Prism test MPa
E_{bp} =	Modulus of Elasticity of Brick Parallel to the Bed Joint MPa
E_{cs} =	Secant Modulus at Ultimate strength
E_o =	Initial tangent modulus
E_{mc} =	Modulus of Elasticity of mortar obtained from mortar cylinder
E_{mp} =	Modulus of Elasticity of mortar obtained from Prism test
E =	Initial tangent modulus of Brick Prism
L_b =	Total brick thickness for gauge length
L_m =	Total Mortar thickens for gauge length
L_t =	Total gauge length
S =	Standard Deviation
$\bar{X}$ =	Mean
σ_n =	Normal stress
σ' =	Average Crushing Strength of Prism
ε' =	Strain Corresponding to Crushing Strength of Prism
ε_t =	Strain considering to total gauge length in Prism Test
ε_b =	Strain in Brick in Prism Test
ε_m =	Total strain for Mortar
γ^t =	Total shear strain for mortar in shear couplets
τ =	Shear stress in shear couplets

REFERENCES

Ali, S. S., (1987), "Concentrated Loads on Solid Masonry", Ph. D. Thesis, University of Newcastle. Australia.

Dhanasekar, M., (1985), "The Performance of Brick Masonry Subjected to in-Plane Loading", Ph.D. Thesis, The Univ. of Newcastle, Australia.

Hendry, A.W., (1981) Structural Brickwork, The Macmillan Press Ltd.

Hossain M.M., (1997), "Non-linear Finite Element Analysis of Wall-beam Structures", Ph.D. Thesis, Bangladesh University of Engineering and Technology, Dhaka.

Page and Marshal, A.W. and Marshal, R., (1985), "The Influence of Brick and Brickwork Prism Aspect Ratio on the Evaluation of Compressive Strength," Proc. 7th. Brick Mas. Conf., Melbourne, pp. 653-664.

Plowman, J.M., (1965), "The Modulus of Elasticity of Brickwork", Proc. Br. ceram. Soc., 4, pp. 37-44.

Powell, B., and Hodgkinson, H.R., (1976), "The Determination of Stress/Strain Relationship of Brickwork", Proc. of the 4th Int. Brick Mas. Conference (Brugge), paper 2.a.5.

Sahlin, S., (1971), Structural Masonry, Prentice-Hall, Englewood Cliffs, N.J., pp. 59-61.

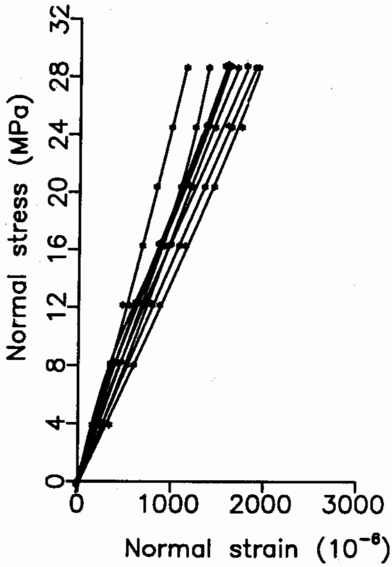
APPENDIX

Table A. 1. Compressive and Tensile Strength of Brick (All values are in MPa)

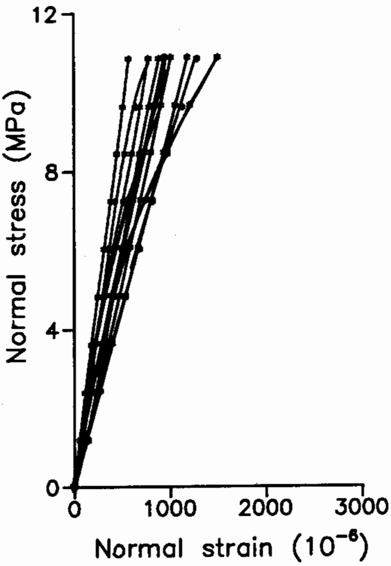
Specimen No	Compressive Strength			Tensile Strength (indirect test)
	Load Normal to Bed Joint	Load Parallel to the Bed Joint	Standard Test	Split Tensile
1	75.6	39.12	55.35	3.53
2	56.7	47.77	71.96	3.75
3	54.0	46.33	58.12	2.86
4	81.0	36.86	66.42	3.57
5	77.0	36.04	77.49	2.68
6	52.65	47.77	60.89	3.80
7	67.5	32.54	74.73	3.51
8	64.8	36.04	60.89	2.68
9	54.0	35.42	69.19	3.35
10	45.9	44.07	66.42	2.68
$\bar{X}$	62.91	40.20	66.15	3.24
S	11.41	5.44	6.94	0.44
C. of V (%)	18	13.50	11	13.6

$\bar{X}$= Mean, S=Standard Deviation, C. of V. = Coefficient of Variation

Note: Ration of compressive strength, using load parallel to bed to compressive strength using standard test is 0.60.



(a) stress-Strain diagram for bricks (Load parallel to bed)



(b) Stress-Strain diagram for bricks
(from Prism test)

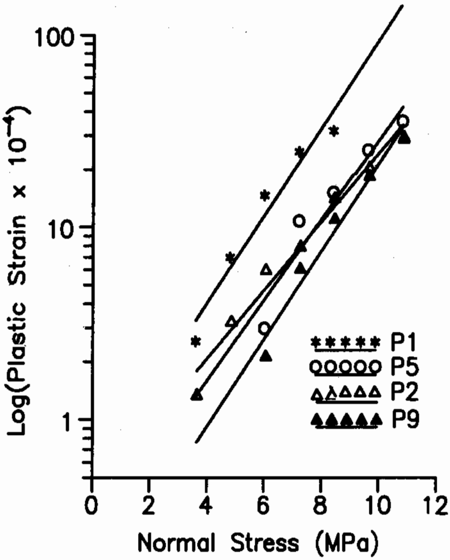
Fig A1 Stress-strain Diagram for Bricks
(Uniaxial Compression Test and Prism Test)

Table A. 2. Compressive and Tensile Strength of Mortar (All values of strength are in MPa)

Specimen	Compressive Strength**		Tensile Strength*
No	2 in. cube	6 in. cylinder	Prism
1	12.80	11.68	0.971
2	12.40	11.76	0.960
3	12.30	11.68	1.017
4	12.42	12.58	0.914
5	13.27	12.58	0.937
6	13.52		0.994
7	11.56		1.000
8	11.24		0.971
9	12.59		0.902
10	12.74		1.017
$\bar{X}$	12.5	12.0	0.97
S	0.66	.043	0.038
C. of V (%)	5.0	4.0	4.0

Note : ** Determined from tests on 2 in. cube and 3 in. X 6 in. cylinder at 28 days

* Determined from Splitting test on 100 mm X 50 mm X 40 mm prism at 28 days



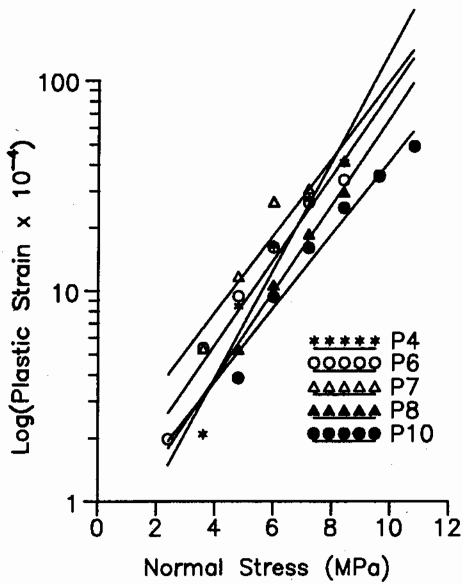


Fig A 2. Semil Logarithmic Plot of Plastic Normal Strain Vs. Normal Stress

Table A. 3. Compression Test on Brick (Load Parallel to Bed Joint) (Strain Reading on 30 mm Gauge Length, X 10^{-6})

Stress MPa	Specimen No										$\bar{X}$	S	C of V%
	1	2	3	4	5	6	7	8	9	10			
4.12	243	246	232	304	304	172	354	228	250	240	257	48	19
8.24	385	466	372	541	541	366	616	368	415	388	446	85.6	19.2
12.36	614	719	491	723	811	564	892	698	810	650	697	115.8	16.6
16.47	883	881	941	974	1096	701	1165	912	1011	875	944	122.4	13
20.59	1130	1162	1112	1243	1369	850	1470	1169	1201	1145	1185	155.5	13.1
24.71	1386	1382	1265	1480	1656	1012	1768	1413	1619	1384	1437	203	14.1
28.83	1596	1597	1405	1718	1910	1170	1946	1641	1817	1580	1638	221	13.5
32.95	1790	1800	1592	1957	2224	1372		1877		1800	1802	234	13
37.07	1970	2032	1691			1528					1805	205	11
41.18		2321	1897			1698					1972	260	13
45.30		2574											
ε_{cu} (10^{-5})	208.8	274.2	238.7	240.8	239.4	205.1	219.0	202.2	224.9	221.7	227.5	20.56	9.0
E_o (Gpa)	19.27	17.76	19.41	16.18	15.00	23.50	13.43	18.55	16.94	18.95	17.90	2.63	14.7
E_{cs} (GPa)	18.74	17.42	19.40	15.31	15.00	23.30	13.43	17.83	15.75	18.95	17.51	2.68	15.3

$\bar{X}$ = Mean, S = Standard Deviation, C. of V. = Coefficient of Variation

E_O = Initial Modulus of Elasticity; E_{CS} = Secant Modulus of Elasticity at ε_{cu} and ε_{cu} is the strain at f'_c.

Table A. 4. Compression Test on Brick Bonded Prism (Load Normal to Bed Joint)
(Normal stress -strain readin* forBrickX 10^{-6})

Stress MPa	Prism No										$\bar{X}$	S	C. of V%
	1	2	3	4	5	6	7	8	9	10			
1.2	114	58	60	136	147	88	148	83	91	137	106	33	31
2.4	241	162	133	114	225	244	158	265	185	179	273	54	27
3.6	210	214	177	312	378	246	372	302	324	400	293	74	25
4.8	312	303	246	408	530	348	488	405	405	536	398	90	22.5
6.0	351	402	316	501	683	454	603	516	539	671	504	119	23.6
7.2	426	517	386	590	821	572	711	632	747	810	621	144	23
8.4	532	603	446	682	969	748	821	744	976	935	745	174	23.4
9.6	648	689	511	784	1132	926	925	852	1210	1060	874	210	24
10.8	780	776	573	887	1287	975	1028	957	1500	1186	995	257	25.8
12.0	927	867	650	995	1442		1123	1064	1488	1299	1100	260	23.4
13.3	1036	952	727	1101	1586		1202	1157	1582	1449	1200	270	22
14.5	1172	1037	804	1211	1715			1247	1573	1515	1280	280	22
15.7	1309	1130	884		1855				1671	1600	1410	330	23
16.9	1455	1187			1994				1895	1742	1655	296	18
18.1	1625	1251			2124				2123		1780	340	19
19.3		1329			2203				2278		1937	43	22
20.5		1448			2225								
f'_{pm} (MPa)	19.0	21.2	16.8	14.8	21.2	19.3	15.7	16.3	18.8	18.4	18.2	2.1	11
E_o (Gpa)	16.3	15.9	19.3	11.2	9.4	14.3	9.3	12.3	12.3	9.0	12.9	3.28	25

Note : E_o = Initial Tangent Modulus of Brick when load is normal to bed (obtained from prism test)

f'_{pm} = Prissm Stength in MPa

* Measured in the middle height of middle brick in the direction of the load applied in the Prism Test.