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A Review on Modes of Failure and Factors affecting the Strength of Brick Masonry

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Abstract: The strength of masonry depends upon the strength of masonry units, mortar and the bond between them.
The strength of the component materials is defined by standardized tests, which don't necessarily reflect the state of stress in the component material in brickwork, but serve as index values in the selection of design stresses. This is only an empirical approach, which provides an acceptable basis for the structural design of brickwork. The approach is not altogether satisfactory as it gives little insight into the behavior of the brick mortar composite
Research work has shown that the following factors are of importance in determining the compressive strength of brick masonry. These are strength of unit, geometry of unit, strength of mortar, deformation characteristics of unit and mortar, joint thickness, suction of units, water retentivity of mortar and brick work bonding. Some of these factors, such as unit characteristics are determined in the manufacturing process, while others such as mortar properties are subjected to variations in constituent materials, proportioning, mixing and accuracy of construction.
It was concluded that the behavior of grouted unreinforced brick masonry panel was isotropic and the orientation of bed joint has no significant role in the failure criterion. Whereas the ratio of the horizontal to the vertical load has significant influence on the failure mode of clay bricks and hollow clay brick layers of panels. Also it was observed that the masonry strength under equal biaxial compression is higher by about 36% on average than that under uniaxial compression.
Keywords: Stabilized mud, Brick prism, Lateral deformation, masonry units, bed materials.

I. INTRODUCTION

Masonry has been the choice of Architects, Engineers and Builders through civilization for its beauty, versatility and durability. Sun-baked clay bricks were used in the construction of buildings more than 6000 years ago. The evidence of which can be seen today at ruins such as Harappa Buhen and Mohenjo-Daro. The Roman further distinguished those, which had been dried by the sun and air, and those, which were burnt in a kiln. They found the kiln-fired bricks were more durable in harsh weather condition and they introduced kiln-fired bricks to the whole of the Roman Empire. The Egyptian pyramids(stone masonry 2500 B.C.), Elamite Ziggurat a choga zambil in Iran (a temple tower with mud brick masonry 1250 B.C.), Great wall of China(21196km long -built, rebuilt and maintained between 221B.C.-206B.C.),The Coliseum of Rome(stone amphitheater A.D.70-72), Sun pyramid at Teotihuacan, Maxico with 66meter height (600 A.D.) Taj Mahal of India (1632), are some of the world's most significant architectural achievements, which have been built with masonry.

A large proportion of brickwork building for residential and other purposes are satisfactory designed and built in accordance with empirical rules and practices without the need for special structural consideration. However, the empirical rules cannot be employed for the buildings more two stories without using very thick wall which in turn result in wastage of materials and other disadvantages. As the masonry construction become more elaborate, use of brick become more innovative, which led to the development of concrete block/brick. Joseph Gibs made the concrete blocks in U.K. in 1850. Indeed, after a considerable time i.e. it is only since 1950s that the application of structural engineering principle to design the brickwork has resulted in the re adoption of this material for certain classes of multistoried buildings. For several centuries masonry continued to remain as the leading building material, but with the exploration of concrete and steel, the high performance building material at the end of 19^{th} century, the use of masonry as a structural material taken a back seat. However, the strength of masonry is comparable to that of high- performance materials. The building made of masonry even after one or two hundreds of years are found to be maintenance free. Further with steady rise in cost of steel and concrete, brick/block masonry offers cheaper alternatives. Due to development of soil stabilization with cement the stabilized mud block also came into the practice since last five decades. Research work has shown that the following factors are of importance in determining the compressive strength of brick masonry.

These are strength of unit, geometry of unit, strength of mortar, deformation characteristics of unit and mortar, joint thickness, suction of units, water retentivity of mortar and brick work bonding. Some of these factors, such as unit characteristics are determined in the manufacturing process, while others such as mortar properties are subjected to variations in constituent materials, proportioning, mixing and accuracy of construction.

A. *Effect of bed Materials on the Compressive Strength of Brick Masonry*

A number of experiments was conducted on the brick prism by the Structural Clay products Research Foundation in the United States (1967) in order to examine the effect of compressive strength of brickwork with different bedding materials. Some of the outcome of the experiments has been summarized below in table 1.

Table 1. Effect of different joint materials on the compressive strength of brick prism (Monk1967)

Joint material	Compressive strength (N/mm^2)	Ratio of prism strength to brick strength
Aluminium sheet (0.8mm)	106	0.96
Mortar (1:0.5:4.5) (cement: lime: sand)	44	0.40
Dry sand contained by adhesive tape	65	0.59
Ground surface	98	0.89

The influence of bedding material on the compressive strength of brickwork was also examined by Morsy (1968). The experiments were conducted on brick prism with different jointing materials from rubber to steel with large variations in their stiffness and the result was summarized in table 2.

Table 2. Effect of joint materials on the compressive strength of three brick stack prism

Joint material	Compressive strength (N/mm^2)	Ratio of Prism Strength to brick strength
Steel	56.48	1.40
Ply wood	46.39	1.15
Hard board	43.89	1.09
polythene	16.99	0.42
Rubber with fiber	11.71	0.29
Soft rubber	06.99	0.17
No joint material	37.20	0.93
Mortar (1:0.25:3)	14.00	0.35

From the above table it may be observed that there is an eight-fold change in the prism strength if rubber is substituted by steel in the bedding material. This is due to tensile stresses induced in steel restraining the lateral deformation of the bricks, which ultimately induces a state of tri axial compressive stress in the brick.

The effect of bed materials on brickwork was reported by Astbury and West (1969). According to the investigation it was shown that the brick work cube constituted with loose brick with flat bedding plane have compressive strength two times greater than those obtained from cube with normal mortar joints Francis et al. (1971) reported a similar effect in relation to brick work prism.

B. Failure of Brick Masonry based on Elastic Theory

Based upon the elastic analysis a number of attempts have been made in order to derive formulae for masonry strength in compression. The earliest attempt was made by Haller in the year 1959. But on the basis of results, the formulae proposed by Haller, the values of brickwork strength were found to be greater than uniaxial strength of brick and thus not valid in quantitative sense.

The elastic behavior of brick work was also examined by Francis et.al (1971) and Lanczner (1972). Conventional Masonry is a heterogeneous, inelastic and anisotropic material consists of brick unit and binding material called mortar. The characteristic properties (stiffness, strength and ductility) of both the materials are different. Brick units are considered as an elastic brittle material in nature having compressive strength as well tensile strength about one tenth of its compressive strength. Whereas mortar is considered as elastic brittle material showing larger deformation with respect to brick unit due to lower young's modulus. Further when the masonry is subjected to an external loading the distribution of stresses and strains at the interface of the masonry becomes complex due to the composite nature of masonry.

The tendency of mortar to expand laterally due to its lower young modulus is being restricted by the bonding and frictional forces developed at the interface between masonry units and mortar. This platen effect induces shear stresses at the interface. Ultimately the mortar undergoes tri axial compression and the masonry units undergo biaxial tension coupled with vertical compression as shown in fig.1. This causes failure of masonry parallel to the axis of loading.

Due to this phenomenon the strength of masonry unit is much more than strength of masonry in compression.

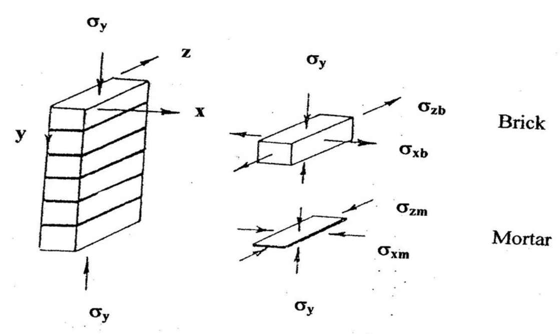

Fig.1. Stresses in brick-mortar composite

C. Empirical Studies on the Compressive Strength of Brick Work

A series of experimental investigations have been done for the determination of parameters contributing the strength of brickwork. The basic parameters are brick strength and mortar strength, which have significant contribution in the determination of the strength of brickwork. Codes of practice on the brick strength and mortar strength were solely based upon the earlier studies carried out by different researchers. A well-known example of such work is reported by Thomas (1953) and the summary of which has been reflected in fig. 2.below.

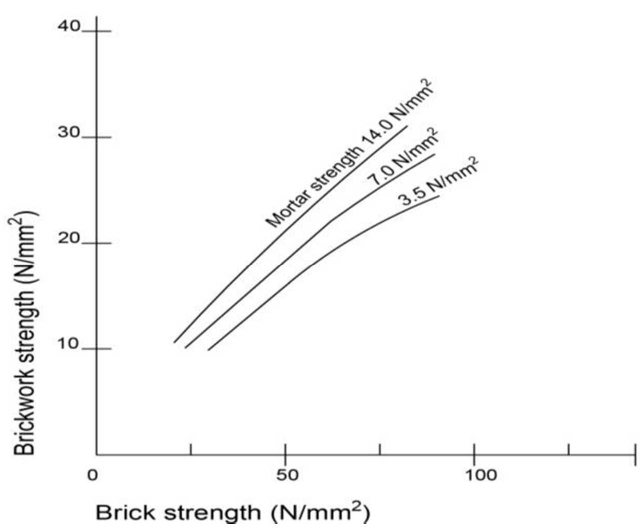

Fig.2. Crushing strength of brick work wall and piers (Thomas 1953)

D. Effect of Brick Work Bond on the Strength of Masonry

Many test results show that the type of bond used in a particular type of wall has very insignificant role to play on the masonry strength (Sinha and Hendry, 1968) but few test results on wall made up with stretcher bond with two leaves without having header gives lower strength than normally bonded brick work of same material (Prod. Tech. Bur. London. 1968)

E. The Strength and Deformation properties of Brick Work in Compression

In order to understand the stress-strain relationship and to determine young modulus of brickwork for the purpose of structural design several measurements were made on walls and piers. The same was determined by Powell and Hodgkinson (1976). The four types of brickwork using four different types of brick in each case were loaded in compression up till failure under suitable load controlling technique. The results so obtained was summarized in following table 3

Table 3: Compressive Strength of different types of brick and brick Work

Brick type	Brick compressive strength (N/mm^2)	Brick work compressive strength (N/mm^2)
A-16 hole perforated	69.6	19.93
B-Class A, Blue engineering	71.1	27.65
C-Fletton	25.5	9.33
D-Double frogged stiff plastic	45.3	20.10

On plotting curves between stress and strain it was observed that there was variation in results between the specimens of the same material but on the other hand a fair consistency was also observed between the specimens. It was noted that all the four curves are of the same form for practical purposes.

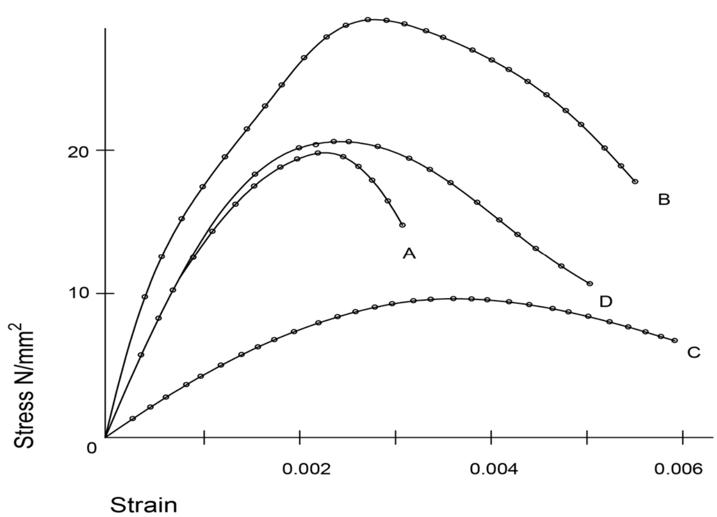

Fig. 3. Stress-strain curve for brick work in 1:0.25:3 (Powell and Hodgkinson) in compression

F. The Strength and Deformation of Brick Work in Shear

In actual practice brick masonry also subjected to racking shear due to lateral loads like earthquake and wind load in addition to compressive load. In order to determine the shear resistance of brick work, a series of tests were carried out in a no. of countries both on model and full scale specimens. The outcome of tests conducted on story height shear wall on full scale brick work and model specimen brick work consisting wire cut bricks in 1:0.25:3 as reported by Hendry and Sinha (1971) has been shown vide fig. 4 below.

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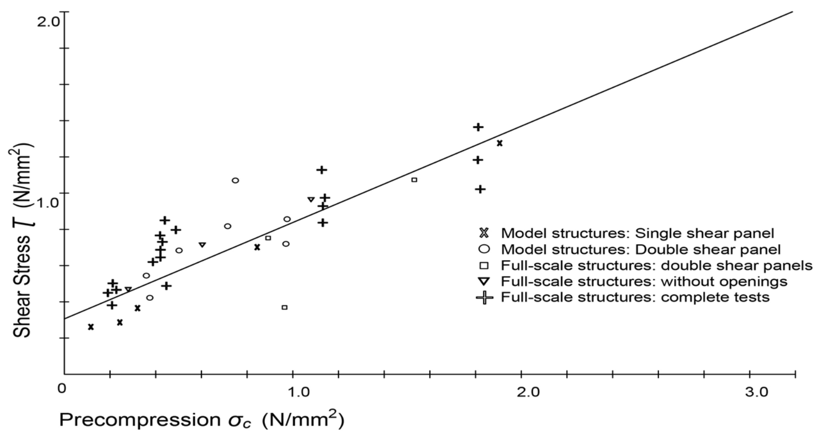

Fig. 4 Shear strength against pre compression: results of full scale, model and small specimen tests

The same type of test was also conducted by Pieper and Trautsch (1971), Chinwah (1972) and by Schneider (1976). Based upon the results obtained the following expression was proposed

$\tau = \tau_0 + f\,\sigma_c$ N/sq. mm; constant τ_0 depends upon properties of the material used.

The test results as obtained above has been tabulated in table 4 below Variation of shear strength and pre compression in brick work consisting different types of bricks as proposed by different researchers

Table 4 Variation of shear strength and pre compression

Source	Type of brick	Mortar	τ_0	f
Hendry and Sinha	Wire cut clay	1:0.25:3	0.30	0.50
Chinwah	Wire cut clay	1:0.25:3	0.25	0.34
Pieper and Trautsch	Solid sand lime Solid sand lime	1:2:8 1:0:4	0.20 0.70	0.84 1.04
Schneider	Calcium silicate	1:1:6	0.14	0.30

G. The Strength of Brick Work in Tension

As the tensile strength of brick work is comparatively very small, it is seldom considered in the code of practice for the design of brickwork but the same becomes significant in the design when brick panel is loaded laterally. Tensile stresses developed in the brickwork due to in plane/out of plane bending. In case when there is in plane stress, tension is developed across the bed joint of the brickwork and its magnitude depends upon the bond between brick and mortar.

The relationship between moisture content of brick at the time of laying and bond tension as given by Sinha is shown inthe following fig.5

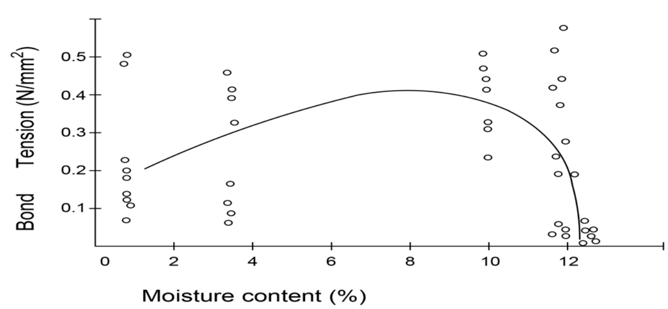

Fig.5 Relationship between moisture content of brick and bond tension of brick masonry couplets (Sinha)

From the above fig it is clear that there is no clear relationship between moisture content and tensile bond strength. Very low values are found as the bricks approached their saturated moisture content. Flexural tensile strength as defined in terms of modulus of rupture has more significant role than direct tensile strength for all practical purposes. A no. of experiments has been carried out on wall panels subjected to wind load in order to determine the flexural tensile strength of brick work. It is obvious that the flexural stress developed in wall panel due to the bending at right angle to the bed joint is many times greater than the flexural stress developed parallel to the bed joint. The ratio is not found constant and varies with the strength achieved as reported by many researchers.

H. Behavior of Concrete and Masonry under Cyclic Loading

Behavior of brick masonry under cyclic loading becomes more significant in the design of brick structure where there is reduction in compressive stress due to fluctuating live load occurs. It affects the material ductility, stiffness, degradation and energy dissipation characteristics which ultimately caused by the imposed deformation, no. of cycles and the level of loading which the material is subjected to.

The study reveals that cyclic stress-strain history possesses locus of envelope curve, locus of common point curve and locus of stability point curve. All the three fundamental curves have great contribution in designing brickwork structures. The repeated cyclic load causes accumulation of plastic strain in the material which ultimately responsible for determining the value of allowable stress in the material where there is reduction in compressive strength due to fluctuation in the live load.

II. SUMMARY AND CONCLUSIONS

This chapter contains the review of literature pertaining to the present study carried out. The review includes the behavior of Rat-Trap bonded brick masonry and it's uses in the present scenario, in plane/out of plane behavior of brick masonry, failure of conventional brick masonry under compression and the effect of different bed materials on the compressive strength of brick masonry. The review also includes the explanation of failure theory of brick masonry based upon elastic analysis. In the present chapter, the outcome of empirical studies on the strength of brick masonry along with the factors affecting the same as carried out by different researchers have been reported. In addition, the strength of brick masonry in shear as well in tension has been discussed in context with the earlier investigations.

Behavior of concrete and masonry under cyclic loading and their importance in designing the brick structure has also been outlined in this chapter.

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