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# Influence of normal stress on the flexural and shear strength of masonry – an experimental investigation

Mangala Keshava*, ✉ S. Raghunath*, P. Vivek* and K.S. Jagadish**

✉ Email: mangala_k@hotmail.com

*Department of Civil Engineering, BMS College of Engineering, Bangalore - 560 019, India.

**Department of Civil Engineering, RV College of Engineering, Bangalore - 560 058, India.

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In India, un-reinforced masonry walls are often used as the main structural component of load bearing structure and are responsible for carrying the vertical and lateral loads. These loads cause flexure and shear combined with compression within the masonry wall. The compressive strength of the walls subjected to axial loads primarily depends on the compressive strengths of the brick/ block unit and mortar and also the interaction between the two. Tests on full-scale walls have indicated that, walls subjected to eccentric loads, have failed through the development of horizontal flexural cracks. This is true even for slender walls subjected to axial loads. However, thick walls subjected to axial loads tend to fail by developing shear and/or vertical tensile cracks. It is thus apparent that flexural strength and shear strength also play a significant role in governing the load carrying capacity of walls. Walls supporting unequal slab spans, walls subjected to lateral loads during an earthquake, masonry domes, vaults and arches are a few examples of masonry subjected to flexure and shear.

The flexural strength of masonry is very low when compared to its compressive strength mainly because it is governed by the interface bond strength. Flexural bond strength may be used as a measure of bonding between two masonry materials viz. block/brick and mortar. The code of practice BS 5628-1992[1] describes the testing of small brick/block specimens (wallettes) under four-point loading as a standard test for determination of the flexural bond strength of masonry bed joints. The test provides an index of wall strength derived from its flexural performance.

Apart from the method prescribed in BS 5628-1992[1], there are several other methods of determining the flexural bond strength of masonry. These include the modified bond wrench test[2], direct pull tests, crossed couplet test and bending test on z-shaped configuration specimens[3] under three point bending. Each of these methods has certain advantages and limitations.

While several investigations on flexural and shear-bond strengths of brick masonry have been carried out in western countries, such investigations in Indian conditions are scanty. Attempts have been made to establish a relationship between the material properties and its flexural strength. Sarangapani[2] has obtained the flexural bond strength of masonry by testing stack-bonded prisms using a modified bond wrench test set-up. Sarangapani *et al*[4] determined the flexural strength of stack bonded brick prism using a modified bond wrench test using different mortar types. Here the flexural strength reported is in the range of 0.088 MPa to 0.128 MPa. Raghunath[5] has reported the flexural bond strengths of prisms made of table moulded bricks with CM 1:6 as 0.088 MPa, while that for a half-brick masonry wallette tested normal-to-bed-joints was 0.137 MPa and parallel-to-bed-joints was 0.36 MPa.

Lateral loads in a masonry building are often resisted by walls in the plane of the applied load i.e shear walls. Such walls should be designed so as to limit the shear stresses within the permissible values of shear stress. The permissible shear stress is in turn dependent on the compressive stress (normal stress). A masonry shear wall subjected to lateral in-plane loads may fail in any one of the three ways, viz. sliding failure, flexural failure or diagonal shear failure. A combination of the failure modes may also occur. The shear capacity of masonry mainly depends on its shear-bond strength, which is the shear strength of a typical brick/block-mortar interface. This is often obtained by the well known triplet test. To determine the shear strength of masonry walls, several types of experiments such as the shear-bond strength[6], off-axis compression test[7], in-plane tensile strength[8] and the racking tests[9] can be considered.

Well known methods to determine the shear strength of masonry have been discussed by Hendry[6]. Some have been reviewed by Riddington and Naom[10]. Sarangapani[2] has discussed the shear strengths developed by brick masonry using a modified brick triplet test.

Unreinforced brick/block masonry construction is a commonly adopted choice for construction of low rise buildings in India. On the other hand, from the literature review, it can be seen that publications on the flexural and shear strengths of brick masonry in India is scanty. In the present investigation, the focus was to understand the influence of normal stress on the flexural and shear strengths of brick/block masonry.

## PRESENT INVESTIGATION

Tests on masonry wallettes are frequently undertaken for establishing the mechanical properties of masonry. These properties include compression, shear, tension and flexural strengths which are determined by carrying out tests on masonry wallettes. Tests were carried out on two types of masonry materials namely the locally available table moulded bricks and solid concrete blocks from Bengaluru. The following are the objectives of the study;

(i) Influence of normal stress on the flexural behavior of half-brick thick masonry wallettes
(ii) Influence of normal stress on the flexural behavior of one-brick thick masonry wallettes
(iii) Influence of normal stress on the flexural behavior of 150 mm thick stack bonded concrete block masonry prism
(iv) Influence of normal stress on the shear strength of brick masonry triplets
(v) Influence of normal stress on the shear strength of concrete block masonry triplets

In the present study, the flexure test method prescribed in BS 5628-1992[1] has been adopted. The lateral flexural load was applied while the specimens were subjected to normal stress. Variation of normal stress was a parameter in the study.

The present study also focused on the triplet test as mentioned by Hendry[6]. This was carried out on the brick and block masonry specimens. The triplets were subjected to normal stress along the direction normal-to-bed-joints and sheared along the bed-joints.

Tests to determine the flexural strength and shear strength of masonry were carried out on a rigid loading frame of 2000.0 kN capacity. Accessories such as the jacks, proving rings and props were used to make all the necessary measurements required for testing the specimens.

### Basic Tests on masonry and its constituents

Several tests were carried out to understand the strength and elastic properties of masonry and its constituents used in the present investigation. Tests such as the dimensionality test as per IS 1077-1992[11], water absorption as per IS 3495-1992[12] and initial rate of absorption as per ASTM 62-10[13] were conducted on table moulded brick specimens. Also, structural properties such as the compressive strength as per IS 3495-1992[12], flexural strength[14] and modulus of elasticity[2] of bricks, were evaluated. Mortar mix of 1:6 was used to prepare the masonry specimens. Representative mortar cubes were tested to determine its compressive strength as per IS 2250-1981[15]. Flexural strength was evaluated by testing mortar bars as per IS 10078-1982[16]. Also, mortar briquettes were tested to evaluate the direct tensile strength as per ASTM C 109-08[17]. Basic tests on solid concrete blocks were carried out to determine its dry density, water absorption, initial rate of absorption, compressive strength, flexural strength and modulus of elasticity, similar to that of bricks. Brick masonry prisms were cast to evaluate its compressive strength normal-to-bed joints and parallel-to-bed joints[5]. Also, modulus of elasticity was evaluated along the two above mentioned directions[5]. The number of samples tested and the test results obtained have been presented in Table-1.

### Flexural tensile strength test

The main objective of the test was to evaluate the flexural strength of masonry as per BS 5628-1992[1]. Three types of masonry prisms were cast such that the span length was greater than twice the width of the specimen. The first was the half-brick thick masonry prism of dimension (lxbxh) 350 × 105 × 750 mm (tested normal-to-bed joints) and 335 × 105 × 725 mm (tested parallel-to-bed joints). The second was of one-brick-thick masonry prism of dimension 350 × 230 × 750 mm and third, the solid concrete block masonry prism of dimension 400 × 150 × 840 mm. Four levels of normal stress were applied on the specimens. The normal stress levels applied included 0.025MPa, 0.125 MPa, 0.2 MPa, 0.4 MPa and 0.5 MPa for brick and concrete block specimens tested normal-to-bed joints. Brick specimens tested parallel-to-bed joints were subjected to only one normal stress level of 0.025 MPa. All the specimens were tested under hinged-hinged boundary condition. It is to be noted that hinged-hinged boundary condition was simulated by using carefully designed and fabricated boundary elements. The rate of loading was maintained at a very low rate of 0.5kN/min.

A schematic diagram showing the details of the test set-up for flexure is given in Fig. 1. The entire assembly of the test set-up along with a one-brick thick masonry wallette is indicated in the Fig. 2. An average mortar joint of 13mm was maintained. The specimens were tested till failure. The results of the flexural strength tests have been tabulated in Table 2 and Table 3.

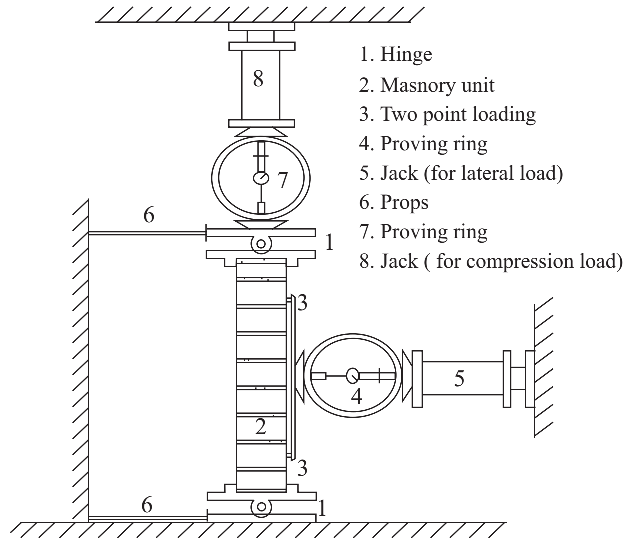



Fig. 1 Schematic digram showing details of the test setup for flexure

TABLE-1

TEST RESULTS OF THE BASIC PROPERTIES OF MASONRY AND ITS CONSTITUENTS

| Sl.No | SpecimenType<br>Dimensions of the specimens ( mm) | Test conducted<br>(No. of specimens tested) | Result obtained | C O V<br>( % ) |
|---|---|---|---|---|
| 1 | Table moulded brick (226×105×75) | Dimensionality test (20) | 226 × 105 × 75 (mm) | -- |
| | | Water Absorption(06) | 15.80 % | 3.33 |
| | | Initial Rate of Absorption(06) | 3.82 Kg/m$^2$/min | 6.62 |
| | | Compressive Strength(06) | 8.80 MPa | 4.38 |
| | | Flexural Strength (06) | 0.37 MPa | 20.46 |
| | | Modulus of Elasticity (06) | 520.1 MPa | -- |
| 2 | Mortar cubes 70.6 × 70.6×70.6 Mortar bars 160×40×40 Mortar Briquette 25.4×25.4 | Compressive strength<br>Flexural strength<br>Direct Tensile strength | 5.88 MPa<br>2.19 MPa<br>0.6 MPa | 3.06<br>11.50<br>15.19 |
| 3 | Stack bonded Brick Masonry Prisms 230×105×335 (b × t × h) | Compressive strength (Normal-to-bed joints)<br>Modulus of elasticity (Normal-to-bed joints) | 1.41MPa<br>385.0 MPa | 21.47<br>-- |
| 4 | Brick Masonry Prisms 246×105×465 (b × t × h) | Compressive strength (parallel-to-bed joints)<br>Modululs of elasticity (Parallel-to-bed joints) | 0.873 MPa<br>1171.0 MPa | 42.62<br>-- |
| 5 | Solid Concrete Blocks 200×150×400 | Dry Density | 2.09 g/cc | 2.26 |
| | | Compressive Strength | 3.45 MPa | 7.49 |
| | | Water Absorption | 7.23 % | 5.71 |
| | | Initial Rate of Absorption | 2.58kg/m$^2$/min | 24.64 |
| | | Modulus of Elasticity | 4390.0 MPa | -- |
| | | Flexural Strength | 1.01 MPa | 3.1 |

Fig. 2 Flexure test set up with the brick masonry wallette specimen

| TABLE 2<br>LATERAL LOAD AT FAILURE OF BRICK AND SOLID CONCRETE BLOCK MASONRY (NORMAL-TO-BED JOINTS) | | | |
|---|---|---|---|
| Applied Normal Stress (MPa) | Lateral load (N) at failure of Half-brick masonry Wallette | Lateral load (N) at failure of One-brick masonry Wallette | Lateral load (N) at failure of 150mm Solid concrete block masonry Prism |
| 0.025 | 834.0 | -- | -- |
| | 834.0 | -- | -- |
| | 834.0 | -- | -- |
| | 834.0 | -- | -- |
| 0.125 | 1422.0 | 4414.50 | 2280.83 |
| | 1619.0 | 4537.13 | 2354.40 |
| | 1521.0 | 4537.13 | 2354.40 |
| | 1619.0 | 4684.28 | 2305.35 |
| 0.2 | 2502.0 | 5223.83 | 2697.75 |
| | 2207.0 | 5518.13 | 2820.38 |
| | 2256.0 | 5420.03 | 2943.00 |
| | 2502.0 | 5591.70 | 2820.38 |
| 0.4 | 3924.0 | 10055.25 | 4659.75 |
| | 3581.0 | 9859.05 | 4757.85 |
| | 3777.0 | 9760.95 | 4537.13 |
| | 3924.0 | 9908.10 | 4537.13 |
| 0.5 | 4366.0 | 12924.68 | 6057.68 |
| | 4464.0 | 13120.88 | 5861.48 |
| | 4610.7 | 12998.25 | 6278.40 |
| | 4464.0 | 12802.05 | 5861.48 |

**Shear strength test**

The shear strength of masonry was evaluated by conducting tests on brick and block triplets subjected to varying normal stress levels. It may be noted that triplet shear test induces double shear failure.

| TABLE 3<br>LATERAL LOAD AT FAILURE OF BRICK MASONRY (PARALLEL-TO-BED JOINTS) | |
|---|---|
| Applied Normal Stress (MPa) | Lateral load (N) at failure of Half-brick masonry Wallette |
| 0.025 | 2599.65 |
| | 2648.70 |
| | 2795.85 |
| | 2452.50 |

The triplets were cast such that the middle unit was projecting higher than the adjacent units by 15mm. The schematic diagram of the shear test set up is indicated in Fig. 3.The test set up for a typical brick specimen and block specimen are shown in Fig. 4 and Fig. 5. For each normal stress level, 4 specimens were tested under the loading frame. A cement-sand mortar mix of proportion 1:6 and thickness of 13mm was maintained. For each level of normal stress, the shear load was applied until failure of the specimen. The results of the shear test are presented in Table 4.

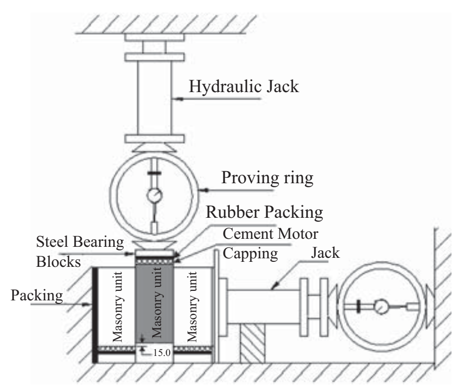



Fig. 3 Schematic diagram of the shear test set up

## RESULTS AND DISCUSSIONS

**Flexure Behaviour**

All the specimens tested under flexure, failed by the propagation of the initial development of horizontal flexural cracks at or near the mid-span. The subsequent horizontal flexural cracks were noticed at the adjacent bed joints. The eventual failure was by development of the cracks over the entire depth of the specimen. None of the specimens failed 'suddenly', which is usually noticed in modified bond wrench test[2]. It is thus apparent that the presence of normal stress does indeed impart some amount of stability to the cracked specimens, without allowing them to open up suddenly. This post cracking phase was significantly noticed in all the specimens. Typical specimens after failure are shown in Figs. 6 to 8 respectively.

TABLE 4

SHEAR LOAD AT FAILURE OF BRICK AND SOLID CONCRETE BLOCK TRIPLETS

| Applied Normal Stress (MPa) | Shear load (N) at failure of Table moulded brick triplet | Shear load (N) at failure of Solid concrete block triplet |
|---|---|---|
| 0.025 | 2562.50 | -- |
| | 3053.00 | -- |
| | 2856.80 | -- |
| | 3053.00 | -- |
| 0.125 | 4034.00 | 41692.50 |
| | 4181.15 | 25203.75 |
| | 4151.15 | 31882.50 |
| | 3935.90 | 30607.20 |
| 0.2 | 6977.00 | 61999.20 |
| | 7124.15 | 91429.20 |
| | 6878.90 | 77106.60 |
| | 6977.00 | 78970.50 |
| 0.4 | 12373.50 | 80442.00 |
| | 13010.15 | 118308.60 |
| | 13353.50 | 131061.60 |
| | 12372.50 | 126058.50 |
| 0.5 | 17866.10 | 136849.50 |
| | 17669.90 | 150289.20 |
| | 17866.10 | 145874.70 |
| | 17473.70 | 122428.80 |

A plot of normal stress versus flexural strength clearly indicates that the flexural strength increases as the normal stress increases. The benefits of postponing the brittle mode of failure can be clearly noticed.

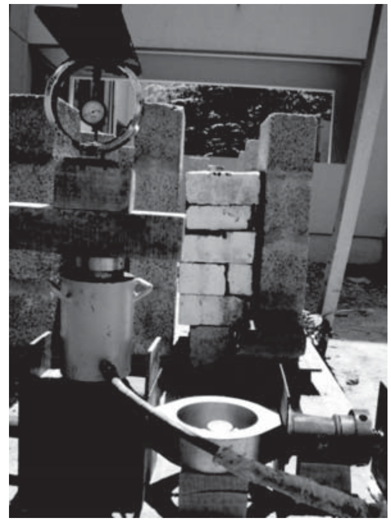


Fig. 4 Shear test set up for the brick triplet

Fig. 5 Shear test set up for the concrete block triplet

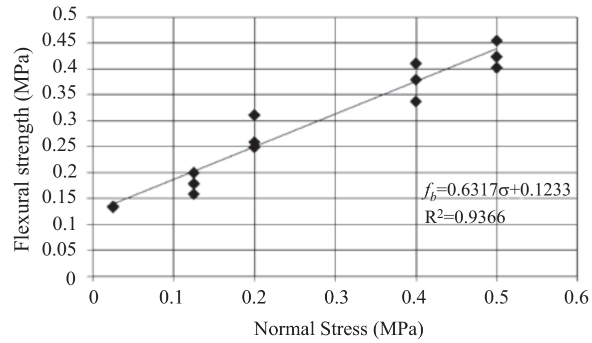
Fig. 6 Observed failure pattern of the half-brick thick masonry wallette


Fig. 7 Observed failure pattern of the one-brick thick masonry wallette

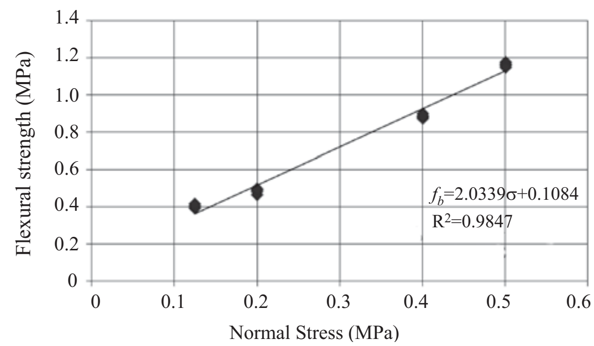
Fig. 8 Observed failure pattern of the concrete block masonry prism

Figure 9 shows the influence of normal stress on flexural strength of half-brick thick and one-brick thick masonry wallette respectively. For the computation of the flexural strength, moments were obtained by beam-column equation. For the half-brick specimens the relationship between flexural strength and normal stress is $f_b = 0.632\ \sigma + 0.123$ (in MPa), while for the one-brick specimen the relationship is $f_b = 2.034\ \sigma + 0.108$ (in MPa). It can be noticed that a linear fit appears to be appropriate. It can be noticed that the influence of normal stress on flexural strength is more predominant for one-brick thick wallettes.

Similarly Fig-10 shows the influence of normal stress on the flexural strength of solid concrete block prisms. Here also, the influence of normal stress is quite significant. The relationship between the flexural strength and the normal stress obtained is $f_b = 2.117\ \sigma + 0.211$ (in MPa).




(a)




(b)

Fig. 9 Flexural strength vs Normal Stress of (a) half-brick-thick wallette; (b) One-brick-thick wallette

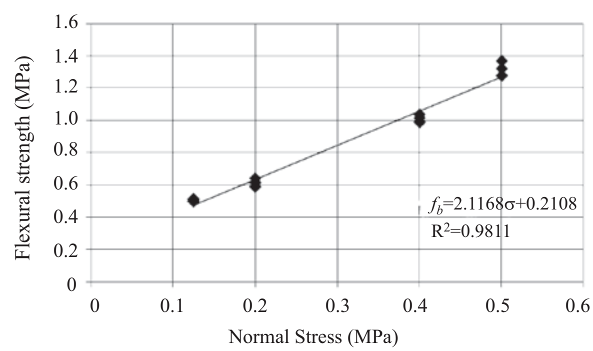



Fig.10 Flexural Strength vs Normal Stress of solid concrete block prism

**Shear Behaviour**

All the triplets, expectedly, failed at the brick/block–interface, especially the interface without frog in case of brick triplets, similarly in the case of concrete block specimens, one of the inter face got separated. Shear failure of either mortar or bricks/blocks were never noticed in any of the specimens, thus clearly indicating the relatively high shear strength of bricks/blocks and mortars compared to that of their interface. The failure was typically brittle in nature. The presence of normal stress did not alter the failure pattern. The respective specimens after failure are shown in Fig-11 and Fig-12.

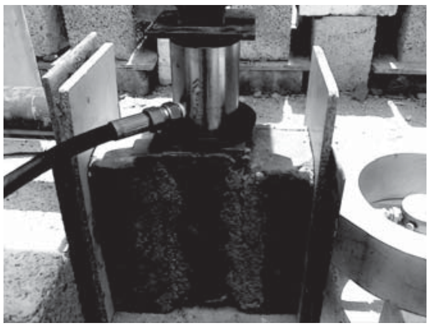


Fig.11 Observed failure Pattern of the brick triplet

Fig.12 Observed failure Pattern of the concrete block triplet

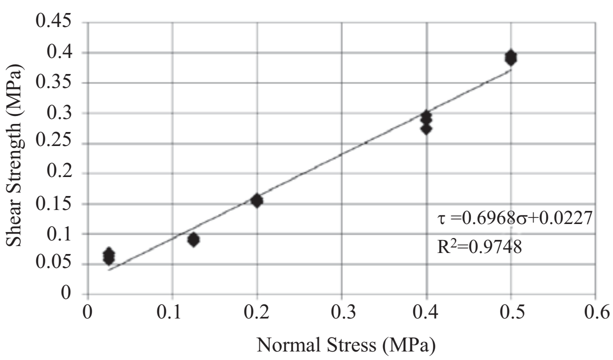



Fig.13 Shear Strength vs Normal Stress of brick masonry triplets

The relationship between the shear strength and normal stress for the two types of specimens tested is $\tau = 0.697\,\sigma + 0.023$ (in MPa) for brick masonry triplet, as shown in Fig-13, while for concrete block masonry triplet it is $\tau = 2.22\,\sigma + 0.099$ (in MPa) as shown in Fig.14. It is thus apparent that the concrete block masonry is far more superior in resisting shear. Perhaps this may be due to the rough texture of the blocks. It is now important to compare this with the relation given in IS: 1905-1987[18] which is $\tau = 0.166\,\sigma + 0.1$ (in MPa), subject to a maximum of 0.5MPa.

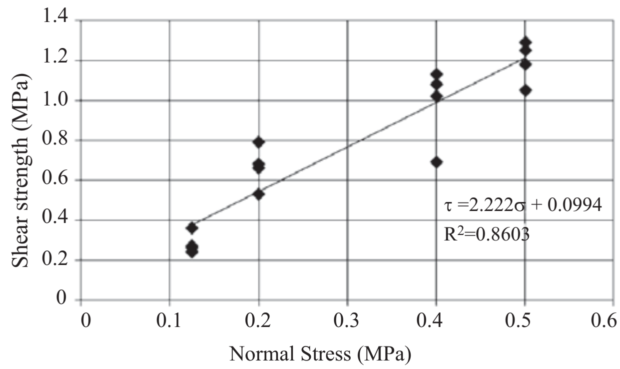



Fig.14 Shear Strength vs Normal Stress of solid concrete block masonry triplets

## CONCLUSIONS

When the masonry walls are subjected to lateral loads, they tend to develop flexural stresses due to out-of-plane bending and significant shear stresses due to in-plane shear. A stress analysis of any masonry building to identify the nature and magnitude of the stresses is crucially dependent on properties such as the modulus of elasticity. Also, if the failure pattern of the wall has to be understood, these stresses have to be compared with the corresponding strengths. Generally, load bearing masonry in India is restricted to about 3 storeys in height. A critical wall in such a structure supporting a moderate span of 4.0m slab would develop a normal stress of about 0.5 MPa at the base. Such a wall, when subjected to lateral in-plane and out-of-plane loads, tends to develop flexural and shear stresses. Therefore the flexural and shear strength have to be obtained in the presence of such normal stresses. The results of the present investigation clearly indicate the influence of normal stress on the flexural and shear strength of masonry.

The flexural strength of half-brick masonry wallettes was found to be $f_b = 0.632\,\sigma + 0.123$ (in MPa), while for the one-brick masonry wallettes the relation was found to be $f_b = 2.034\,\sigma + 0.1084$ (in MPa). It is thus clear that the vertical mortar joint in one-brick thick masonry enhances the flexural strength with increasing normal stress. However, at zero normal stress the flexural strengths are comparable. It is also interesting to note the relationship in case of concrete block masonry which was found to be $f_b = 2.117\ \sigma + 0.211$(in MPa). It is thus clear the concrete block masonry possesses higher flexural strength both at zero normal stress and in the presence of normal stress.

The relationship between shear strength and normal stress for brick and block triplets were found to be $\tau = 0.697\sigma + 0.023$ (in MPa) and $\tau = 2.22\ \sigma + 0.099$ (in MPa). It is again clear that block work masonry is superior when compared to burnt brick masonry.

The relatively better performance of massive masonry buildings in comparison with light masonry buildings during the Bhuj earthquake is indicated by Jagadish[19]. The influence of normal stress on the flexural and shear behavior explains the better performance of such massive masonry buildings during earthquakes. However, while designing a wall of a single storey building or a free standing wall, the normal stress need not be considered. For such walls the flexural and shear strength in the absence of the normal stress dictates the design criteria.

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