



Experimental Investigations on Axially and Eccentrically Loaded Masonry Walls

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Abstract In India, un-reinforced masonry walls are often used as main structural components in load bearing structures. Indian code on masonry accounts the reduction in strength of walls by using stress reduction factors in its design philosophy. This code was introduced in 1987 and reaffirmed in 1995. The present study investigates the use of these factors for south Indian masonry. Also, with the gaining popularity in block work construction, the aim of this study was to find out the suitability of these factors given in the Indian code to block work masonry. Normally, the load carrying capacity of masonry walls can be assessed in three ways, namely, (1) tests on masonry constituents, (2) tests on masonry prisms and (3) tests on full-scale wall specimens. Tests on bricks/blocks, cement-sand mortar, brick/block masonry prisms and 14 full-scale brick/block masonry walls formed the experimental investigation. The behavior of the walls was investigated under varying slenderness and eccentricity ratios. Hollow concrete blocks normally used as in-fill masonry can be considered as load bearing elements as its load carrying capacity was found to be high when compared to conventional brick masonry. Higher slenderness and eccentricity ratios drastically reduced the strength capacity of south Indian brick masonry walls. The reduction in strength due to slenderness and eccentricity is presented in the form of stress reduction factors in the Indian code. These factors obtained through experiments on eccentrically loaded brick masonry walls was lower while that of brick/block masonry under axial loads was higher than the values indicated in

the Indian code. Also the reduction in strength is different for brick and block work masonry thus indicating the need for separate stress reduction factors for these two masonry materials.

Keywords Brick/concrete block masonry · Axial/eccentric loads · Stress reduction factor

Introduction

Masonry predates history, at the same time continues to be a unique form of construction currently. Two to three storeyed structures are constructed using brick/block masonry due to certain inherent advantages as compared to framed structures. The boom in new building materials followed by the mechanization in its production has enlarged the field of production of masonry units. In addition to stones and bricks, usage of hollow/solid concrete blocks and soil stabilized blocks have become popular forms of masonry construction in south India.

The behavior of masonry is influenced by the properties of its constituent materials such as the masonry units and mortar. It is reported that the table moulded bricks found in South India possess very low strength in the range of 3.0–8.0 MPa (Gumaste 2004) which is mainly due to inefficient burning of bricks in kilns commonly found in semi-urban and rural areas. As a result of this, masonry construction is restricted to two/three storeys only. On the other hand use of solid and hollow concrete block masonry construction is gaining popularity as it has an advantage of being produced with desired strengths using cement in its mix proportion.

There are several factors which affect the compressive strength of masonry and these in turn affect the load

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carrying capacity of walls [1]. Among them the slenderness of the wall, the eccentricity of applied load and the basic strength and elastic property play a crucial role.

While there are a number of reports on the strength and elastic properties of typical south Indian masonry [2–4], the studies on full-scale walls are quite limited. Few experiments on brick masonry wall specimens were conducted by [3, 4] under axial and eccentric loads. Half-brick masonry walls of slenderness ratio 22.42 tested axially exhibited wall strength of 1.08 MPa, while one-brick masonry wall of Slenderness ratio 10.24 showed strength of 1.32 MPa. Both the walls exhibited typical failure patterns characteristic of axially loaded walls. Three brick walls of slenderness ratio 13.4 and an eccentricity ratio of 0.4 were tested by [3]. The wall strengths observed were 0.45, 0.44 and 0.36 MPa. These walls were not provided with lateral restraints on the top and it is reported that a brittle failure was observed in all the three walls.

The present investigation focused on three levels of testing. Two masonry materials (table moulded bricks and concrete blocks) locally available were taken up for the study. In the first level, determination of compressive strength and modulus of elasticity of both the masonry

units and mortar was done in a Universal Testing Machine as per the available Indian Standards. The second level of investigation was on small masonry specimens and subjected to uniaxial compression in an UTM. The third level included full-scale brick/block wall specimens subjected to compression and were tested in a loading frame. Fourteen walls were tested. Eight walls made up of brick/block were subjected to axial load, while six brick walls were subjected to eccentric loads. The load carrying capacity of walls was recorded and the reduction in strength observed is presented in the form of stress reduction factors. These reduction factors have further been compared with that presented in the Indian code. The following are the objectives identified in this study;

- To determine the load carrying capacity of brick masonry wall specimens under axial/eccentric loading.
- To determine the load carrying capacity of concrete block (solid and hollow) masonry wall specimens under axial loading.
- To compare the Stress reduction factors of brick/block masonry walls obtained experimentally with IS: 1905-1987 codal provisions.

Table 1 Properties of constituent materials of masonry

Constituent material	Test conducted	Number of specimens tested	Test results	Coefficient of Variation (COV)
Table-moulded bricks	Dimensionality	30	L = 220–230 mm B = 105–108 mm H = 75–82 mm	–
	Dry density	30	1.74 g/cc	5.24%
	Water absorption	42	13.82%	14.99%
	Compressive Strength	42	5.85 MPa	35.13%
	Stress–strain Characteristics	20	E = 552.31 MPa R ² = 0.96	–
Solid concrete blocks of 150 mm thickness	Dimension	16	400 × 150 × 200	–
	Dry density	08	2.09 g/cc	2.20%
	Water absorption	16	5.38%	37.0%
	Compressive Strength	16	4.57 MPa	28.1%
	Stress–strain Characteristics	06	5120.1 MPa R ² = 0.94	–
Hollow concrete blocks of 150 mm thickness	Dimension	08	400 × 150 × 200	–
	Dry density	06	1.16 g/cc	1.57%
	Water absorption	06	5.33%	15.73%
	Compressive Strength	08	6.08 MPa	14.84%
	Stress–strain Characteristics	06	E = 5898.0 MPa R ² = 0.98	–
Cement-sand mortar of mix 1:6 with w/c of 1.2	Compressive Strength	48	9.42 MPa	20.97%
	Stress–strain Characteristics	03	1888.6 MPa R ² = 0.94	–

Methodology Adopted

Level-1: Tests on Constituent Materials of Masonry

Brick/block samples were randomly collected from in and around Bangalore city. These masonry units were tested to determine the dimensions (IS: 1077-1992), dry density, water absorption, compressive strength (IS: 3495-1992) and modulus of elasticity [2, 4]. The stress–strain behavior of bricks and blocks were determined by subjecting the units to a uni-axial compression load parallel to its length in a 600 kN UTM. Also, cement-sand mortar of mix 1:6 was tested to evaluate its compressive strength and modulus of elasticity using 70.6 mm size mortar cubes and mortar prisms of dimensions 300 mm × 150 mm × 150 mm (IS: 2250-1981). The test results of brick/block and mortar are presented in Table 1.

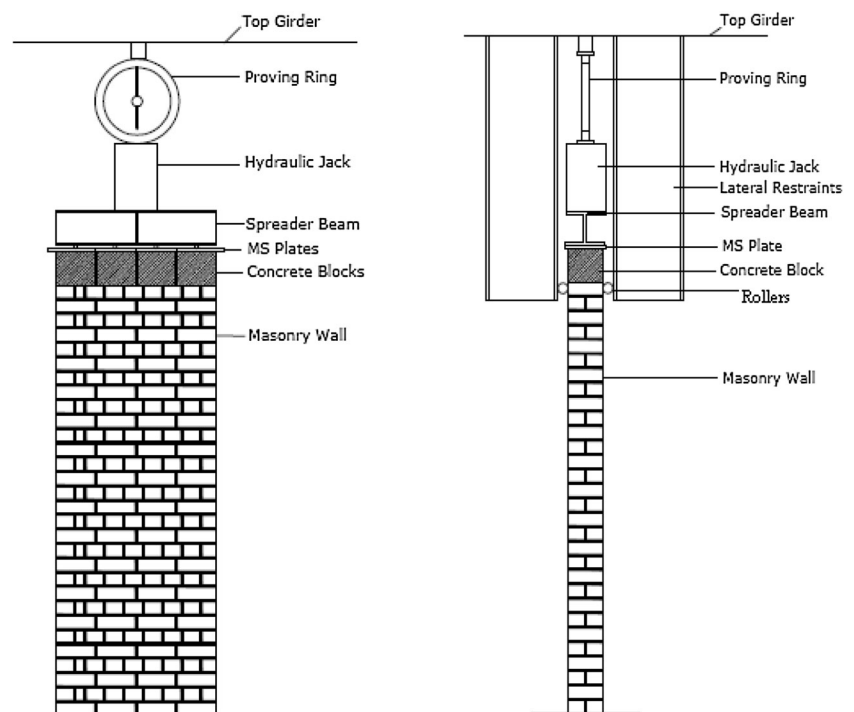
Level-2: Test on Small Specimens (Masonry Prisms)

Brick prisms and stack-bonded block masonry prisms were cast with a height to thickness ratio between 2 and 5 as per IS: 1905-1987 [5]. All the specimens were cured for 28 days and tested normal-to-bed-joints under uni-axial compression in a 600 kN UTM (IS: 1905-1987). For gradual increments of load the corresponding deformation was recorded with the help of a De-mountable strain gauge. After about 25 readings the gauge was removed and the specimen was subjected to ultimate load up to failure. The ultimate compressive strength was computed by applying suitable correction factors as presented in IS: 1905-1987. A graph of stress vs strain was plotted and the chord modulus was determined. The chord modulus of elasticity was taken between 0.05 and 0.33 of the maximum compressive strength [6] obtained from the prism test conducted on 6

Table 2 Compressive strength and modulus of elasticity of brick and block masonry prisms

Notation	Description	Dimensions, mm	Number of specimens tested	Corrected compressive strength (COV), MPa	Chord modulus, MPa
TMBP-230-N	230 mm thick table moulded brick prism (normal-to-bed-joints)	222 × 222 × 533	06	1.36 (17.72%)	E = 499.41 R ² = 0.95
SCBP-150-N	150 mm thick solid concrete block prism (normal-to-bed-joints)	400 × 150 × 648	06	5.01 (10.20%)	E = 5596.81 R ² = 0.99
HCBP-150-N	150 mm thick hollow concrete block prism (normal-to-bed-joints)	400 × 150 × 672	06	4.48 (3.53%)	E = 5868.22 R ² = 0.97

Fig. 1 Schematic diagram of an axially loaded masonry wall



specimens. The corrected compressive strength and chord modulus thus obtained have been presented in Table 2.

Level-3a: Tests on Full-Scale Wall Specimens Under Axial Load

Full-scale wall specimens were tested in a loading frame of capacity 2000 kN. The frame has a clear height of 3.5 m and a width of 3.0 m. To ensure a proper loading arrangement and boundary condition, the step-wise loading assembly and lateral restraints were provided during the testing operation. The loading assembly consisted of a proving ring, load spreading arrangements-an upper loading beam and lower loading beam (steel sections), MS plates and a rich mix of concrete bed spread over the entire width of the wall specimen. Partial restraint at the top of

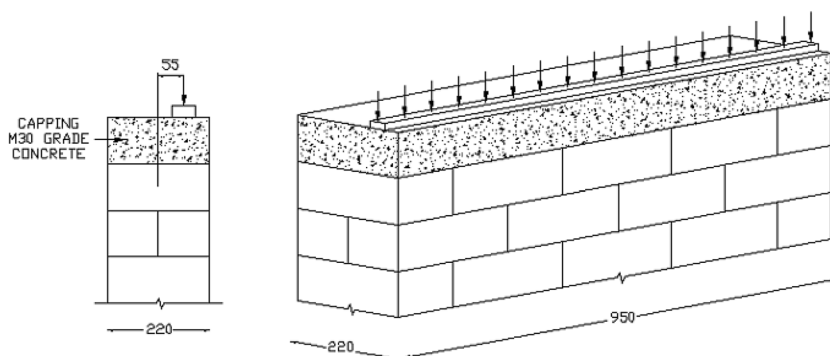
the wall specimen was provided with the help of lateral restraints (steel sections) which was provided with steel rollers. These arrested the out-of-plane movement of the wall while allowing compression and rotation (Fig. 1).

Full-scale walls made up of table moulded bricks, solid concrete blocks and hollow concrete blocks were tested under axial loads. Based on the criteria, that the width of a wall specimen should be a minimum of four times its thickness, the width of the walls was fixed. Brick walls were half-brick and one-brick in thickness, while the concrete block masonry wall was of 150 mm thickness. The effective height of the wall was assumed to be $0.85H$ (H being the actual height of the wall) for walls with lateral restraints and $1.5H$ for two walls where it was not provided. From this the slenderness ratio of the walls were computed.

Table 3 Details of test on full-scale walls

Wall no.	Notation	Description	Dimension (l × t × h), mm	SR	e/t
1	TMB-225-A-1	Axially loaded one-brick thick masonry, wall nos. 1, 2 3 and 4	950 × 225 × 1550	6.0	0
2	TMB-225-A-2		950 × 225 × 1550	6.0	0
3	TMB-230-A-3		1050 × 230 × 2430	15.85	0
4	TMB-220-A-4		950 × 220 × 2500	9.66	0
5	TMB-105-A-5	Axially loaded half-brick thick masonry, wall no. 5	1060 × 105 × 2440	19.75	0
6	SCB-150-A-6	Axially loaded 150 mm thick solid concrete block masonry, wall no. 6	1030 × 150 × 2560	14.51	0
7	HCB-150-A-7	Axially loaded 150 mm thick hollow concrete block masonry, wall nos. 7 and 8	830 × 150 × 2600	14.73	0
8	HCB-150-A-8		830 × 150 × 2600	14.73	0
9	TMB-225-E-9	Eccentrically loaded one-brick thick masonry, wall nos. 9,10 and 11	950 × 225 × 1550	6.0	1/4
10	TMB-225-E-10		950 × 225 × 1550	6.0	1/4
11	TMB-230-E-11		1050 × 230 × 2430	15.85	1/6
12	TMB-220-E-12	Eccentrically loaded one-brick thick masonry, wall nos. 12, 13 and 14	950 × 220 × 2500	9.66	1/4
13	TMB-220-E-13		950 × 220 × 2500	9.66	1/4
14	TMB-220-E-14		950 × 220 × 2500	9.66	1/4

Fig. 2 Schematic diagram of an eccentrically loaded masonry wall



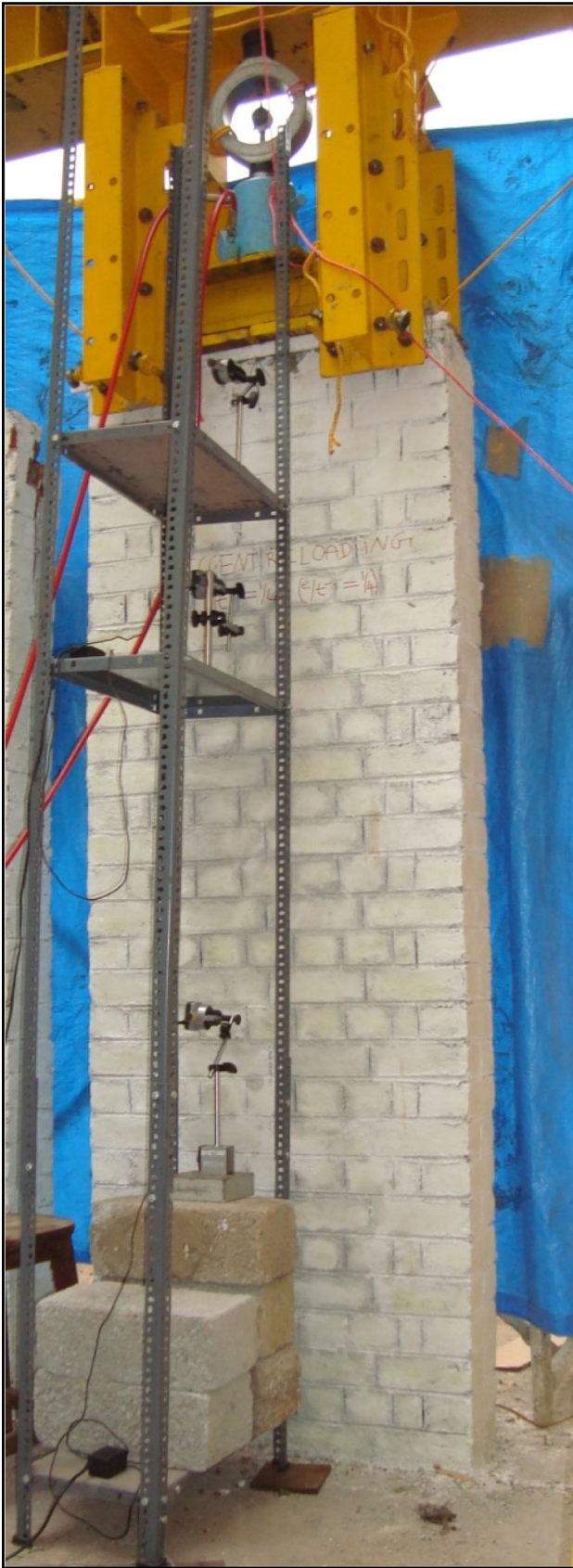


Fig. 3 TMB-220-A-4 (with lateral restraint)



Fig. 4 TMB-230-E-11 (without lateral restraint)

River sand passing through 2.36 mm sieve as specified in IS: 2116-1980 [7] was used to prepare the mortar along with 53 grade Ordinary Portland Cement. A mix of 1:6 and an average joint of 12 mm thickness was maintained throughout. The mean strength of the mortar used was 9.42 MPa. The bricks were pre-wetted for 15 min before laying and the wall was continuously cured for a period of 28 days. A fair face on one side of the wall was ensured. Dial gauges were mounted on one face of the wall at some heights, in order to monitor the lateral out-of-plane deflections that may arise due to any inherent eccentricities.

Masonry walls are subjected to variation in slenderness ratio and eccentricity ratio. Generally, the height of a masonry wall in a building is between 3.0 and 4.0 m with a wall thickness of 150–230 mm which translates into slenderness ratios ranging from 9.0 to 20.0. Two eccentricity ratios were adopted viz., 1/4 and 1/6. This is in the mid-range of ratios prescribed in IS: 1905-1987, which induce bending stresses in addition to compressive stress in

masonry. The details of the tests on full-scale walls have been indicated in Table 3.

The failure patterns observed were typical in all walls. Vertical cracks were observed in the upper two-third portion of the walls. With further increase in the load, the cracks progressed below the mid-height of the wall and several vertical cracks were observed dividing the wall into strips of masonry. Also, in case of one-brick thick masonry walls, vertical crack was observed which divided the thickness of the wall into two leaves.

Level-3b: Tests on Full-Scale Wall Specimens Under Eccentric Load

A schematic sketch of a typical eccentrically loaded wall is shown in Fig. 2. These walls were subjected to moment, induced due to eccentric loads. Six brick masonry walls were tested. Five walls were investigated for an eccentricity ratio of 1/4 and provided with lateral restraints. A projection made of rich cement mortar mix 1:2 of dimension 50 mm × 25 mm was cast along the entire length of the wall specimen at the designated eccentricity. The centre line of the loading coincided with that of the C.G. of the projection thus facilitating an eccentric load being applied in the form of an UDL on the wall specimen. The rest of the stair-case loading arrangement was same as in the case of tests carried out on axially loaded walls. These walls exhibited horizontal flexure cracks at the brick/mortar interface on the tensile face of the wall. Spalling of



Fig. 5 Typical vertical cracks in TMB-225-A-2



Fig. 6 Spalling in TMB-225-E-9 & TMB-225-E-10



◀ **Fig. 7** Vertical separation in TMB-230-A-3

masonry was noticed on the compression face. One wall was subjected to an e/t of $1/6$ ($e = 39.0$ mm), and was not provided with lateral restraint. This wall broke up into three pieces and collapsed at the ultimate load, thus exhibiting a brittle failure.

Behaviour of Axially Loaded and Eccentrically Loaded Masonry Walls—A Comparison

A typical masonry wall with lateral restraint and without lateral restraint is shown in Figs. 3 and 4. Figures 5, 6, 7, 8, 9, 10, and 11 indicate the behaviour of masonry brick/block walls under axial loads and brick walls under eccentric loads. Figure 5 and 6 bring out the behaviour of brick masonry walls under the axial and eccentric load ($e/t = 1/4$) for a slenderness ratio of 6. On observation wall TMB-225-A-2 has developed vertical cracks while wall TMB-225-E-9 and E-10 were subjected to spalling on one side and horizontal cracks on the other side indicating the development of tension in the wall.

The walls TMB-230-A-3 and TMB-230-E-11 were built with slenderness ratio 15:85. No lateral restraints were provided. The axially loaded wall developed a vertical separation and for the eccentrically loaded wall ($e/t = 1/6$) a sudden failure occurred breaking the wall into three pieces. The failure of the two wall specimens is shown in Figs. 7 and 8. Figure 9 presents the wall TMB-220-A-4, axially loaded which failed due to several vertical cracks developed on both faces of the wall. For the same slenderness ratio of 9.66, an eccentrically loaded wall TMB-220-E-13 ($e/t = 1/4$), failed typically due to spalling on one side and simultaneously due to horizontal cracks on the other side was noticed (Fig. 10). Two walls made up of hollow concrete blocks were cast. A typical wall specimen HCB-150-A-7 is shown in Fig. 11. The wall was axially loaded and provided with lateral restraints. Its slenderness ratio was 14:73. From the figure it can be seen that the wall primarily failed due to the development of a vertical crack at the centre of its thickness.

Stress Reduction Factor (SRF)

The reduction in the load carrying capacity of a masonry wall is mainly due to inherent characteristics of its constituent materials, type of loading such as axial/eccentric and the boundary conditions of the wall. This is normally accounted in the design criteria of masonry by introducing a suitable term to accommodate these parameters. This



Fig. 8 TMB-230-E-11 (brittle failure—collapse of the wall)



Fig. 9 Vertical cracks in TMB-220-A-4

term expressed as a factor is defined as the ratio of the wall strength to the masonry prism strength. The British code (1992) [8] and the Euro code (1996) [9] address the reduction in wall strength through the term capacity reduction factor. The Masonry Standards Joint Committee [6] uses the term as the strength reduction factor. As per IS:



Fig. 10 Spalling in TMB-220-E-13

1905-1987, this factor is one of the three factors (area reduction factor, stress reduction factor and shape modification factor) which are multiplied with the basic compressive stress to obtain the permissible compressive strength of masonry. The code has specified a set of stress reduction factors for varying slenderness ratio (6–27) and eccentricity ratios of $e/t = 0$ to $e/t = 1/3$.

Table 4 presents the Stress Reduction Factors (SRF) computed from the experimental investigation on 14 masonry walls and 5 brick masonry walls tested by the researchers [3, 4]. The wall strength indicated is the ultimate strength of the walls obtained from experiments. The prism



Fig. 11 Lateral splitting of HCB-150-A-7

strength is the corrected compressive strength calculated based on the h/t ratios of masonry prisms tested under uniaxial compression. The SRF computed is the ratio of the wall strength to the prism strength [1]. As both the wall and prism strengths were obtained from experiments, it is presented as SRF from experiments in the table. Further these SRF were compared with that of factors given in IS code which appears in Table 9 of IS: 1905-1987. The values indicated in Table 4 were obtained after interpolating the values given in Table 9 of IS code for the respective SR and e/t combination. Details of wall nos. 15 and 16 were obtained from the study carried by the investigators [4]. It is reported that these walls were axially loaded. Walls numbered 17, 18 and 19 were subjected to eccentric loads beyond the eccentricity ratio (e/t) of $1/3$ as reported by the researchers [3]. For these five walls, the

Table 4 Stress reduction factors

Wall No.	Notation	SR	e/t	Wall strength	Prism strength	SRF from experiments	SRF as per the code
1	TMB-225-A-1	6.0	0	1.64	1.36	1.21	1.00
2	TMB-225-A-2	6.0	0	1.72	1.36	1.26	1.00
3	TMB-230-A-3	15.85	0	1.62	1.36	1.19	0.73
4	TMB-220-A-4	9.66	0	1.28	1.36	0.94	0.90
5	TMB-105-A-5	19.75	0	1.29	1.66	0.78	0.63
6	SCB-150-A-6	14.51	0	3.06	5.01	0.61	0.77
7	HCB-150-A-7	14.73	0	4.22	4.48	0.94	0.76
8	HCB-150-A-8	14.73	0	3.61	4.48	0.81	0.76
9	TMB-225-E-9	6.0	1/4	1.06	1.36	0.78	1.00
10	TMB-225-E-10	6.0	1/4	1.16	1.36	0.85	1.00
11	TMB-230-E-11	15.85	1/6	0.64	1.36	0.47	0.63
12	TMB-220-E-12	9.66	1/4	0.91	1.36	0.67	0.85
13	TMB-220-E-13	9.66	1/4	0.97	1.36	0.71	0.85
14	TMB-220-E-14	9.66	1/4	1.06	1.36	0.78	0.85
15	720 × 105 × 2770*	22.42	0	1.08	1.77	0.61	0.55
16	970 × 230 × 2770*	10.24	0	1.32	1.01	1.31	0.88
17	475 × 225 × 2010**	13.40	0.4	0.45	2.05	0.22	0.58
18	475 × 225 × 2010**	13.40	0.4	0.44	2.05	0.22	0.58
19	475 × 225 × 2010**	13.40	0.4	0.36	2.05	0.18	0.58

* Ref. [4], ** Ref. [3]

compressive strength and prism strength have been obtained through the experiments [3, 4]. From their data the SRF is computed accordingly and presented in Table 4. Finally for the walls nos. 15 and 16, SRF have been interpolated and walls nos. 17, 18 and 19 it is extrapolated from the values presented in Table 9 of IS code. Hence, it can be observed from Table 4, that the IS codal values indicated for axially loaded walls are lower while for eccentrically loaded walls it is higher when compared with the experimental observations on the nineteen tested walls except for one wall. This is true for brick and hollow concrete block masonry. The IS codal SRF value for axially loaded solid concrete block masonry was found to be higher when compared with the respective experimental value.

Results and Discussions

The experimental investigations on brick/block masonry and its constituents are summed up in the following manner.

- The compressive strength of the locally available bricks in Bangalore was found to be 5.85 MPa and the modulus of elasticity 552.31 MPa. The compressive strength of brick masonry prisms was found to be 1.36 MPa and the modulus of elasticity 499.41 MPa. The compressive strength of brick masonry walls

subjected to axial loads was found to lie between 1.28 and 1.72 MPa. From these it can be observed that there is a reasonable decrease in the strength of brick masonry when compared with the strength of the masonry unit (brick).

- The strength of brick masonry when subjected to axial loads was found to be in the range 1.28–1.72 MPa for SR ranging from 6.0 to 19.75. For brick masonry subjected to eccentric load, the strength observed for walls of SR 6 and 9.66 and $e/t = 1/4$ was between 0.91 and 1.16 MPa. For one wall of SR 15.85 and $e/t = 1/6$ the wall strength obtained was 0.64 MPa.
- The compressive strength of the locally available solid concrete blocks in Bangalore was found to be 4.57 MPa and the modulus of elasticity 5120.10 MPa. The compressive strength of solid concrete block masonry prisms was found to be 5.01 MPa and the modulus of elasticity 5596.81 MPa. The compressive strength of block masonry walls subjected to axial loads was found to lie between 3.06 and 4.22 MPa. It can be noticed here that although the blocks exhibited the same compressive strength as that of bricks, the modulus of elasticity of blocks is nine to eleven times than that of brick. Also the reduction in block (solid/hollow) masonry wall strength is lesser when compared with the reduction of brick masonry wall strength.
- In case of concrete block masonry, the wall strengths ranged between 3.06 and 4.22 MPa for SR 14.51 and

14.73. This indicates that block masonry has better load carrying capacity when compared with brick masonry.

- The stress reduction factors computed from experiments on axially loaded brick and hollow-concrete masonry walls have shown higher values when compared with the values presented in the Indian code. On the other hand, the stress reduction factors obtained from experiments on eccentrically loaded brick walls have shown lower values when compared with the factors in the Indian code.

Conclusion

From the present study, it can be concluded that as the brick strength is low in south India, the wall strength in turn is lower. Hence, the combined effect of slenderness and eccentricity which is usually expressed in terms of stress reduction factor is also low for walls made up of bricks from the southern parts of India. The major finding from this investigation is that the stress reduction factors indicated in the Indian code seem to underestimate for axially loaded brick/hollow concrete block work and overestimate for the eccentrically loaded brick work masonry.

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