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USE OF SMALL-SCALE BURNT CLAY BRICK FOR SHAKE TABLE TESTS OF MASONRY WALLS

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ABSTRACT

Small-scale modeling of clay brick masonry for studies of behavior upto failure poses many challenges such as, manufacturing small-scale bricks and laying them to create masonry that meets necessary similitude laws. In an ongoing study on out-of-plane behavior of brick masonry under earthquake loads, half-scaled models of masonry walls were used as test specimens for shake table simulation. These models used burnt clay bricks manufactured in the same kilns as used for the prototypes. The suitability of the half-scaled bricks in simulating prototype characteristics was studied through several material tests on brick units and masonry assemblages. This included tests for compressive strength, water absorption, and initial rate of absorption of brick units and diagonal tension (shear) and axial compression tests for masonry assemblages. In masonry assemblage tests, the effect of bond type was also examined through diagonal tension test on half-brick (Running bond) and full-brick thick (English bond) assemblages for both model and prototype masonry. Though there was considerable difference in axial compressive strength of model and prototype brick units, reasonable agreement in strength and stiffness properties of masonry was observed. These preliminary results support the suitability of modeling and capability of predicting behavior of prototype masonry walls using half-scaled bricks produced in the same manner as prototype.

Introduction

Basic information concerning the seismic response of masonry can be obtained by cyclic testing of masonry walls. However, complexity in the behavior of various form of masonry construction system require experimental investigation of seismic behavior using more realistic simulation of earthquake loads such as shake table tests. The development of advanced technologies has made possible the installation of large, multi-degree of freedom shaking-tables, which are capable of driving large masses of prototype-sized structures with a high degree of accuracy of reproduction of the recorded or artificial seismic ground motions. However, these testing facilities are rare because of the high costs involved in installation, operation and maintenance of sophisticated equipments and construction and testing of prototype structures.

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Therefore, reduced models of structures are still tested on simple earthquake simulators in many laboratories. The accuracy of model replicating the actual prototype behavior depends on the nature of quantities predicted and the material used for model. Generally, fair predictions have been observed with non-linear models for quantities related to strength and deformations

When the physical dimensions of the test specimens are reduced, overall behavior of the structure changes due to many parameters, such as stress and strain gradients, adhesion between mortar and masonry units etc, (Tomaževič 2000). Nevertheless, the important measure for accurate simulation is that the damage patterns and failure mechanisms obtained during the model tests should be similar to those observed on the prototype buildings after earthquakes. However, if behavior of model-sized wallets is similar to the behavior of prototype-sized walls, it can be expected that the global seismic behavior of the building will be also accurately simulated by testing the model on the shaking-table (Tomaževič 2000). Previous work by Abboud (1990) and Long (2005) suggest that direct modeling of concrete masonry is feasible and thus can be used for dynamic studies.

Another, important aspect while simulating the dynamic behavior of reduced model is the effect of the strain-rate (higher strain-rate due to compressed time scale). A study by Abrams (1996) showed that the rate of strain can appreciably effect the crack propagation and damage of structure tested at high rate could be less than that for tested at relatively slower rate. However, the reduced-scale components was found to have the same sequence, frequency content of records and general wave-form characteristics as a similar system comprised of large-scale components. It was concluded that the reduced scale model could be used to capture the general characteristics within the non-linear range of response and will be sufficiently precise to study the overall behavior of the structural system and its global failure mechanism.

The preliminary study presented herein was undertaken to evaluate the feasibility of using half-scaled brick masonry units for physical modeling of full-scaled infill masonry panels. The study evaluates half-scaled brick masonry at the unit and the assemblage levels, with the expectation that the program will extend to include evaluation of walls and sub-systems.

Modeling for Shake Table Test

For a reliable correlation study with the prototype, one of the most important considerations is the appropriate modeling as per similitude relations. For practical consideration and simplification, assuming that for model and prototype masonry, the modulus and density ratio are unity, then the similitude relations to be satisfied for dynamic modeling are listed in Table 1. Structurally ineffective masses need to be added to reduced-scaled models for proper simulation of both gravitational and inertial forces (Mills et al. 1979). For out-of-plane ground motions, the inertia forces are predominant forces on masonry walls panels and may cause instability in the walls, especially in slender walls with large height-to-thickness ratio. In this particular case, the artificial mass should also be distributed throughout, as resulting inertia forces are uniformly distributed.

For the required mass density ratio, $S_\rho = 2$ for half-scaled models, additional structurally ineffective distributed mass can be calculated as follows. Let ρ_1 is the density of the material to be added to the brick, then from the similitude conditions.

$$\rho_1 = \left[\frac{S_E}{S_L} - 1\right]\rho \tag{1}$$

Table 1. Similitude requirements for dynamic shake table test

Parameter	Scale factor	Replica model value
Length scale ratio, S_l	l_m/l_p	1/2
Modulus Ratio, S_E	E_m/E_p	1
Mass density ratio, S_ρ	ρ_m/ρ_p	2
Acceleration scale ratio, S_a	a_m/a_p	1
Time scale ratio, S_t	t_m/t_p	$1/\sqrt{2}$
Frequency scale ratio, S_ω	ω_m/ω_p	$\sqrt{2}$
Mass scale ratio, S_M	M_m/M_p	1/4

Using Equation 1; the density of the material to be added to the model brick is $\rho_l = \rho = 1.77$ g/cc. Hence, for the considered half-scaled model bricks, the additional weight to be added is equal to mass of that brick, which is approximately 0.435 kg. Lead blocks of 60 mm diameter, 28 mm height, and an average mass of 0.865 kg were attached to account for mass of two bricks. These were fixed in regular grid pattern on both faces of the wall as shown in Fig. 1. The details about the test setup and results of preliminary study on out-of-plane behavior of infilled masonry panel are discussed in Rai et al. (2009).

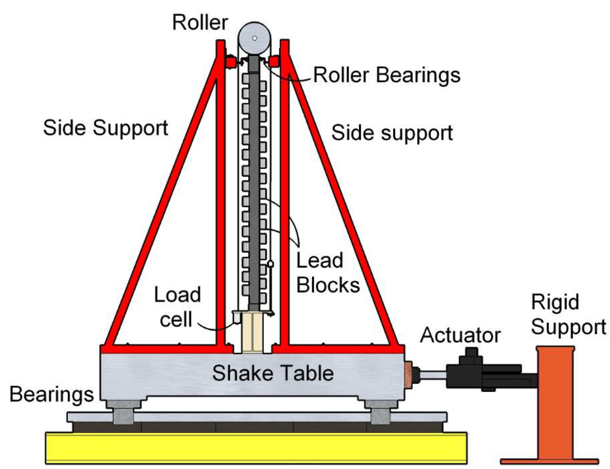


Figure 1. Test setup for shake table test of masonry panel

Experimental Program

To verify the feasibility of assumed scale factors for replica model, a series of tests were performed to obtain basic data on physical and mechanical properties of brick units and masonry assemblages of full and half-scaled specimens.

Material Tests

Prototype and Model Brick Units

The 230 mm stretcher prototype brick unit, as shown in Fig. 2, is commonly used in large parts of the world including India. Also shown in Fig. 2, a half scaled model of the brick unit manufactured using the same process and fired in the same kiln as for the prototype brick units. The average dimension of prototype brick was measured as 229.03×109.78×71.85 mm, which conforms to IS 1077 (1992). Two sets of model bricks were used in this study: Set-A bricks were used in a previous study on in-plane cyclic behavior of masonry (Paikara and Rai 2006) and Set-B model bricks would be used for future dynamic studies on masonry panels.

Table 2 shows a comparison of geometric properties of the half-scaled brick with the prototype bricks. Volume of prototype bricks were found to vary from 1440×10^3 to 1760×10^3 mm^3 [mean 1580×10^3 mm^3, coefficient of variation (COV) 7.8%] and for model bricks it varied from 250×10^3 to 262×10^3 mm^3 (mean 257×10^3 mm^3, COV 1.8%). The average volume ratio of model brick to that of the prototype is about 0.16, which results in an average length-scaling ratio of 0.55. Also, it is evident from the scaling ratio listed in Table 2 that model bricks were indeed half the size of prototype bricks. Moreover, both prototype and model bricks fulfill the basic geometric requirement of half width-to-length ratio, which is important for laying bricks in various masonry bonds (English, Flemish bond, etc.).

Figure 2. Prototype and model brick unit

Table 2. Geometric Properties of Brick Masonry Units

Properties	**Full-scaled**	**Half-scaled**		**Scaling Ratio**	
		Set-A	**Set-B**	**Set-A**	**Set-B**
Length (mm)	229.0	120.2	120.4	0.52	0.53
Width (mm)	109.8	59.5	61.8	0.54	0.56
Height (mm)	71.9	36.6	38.5	0.51	0.54
Volume (10^3mm^3)	1580 [7.8]*	254 [2.8]	257 [1.8]	0.54	0.55

* Figures in [] bracket indicate percent coeff. of variation (COV)

Test for initial rate of absorption (IRA), water absorption (WA) and compressive strength were carried as per ASTM C 67-09 (2009) and IS 3495 (BIS 1992a), respectively. The rate of absorption can have an important effect on the interaction between freshly laid mortar and the brick units and subsequently on masonry bond strength. These properties are important in order to assist in mortar selection and material handling in the construction process. Table 3 shows that absorption properties (WA and IRA) and density are similar for both prototype and model brick unit, however, compressive strength shows significant variation. Lower IRA values were found for half-scaled brick units with higher compressive strength, which reaffirms the observation made by Kaushik et al. (2007). The compressive strength of half-scaled bricks was about 1.5 to 2.0 times that of prototype bricks. The increased strength of model bricks is probably due to varying effect of pressure and baking during manufacturing process as well as due to size effects (Harris and Sabnis 1999). The characteristic crushing failure of prototype and model bricks units are shown in Figs. 3a and 3b.

Table 3. Material Properties of Brick Masonry Units

Properties	Full-scaled	Half-scaled		Scaling Ratio	
		Set-A	Set-B	Set-A/ Full	Set-B/ Full
Density (kg/m^3)	1768.1 [4]*	1783.9 [4]	1768.7 [4]	1.01	1.00
Water Absorption (%)	14.0 [15]	13.9 [5]	14.4 [7]	0.99	1.02
Initial Rate of Absorption (kg/m^2/min)	2.8 [13]	2.9 [11]	3.2 [8]	1.04	1.14
Compressive Strength (MPa)	21.9 [17]	46.0 [7]	33.9 [15]	2.10	1.55

* Figures in [] bracket indicate the percent coeff. of variation

Mortar

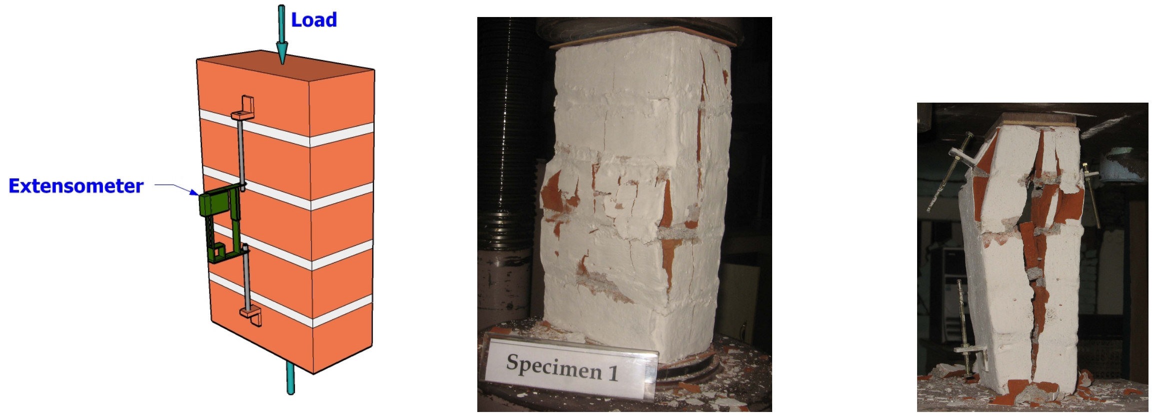
Lime cement mortar of proportion 1:1:6 (cement: hydraulic lime: sand) by weight was used to prepare the masonry. The water-binder ratio of 0.66 was determined for mortar used with Set-A model bricks, whereas this ratio was 0.85 for Set-B model bricks. An average 28-days compressive strength, f_j of 50 mm mortar cubes was 4.53 MPa and 8.5 MPa for Set-A and Set-B model bricks, respectively. Such a significant variation in compressive strength may be due to quality and hydraulicity of lime, among other factors. Both mix satisfies the minimum expected compressive strength requirement of 3 MPa for structural masonry as per IS 2250 (1981). The typical failure of mortar cubes is shown in Fig. 3c.

(a) (b) (c)

Figure 3. Typical failure modes: (a) prototype brick (b) model brick and (c) mortar cube

Compressive strength of Brick Assemblages (Prism test)

Five-brick tall full-scaled and half-scaled brick masonry prisms were constructed and moist cured for 28 days before testing. Assemblages were constructed in the laboratory by an experienced mason. Generally, prototype masonry has mortar joint thickness in range of 10-12 mm and to satisfy length ratio of modelling, the model masonry should have 5-6 mm thickness for the mortar joint. However, due to practical difficulties, an average thickness of 7 mm was obtained for the mortar joint and the same mortar joint thickness was maintained in all the specimens. The approximate height of prototype and model masonry prism with 10 mm and 7 mm thick mortar joints was about 400 mm and 218 mm, respectively. Before testing, the prism surfaces were leveled with Plaster of Paris and the testing was carried out using servo-hydraulic actuator in displacement control mode at the rate of 1.0 mm/min. The displacement and load were measured with the help of an extensometer and load cell, which is in-built with the actuator arm. The schematic arrangement for compression test and typical failure of masonry prisms are shown in Fig. 4. and the summary of results including prism strength and modulus of elasticity are given in Table 4



(a) (b) (c)

Figure 4. Compression testing and typical failure mode of prototype and model masonry prism.

Table 4. Results of the prism test

Specimen	Half-scaled brick prisms				Full-scaled brick prisms	
	Set-A		Set-B			
	Peak strength (MPa)	Modulus (MPa)	Peak strength (MPa)	Modulus (MPa)	Peak Strength (MPa)	Modulus (MPa)
1	5.63	2644.4	4.19	#	5.63	2045.6
2	4.57	3215.9	4.92	2349.0	6.31	4322
3	5.86	2760.4	5.06	2948.3	4.85	1773.4
4	5.24	2281.1	2.77*	2562.1	4.50	2297.2
Average	5.37 [8]	2725.5 [14]	4.72 [10]	2673.1 [9]	5.32 [15]	2609.5 [45]

* Value neglected in average strength as prism failed due to flexural bending
# Strain values ignored due to erroneous extensometer readings

The variation of peak strength and elastic modulus for the half-scaled prism with full-scaled were observed to be within 15% for both Set-A and Set-B model bricks. In addition, similar stress-strain characteristics were obtained for full and half-scaled prisms as shown in Fig. 5, indicating that the half-scaled masonry does replicate the axial compressive behaviour of the prototype masonry. A correction factor was applied for compressive strength to account for the aspect ratio other than h/t = 5 as per IS 1905 (1987). For a mean h/t ratio of 3.9 and 3.6 for prototype and model masonry specimen, the correction factors were determined as 0.94 and 0.92, respectively. Failure of majority of these specimens was due to the formation of vertical splitting cracks along their height. Failure of few specimens took place because of bond failure by flexural bending of specimens, probably due to 'poor' alignment of the specimen with the loading arm of actuator, and such results have not been included in the study.

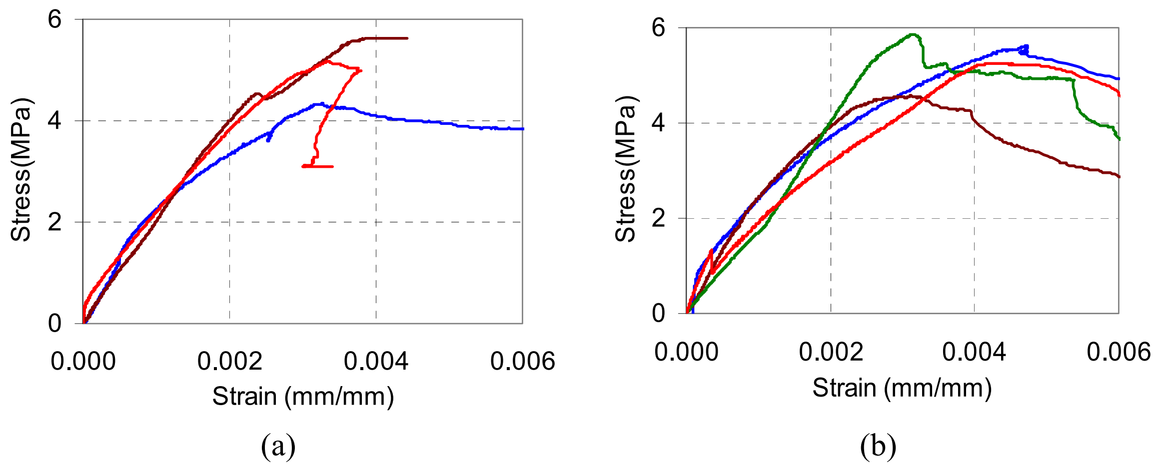


Figure 5. Typical compressive stress-strain curves for (a) full-scaled and (b) half-scaled prism

For North-Indian bricks Kaushik et al. (2007) have expressed the compressive strength of masonry as a function of compressive strength of brick, f_b, and mortar, f_j, and proposed following relation

$$f_m{}' = 0.63 f_b^{0.49} f_j^{0.32} \tag{2}$$

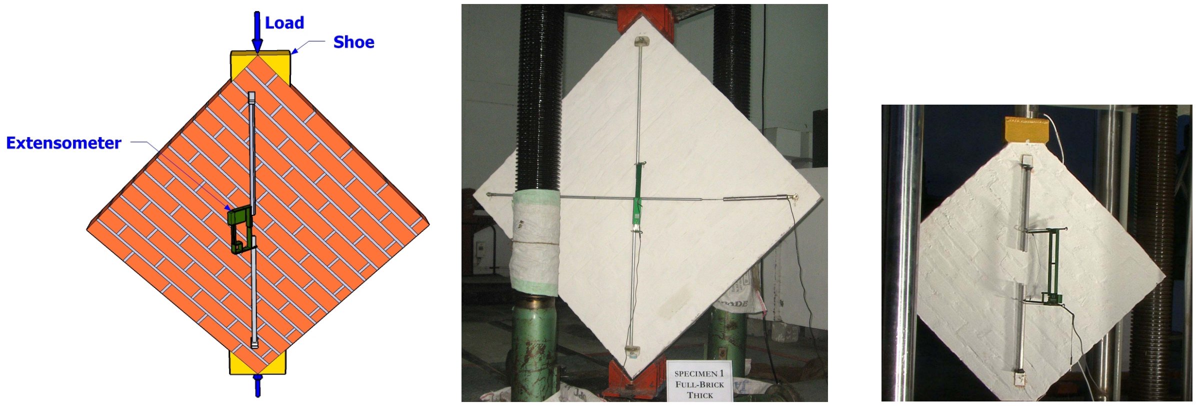
The compressive strength of prism determined using Eq. 2 was compared with experimental values, as shown in Table 5. The proposed relation is very good in predicting the prism compressive strength of full-scaled masonry with about 7% difference. However, for model masonry the predicted strength shows a difference in the range of 24-49% and hence, based on this preliminary study the proposed expression by Kaushik et al. (2007) needs to be further modified for the model masonry.

Table 5. Comparison of experimental and predicted prism compressive strength

Scale		**Prism Strength $f_m{}'$ (MPa)**		**Difference (%)**
		Experiment	Predicted	
Full-scaled		5.32	5.67	6.6
Half-scaled	**Set-A**	5.37	6.67	24.2
	Set-B	4.72	7.03	48.9

Diagonal tension test

To measure the diagonal shear strength of the masonry, three half-brick thick and full-brick thick specimens using prototype and model bricks were made and tested as per ASTM E-519-07. As ASTM E 519-07 recommends a size of 1.2 m × 1.2 m for full-scaled wall specimen, the dimensions would be 0.60 m × 0.60 m for a half-scaled model. The half-brick (Running bond) and full-brick thick (English bond) specimens were tested to examine the effect of type of bond. The same thickness of mortar joint was maintained as in prism specimens tested for compressive strength.



(a) (b) (c)

Figure 6. Test setup for diagonal compression test of half-scaled and full-scaled masonry

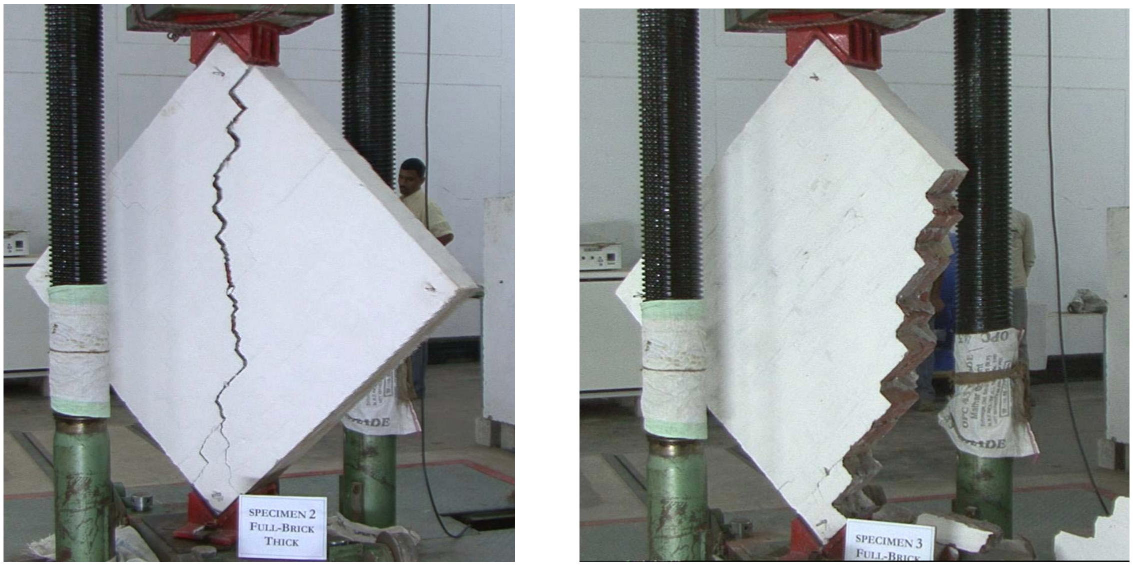
Extensometer and LVDT were used to measure the vertical shortening and horizontal expansion, respectively as shown in Fig. 6. The testing was carried out under 6000 kN displacement control column testing machine at the rate of 0.6 mm/min and 1 mm/min for half-brick and full-brick thick specimen, respectively. Shear stress, S_s of masonry at applied load, P was determined by using the following equation

$$S_s = \frac{0.707P}{A_n} \tag{3}$$

A_n- the net area of the specimen (mm^2), is given by the average of the width and height of the specimen multiplied by its thickness.

The shear strength, S_s of half-brick and full-brick thick model and prototype specimens determined using Eq. 3 are summarized in Table 6 and the typical failure mode is shown in Fig. 7. The unexpected failure mode was observed for full-brick thick prototype specimen 3 (Fig. 7b), which resulted in much lower strength than other specimens. The significant variation in shear strength of model and prototype masonry is probably due to difference in mortar joint strength. Shear strength normalized with compressive strength of mortar joint shows a maximum of 12 % variation between values for model and prototype masonry. The specimens laid in English bond showed 1.25 times higher S_s value compared to running bond specimen for the half-scaled masonry and this effect could be attributed to presence of header bricks at alternate bed joints. Similar behavior was observed for prototype masonry as well, if full brick thick specimen 3 is not considered for average shear strength due to different failure mode. The reasonable agreement of shear strength further reaffirms that the half-scaled masonry represent good model of the prototype masonry.

As observed from series of tests on model and prototype masonry, the modulus and density ratio have been nearly unity. Therefore, the aforementioned similitude relations (Table 1) can be used with sufficient precision to predict the behavior of prototype structure. With the use of half-scaled bricks to model prototype masonry walls, specimens can be accommodated and tested within the space constraints. In addition, it is possible to attach the required non-reinforcing mass to the wall surface to generate required inertia force. However, it could become practically difficult with bricks smaller than half-scaled, even when larger acceleration ratio is employed.



(a) (b)

Figure 7. (a) Typical diagonal tension of different specimens (b) ‘odd’ failure of full-brick thick prototype specimen

Table 6. Results of the diagonal tension test

Specimen	Half-scaled Specimens S_s (MPa)		Full-scaled Specimens S_s (MPa)	
	Half-brick	**Full-brick**	**Half-brick**	**Full-brick**
1	0.17	0.23	0.40	0.41
2	0.26	0.26	0.50	0.48
3	0.17	0.27	0.39	0.31*
Average	0.20 [25]	0.25 [7]	0.43 [14]	0.45 [11]
Avg. normalized shear strength (S_s/f_j)	0.044	0.055	0.05	0.053

* Value not considered in average shear strength

Conclusions

A series of tests has been conducted to verify the suitability of reduced half-scaled model brick to adequately represent the behavior of full-scaled masonry unit and assemblages. From the results, it can be concluded that the half-scaled burnt clay masonry unit introduced is a good model of the prototype unit. Both prototype and model brick units had similar density, IRA and WA properties. Though half-scaled bricks exhibited higher strength than full-scaled bricks, the behaviour of masonry assemblages in axial compression and diagonal tension showed reasonable agreement in strength and stiffness. These preliminary results support the feasibility of modelling full-scaled masonry using half-scaled units as a direct model for variety of loading conditions, including shake table test with necessary artificial mass simulation.

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