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SMALL-SCALE MODELLING OF CONCRETE MASONRY USING ½-SCALE UNITS: A PRELIMINARY STUDY

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ABSTRACT

Physical and economic limitations can make laboratory testing of full-scale masonry wall sub-systems and buildings unfeasible, particularly for dynamic loading. Small-scale modelling may be used to predict behaviour of these structures. This paper presents the results of preliminary testing of half-scale concrete masonry units for modelling in-plane behaviour of masonry shear walls. Material properties and behaviour of half-scale and full-scale masonry units and assemblages are examined. Strength, stress-strain characteristics, and failure modes of assemblages in axial compression and diagonal tension are compared and discussed. Half-scale masonry is found to behave as a good model of full-scale masonry, particularly for grouted specimens. Strength and stress-strain curves are comparable. The differences encountered are attributable to size effects, normal variation of masonry properties, and differences in block strength. These results support the feasibility of modelling full-scale masonry shear walls and buildings using half-scale units.

KEYWORDS: concrete masonry, small-scale modelling, prisms, wallettes, testing

INTRODUCTION AND PROBLEM STATEMENT

Laboratory testing of full-scale masonry wall sub-systems and buildings can be impractical due to space limitations, construction and testing constraints, and financial restrictions. A potential solution to this problem is modelling full-scale walls and buildings using half-scale concrete masonry units, which, in fact, results in one eighth the volume of material. It is hoped that, unlike smaller-scale units, half-scale units may behave as a direct model, thus eliminating the need for scale factors in relating masonry behaviour.

The Centre for Effective Design of Structures at McMaster University is launching a comprehensive program to address the issues associated with experimental testing of masonry wall sub-systems, flanged walls, and nominally reinforced, partially grouted walls. The preliminary study presented herein was undertaken to evaluate the feasibility of using half-scale concrete masonry units for physical modelling of full-scale masonry shear walls. The study evaluates half-scale concrete masonry at the unit and the assemblage levels, with the expectation that the program will extend to evaluation of walls and sub-systems.

Small-scale modelling research at Drexel University over the past 30 years [1,2] has included experimental testing of masonry using one-quarter and one-third scale units. In structural modelling [1], a "practically true" model may be applied if the self-weight of the structure is neglected and the stress-strain curves of model and prototype assemblages are the same. Previous work by Abboud, Hamid and Harris [2] revealed that direct modelling of concrete masonry is feasible. Scale factors for concrete masonry, as discussed by Harris and Sabnis [1], are used when direct modelling is not possible.

EXPERIMENTAL PROGRAM

The series of tests performed in the Applied Dynamics Laboratory at McMaster University were carried out to provide basic data on physical and mechanical properties of units and assemblages and to permit comparison between full and half-scale results.

Tests of Materials

The most commonly used concrete block is a standard 20 cm hollow stretcher unit such as shown in Figure 1. Therefore, this was chosen as the full-scale version of the block to be modelled. In this case, the block had frogged ends, pear shaped cells, and the face shells and webs had flares at the top in addition to the normal taper required for demoulding. As shown in Table 1, the minimum face shell and web thicknesses of 33.2 mm and 27.4 mm are 1.2 mm and 1.4 mm greater than the normal minimums for Ontario block, which, in turn, exceed the CSA A165.1 (3) minimum requirement of 30 mm and 25 mm, respectively.

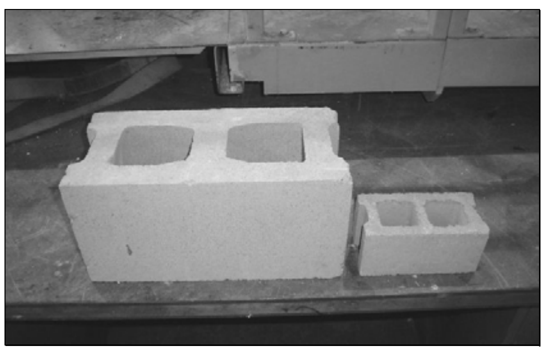


Figure 1 - Concrete masonry units

Table 1 - Geometric Properties of Concrete Masonry Units

Scale	Width (mm)	Height (mm)	Length (mm)	Face shell thickness (mm)	Face shell thickness : width ratio	Web thickness (mm)	Web thickness : length ratio	% solid
Half	90	89	185	15.6	0.17	13.3	0.07	51.2
Full	190	190	390	33.2	0.17	27.4	0.07	55.1

For the scale block, availability of the 90 mm high external parts of the block moulds for half-height blocks dictated a scale of 90÷190=0.474. Therefore, what we have called "half-scale" is actually 47.4% scale. In this regard, specified 90 mm block thickness, 15.5 mm minimum face shall thickness, and 12.3 mm web thickness conform to this scale. However, the half-scale block shown in Figure 1 differs from the prototype full-scale unit in that it has rectangular cells and no flares were added to increase face shell and web thicknesses. This, plus a depression in the web, accounts for the slightly lower percent solid for half-scale block. The measured dimensions in Table 1 differed slightly from the specified values, but part of that difference can be attributed to difficulty in measuring thicknesses accurately.

The half-scale units were manufactured using the same concrete mix used for the full-scale block. However, as shown in Table 2, differing effects of pressure and vibration during manufacture led to some difference in properties. The test data presented in Table 2 were obtained in accordance with ASTM C140 [4] and shows that the concrete density was 5.2% higher in the half-scale unit. Therefore, it is not surprising that the half-scale unit is 20% stronger. An additional factor contributing to the apparent difference in concrete strength is the use of average cross-sectional area based on the volume of material in the block. By this method, average net area is slightly underestimated for half-scale units due to presence of a web depression. The calculated average area of the full-scale block is made larger by the presence of the flared shapes of the face shells and webs. The average net area used in determining compressive strength was 8490 mm^2 for half-scale block and 40770 mm^2 for full-scale block. The ratio of these two areas is 0.208, which is less than the scale value of 0.474^2=0.225. A more appropriate measure might be to use mid-height area, in which case the area ratio would be 8897/40335=0.221 and the strength ratio would be 27.8/24.6=1.13.

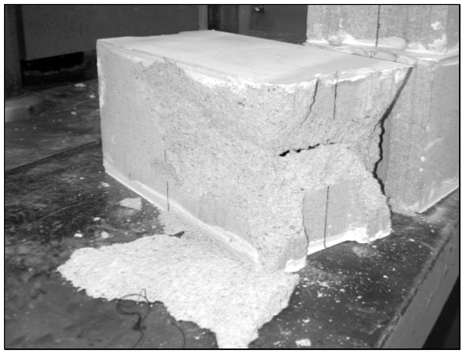
Table 2 - Material Properties of Concrete Masonry Units

Property	Half-scale		Full-scale	
	Average	c.o.v.*	Average	c.o.v.
Density (kg/m^3)	2277	1.5%	2166	0.2%
Absorption (kg/m^3)	115.8	4.4%	139.8	1.1%
Net area compressive strength (MPa)	29.2	5.4%	24.4 (units) 25.2 (coupons)	11.4% 7.6%
Splitting tensile strength (MPa)	2.35	30.1%	2.48	3.9%

* coefficient of variation

Only three full-scale units were available for compression testing, so additional coupons cut from the face shells of prism units were also tested. As specified in ASTM C140 [4], these coupons were cut to dimension ratios of 2:1 height-to-thickness and 4:1 length-to-thickness. Splitting tensile strength tests were performed in accordance with ASTM C1006 [5]. Only one full-scale unit was available for testing, so two splitting tensile tests were performed on the face shells of this unit. Four half-scale units were tested, because there was considerable variability in the test results. One tensile strength value was less than one-half the highest value; if the low value is removed, an more reasonable average splitting tensile strength of 2.68 MPa with c.o.v. of 11.5% is obtained.

Results of physical testing of units are presented in Table 2. Full-scale units tested for compressive strength failed by semi-conical breaks near end webs, as shown in Figure 2a. Half-scale units appeared to fail by a similar mode, although failure was more pronounced in face shells than in end webs (Figure 2b). Most of the splitting tensile strength specimens fractured in a clean tensile split along the line of loading. One of the half-scale units also fractured in the end web between the split face shells. No visible voids or impurities were noted in the split specimens.



(a) Full-scale

(b) Half-scale

Figure 2 - Failure modes of units

Mortar and Grout
Type S Portland cement-lime mortar was used to construct assemblages. Grouted specimens were filled with fine grout of 267 mm (10½”) slump. The average compressive strength of block moulded grout used in the prisms and wallettes was 66 MPa. On average, it was 67.1 MPa and 64.9 MPa, respectively, for the half-scale and full-scale specimens. This extremely high strength may have occurred because of use of a large amount of plasticizer in the commercial mix and was unexpected.

Construction of Specimens
Assemblages were constructed in the laboratory by an experienced mason and grouted six days after construction. The mason reported no serious difficulties constructing half-scale specimens with 5 mm mortar joints. Half-scale prisms were grouted with lower-slump grout than full-scale specimens; water was added to increase workability before grouting full-scale specimens. Grout in full-scale prisms was consolidated using a mechanical vibrator. Upon removal of plywood from ends of the full-scale grouted specimens, large voids (missing grout) were found at the ends of some specimens. These voids were filled and patched 48 hours after initial grouting.

The end blocks of prisms and wallettes were constructed of one-quarter and three-quarter cut blocks, as shown for prisms in Figure 3. This block arrangement, discussed by Halucha [6], eliminated the problem of filling frogged block ends with grout. This geometry results in a full cell in the centre of the prism and half cells at the ends.

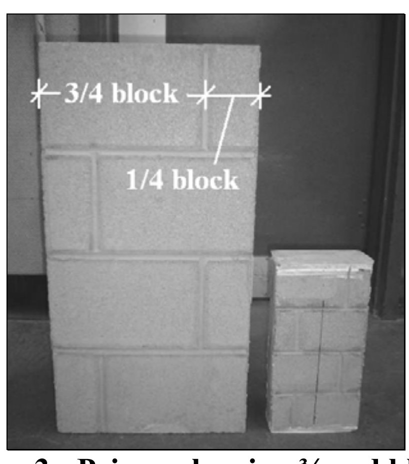


Figure 3 - Prisms showing ¾ end blocks

Test Setup and Instrumentation of Prisms

Four-block high prisms were tested in accordance with ASTM C1314 [7]. Full-scale specimens were tested using 127 mm thick top bearing plate and bottom roller between two 20 mm thick plates. Two 25 mm-stroke linear potentiometers were used to measure strain over three blocks and bed joints (gauge lengths of 600 mm for full-scale, 280 mm for half-scale). Potentiometers were placed on opposite faces of the prism, with displacement measured at 2-second intervals throughout the testing. The data presented in this paper were obtained from potentiometers. To back up potentiometer data, mechanical strain gauge (demec) and dial gauge readings were obtained for full and half-scale prisms, respectively. Demec measurements were taken over one block and one mortar joint (200 mm gauge length), with four demec readings were taken at each load increment. Dial gauges on half-scale prisms were placed at the same gauge length as potentiometers. The results obtained from mechanical methods corresponded with potentiometer data, so these are not explicitly included herein. Prism test setups are shown in Figure 4.

(a) Full-scale **(b) Half-scale**

Figure 4 - Prism test setup

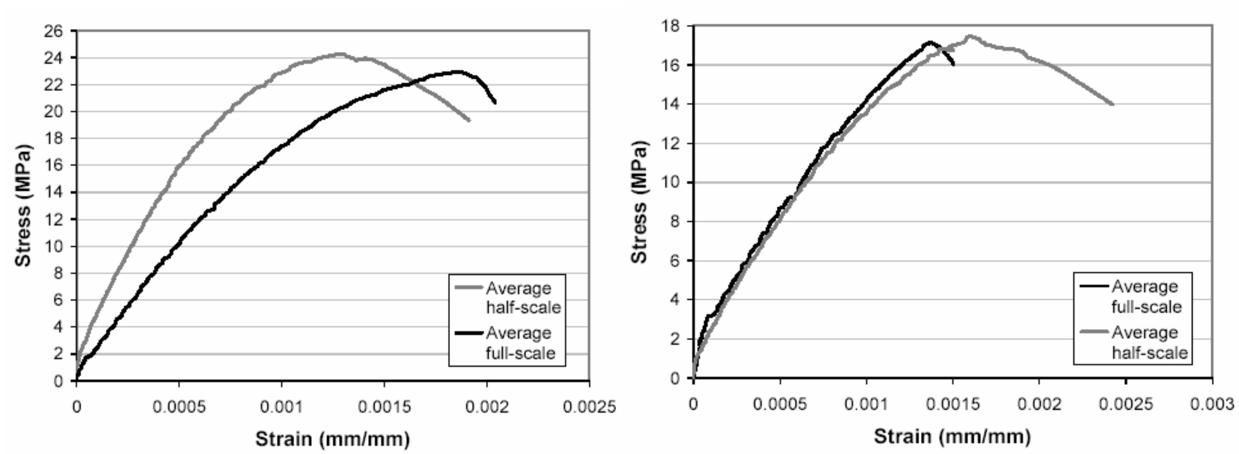
Results

The results obtained from axial compression tests are summarized in Table 3. The areas used to calculate f'_m for hollow prisms were based on effective mortared area of 187×16×2=5984 mm^2 and 396×75.4=29858 mm^2 for half-scale and full-scale, respectively. For grouted prisms, the respective areas were 187×90=17010 mm^2 and 396×190=75240 mm^2.

Table 3 - Axial compression results – prisms

Specimen	Hollow				Grouted			
	Half-scale		Full-scale		Half-scale		Full-scale	
	P (kN)	f'_m (MPa)	P (kN)	f'_m (MPa)	P (kN)	f'_m (MPa)	P (kN)	f'_m (MPa)
1	140.2	23.4	728.0	24.4	262.3	15.4	1259.7	16.7
2	137.0	22.9	635.0	21.3	292.3	17.2	1136.8	15.1
3	158.1	26.4	693.8	23.2	334.8	19.7	1471.2	19.6
Average	145.1	24.2	685.6	23.0	296.5	17.4	1289.2	17.1
c.o.v.	7.8%		6.9%		12.3%		13.1%	

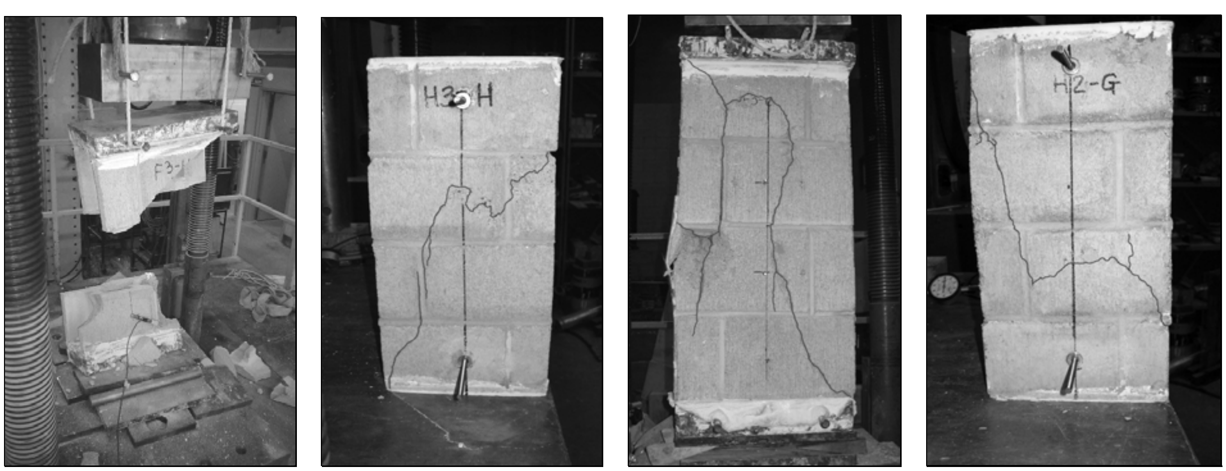
For hollow and grouted prisms, the ratio of half-scale to full-scale compressive strength was 1.05 and 1.02, respectively. These results show excellent similarity between the model and prototype masonry strength. The average stress-strain curves obtained for hollow (Figure 5a) and grouted prisms (Figure 5b) show good correlation. The full-scale hollow curve for specimen 2 was shifted to pass through the origin and to eliminate a "jump" in potentiometer data.



(a) Hollow prisms **(b) Grouted prisms**

Figure 5 - Stress-strain plots for prisms

The strain at ultimate stress for all prisms was less than the expected minimum of 0.002 [8]. This could be partly due to the gauge length covering 3 blocks, so strain is measured away from the centre of the prism where failure initiates. Full-scale hollow prisms tended to fail by cracking through webs and face shells, usually in an explosive failure, (Figure 6a). Failure modes of half-scale hollow prisms included diagonal cracking through face shells (Figure 6b) and horizontal cracking through blocks. Vertical cracks in the webs were also present, suggesting imminent face shell separation. Grouted full-scale prisms also failed by diagonal (cone and shear) breaks combined with vertical cracking, as seen in Figure 6c, with some face shell separation and cracking of grout evident at prism ends. Half-scale grouted prisms typically displayed similar failure modes: diagonal and/or horizontal shear cracks through face shells (Figure 6d), with some cracking of grout at prism ends.

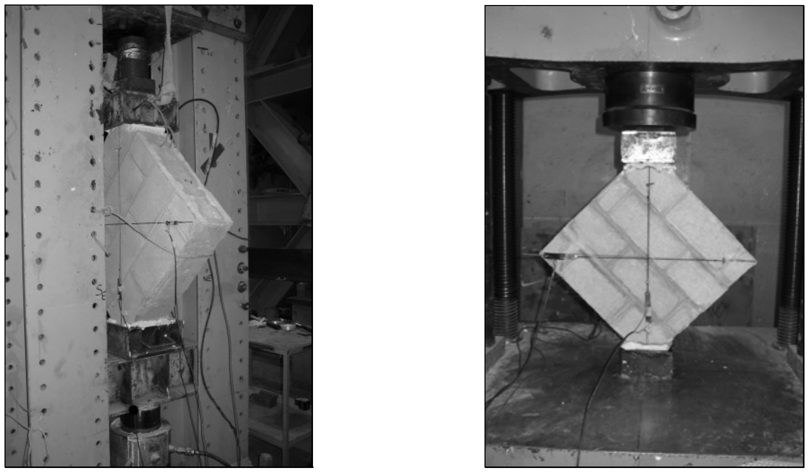


(a) Full-scale hollow **(b) Half-scale hollow** **(c) Full-scale grouted** **(d) Half-scale grouted**

Figure 6 - Typical failure patterns of prisms

Test Setup and Instrumentation of Wallettes

Wallettes were tested in accordance with ASTM E519 [9]. Specimens were two blocks long by four courses high. Shortening of the vertical diagonal and lengthening of the horizontal diagonal were measured using 25 mm-stroke linear potentiometers, with two potentiometers placed on each face of the wallettes. Displacement measurements were recorded at 2-second intervals using a computer data acquisition system. Gauge lengths of 720 mm and 360 mm were used for full and half-scale wallettes, respectively, to measure strain over an equal number of blocks and mortar joints. Typical wallette test setups are shown in Figure 7.



(a) Full-scale **(b) Half-scale**

Figure 7 - Wallette test setup

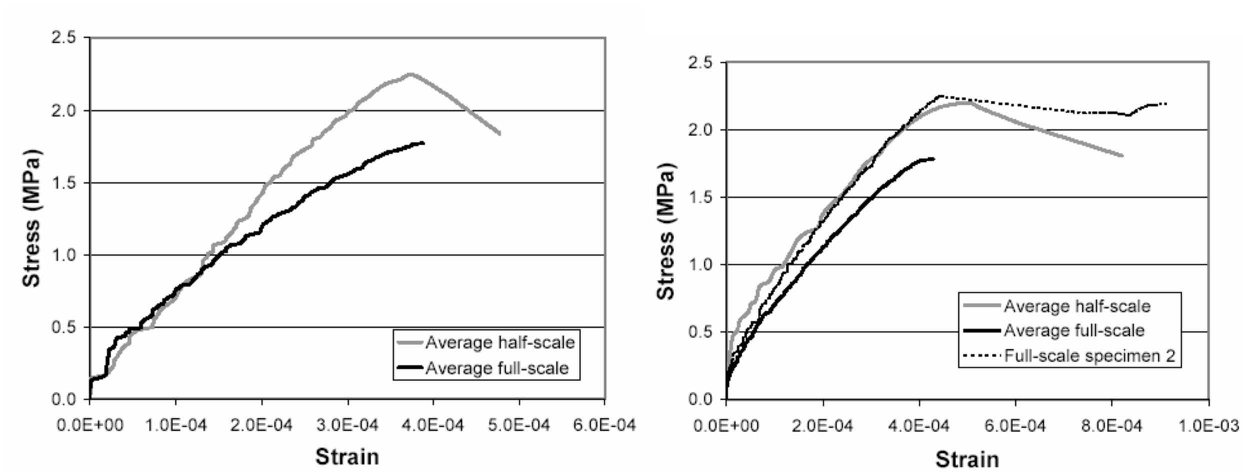
Results

The results obtained from diagonal tension tests are summarized in Table 4. As specified in ASTM E519 [9], the areas used to calculate shear strength for hollow wallettes were based on average specimen dimensions and percent solid of units. These values were 374×90×0.51= 17167 mm^2 and 793×190×0.55=82869 mm^2 for half-scale and full-scale, respectively. For grouted prisms, the respective gross areas were 374×90=33660 mm^2 and 793×190=150670 mm^2. Although ASTM suggests calculating diagonal tensile strength based on average net area for hollow wallettes, this may not accurately represent actual failure modes. Web areas contribute little to strength when failure occurs at mortar joints or through face shells. More appropriate measures may be effective mortared area for failure by debonding or average face shell thickness if cracks form through face shells. The areas for half-scale and full-scale specimens, respectively, would be 374×15.6×2=11669 mm^2 and 793×75.4=59792 mm^2 for effective mortared area and 374×16.5×2=12342 mm^2 and 793×34.5×2=54717 mm^2 for average face shell thickness.

Of the three full-scale grouted wallettes tested, only Specimen 2 achieved shear strength comparable to the half-scale units. Upon inspection after failure, several partially ungrouted cells were discovered in the centre of the two specimens with lower strengths. If these two wallettes are excluded from the results, the ratio of half-scale to full-scale diagonal tensile strength is 1.27 for hollow specimens and 0.98 for grouted specimens. The average stress-strain curves obtained for hollow (Figure 8a) and grouted wallettes (Figure 8b) follow. As expected, grouted wallettes show more similar stress-strain behaviour than do hollow, particularly when full-scale Specimen 2 is compared to half-scale wallettes.

Table 4 - Diagonal tension results – wallettes

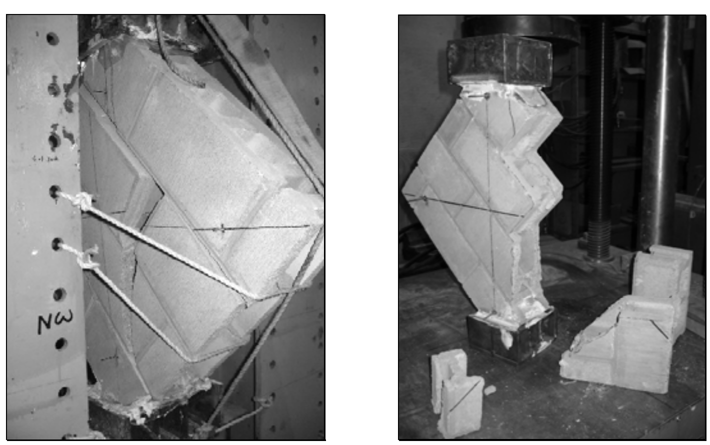
Specimen	Hollow				Grouted			
	Half-scale		Full-scale		Half-scale		Full-scale	
	P (kN)	f'_d (MPa)	P (kN)	f'_d (MPa)	P (kN)	f'_d (MPa)	P (kN)	f'_d (MPa)
1	49.6	2.04	205.2	1.75	105.3	2.21	309.2	1.45
2	51.4	2.12	187.4	1.60	107.5	2.26	479.4	2.25
3	62.4	2.57	229.5	1.96	101.5	2.13	349.9	1.64
Average	54.4	2.24	207.4	1.77	104.8	2.20	379.5	1.78
c.o.v.	12.7%		10.2%		2.9%		23.4%	



(a) Hollow wallettes **(b) Grouted wallettes**

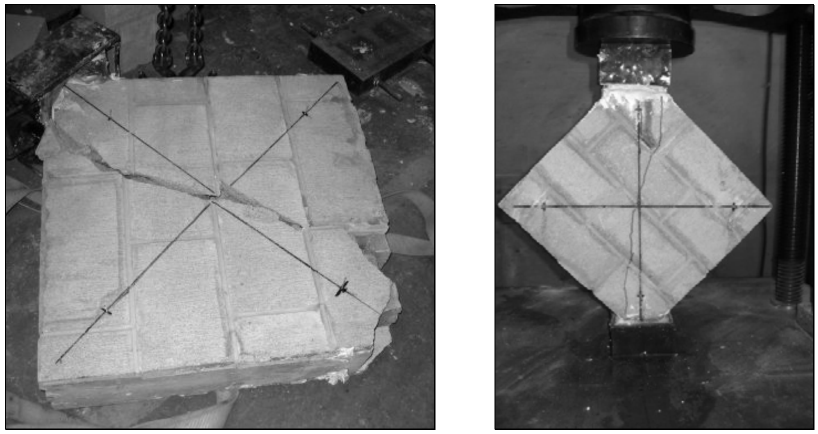
Figure 8 - Stress-Strain Plot

Hollow wallettes failed by a combination of bed joint failure and vertical cracking. Figure 9a shows cracking in a full-scale wallette and Figure 9b shows a half-scale wallette after failure. Both full-scale and half-scale grouted wallettes failed by vertical cracking along the loading path, as shown in Figures 10a and 10b.



(a) Full-scale **(b) Half-scale**

Figure 9 - Typical failure patterns of hollow wallettes



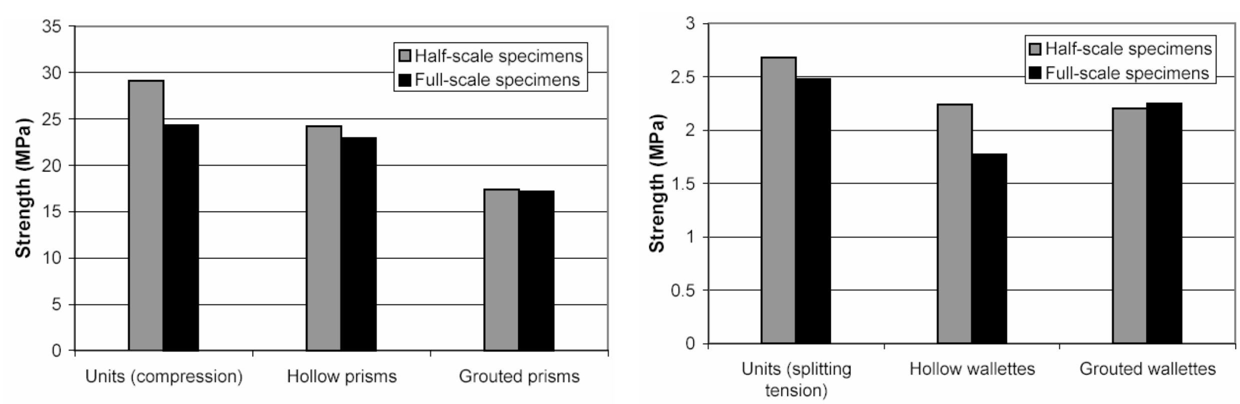
(a) Full-scale (b) Half-scale

Figure 10 - Typical failure patterns of grouted wallettes

DISCUSSION OF RESULTS

Based on the results presented, half-scale concrete masonry acts as a good model of full-scale masonry. Figure 11 shows comparison of strength of half-scale units and assemblages to full-scale specimens. In general, half-scale masonry exhibited slightly higher strength than full-scale masonry. This is attributable to normal variation of block properties and to size effects, as explained in Harris and Sabnis [1]. Some degree of scatter of masonry strength is expected, even when specimens are constructed of units with the same strength. Work by Chahine [10] revealed that f'_m values of prisms constructed of blocks from different manufacturers but with the same strength varied by as much as 18%.

In half-scale specimens, the scaled mortar joint loses water more rapidly to absorptive units, causing a slight increase in masonry strength for hollow specimens. In assemblages constructed of hollow blocks, higher strength is expected of the model masonry since half-scale block strength was about 20% higher than full-scale, depending on cross-sectional area used. The difference in block strength has less impact on variation of strength of grouted specimens. The lack of flare in half-scale units could also explain higher masonry strength in grouted specimens, as high-strength grout comprises a greater proportion of the specimen.



(a) Compressive strength (b) Tensile strength

Figure 11 - Comparison of strength of units and assemblages

CONCLUSIONS

A series of tests has been presented to relate material properties and behaviour of half-scale and full-scale masonry. From the results, it is concluded that the half-scale concrete masonry unit introduced is a good model of the prototype unit. Very good strength comparisons and stress-strain characteristics, particularly for grouted specimens, were noted. These results support the feasibility of modelling full-scale masonry using half-scale units as a direct model. Half-scale masonry should be especially useful for modelling in-plane behaviour of fully grouted masonry shear walls.

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