CHAPTER 5

INVESTIGATION OF FLEXURAL STRENGTH FOR DRY-STACK MASONRY

5.1 Introduction.

The objective of the study was to investigate the flexural strength of dry-stack masonry wall panels discussed in chapter four. The dry-stack wall panels investigated resembles the category of wall panels without pre-compression, a typical type of walls found in low-rise buildings in conventional masonry. Wallettes were constructed in the laboratory using interlocking blocks of 9 and 16 MPa unit strength, 4 mm depth of interlocking mechanism in the bed face, laid in a stretcher bond.

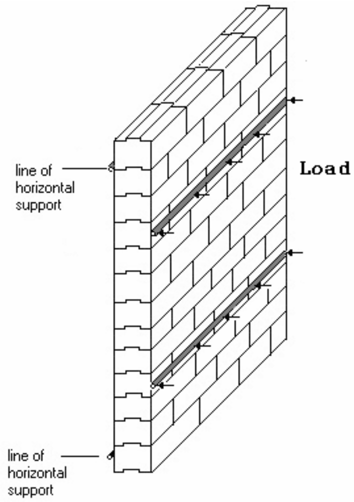
A study was conducted to establish the flexural strength of the dry-stack masonry under vertical and horizontal bending. Formats of wallettes tested were selected in such a way that an adequate number of courses and dry stack joints were tested. Two formats of wallettes were tested. Format 1 consists of similar specimens tested under vertical bending, span normal to bed joints simulating a wall supported by floor and roof framing in normal construction. Format 2 specimens were tested under horizontal bending simulating a wall with span parallel to bed joints, which in normal masonry construction is laterally supported by i.e. returns. The wallets of each format were tested under four point loading. The load was applied by using a hydraulic jack connected to a loading cell.

For comparison similar specimens with horizontal joints laid in mortar and vertical joints dry-stack also were constructed and tested in a similar manner. A dial gauge was used to monitor the deflection at the middle of the specimen. The values of the two orthogonal directions obtained were used to determine the orthogonal ratio for the masonry tested. The procedure followed in this investigation is not standard since to the knowledge of the author, no such experiments have been performed before.

5.2 Flexural Test of the Specimens under Vertical Bending.

5.2.1 Introduction

Wallettes of format 1 were constructed and tested under four-point load as shown in Figure 5.1. The wallettes were 1495 mm high (13 courses) and 960 mm long (4 blocks). The dimensions of the interlocking blocks used were 240 mm length x 115 mm height x 220 mm width as shown in Figure 5.2. The positions of the outer bearings were about 100 mm from the edges of the wallettes under test. The spacing of the inner bearing was 640 mm, about 0.5 times that of the outer bearing (see Appx. C). The wallettes were dry stacked and tested immediately. No special treatment i.e. curing and age considerations, was required as in conventional masonry. To minimise the friction at the bottom of the specimens, pieces of maisonette with rollers between them were first laid and then the wallettes were built on top. Loading from the hydraulic jack supported to a rig frame was transmitted to the rigid steel frame then to the bearings. Rubber packing was introduced between the steel bearings and the specimen for protection. The load was applied at a rate of approximately 1.0 kN/min. The deflection of the specimen at the middle was monitored using a dial gauge.



(a) elevation b) side view

Figure 5.1 Wallette set up

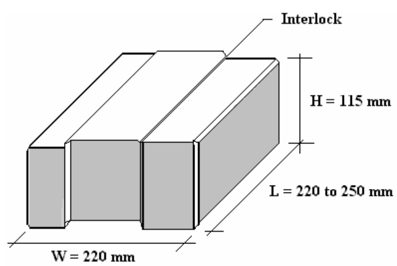
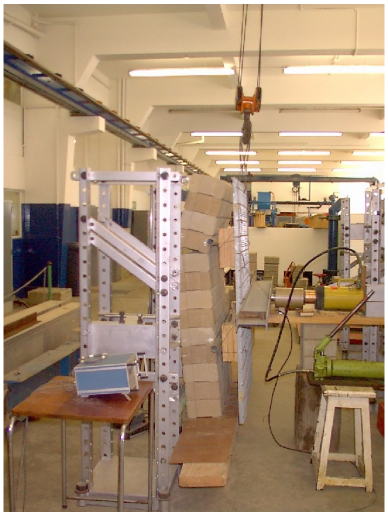


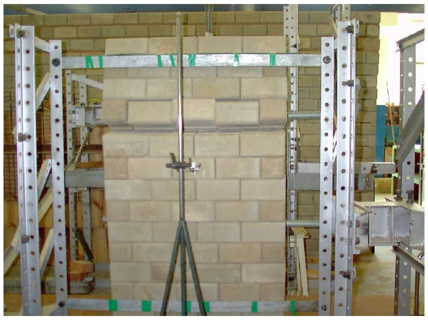
Figure. 5.2 Interlocking Block

5.2.2 Testing of 9 MPa specimens all joints dry-stack

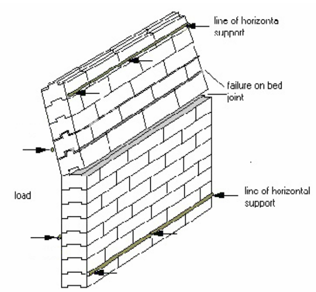
Three similar specimens of 9 MPa units strength were constructed and tested as shown in Figure 5.1. Figure 5.3 shows the typical mode of failure of the specimens tested under vertical bending, which was characterised by the load-deformational response with load increase. This was also accompanied by the gradual opening of the bed joints above the mid-section stretching across the entire length of the specimen. The average ultimate load at the point of failure was 1.5 kN. See test results summary in Appendix C-1. At the failure load, the maximum opening of the bed joints due to the rotation of the units along vertical axis was observed to be about 50 mm, resulting into sliding of the units out of the interlocking mechanism. The specimens continued to deflect with decrease of lateral pressure resistance allowing further rotation of the units before the loading was stopped. All the vertical joints practically remained closed. Failure of the interlocking mechanism by shear was also observed around the failure zone. The bottom section of the specimens experienced insignificant deflection likely due to the self-weight of the specimen.



(a) side view



(b) elevation



c) isometric view

Figure. 5.3 Typical mode of failure wallette format 1

5.2.3 Testing of 16 MPa specimens all joints dry-stack

Four similar specimens of 16 MPa units strength were constructed and tested in a similar manner under vertical bending (Fig. 5.1). Typical mode of failure was also similar to the 9 MPa specimens with average ultimate load of 2.0 kN at point of failure. All vertical joints practically remained closed. Failure of the interlocking mechanism by shear was also observed; fewer units failed as compared to 9 MPa specimens. The summary of the test results is shown in Appendix C-3.

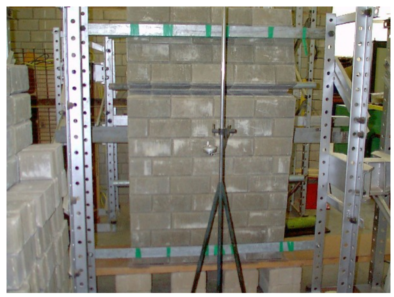


Figure 5.4 Typical mode of failure 16 MPa specimens

5.2.4 Testing of 9 MPa specimens with horizontal joints laid in mortar and vertical joints dry-stack

Two specimens of 9 MPa units strength were constructed in the laboratory with horizontal joints laid in ordinary sand cement mortar (1:3) and vertical joints dry-stack. The specimens were constructed on a timber base to enable lifting to the testing rig without structural disturbance. The specimens were cured and tested at the age of 14 days. The specimens were of similar dimensions as the dry-stack specimens, and therefore tested under vertical bending using similar test set-up and procedure as shown in Figure 5.1. Typical mode of failure was characterised by the tensile failure of the specimen between the loading points, followed by opening of the horizontal joints of an entire course above the mid-section as shown in Figure 5.5. The average failure load was 2.25 kN. The summary of the test results is shown in Appendix C-5.

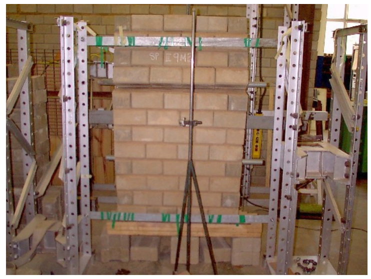


Figure 5.5 Typical mode of failure 9 MPa specimen in mortar

5.2.5 Testing of 16 MPa specimens with horizontal joints laid in mortar and vertical joints dry-stack

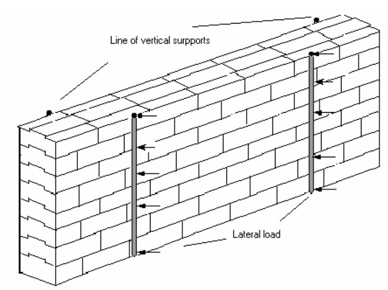
Two specimens of 16 MPa units strength were constructed in the laboratory with horizontal joints laid in ordinary sand cement mortar (1:3) and vertical joints dry-stack. The specimens were constructed on timber base to enable lifting to the testing rig without structural disturbance. The specimens were cured and tested at the age of 14 days. The specimens were of similar parameters as the dry-stack specimens and therefore tested under vertical bending using similar test set-up and procedure as shown in Figure 5.1. Typical mode of failure was characterised by the tensile failure of the specimen between the loading points above the mid section as shown in Figure 5.6. The average ultimate load was 3.10 kN. The summary of the test results is shown in Appendix C-7.

Figure 5.6 typical mode of failure 16 MPa specimens in mortar

5.3 Flexural Test of Specimens under Horizontal Bending

5.3.1 Introduction

Wallettes of Format 2 were constructed and tested under four-point load. The dimensions of the wallettes were 920 mm high (8 courses) and 1680 mm long (7 blocks). The positions of the outer bearings were 100 mm from the edges the wallettes under test. The spacing of the inner bearing was 660 mm. 9 MPa and 16 MPa interlocking blocks of 220 mm width x 115 mm height x 240 mm length, 4 mm depth of interlock were used. The specimens were loaded under four point loading and lateral pressure applied by means of a hydraulic jack supported by a rig frame. Figure 5.7 shows the experimental set up. Deflection at the middle of the wallettes was recorded using a dial gauge. The load was applied at a rate of approximately 1.0 kN/min.



(a) elevation (b) side view

Figure 5.7 Wallette format 2 - set up

5.3.2 Testing of 9 MPa specimens all joints dry-stack.

Three specimens made of 9 MPa units strength were constructed with all joints dry-stack. The typical mode of failure of the wallettes under horizontal bending was characterised by the gradual rotation of the units around the vertical axis with load increase leading into opening of the perpend joints in the area between the loading points (Fig. 5.8c) accompanied by the formation of uniform curvature to the entire section (Fig. 5.8 (a) and (b)). The average lateral load at failure was 12.4 kN. Failure of the interlocking mechanism by shear was also observed. The bed joints remained very tightly closed. A summary of the test results are shown in Appendix C-9.

(a) plan - before load removal

(b) plan- after load removal

c) elevation

Figure 5.8.Mode of failure wallette format 2 (9MPa) - under horizontal bending after load removal.

5.3.3 Testing of 16 MPa specimens all joints dry-stack.

Three specimens made of 16 MPa units strength were constructed with all joints dry-stack and tested under horizontal bending. The typical mode of failure was characterised by the gradual rotation of the units along the horizontal axis similar to 9 MPa specimens, with ultimate average lateral load of 14.4 kN at point of failure. Failure of the interlocking mechanism by shear was also observed. The bed joints remained very tightly closed. Figure 5.9 shows the typical mode of failure. A summary of the test results is shown in Appendix C-11.

Figure 5.9 Typical modes of failure 16 MPa specimens dry-stack

5.3.4 Testing of 9 MPa specimen with horizontal joints laid in mortar and vertical Joints dry-stacked

Two specimens made of 9 MPa units strength were constructed in the laboratory on a timber base to enable lifting of the specimen to the testing rig without structural disturbance. The specimens were cured and tested at the age of 14 days. The mode of failure was characterised by tensile failure of the vertical joints between the loading points (Fig. 5.10). The average load at the point of failure was 17.05 kN. A summary of the test results is shown in Appendix C-13.

Figure 5.10 Typical mode of failure 9 MPa specimens laid in mortar

5.3.5 Testing of 16 MPa specimen with horizontal joints laid in mortar and vertical Joints dry-stacked

Two specimens of 16 MPa units strength were constructed in the laboratory on a timber base to allow lifting to the testing rig without disturbing the specimen. The specimens were cured and tested at the age of 14 days. The mode of failure was characterised by tensile failure along the vertical joints between the loading points as shown in Figure 5.11. The average load at point of failure was 18.05 kN. A summary of the test results are shown in Appendix C-15.

a) specimen 1 b) specimen 2

Figure 5.11 mode of failure 16 MPa specimens in mortar

5.4 Flexural tests results discussion

5.4.1 Introduction

The average failure load obtained from the experiments was used to calculate the bending moment capacity of the wallettes. The gross sectional modulus was also calculated (ignoring the 4 mm tolerance between the interlocking mechanisms).

The ultimate normal stress was calculated based on the relation ship between bending moment and sectional modulus of the specimen as follows.

$$f = \frac{M}{S} \text{ ; } \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5.1)$$

Where

f = the ultimate normal stress

M = the bending moment.

S = the sectional modulus of the specimen.

$$S = \frac{bd^2}{6} \text{ ; } \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5.2)$$

Where b = width of the specimen

d = thickness of the specimen, 220 mm

Flexural strength calculations for the tested samples are shown in Appendix C and summarised in Table 5.1 and Table 5.2 below.

Table 5.1 Flexural strength results for fully dry-stack specimens

Units strength	Under vertical bending $f_{kxparal-dry}$	Under horizontal bending $f_{kxperpend-dry}$
MPa	N/mm²	N/mm²
9	0.03	0.15
16	0.04	0.17

Table 5.2 Flexural strength results for the specimens (partially dry-stack) bed joints in mortar and perpend joints dry-stack

Units strength	Under vertical bending $f_{kxparal-pdry}$	Under horizontal bending $f_{kxperpend-pdry}$
MPa	N/mm²	N/mm²
9	0.05	0.21
16	0.07	0.23

5.5 Orthogonal ratio

Conventional masonry is not isotropic (Curtin *et al,* 1995), i.e. does not have similar properties in all directions, and therefore does not provide the same resistance to bending in both directions. The ratios of the values of the respective flexural strengths when spanning vertically and horizontally is defined as the orthogonal ratio, which is used primarily for the calculation of bending moment resistance in panel wall design (Henry *et al*, 1997). Similarly test results suggest that dry-stack masonry does not provide the same resistance to bending in both directions. Orthogonal ratios were calculated using the formula below and the results are given in Table 5.3.

Orthogonal ratio fully dry -stack masonry; $\mu_{dry} = \dfrac{f_{kxparal-dry}}{f_{kxperp-dry}}$ ……………… (5.3)

Orthogonal ratio partially dry-stack masonry: $\mu_{pdry} = \dfrac{f_{kxparal-pdry}}{f_{kxperp-pdry}}$ …………(5.4)

Table 5.3 Calculated Orthogonal ratio

Orthogonal ratio			
Fully dry-stack (μ_{dry})		Partially dry-stack (μ_{pdry})	
9 MPa	0.2	9 MPa	0.24
16 MPa	0.23	16 MPa	0.30

5.6 Discussion

Wallettes Format 2 tested under horizontal bending performed better than wallettes Format 1 tested under vertical bending. The result in Table 5.1 suggests that the dry stack masonry investigated, the flexural strength perpendicular to bed joints is about four times the flexural strength parallel to bed joints. For samples spanning normal to bed joints the bending strength of the bonded specimen is about 60% higher than the dry-stack samples. For samples spanning parallel to bed joints the bending strength of the bonded specimen is about 35% higher than dry-stack samples. The unit strength had no significant influence to the bending strength.

The flexural strength of conventional masonry is largely a function of bond strength between the mortar and the units and the tensile strength of the mortar itself. According to SABS 0164 the flexural strength of conventional masonry under vertical bending depending on the mortar class and the unit compressive strength is between 0.1 N/mm^2 to 0.7 N/mm^2, and under horizontal bending the range is between 0.2 N/mm^2 to 2.0 N/mm^2. The same values are reported in the British code BS 5628. Table 5.4 shows the comparison of allowable stress in flexure between the tested system and conventional masonry.

In the absence of bonding mortar between the joints, the flexural strength of the dry-stack masonry relies on other factors, i.e. friction and the interlocking mechanism of the units. In this investigation the blocks used have “tongued & grooved” type interlocking on the bed and perpend face. The perpend face interlocking mechanism provides good lateral stability to the system. Figure 5.12, shows a column of blocks, which has fallen out of a palette-demonstrating the capability of the interlocking mechanism to hold the units together. The blocks are held together by the bed face interlocking mechanism.

According to Curtin *et al*, (1995), in conventional masonry, the mechanism of unit-mortar adhesion is not fully understood. The mortar joint is considered to be the weakest element of masonry construction difficult to control its quality. Control of the unit manufacture, under factory conditions, may be fairly sophisticated, but control of workmanship on site is far more difficult and the greatest challenge in conventional masonry to date. In dry stacking with minimum use of mortar-bonded joints the control of workmanship on site is relatively easier; an added advantage of dry stacking.

Table 5.4 Comparison of Allowable Stress in Flexure

Type of construction	Mean block strength (MPa)	Mortar strength (MPa)	Allowable Flexural stress (MPa)		Remarks
			Tension normal to bed joint	Tension parallel to bed joint	
WITS dry-stack	9	-	0.15	0.03	Mortar less masonry (present study)
WITS dry-stack	16	-	0.17	0.04	Mortarless masonry (present study)
Conventional	-	5.2	0.21	0.41	N Mortar (ACI 530-92)
	-	12.4	0.28	0.55	S Mortar (ACI 530-92)
	-	17.2	0.28	0.55	M Mortar (ACI 530-92)
	$\geq$ 10.0	5.0	0.07	0.14	M1 Mortar (IS1905-87)
	$\geq$ 7.5	3.0	0.05	0.01	M2 Mortar (IS1905-87)

Source: (Anand 2000)*

Figure 5.12 Units - self-weight support by the interlocking mechanism

5.7 Conclusions

The following are the conclusions, which can be drawn, from the investigations;

1. Dry-stack masonry is not isotropic; it does not provide the same resistance to bending in both orthogonal directions.
2. The dry-stack masonry tested suggests that the flexural strength perpendicular to bed joints is about four times higher than across the bed joints.
3. In dry-stack masonry tested, vertical bending failure occurs as “hinge-like rotation” along a complete row of bed joints near the mid height of the wall.
4. In dry-stack masonry under horizontal bending, the failure line occurs along the dry-stack perpend joints.
5. In dry-stack masonry, in the absence of bonding mortar between the joints the interlocking mechanism in the units influences the flexural strength of the masonry.
6. The interlocking mechanism in the perpend face of the tested blocks, provides good lateral stability to the system.