A STUDY OF THE RELATIONSHIP BETWEEN UNIT, PRISM, AND WALL STRENGTH FOR HOLLOW MASONRY LOADED IN COMPRESSION

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ABSTRACT

Many masonry codes use small masonry specimens to predict the compressive strength of masonry. The Australian Masonry Code uses tests on either individual units or on stack bonded prisms for this purpose. However, a unit or prism test does not necessarily fully represent the behaviour of the masonry in a wall.

This paper describes an investigation of the relationship between wall strength and the compressive strength of hollow units and prisms with particular reference to the Australian Masonry Code. A series of tests were carried out on a range of units and prisms and wallettes constructed from those units. The tests revealed that both the unit and prism strengths were consistently greater than the wall strength, with the best correlation of wall strength being with the 28 day prism strength rather than with the 7 day value as used in the Australian Code. The compressive wall capacity predicted by the Code was consistently much lower than that observed in the tests, indicating that there could well be a case for increasing the value of the capacity reduction factor in the Code provisions.

INTRODUCTION

The Australian Masonry Code AS3700 uses tests on either individual units or on stack bonded prisms to predict the compressive strength of masonry. For face-shell bedded hollow masonry, compression tests can be performed on individual units using face-shell capping, and the masonry compressive strength estimated from the Code for a given mortar type. Alternatively, prism tests can be used to predict the compressive strength. Prisms must be at least two courses high, face-shell bedded and tested using face-shell capping.

A unit or prism test does not necessarily fully represent wall behaviour even if the same unit, mortar strength and bedding type are used. The observed strength in a unit or prism tests can also be influenced by unit or prism geometry (width, height, and number of courses), platen restraint, and other factors (1). The use of a 2 high prism, although convenient, will tend to exacerbate these effects. A prism with at least 3 courses will be more representative of wall behaviour (2).

Because there is no uniformity between different standards, various Codes give different relationships between the unit, prism, and masonry strength. Despite the large number of previous investigations into the behaviour of hollow masonry, the bulk of these studies have related to the unit and prism strength rather than wall strength. The study reported here is a preliminary investigation of the relationship between unit, prism, and wall strength with particular reference to Australian materials and methods.
THE COMPRESSIVE BEHAVIOUR OF FACE–SHELL BEDDED HOLLOW MASONRY

Face–shell bedded hollow masonry subjected to uniaxial compression typically fails through cracking of the web of the units in a plane parallel to the face of the wall: the wall splits in two in its own plane. Shrive (3) has shown that the splitting is caused by tensile stresses at the top and bottom of the centres of the web spanning between the loaded face–shells. The stresses develop from non–uniform stress flow through the units. In carrying out small specimen testing to predict wall strength, it is therefore important that all specimens be face–shell bedded where appropriate, and tested with face–shell capping to induce a failure mechanism as similar as possible to that in the wall (although the wall strength will still be less than that of a unit or prism due to unavoidable differences in size, geometry, etc.).

EXPERIMENTAL PROGRAMME

The experimental programme was aimed at studying the relationship between unit, prism, and wall strength, all loaded in uniaxial compression. Loading eccentricities can change these values significantly both for prisms (4) and for walls (5). The AS3700 provisions are based on the assumption that prisms are concentrically loaded and that eccentricity effects in walls are included in the reduction factor for slenderness and eccentricity.

Three types of hollow concrete units and one hollow clay unit were used in the study. Uniaxial compression tests were performed on individual units, prisms, and wallettes made from these units. A mortar consisting of 1:1:6 (cement:lime:sand) by volume was used for the clay masonry. A 1:0:5 mortar with a methyl cellulose water thickening agent was used for the concrete masonry tests. All the masonry units and mortar ingredients were sampled from the same batch. For the initial mix, the mortar ingredients were batched by volume and weighed. All subsequent mixes were then batched by weight for consistency. The same bricklayer was used throughout the investigation. A summary of the units used is given in Table 1. For the concrete units, all three of the transverse webs were of the same approximate thickness, tapering from the top. However the clay units had a central web which was more than twice the thickness of the end web. This has important ramifications, as it means that for masonry laid in running bond, the central web will be aligned with the end webs of the adjacent units in the course above. Even when the masonry is laid in face–shell bedding, a certain degree of additional support will therefore be provided. This is not the case for the concrete units when no webs align in adjacent courses.

Two sets of tests were performed for each unit type: one set of unit and prism tests when the prisms were 7 days old (using the AS3700 procedures); another set of unit and prism tests in conjunction with the wallette tests at an age well in excess of 28 days to simulate the final wall strength.

UNIT AND PRISM TESTS

The units were tested dry in uniaxial compression with plywood capping 4–6 mm thick on the face–shells. Ten replicates were tested in each case. One set of tests was performed 7 days after the construction of the prisms (in parallel with the prism tests). The other set was performed at the same time as the corresponding wallette tests.

Prism tests were performed at 7 days and in conjunction with the wallette tests. All prisms were two units high and face–shell bedded. Plywood face–shell capping was again used. The prisms were cured in the standard manner under a vapour proof sheet for 7 days and then
allowed to stand in the laboratory until tested. The compressive strength of both units and prisms were calculated using the minimum face–shell area as required by AS3700. Typical unit and prism tests are shown in Figure 1.

TABLE 1. DETAILS OF MASONRY UNITS

<table>
<thead>
<tr>
<th>Series</th>
<th>Unit Type</th>
<th>Dimensions $w \times h \times l$ (mm)</th>
<th>Material</th>
<th>Minimum Face–Shell Area (mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.01</td>
<td>$190 \times 190 \times 390$</td>
<td>Concrete</td>
<td>23790</td>
</tr>
<tr>
<td>2</td>
<td>15.01</td>
<td>$140 \times 190 \times 390$</td>
<td>Concrete</td>
<td>19890</td>
</tr>
<tr>
<td>3</td>
<td>10.01</td>
<td>$90 \times 190 \times 390$</td>
<td>Concrete</td>
<td>20670</td>
</tr>
<tr>
<td>4</td>
<td>Clay</td>
<td>$190 \times 90 \times 290$</td>
<td>Clay</td>
<td>20860</td>
</tr>
</tbody>
</table>

$w$ = width; $h$ = height; $l$ = length.

FIGURE 1. UNIT AND PRISM TESTS
WALLETTE TESTS

The concrete masonry wallettes were 7 courses high and 3 courses wide (1190 mm long x 190 mm thick x 1390 mm high); the clay wallettes were 14 courses high and 4 courses wide (1220 mm long x 140 mm thick x 1395 mm high). The wallettes were built in the laboratory and air cured until tested. Each specimen was tested in uniaxial compression in a loading frame at an age well in excess of 28 days to approximate the final masonry strength. The load was applied from the frame through the face-shells only by seating the top and bottom of the wallette on plaster which was only in contact with the face-shells. After a small initial pre-loading to seat the specimen, the load was applied monotonically to failure. Five wallettes were tested for each unit type. Vertical and horizontal deformations were measured at corresponding locations on each side of the wallettes using linear potentiometric displacement transducers (LPDTs) over gauge lengths which encompassed several bricks and joints. Web splitting in the plane of the wall was monitored by means of LPDTs mounted normal to the wall at three locations on each side of the specimen. A typical testing arrangement is shown in Figure 2.

TEST RESULTS

Units and Prisms

Both units and prisms failed in a predictable manner, with web splitting being the dominant mechanism. In some cases this was accompanied by spalling in one or both of the face-shells. Most of the spalling of the prisms took place adjacent to the joint after initial web cracking. A summary of the test results is given in Table 2. All strengths are based on minimum face-shell area as required by the Australian Masonry Code AS3700. The values of $X_c$ are 95% characteristic strengths calculated in accordance with AS3700. (These procedures account for both sample variability and sample size).

FIGURE 2. WALLETTE TESTING ARRANGEMENT
TABLE 2. UNIT AND PRISM STRENGTHS (MPa)

<table>
<thead>
<tr>
<th>Unit Type</th>
<th>7 Day Test</th>
<th>Strength at Wallette Test Date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit</td>
<td>Prism</td>
</tr>
<tr>
<td></td>
<td>X</td>
<td>V (%)</td>
</tr>
<tr>
<td>20.01</td>
<td>25.8</td>
<td>9.3</td>
</tr>
<tr>
<td>15.01</td>
<td>33.5</td>
<td>6.5</td>
</tr>
<tr>
<td>10.01</td>
<td>26.3</td>
<td>9.5</td>
</tr>
<tr>
<td>Clay</td>
<td>33.6</td>
<td>9.8</td>
</tr>
</tbody>
</table>

X = mean; V = coefficient of variation; Xc = 95% characteristic strength.
For age of wallettes at test, see Table 3.

TABLE 3. WALLETTE STRENGTHS

<table>
<thead>
<tr>
<th>Unit Type</th>
<th>Dimens (lxw)xh (mm)</th>
<th>n</th>
<th>Average Test Age (Days)</th>
<th>X (kN)</th>
<th>V (%)</th>
<th>Xc (kN)</th>
<th>Bedded Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.01</td>
<td>1190x190x1390</td>
<td>5</td>
<td>83</td>
<td>1274</td>
<td>16.0</td>
<td>671</td>
<td>72590</td>
</tr>
<tr>
<td>15.01</td>
<td>1190x140x1390</td>
<td>4</td>
<td>210</td>
<td>1190</td>
<td>3.6</td>
<td>835</td>
<td>60690</td>
</tr>
<tr>
<td>10.01</td>
<td>1190x190x1390</td>
<td>5</td>
<td>162</td>
<td>1215</td>
<td>9.8</td>
<td>763</td>
<td>63070</td>
</tr>
<tr>
<td>Clay</td>
<td>1220x140x1395</td>
<td>5</td>
<td>227</td>
<td>1950</td>
<td>19.4</td>
<td>1093</td>
<td>85400</td>
</tr>
</tbody>
</table>

n = number of specimens; X = mean capacity; Xc = 95% characteristic capacity; V = coefficient of variation.

It can be seen that the mean prism strengths increased significantly with age. Increases from the 7 day strength to the date of wallette testing ranged from 10% to 50%. Changes in unit strengths over these same period were much less consistent and could have been mainly a function of sample variability, particularly for the clay masonry units.

Wallettes

All wallettes were tested well in excess of 28 days when their strengths would have been expected to have reached a constant value. The wallette capacities are summarised in Table 3. The characteristic values have been calculated in accordance with AS3700 allowing for the small sample size, and could change with a larger sample. For the clay masonry wallettes, the
bedded area used in the ultimate strength calculation included a 20% increase in the face-shell area to allow for the contribution of the cross-webs. This proportion was established by inspection of the wallette bed joints after failure.

All the wallettes displayed a similar failure mode. Failure occurred by vertical splitting of the web of the units in the plane of the wallette. In some cases, especially for the 10.01 units, the failure was explosive. In other cases the failure was more gradual with progressive splitting of the web of the units occurring.

Theoretical and experimental studies (2, 6) have shown that the cracking of the web occurs progressively as the load is increased. Final failure takes place when sufficient webs have failed to cause wall instability. In these tests, cracking could be heard at load levels well below the ultimate in some cases, and this was confirmed by the LPDT readings. However the results were not conclusive due to the small number of monitoring positions, and no detailed conclusions can be drawn with regard to the model of progressive failure. More elaborate testing is proposed to study this mechanism in more detail. Examples of failure modes for the concrete and clay masonry are shown in Figure 3.

**RELATIONSHIP BETWEEN UNIT, PRISM, AND WALL STRENGTH**

Table 4 gives the comparative values for the mean strengths of the units, prisms, and wallettes. Comparisons have been made for the strengths of prisms at 7 days (the AS3700 curing period) and for prisms the same age as the wallettes. If the influence on strength of all other factors such as material type and unit size and type is neglected, the results can be pooled and more general conclusions made about the various relationships (although the sample size is still small).
TABLE 4. UNIT, PRISM, AND WALL STRENGTHS  
(All mean values in MPa)

<table>
<thead>
<tr>
<th>Unit Type</th>
<th>Unit Strength (7)</th>
<th>Unit Strength (&gt; 28)</th>
<th>Prism Strength (7)</th>
<th>Prism Strength (&gt; 28)</th>
<th>Wallette Strength (7)</th>
<th>Wallette Strength (&gt; 28)</th>
<th>Wallette Unit (7)</th>
<th>Wallette Prism (7)</th>
<th>Wallette Prism (&gt; 28)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.01</td>
<td>25.8</td>
<td>28.2</td>
<td>22.4</td>
<td>25.5</td>
<td>17.6</td>
<td>0.62</td>
<td>0.79</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>15.01</td>
<td>33.5</td>
<td>30.8</td>
<td>15.5</td>
<td>22.9</td>
<td>19.6</td>
<td>0.64</td>
<td>1.26</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>10.01</td>
<td>26.3</td>
<td>28.5</td>
<td>17.2</td>
<td>24.4</td>
<td>19.3</td>
<td>0.68</td>
<td>1.12</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>33.6</td>
<td>28.5</td>
<td>19.8</td>
<td>21.7</td>
<td>19.0</td>
<td>0.66</td>
<td>0.96</td>
<td>0.88</td>
<td></td>
</tr>
</tbody>
</table>

Average X = 0.65  1.03  0.80
σ = 0.02  0.18  0.07
V (%) = 3.4  17.0  9.0

σ = standard deviation; V = coefficient of variation.

It can be seen that the most consistent correlations occur between unit strength and wallette strength and prism strength and wallette strength, when the units and prisms are the same age as the wallette (the units will in fact be older than this depending on their date of manufacture). The relationship between the 7 day prism strength and wallette strength (the AS3700 procedure) is more variable. This may be due to varying rates of strength increase with age. For practical purposes the disadvantage of increased variability will be offset to some extent by the convenience of a 7 day test as a means of quality control on site.

PREDICTIONS OF WALL STRENGTH BY AS3700 PROCEDURES

The design capacity of a wall is given in AS3700 as

\[ F_{\text{design}} = C_m K f'_m A_b \]

where

- \( C_m \) = capacity reduction factor = 0.45 for compression
- \( K \) = reduction factor for slenderness and eccentricity
- \( f'_m \) = characteristic compressive strength of the masonry
- \( A_b \) = bedded area (i.e., the minimum face-shell area)

Comparisons can therefore be made between the observed wall capacities and Code predictions. In these predictions two values of \( f'_m \) can be used: a more conservative value derived from a lower bound empirical relationship between unit and masonry strengths, or derived directly from prism tests. The comparisons are shown in Table 5. It can be seen that the capacities are well in excess of predicted values even with the inclusion of the partial safety factor \( C_m \), indicating that there may well be grounds for an increase in the value of this capacity reduction factor.
TABLE 5. PREDICTED AND OBSERVED WALL CAPACITIES
(Characteristic Values)

<table>
<thead>
<tr>
<th>Unit Type</th>
<th>Predicted Capacity (I) (kN)</th>
<th>Predicted Capacity (II) (kN)</th>
<th>Expt’l Capacity (kN)</th>
<th>Expt’l Pred. (I)</th>
<th>Expt’l Pred. (II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.01</td>
<td>216.4</td>
<td>504.9</td>
<td>671</td>
<td>3.1</td>
<td>1.3</td>
</tr>
<tr>
<td>15.01</td>
<td>194.7</td>
<td>283.6</td>
<td>835</td>
<td>4.3</td>
<td>2.9</td>
</tr>
<tr>
<td>10.01</td>
<td>130.8</td>
<td>244.1</td>
<td>763</td>
<td>5.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Clay</td>
<td>270.5</td>
<td>490.4</td>
<td>1093</td>
<td>4.0</td>
<td>2.2</td>
</tr>
</tbody>
</table>

CONCLUSION

This study has investigated the relationship between unit, prism, and wall strength for a range of hollow masonry units with particular reference to the provisions of the Australian Masonry Code. The tests revealed that both the unit and prism strength were consistently greater than the wall strength, with the best correlation of wall strength being with prism strength obtained by testing the prism at the same age as the wall, rather than at 7 days as is the current requirement. The compressive wall capacity predicted by the Code provisions was consistently much lower than that observed in the tests, indicating that there could well be a case for increasing the value of the capacity reduction factor in the Code provisions.

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REFERENCES


