FAILURE OF HOLLOW MASONRY SUBJECTED TO CONCENTRATED LOADS

A.W. Page
Senior Lecturer
Department of Civil Engineering & Surveying
The University of Newcastle
N.S.W. 2308, Australia

N.G. Shrive
Professor
Department of Civil Engineering
The University of Calgary
Calgary, Alberta T2N 1N4 Canada

ABSTRACT

Codes of practice typically allow enhancement of bearing stress beneath concentrated loads acting on both solid and hollow masonry because of the confining effect of the adjoining lightly stressed material. However, while this is true for solid masonry, hollow masonry behaves in a substantially different manner, particularly when face-shell bedded. When subjected to uniform compression, face-shell bedded hollow masonry typically fails through cracking of the webs of the units in a plane parallel to the face of the wall due to deep-beam bending of the webs between the loaded face-shells. Here, hollow masonry subjected to concentrated loading is shown to fail in a similar manner by splitting of the webs in the region local to the concentrated load. 83 wallettes of hollow clay and concrete masonry were constructed and subjected to concentrated loads through various sized loading plates. Masonry was tested both plain and with bond beams beneath the loading plate. Details of the experimental instrumentation are provided together with the failure mechanism. Theories of failure for solid walls subjected to concentrated load are shown not to be applicable to face-shell bedded hollow masonry.

INTRODUCTION

Masonry constructed of hollow concrete or clay units using face-shell bedding is common in both North American and Australasia. Concentrated loads are applied to such masonry through, for example, cross beams, roof trusses or prestressing anchorages. Codes of practice typically allow the resulting bearing stress to be higher than design axial stresses because of the confining effect of the adjoining lightly stressed material. This is true for solid masonry, but hollow masonry behaves in a substantially
different manner, especially when it is face-shell bedded.

Face-shell bedded hollow masonry subject to uniform compression typically fails through cracking of the webs of the units in a plane parallel to the face of the wall - that is, the wall splits in two in its own plane. The splitting is caused by deep-beam bending of the web [1]. Theoretical work has suggested that a similar mode of failure can be expected under concentrated loading [2]. This failure mode would be different to that of solid masonry subjected to concentrated loading where cracking occurs under the point of application of the load in a plane perpendicular to the wall [3 - 5]. An experimental study of the failure mechanism of hollow masonry subjected to concentrated loads was performed to assess the theoretical predictions. 83 hollow concrete and clay walllettes were constructed and subjected to concentrated load to failure. Plain masonry as well as one- and two-course bond beams were used in the walllettes. The concentrated load was applied through loading plates of 3 different sizes. The methods used to monitor cracking and failure are described and the failure mechanism observed is discussed. The failure of hollow masonry under concentrated loading is revealed to be a "local" phenomenon, and theories of failure for solid walls subjected to concentrated loading are not applicable to hollow walls.

MATERIALS AND METHODS

Some details of the first stage of the experimental programme have been reported previously [6]. This first stage was aimed at confirming the theoretical predictions [2] and the critical parameters governing the failure of hollow masonry subjected to concentrated loads. A second series of tests was then carried out to examine in particular the mechanism of load dispersion beneath the concentrated load.

Two types of hollow masonry were built, one using standard concrete units, the other using hollow clay units, as shown in Figure 1. All masonry was constructed in running bond using face-shell-bedding and a pre-batched Type N mortar (1:1:6 cement:lime:sand by volume). A weak rather than a strong mortar was used to provide a lower bound to the results. All masonry was built in the laboratory by an experienced masonry using normal construction procedures. A summary of the unit, mortar and masonry properties (using relevant Canadian standards) is given in Table 1.
Summary of Component and Masonry Strengths. Units and prisms were tested in face-shell bedding using fibre board strips as capping. Compressive strengths were calculated using a nominal face-shell-bedded area of 27,300 mm². Mortar and prisms were tested at 28 days.

<table>
<thead>
<tr>
<th>Nominal Dimensions</th>
<th>No. in Sample</th>
<th>Compressive Strength Mean ( \sigma ) N/mm²</th>
<th>C.V. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Unit 400 x 200 x 200</td>
<td>10</td>
<td>18.9</td>
<td>10.3</td>
</tr>
<tr>
<td>Clay Unit 400 x 100 x 200</td>
<td>10</td>
<td>45.9</td>
<td>9.8</td>
</tr>
<tr>
<td>Mortar 50 mm Cube</td>
<td>100</td>
<td>7.6</td>
<td>12.3</td>
</tr>
<tr>
<td>Concrete Masonry Prism (2 High) 400 x 400 x 200</td>
<td>18</td>
<td>16.8</td>
<td>11.3</td>
</tr>
<tr>
<td>Clay Masonry Prism (2 High) 400 x 200 x 200</td>
<td>15</td>
<td>27.4</td>
<td>14.6</td>
</tr>
</tbody>
</table>

The wallettes were 4 units long x 7 courses high for the concrete masonry, and 3 units long x 10 courses high for the clay masonry. These were considered large enough to be representative of walls of these materials. All masonry was air cured in the laboratory for at least 28 days before testing. A summary of the range of wallettes and masonry types is given in Table 2.
TABLE 2
Summary of Wallette Types Tested

<table>
<thead>
<tr>
<th>Type</th>
<th>Bond Beam (Courses)</th>
<th>No. of Specimens</th>
<th>Dimensions 1xhxt (mm)</th>
<th>Loading Plate Widths (mm)</th>
<th>Test Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>A1</td>
<td>1</td>
<td>21</td>
<td>1600x1400x200</td>
<td>160, 240, 320</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>2</td>
<td>21</td>
<td>1600x1400x200</td>
<td>160, 240, 320</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>-</td>
<td>4</td>
<td>1600x1400x200</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>A4</td>
<td>-</td>
<td>3</td>
<td>800x1400x200</td>
<td>800</td>
</tr>
<tr>
<td>Clay</td>
<td>B1</td>
<td>2</td>
<td>21</td>
<td>1200x1000x200</td>
<td>120, 180, 240</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>-</td>
<td>8</td>
<td>1200x1000x200</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>-</td>
<td>5</td>
<td>600x1000x200</td>
<td>600</td>
</tr>
</tbody>
</table>

* C = Concentrated Load  
  E = Eccentric  
  U = Uniaxial Compression  
  A = Axial (Concentric)

The bond beams were reinforced with 2, 12 mm diam. mild steel deformed bars hooked at each end to ensure adequate anchorage [6]. Grouts with mean 28-day cylinder strengths of 9.2, 17.6, 21.6, 23.3, 30.2 and 33.6 N/mm² were used. Details of the bond beams, wallettes and loading configurations are shown in Figure 2.

The concentrated loads were applied through 40 mm thick steel bearing plates set on a plaster bed on the top of the specimens [6]. Three plate
widths were used for each masonry type (see Table 2), corresponding to loaded area ratios of 10%, 15% and 20%. Two types of loading were applied: concentric or with an eccentricity of t/6 (Figure 2). For wallets with no bond beam, the load was applied directly over the hollow core with the plate bearing only on the face-shells (simulating, for example, the loading of a post-tensioned anchorage), and also centrally over the web of the unit. An overall view of a test is shown in Figure 3.

There were three objectives for the instrumentation used during the test: (i) to monitor web cracking in the plane of the wall; (ii) to monitor possible critical cracking beneath the load in a plane normal to the wall (the usual failure mode for solid masonry); and (iii) to assess the degree of load dispersion to the masonry through the bond beam. Deformations were monitored using linear potentiometer displacement transducers (L.P.D.T.s) typically located as shown in Figures 4 and 5.

Progressive web splitting was monitored by measuring the lateral spread of the wall in the through-the-thickness direction by mounting L.P.D.T.'s normal to the wall surface on each side of the specimen on an independent frame. Vertical cracking was measured by L.P.D.T.s mounted on the specimen on a 500 mm horizontal gauge length. In some tests, the degree of load dispersion was monitored by measuring vertical strains immediately below the bond beam in the region of the load by means of L.P.D.T.s mounted externally, and internally by resistance strain gauges glued to the inside of the hollow units before laying. The output from the transducers was fed directly into a data acquisition allowing displacements to be plotted during the test. Progressive vertical and web cracking was readily observed. The load was applied monotonically to failure in each test.

RESULTS & DISCUSSION

All 63 specimens with bond beams exhibited similar failure characteristics. The webs in the region directly beneath the concentrated load in the underside of the bond beam and in the first course immediately below consistently split first. This web splitting commenced at quite low loads in conjunction with a fine vertical crack which formed normal to the plane of the wall in line with the load (similar to a crack which would form in a solid wall loaded in this manner). However, the fine vertical crack did not subsequently increase in width significantly or appear to influence the final failure of the wall. With increasing load, splitting of webs
FIGURE 3. Typical Testing Arrangement  FIGURE 5. Typical Instrumentation

FIGURE 4. Typical Instrumentation (Schematic)

-•-•-• : Longitudinal Displacement

• : Lateral Displacement
progressed along the top course of the hollow masonry and into the courses beneath. The wallette sustained increasing load until sufficient webs had split to cause collapse. There was always very little external evidence of the extensive internal web-splitting. When the concentrated load was applied eccentrically, separation of the loaded face-shell and the side of the bond beam also occurred. Typical examples of the web and bond beam cracking are shown in Figure 6.

An indication of the cracking sequence can be obtained from the displacement readings. Typical results for clay masonry are shown in Figures 7 to 9. The results for concrete masonry are similar. The displacements of the first course below the bond beam (Figure 7), reveal that initial web splitting occurs at the same load as the formation of the vertical crack (about 50% of ultimate). As the load is increased, the size of the web split increases dramatically whereas the vertical crack remains relatively stable. This corresponds to the propagation of web

a) Typical Web Splitting in the First Course below the Bond Beam

(b) Longitudinal Cracking of Underside of Bond Beam

FIGURE 6. Typical Failure for Masonry with Bond Beams (Note the undamaged external appearance of the masonry despite extensive internal web cracking).
splitting along and down the wall, and up into the bond beam. The sequence of splitting down the wall and the total lateral dilation of the wall with increasing load can be seen from Figures 8 and 9.

Previous theoretical work [2, 7] had suggested a possible transition from failure being governed by flexural failure of a weak bond beam to failure being governed by the strength of the underlying masonry. However, the wide range of bond beam grout strengths did not influence the wallette strength or the mode of failure significantly. Results for the concentric loading case are shown in Figure 10. Adequate longitudinal reinforcement was provided by current practice and through-the-wall strength was sufficient even with the weakest grout.

With the limited number of tests on plain masonry, only general observations can be made. Factors such as the size and thickness of the loading plate would be expected to exert more influence than for wallettes reinforced with a bond beam, where local effects are first absorbed by the beam rather than the masonry [2, 7].

For the case of the load applied through a bearing plate directly over a web of both the concrete and clay units, failure again occurred by a combination of vertical cracking normal to the plane of the wall and progressive web-splitting leading to final collapse.

When the load was applied over a hole with the bearing plate spanning between the face-shells, clay masonry still failed by progressive web-splitting with some local spalling of the face shells beneath the loading

![FIGURE 7. Cracking in First Course Below Bond Beam](image-url)
FIGURE 8. Web Cracking Sequence

FIGURE 9. Dilation of Wallette Under Concentrated Load
plate. However, concrete masonry failed by local splitting of the loaded face-shells directly in line with the edge of the plate (the typical tearing stress failure).

In all cases of web-splitting, failure was more localized than for the equivalent bond beam cases. Further, the web-splitting commenced at approximately 60% of the ultimate load, a factor which could be significant in the post-tensioning of hollow masonry. The capacity of the masonry was greater when loaded directly over a web, and when the load was applied concentrically rather than eccentrically.

It is important to note that the mechanism of failure of hollow masonry, through web splitting, is completely different to that of solid masonry [3-5]. Design rules which have been formulated for solid walls will therefore not necessarily be applicable to face-shell-bedded hollow masonry and indeed do not appear to be so. The strengths measured in the tests are compared in Table 3 with the strengths of equivalent solid walls, calculated using standard concrete/masonry strength enhancement theory [8]. The strength of hollow clay masonry is grossly overestimated in all cases. For hollow concrete masonry, the method is conservative.
Comparison of strength of the wallettes to the equivalent strength of a solid wall of thickness equal to that of the two face-shells, using standard concentrated load stress enhancement theory [8].

<table>
<thead>
<tr>
<th>Masonry Type</th>
<th>Loaded Area Ratio</th>
<th>Theoretical Average Stress (N/mm²)</th>
<th>Measured Failure Loads (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Failure Load (kN)</td>
<td>Over Bond</td>
</tr>
<tr>
<td>Clay</td>
<td>0.10</td>
<td>13.2</td>
<td>1018</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>14.1</td>
<td>1085</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>14.7</td>
<td>1130</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.10</td>
<td>2.5</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
<td>2.7</td>
<td>299</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>2.8</td>
<td>311</td>
</tr>
</tbody>
</table>

* The average compressive stress in the masonry from a concentrated load given a lateral tensile stress equal to the splitting tensile strengths of individual units: (5.3 N/mm² for clay and 1.0 N/mm² for concrete).

a Test series 1, masonry strength 16.2 N/mm².

b Test series 2, masonry strength 18.8 N/mm².

The average compressive stress in the masonry from a concentrated load given a lateral tensile stress equal to the splitting tensile strengths of individual units: (5.3 N/mm² for clay and 1.0 N/mm² for concrete).

when bond beams are incorporated in the masonry, but the opposite for plain masonry.

CONCLUSIONS

The results of the study need further analysis and assessment. Subsequently, it should be possible to make recommendations concerning the rational design of hollow masonry subjected to concentrated loading. Meanwhile, the following preliminary conclusions can be drawn:

1. The failure mechanism for face-shell-bedded hollow masonry under concentrated load is fundamentally different to that of solid masonry. Failure occurs by progressive splitting of the webs of the hollow units in the region beneath the concentrated load, rather than by vertical cracking down the wall. Web-splitting occurs locally at relatively low loads and becomes more extensive as the load is increased.

2. For a bond beam of a given size and type, the strength of the grout in the bond beam did not influence significantly the capacity of the masonry to resist a concentrated load.

3. Despite (2) above, the use of a bond beam increased the load resis-
tance of the masonry because the load was partially dispersed by the beam before reaching the hollow masonry. The deeper the bond beam, the more effective was the load dispersion.

4. In the majority of cases, plain masonry walls subjected to a concentrated load also failed by web splitting. Plain masonry had a greater capacity to resist concentrated load applied over a web than over a core.

5. Design rules for predicting the strength of solid masonry are not directly applicable to hollow masonry.

ACKNOWLEDGEMENTS

The masonry units for this project were donated by IXL Industries Ltd., Medicine Hat, Alberta, and Allkind Masonry Concrete Products Ltd., Calgary, Alberta. The assistance of the technical staff of the Department of Civil Engineering, University of Calgary, particularly Mr. D. Tilleman, is most gratefully acknowledged. The contributions of the Local Chapter of the Union of Bricklayers and Allied Craftsmen and the Masonry Contractors Association were gratefully received. The financial support of the Natural Sciences and Engineering Research Council of Canada is acknowledged.

REFERENCES


