1. ABSTRACT

The failure pressures obtained in the tests on 24 full-sized masonry walls referred to in Part (I) of the paper have been compared with the predicted resistances obtained using yield line theory and the method for the design of laterally loaded masonry walls given in BS 5628: Part 1. The former predicted resistances have been calculated using orthogonal flexural strengths obtained from tests on wallets constructed with the same materials as the full sized walls. The latter predicted resistances have been calculated using the characteristic flexural strengths obtained from Table 3 of BS 5828: Part 1. It is concluded from the comparisons of the test results with the predicted resistances that reasonable answers are obtained using the wallette flexural strengths; use of the flexural strengths given in BS 5628: Part 1 over-estimates the predicted resistances of the test walls in the test programme.

2. INTRODUCTION

Part (I) of this paper referred to research that has shown that certain of the fine sands, used in the U.K. for the manufacture of masonry mortars, produce relatively

Keywords: Masonry; Walls; Lateral; Yield Line; Mortar.

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poor bond between masonry units and mortar. This is believed to result from the
presence of fine clay and silt particles in the sands concerned. The research
programme described in Part (I) has been carried out to investigate the effect of the
use of a fine G-grade sand upon the lateral strength of full sized walls. Both 'C' and
'U' shaped walls, with one free vertical edge and one free top edge respectively, see
Part (I) were included in the test programme. The 'C' shaped walls have been tested
because their lateral resistance is particularly sensitive to variations in flexural
strength in the weak direction.

The yield line method forms the basis of the design section of BS 5628: Part 1:
1992 (unchanged in this respect from 1978 Edition) that deals with laterally loaded
masonry walls. In order to investigate the effect of the fine sands on the design of
these walls to BS 5628: Part 1 analyses have been carried out using the characteristic
flexural strengths given in the Code, appropriate to the masonry units and the nominal
mortar designations used. Analyses have also been carried out, using the mean
flexural strengths obtained by the two independent laboratories from wallette tests,
to predict the resistance of the various walls in the test programme. These predicted
resistances have been compared with the experimental failure pressures. The use of
the yield line method for the analysis and design of laterally loaded masonry wall
panels has been considered in detail elsewhere (2) (3). It should be appreciated,
however, that the use of the yield line method for this purpose does not imply that
the cracks which form under ultimate loading are considered to be yield lines in the
sense that they are in reinforced concrete. The use of the method is largely empirical
although it is well known that masonry can behave in a non-linear manner and it also
exhibits a degree of plasticity (4). It is also significant that the yield line method deals
with a snapshot of the behaviour of laterally loaded panels at the point of ultimate
failure; it is of no interest from the point of view of the method how the panel
behaves prior to, or after, failure.

Figure and Table numbers in this Part follow on from those used in Part (I).

3. CALCULATIONS

3.1 Predicted Resistances

Calculation of the predicted resistances of the 20 walls tested at the University of
Plymouth and the 4 walls tested at British Ceramic Research Limited (BCRL) has
been carried out using characteristic flexural strengths obtained from BS 5628: Part
1 and mean flexural strengths from the wallette results obtained in the test
programme. The experimental wallette strengths and details of the walls themselves
are given in Tables 5 and 6 respectively of Part (I) of this paper. The BS 5628: Part
1 characteristic flexural and mean experimental wallette strengths are given in Table
7 of this Part.

The mean flexural strengths from the wallette tests, rather than the characteristic
strengths, have been adopted for prediction purposes because, whilst the latter values
are required in the context of design values, the purpose here is to see how closely
the method of analysis predicts the ultimate resistances. The variability of the
individual wallette results tends to depress the characteristic value of each set, especially in the weak direction of bending, and would thus lead to an underestimate of the ultimate resistance of the full sized wall tests.

3.2 Calculations to BS 5628: Part 1

The design method for wall panels subjected mainly to lateral loads, given in BS 5628: Part 1, is based on the yield line theory and is described as an approximate method. Bending moment coefficients are tabulated in the Code for a range of panels having different edge conditions (free, simple support or continuous support), orthogonal strength ratios (flexural strength in the strong direction of loading divided by that in the weak direction) and aspect ratios (height to length of panel). The design bending moment per unit length is given by:

\[ \alpha W_k \gamma_f L^2 \]

and the design moment of resistance is given by:

\[ \frac{f_{kx}}{\gamma_m} Z \]

Where
- \( \alpha \) is the bending moment coefficient
- \( \gamma_f \) is the partial safety factor for load
- \( L \) is the length of the panel between supports
- \( W_k \) is the characteristic wind load per unit area
- \( f_{kx} \) is the characteristic flexural strength
- \( \gamma_m \) is the partial safety factor for materials
- \( Z \) is the section modulus

By equating these expressions and solving for \( W_k \), the predicted resistance of the wall panel is obtained, taking the value of \( \gamma_f \) and \( \gamma_m \) as unity to enable direct comparison to be made with experimental failure pressures. BS 5628: Part 1 permits the self weight stress of the upper portion of a wall panel to be allowed for where it acts to increase the flexural strength of that panel. This is done by modifying the orthogonal ratio accordingly. In these analyses the increase is appropriate for the 'C' shaped panels with the top, bottom and one vertical edge supported; it is not appropriate for the panels with their top edges free. BS 5628: Part 1 does not, however, deal with edge supports intermediate between simple and continuous.

Although simple supports were provided to the vertical and top edges of the experimental walls, the effect of the self weight of the walls is to provide some degree of fixity along the bottom edge. The calculations have, therefore, been carried out, for comparative purposes, assuming a simple support to the bottom edge of the walls and again allowing for the partial fixity provided by the self weight of the wall.
3.3 Predictions Using Wallette Flexural Strengths

The method for calculating the predicted wall resistances based on the mean flexural strengths obtained from the wallette tests is effectively the same as used for the BS 5628: Part 1 calculations. Again, allowance has been made for the enhancement of the flexural strength in the weak direction as a result of the effect of the self weight of the upper portion of the walls, where appropriate, so that predicted resistances are given on the assumption of both a simple support at the base and allowing for partial fixity at the base due to self weight.

The University flexural strengths used for the AAC wall calculations are based on the 'docked' wallette results, as required by BS 5628: Part 1, Appendix Clause A.3.1. The flexural strengths used for the analyses of the SDP brick wall constructed with the lime mortar were also based on the 'docked' wallette results; however, those used for the wall built with plasticised mortar used the undocked wallette results. The reason for this is that SDP bricks often have a suction rate close to the critical value given in Appendix A3 to BS 5628: Part 1, above which bricks are required to be docked if the water retentivity of the mortar is not adjusted.

3.4 Summary of Calculations

Four predicted resistances have been calculated for each of the twenty-four walls, as described above. These predicted resistances are given in Table 8 corresponding to the following conditions:

(a) The use of mean wallette flexural strength obtained by the University and BCRL for their respective walls.
(b) The use of BS 5628: Part 1 values for characteristic flexural strength, \( f_{kx} \).
(c) The assumption of simple support at the d.p.c. for both cases a) and b).
(d) The assumption of partial fixity, due to self weight, at the d.p.c. for both a) and b).

The experimental failure pressures and calculated resistances have been plotted on Figures 3 and 4 for Conditions (a) and (b) respectively. The occurrence of the plotted results in pairs is due to the small differences in calculated loads for Conditions (c) and (d).

4. DISCUSSION OF RESULTS

4.1 Predictions Based on Wallette Results

In general, Figure 3 shows that the wall resistances calculated using the mean flexural strengths obtained from wallettes compare well with the experimental failure pressures from the corresponding full sized tests with the CS brick wall strengths being slightly underestimated in all cases. The worst prediction is for the walls built of MWA
Figure 3

Wall test failure pressure – calculated resistance based on code flexural strengths
Figure 4
Wall test failure pressure \( v \) - calculated resistance based on wallette results
bricks, one being overestimated and one being underestimated. This is a result of the mean wallette strength corresponding to each of the two full sized walls differing by a considerable amount (a factor of 2 in the weak direction). The resistance of one of the SDP walls is also significantly overestimated, this time because of the difference between the mean flexural strengths in the weak direction of the wallettes made with lime mortar (docked) and with plasticised mortar, the former being almost three times as strong.

4.2 Predictions Using $f_{kx}$ Values from BS 5628: Part I

It can be seen from Figure 4 that the use of BS 5628: Part 1 values of characteristic flexural strength produces calculated resistances which compare badly with the actual experimental failure pressures, in all cases overestimating the ultimate resistance. The reason for the poor comparison is that the mean flexural strengths obtained from the wallette tests are generally lower than the corresponding characteristic flexural strengths given in BS 5628: Part 1, see Table 7.

Table 7 Flexural strengths from wallettes and BS 5628: Part 1 used in analyses

<table>
<thead>
<tr>
<th>UNIT</th>
<th>DIRECTION OF FLEXURAL STRENGTH</th>
<th>FLEXURAL STRENGTHS (N/mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BS 5628 $f_{kx}$</td>
</tr>
<tr>
<td>ACC</td>
<td>Strong</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>Weak</td>
<td>0.25</td>
</tr>
<tr>
<td>CS</td>
<td>Strong</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Weak</td>
<td>0.3</td>
</tr>
<tr>
<td>SDP</td>
<td>Strong</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Weak</td>
<td>0.3</td>
</tr>
<tr>
<td>MWA</td>
<td>Strong</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>Weak</td>
<td>0.4</td>
</tr>
</tbody>
</table>

NOTE:

$f_{kx}$ values are characteristic values from BS 5628: Part 1: 1992.
Wallette values are mean values from Table 5 in Part 1.

Despite this, all results still fall on or above the minimum global factor of safety line shown on the Figures. This line represents the minimum overall factor of safety which would be used in the design of a laterally loaded wall and figure 4 shows that, even though the characteristic flexural strengths given in BS 5628: Part 1 are greater than the wallette strengths for this particular fine sand, design to BS 5628 would still result in a factor of safety of greater than unity.
### Table 8 Calculated resistance -v- test failure pressure

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>WALL REF:</th>
<th>CALCULATED RESISTANCE (kN/m²)</th>
<th>TEST FAILURE PRESSURE (kN/m²)</th>
<th>PANEL SHAPE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>USING WALLETTE MEAN FLEXURAL STRENGTHS</td>
<td>USING CODE f&lt;sub&gt;n&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>S.S.</td>
<td>P.F.</td>
<td>S.S.</td>
</tr>
<tr>
<td>Laboratory</td>
<td>See Table 6 Part (l)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AAC (lm) Plymouth (P/M)</td>
<td>1</td>
<td>1.22</td>
<td>1.30</td>
<td>1.39</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.91</td>
<td>1.04</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.42</td>
<td>0.47</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.66</td>
<td>0.74</td>
<td>0.79</td>
</tr>
<tr>
<td>AAC (lm) P/M</td>
<td>2</td>
<td>1.17</td>
<td>1.25</td>
<td>1.39</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.92</td>
<td>1.02</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.41</td>
<td>0.46</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.65</td>
<td>0.73</td>
<td>0.79</td>
</tr>
<tr>
<td>Calcil (lm) P/M</td>
<td>5</td>
<td>1.26</td>
<td>1.37</td>
<td>2.67</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>0.62</td>
<td>0.74</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.38</td>
<td>0.45</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.39</td>
<td>0.48</td>
<td>1.14</td>
</tr>
<tr>
<td>Calcil (pm) P/M</td>
<td>6</td>
<td>1.52</td>
<td>1.62</td>
<td>2.67</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>0.59</td>
<td>0.71</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.44</td>
<td>0.49</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>0.37</td>
<td>0.44</td>
<td>1.14</td>
</tr>
<tr>
<td>SDP (lm) P/M</td>
<td>17</td>
<td>1.80</td>
<td>1.99</td>
<td>1.72</td>
</tr>
<tr>
<td>SDP (pm) P/M</td>
<td>18</td>
<td>0.81</td>
<td>0.96</td>
<td>1.72</td>
</tr>
<tr>
<td>MWA (lm) P/M</td>
<td>19</td>
<td>1.39</td>
<td>1.66</td>
<td>2.20</td>
</tr>
<tr>
<td>MWA (pm) P/M</td>
<td>20</td>
<td>2.45</td>
<td>2.94</td>
<td>2.20</td>
</tr>
<tr>
<td>AAC (lm) BCRL</td>
<td>9R</td>
<td>0.49</td>
<td>0.55</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td>11R</td>
<td>0.35</td>
<td>0.40</td>
<td>0.74</td>
</tr>
<tr>
<td>Calcil (lm) BCRL</td>
<td>13R</td>
<td>0.61</td>
<td>0.67</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>15R</td>
<td>0.39</td>
<td>0.43</td>
<td>1.06</td>
</tr>
</tbody>
</table>

S.S. simple support 3 edges, 1 edge free.  
P.F. as S.S. but partial fixity to bottom edge.  
pm plasticised mortar, designation (iii).
4.3 Comparison of Laboratories

The calcium silicate wallets tested at both laboratories showed similar mean flexural strengths, although the failure pressures of the equivalent walls were higher at Plymouth, particularly for the 5.5m long wall. In the case of the AAC walls and wallets, the Plymouth results were higher in all cases, particularly for the strong direction wallette flexural strength and for the 2.7m long wall. In both these cases, the Plymouth results were twice those of BCRL. However, because both wallets and wall strengths showed similar trends, the calculated resistances compare reasonably well with the actual failure pressures.

4.4 Wall Shape

Generally, the predictions for the 'C' shaped walls were no worse than those for the equivalent 'U' shaped walls. The exceptions to this were the two 5.5m long AAC 'C' shaped walls, for which the predicted resistances were overestimated by about 50 per cent.

4.5 Mortar

From the results, it is clear that the poorer bond strength of mortars made with a sand containing significant amounts of clay fines, as noted in Part (1) of this paper, and reflected in the low flexural strengths of wallets built with these mortars, similarly affects the ultimate resistance of full sized walls. The good prediction of the resistances of the walls using the wallette mean strengths also supports the use of the yield line approach for the design of laterally loaded wall panels. Both the wallette results and the full sized wall results indicate no significant differences between the strengths obtained using lime and plasticised mortars. If anything, the strengths obtained using plasticised mortars were generally slightly higher than for the equivalent wallets and walls built with lime mortar.

5. CONCLUSIONS

The experimental work carried out at Plymouth University and BCRL demonstrates that the low flexural strengths obtained from wallets built with a G grade sand with significant amounts of clay fines are also reflected in the low ultimate failure pressures of full sized walls built of the same materials.

The application of the yield line method, using mean flexural strengths obtained from wallette tests, to the prediction of the lateral resistances of the full sized walls, produced calculated resistances that generally compared well the experimental failure pressures obtained for all of the materials used, i.e. AAC blockwork, calcium silicate brickwork and two types of clay brickwork. This shows consistency between the experimental results and the use of the yield line method.

BS 5628: Part 1 characteristic flexural strengths produced poor comparisons between calculated resistances and experimental failure pressures, because the wallette strengths were generally lower than the characteristic strengths given in BS 5628: Part