The Lateral Resistance of Cavity Walls with Dissimilar Leaves

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Abstract

As part of the experimental programme at the British Ceramic Research Association on the resistance of masonry walls to lateral loading a number of cavity walls have been tested. These have had one leaf of brick and the other of either a different brick or concrete block; various types and distribution of ties were incorporated. Predicted strengths, using yield line theory and strengths obtained from design in accordance with British Standard Code of Practice BS 5628 : Part 1 are compared with experimental strengths and the results are discussed.

1. INTRODUCTION

An extensive programme of testing of masonry panel walls subjected to lateral loading has been carried out at B.C.R.A. and has been reported in a number of papers[1 2 3]. The design guidance contained in one of these papers[2] was used in drafting the lateral load section of BS 5628 Part 1[4], the British Code of Practice for Structural Masonry.

In the U.K., the most common form of construction using masonry which is laterally loaded is the cavity wall, often consisting of leaves of dissimilar masonry materials connected together by wall ties of different types. The paper[1] referred to above reported 19 full scale tests on laterally loaded cavity walls and a subsequent paper[3] reported 20 further tests. Whilst it was shown in these papers that the experimental failure pressure on the cavity walls was, in the majority of cases, at least equal to the sum of the strengths obtained from tests on single leaf walls corresponding to the individual leaves of the cavity walls, these have never been examined in relation to the design guidance given in BS 5628.

Further lateral loading tests at B.C.R.A. have included 19 other walls having leaves of different materials. In this paper comparisons are made between the predicted strengths of all the above mentioned walls with different leaves and their actual strengths, and the results from the design method given in BS 5628 : Part 1 are compared to the experimental results.

2. EXPERIMENTAL

The walls considered in this paper are listed and briefly described in Table 1. All walls were built within a steel frame and a uniformly distributed load was applied by means of an inflatable air bag. The test procedure has been described in detail in a previous paper[1]. Two types of brick and three types of concrete block have been used for the leaves of the cavity walls listed in Table 1, together with two types of wall tie. The width of cavity and spacing of wall ties has also been varied in some of the wall tests.

3. PREDICTED WALL STRENGTHS

Nine of the walls listed in Table 1 were analysed in a previous paper[2], using a yield line approach to calculate predicted failure pressures for the individual leaves. These predicted pressures were then summed for comparison with the actual failure pressures of the cavity walls. No reference was made to the effect of the wall tie strength or behaviour under load upon the strength of the cavity walls. The flexural strengths and vertical edge restraints used to calculate these predicted strengths were obtained from small specimen wallette tests using similar masonry units and mortar to the full scale tests. The wallette tests are described elsewhere[1].

Calculated predicted strengths for the walls listed in Table 1 are given in Table 2. It should be noted that a small allowance has been made in the calculation for a partial fixing moment at the bottom of each wall leaf to allow for a self-weight stability moment. As before, the individual leaf predicted failure loads have been added together to give the wall predicted pressure for comparison with the actual test wall failure pressure. The predicted wall strengths have been plotted against experimental failure pressures in Figure 1. The summation of the actual individual leaf test failure pressures have been included in Table 2 for comparison with predicted values.

A summary of the experimental ultimate compressive strengths of wall ties available from different sources has been published by the Building Research Establishment[5]. Using mean values from this source for the vertical twist and butterfly ties used in the tests the influence of tie strengths can be obtained by consideration of the load to be transferred to the leaf not directly loaded by the air bag. Thus, assuming that the loaded leaf carries its maximum load as a single leaf wall, the ultimate strength of the wall may be estimated as the sum of the strength of the loaded leaf, and the load which can be transmitted by the wall ties to the unloaded leaf or the strength of that unloaded leaf, whichever is the lesser. This is not strictly true since it would be necessary for the loaded leaf and the wall ties or unloaded leaf to attain their individual ultimate loads simultaneously, unless composite action is allowed for. However, it is a useful assumption to make at this stage.

The minimum ultimate compressive strength of butterfly ties in a 50mm cavity, quoted by the BRE[5] is 533 N, giving a force/m^2 that can be transmitted by these ties when used at the centres given in BS 5628 for a 50mm cavity of 1.33 kN. The equivalent value for vertical twist ties based on a BRE minimum ultimate compressive strength of 7560 N is 18.9 kN. Obviously, by inspection of the wall strengths in Table 2, a compressive tie failure is possible only when butterfly ties are being used. Assuming the loaded leaf reaches its ultimate load, the walls with butterfly ties in Table 2 whose strength would be governed by tie strength have been marked by an asterisk, and the sum of the predicted failure pressures given as that for the loaded leaf plus 1.33 kN.

4. BS 5628 : PT.1 : DESIGN METHOD

BS 5628 states that the design moment of resistance of a cavity wall should be taken as the sum of the design moments of resistance of the two leaves, with the proviso that, where butterfly or double triangle wall ties are used, the ties must be capable of transmitting the necessary compressive force. The Code of Practice goes on to say that when the two leaves of a cavity wall have different orthogonal ratios, the design moment may be calculated assuming that the applied horizontal force is shared between the two leaves in proportion to their design moments of resistance. However, it is unnecessary to adopt this alternative approach, since, even when the two leaves have different orthogonal ratios, the sum of the individual leaf strengths is easily obtained.

BS 5628 gives characteristic strengths in compression for vertical twist and butterfly wall ties and using these together with the characteristic flexural strengths, from Code Table 3, appropriate to the masonry unit and mortar designation being considered, design loads for cavity walls can be calculated. In Code Table 9 bending moment coefficients are given for wall panels with various edge support conditions - 3 or 4 sided, simple (pinned) or continuous (fixed) supports; partial safety factors are given for use in the calculations of design loads. For the purposes of this paper partial safety factors have been omitted from the loads calculated to BS 5628 so that a calculated failure load can be compared to the experimental one. Two different loads have been calculated for each cavity wall, the first assuming simply supported edges and the second fixed support to the vertical edges. As the test walls had some rotational restraint to their vertical edges the true case will be somewhere between the two calculated. However, the designer using the bending moment coefficients in BS 5628 has only the extreme options, so these calculated loads are given in Table 3 together with a note as to whether the wall tie strength governs or otherwise. Since direct guidance is given in BS 5628, the simplified assumption proposed in Section 3 has been used again here, this time with the characteristic tie strengths in the codes, giving forces/m^2 of 1.25 kN and 10.0 kN for butterfly and vertical twist ties respectively at the code spacing for 70mm cavities. Where tie strength controls the result in the 'sum' columns has been modified accordingly. The simple and fixed loads have been plotted against the actual failure loads in Figures 2 and 3 respectively. The 45^{o} line shown on each Figure represents exact correspondance between them. Results above the line

indicate that at least the minimum global factor of safety given in BS 5628 ($\gamma_m \times \gamma_f$) will be achieved.

5. DISCUSSION

The aim of design is to ensure that laterally loaded cavity walls have an adequate factor of safety against ultimate failure. The method of analysis used must, before it can be used with confidence, be shown to be valid by experimentation. Whilst the use of yield line theory for masonry wall design has been questioned on theoretical grounds, it has been shown empirically[2] to predict adequately the ultimate strength of single leaf walls over a wide range of conditions. It has also been shown[3] that the experimental lateral strength of cavity walls is usually greater than the sum of the experimental strengths of the individual leaves for a variety of combinations of masonry materials panel size and wall tie type. Table 2 and Figure 1 show that yield line prediction based on the sum of the predicted strengths of the individual leaves, allowing, where appropriate for the strength of the wall ties, give, in general, conservative estimates of experimental cavity wall strengths. With one exception, all the results for walls having vertical twist type wall ties fall on or above the exact prediction line, and for walls with 150mm cavities well above the line. This implies some composite action between the leaves and that the BS 5628 requirement for doubling the number of ties in walls with 150mm cavities may be unnecessary. In the walls having butterfly ties the results are closer to the exact prediction line with four results falling below it, there being a minimum ratio of actual failure pressure to predicted of 0.82. The tie strength governs the predicted wall strength in eleven of the sixteen walls having butterfly ties (Table 2) whereas collapse of the wall ties was actually noted in five of these walls at failure, Figure 4. Thus the tie strength used in this paper may not have been as great as the actual strength of the ties in the test walls.

In BS 5628 the bending moment coefficients are for simple support or full continuity at the edge supports. In the test panels the restraint afforded by the test frame to the vertical edges was intermediate between the two cases, being estimated as ranging from 0.4 to 0.7 of full fixity for various walls. A designer faced with these walls would assume that the supported edges had only simple restraint. The strengths of the test walls calculated on this basis are given in Table 3 and Figure 2. It can be seen from Figure 2 that all the results fall well above the line representing the minimum factor of safety line (45°), as would be expected because of the partial edge restraint in the tests. If the bending moment coefficients for full continuity over the vertical supports were to be used, the results would be as shown in the final column of Table 3 and in Figure 3. Again where necessary the wall tie strength has been allowed for in the results. It can be seen from Figure 3 that most results still fall above the 45° line and that all would have a substantial factor of safety.

6. CONCLUSIONS

1. When the predicted lateral strengths of the single leaves of a cavity wall, obtained using yield line analysis, flexural strengths from wallette tests and allowing for partial edge restraint, are added together, a safe prediction of the lateral strength of the cavity wall, for the range of walls considered, is obtained.

2. The cavity walls having vertical twist ties generally exhibited greater strengths than the simple addition of the strength of the two leaves; this suggests some composite action which might permit the design strength of such walls to be enhanced.

3. The increase in the number of wall ties for 75-150mm cavity walls required by BS 5628 may be unnecessary. The experimental results for 150mm cavity walls suggest that there may be an enhancement due to composite action over similar walls with narrower cavities.

4. Design of laterally loaded cavity walls in accordance with BS 5628: Part 1 ensures an adequate factor of safety against ultimate failure for the range of walls considered, When the wall strength is based on the sum of the individual leaf strengths or of one leaf and wall tie strengths when appropriate. However the fact that even some of these walls with leaves of the same thickness suffered failure due to tie collapse indicates that stiffer ties than butterfly ties are required for safe designs on walls with leaves of widely different stiffness.

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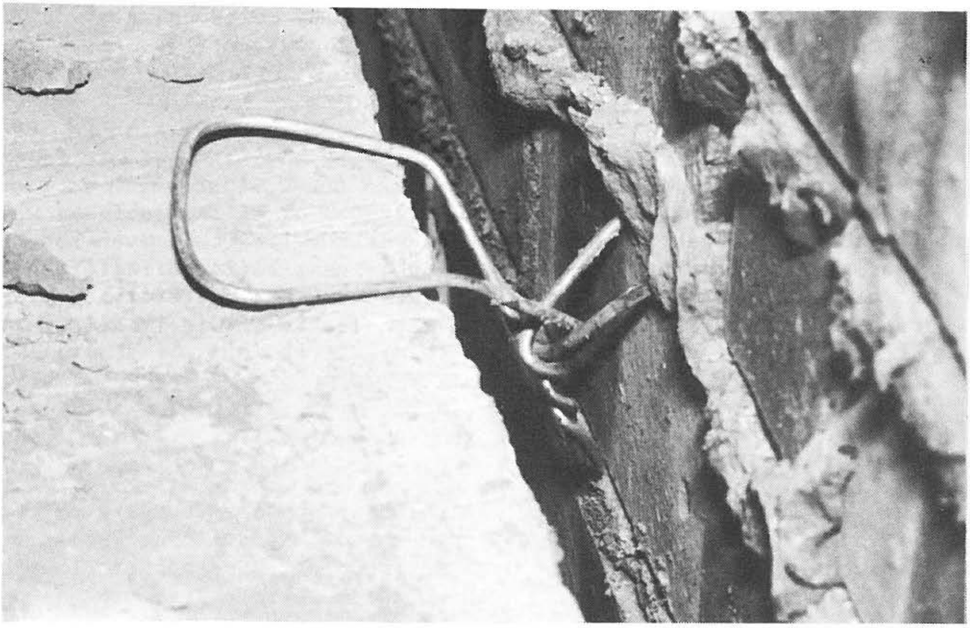

FIGURE 4: Buckled Butterfly Wall Tie After Test

TABLE 1

Storey Height (2.6m) Cavity Walls with Leaves of Different Units

Wall No	Length m	Loaded Leaf		Unloaded Leaf		Wall Tie Type	Comments
		Unit	Mortar Designation	Unit	Mortar Designation		
1053	5.50	A	(iii)	100 AAC	(iii)	Vertical	
1087	5.50	100 AAC	"	A	"	Twist	
1057	5.50	A	"	B	"	"	Wall ties at
1022	5.50	A	"	B	"	"	225 x 450
1242	3.66	A	"	B	"	"	
1049	5.50	B	"	100 AAC	"	"	
1241	4.57	B	"	100 AAC	"	"	
1240	3.66	B	"	100 AAC	"	"	
1084	5.50	100 AAC	"	B	"	"	
1058	5.50	B	"	LWA	"	"	
1068	5.50	B	"	DA	"	"	
1093	5.50	DA	"	B	"	"	
1118	5.50	A	"	B	"	Butterfly	
1130	4.57	A	"	B	"	"	
1122	3.66	A	"	B	"	"	
1112	5.50	B	"	100 AAC	"	"	
1113	4.57	B	"	100 AAC	"	"	
1115	3.66	B	"	100 AAC	"	"	
1146	2.72	B	"	100 AAC	"	"	
1199	5.50	B	"	100 AAC	"	Vertical	150mm Cavity
1210	4.57	B	"	100 AAC	"	Twist	"
1221	3.66	B	"	100 AAC	"	"	"
1247	5.50	A	"	B	"	"	"
1243	4.57	A	"	B	"	"	"
1233	3.66	A	"	B	"	"	"
1270	5.50	B	"	100 AAC	"	"	" †
1300	5.50	B	"	100 AAC	"	"	"
1289	5.50	A	"	100 AAC	"	"	" †
1308	5.50	A	"	100 AAC	"	"	"
1287	5.50	B	"	100 AAC	"	Butterfly	+
1299	3.60	B	"	100 AAC	"	"	+
1279	2.40	B	"	100 AAC	"	"	+
1357	5.50	B	"	200 AAC	"	"	
1358	4.57	B	"	200 AAC	"	"	
1359	3.66	B	"	200 AAC	"	"	
1360	2.70	B	"	200 AAC	"	"	
1406	5.50	B	"	100 AAC	"	"	□
1407	5.50	B	"	100 AAC	"	"	Δ

Notes:

1. All walls, except where noted otherwise, have 70mm approximate cavity width with 2.5 wall ties/m^2
2. All walls, except where noted otherwise, have the same edge support conditions for both leaves, i.e. free at top, partial restraint to vertical edges and simple support at the bottom (d.p.c.)
3. Key
   - A - wire cut facing clay brick
   - AAC - autoclaved aerated concrete block
   - LWA - lightweight aggregate concrete block
   - + - wall supported top and bottom and one vertical edge
   - B - semi-dry pressed frogged clay brick
   - DA - dense aggregate concrete block
   - † - 450 x 450 wall tie spacing
   - Δ - unloaded leaf supported on all four edges
   - □ - loaded leaf supported by wall ties only

TABLE 2

Cavity Walls - Predicted Failure Pressures

Wall No	Actual Failure Pressure (kN/m^2)	Sum of Leaf Actual Failure Pressures (kN/m^2)	Actual Failure Pressure / Sum of Single Leaf Pressures	Sum of Predicted Leaf Failure Pressures (kN/m^2)	Actual Failure Pressure / Sum of Predicted Pressures
1053	3.9	3.2	1.22	3.30	1.18
1087	3.9	3.2	1.22	3.30	1.18
1057	6.4	4.4	1.45	4.06	1.58
1022	4.0	4.4	0.91	4.06	0.99
1242	6.9	6.9	1.00	7.70	0.90
1049	3.4	2.8	1.21	2.36	1.44
1241	5.1	3.4	1.50	3.20	1.59
1240	5.6	4.7	1.56	4.66	1.20
1084	3.2	2.8	1.14	2.36	1.36
1058	3.7	3.3	1.12	2.84	1.30
1068	4.9	4.1	1.20	2.85	1.72
1093	5.4	4.1	1.32	2.85	1.89
1118	5.0	4.4	1.14	4.06	1.23
1130	4.8	5.1	0.94	4.73*	1.01
1122	5.8	6.9	0.84	6.04*	0.96
1112	3.2	2.8	1.14	2.56	1.25
1113	3.5	3.4	1.03	3.20	1.09
1115	3.8	4.7	0.81	4.32*	0.88
1146	5.2	5.3	0.98	6.34*	0.82
1199	3.8	3.0	1.27	2.56	1.48
1210	6.4	3.4	1.91	3.20	2.00
1221	6.6	4.7	1.40	4.66	1.42
1247	5.4	4.6	1.17	4.06	1.33
1243	6.7	5.1	1.31	5.39	1.24
1233	9.3	6.9	1.35	7.70	1.21
1270	3.9	3.0	1.30	2.56	1.52
1300	3.8	3.0	1.27	2.56	1.48
1289	4.6	3.2	1.44	3.50	1.31
1308	3.9	3.2	1.22	3.50	1.11
1287	2.4	2.2	1.09	2.57	0.93
1299	3.4	3.4	1.00	3.17*	1.07
1279	8.0	5.3	1.51	4.13*	1.94
1357	3.8	5.4	0.70	2.89*	1.31
1358	5.2	5.7	0.91	3.32*	1.57
1359	6.0	7.0	0.86	4.32*	1.39
1360	6.6	9.4	0.70	6.34*	1.04
1406	2.0	-	-	-	-
1407	3.7	3.5	1.06	2.89*	1.28

* Compressive strength of wall tie governs

TABLE 3

Calculated Ultimate Strength in Accordance with BS 5628 : Part 1

Wall No	Actual Failure Pressure (kN/m²)	BS 5628 Calculated Strength Simple Edge Restraint			BS 5628 Calculated Strength Full Continuity Along Vertical Edges		
		Loaded Leaf (kN/m²)	Unloaded Leaf (kN/m²)	Sum (kN/m²)	Loaded Leaf (kN/m²)	Unloaded Leaf (kN/m²)	Sum (kN/m²)
1053	3.9	1.39	0.47	1.86	2.23	0.75	2.98
1087	3.9	0.47	1.39	1.86	0.75	2.23	2.98
1057	6.4	1.39	0.83	2.22	2.23	1.37	3.60
1022	4.0	1.39	0.83	2.22	2.23	1.37	3.60
1242	6.9	2.59	1.50	4.09	2.59	1.50	6.99
1049	3.4	0.83	0.47	1.30	1.37	0.75	2.12
1241	5.1	1.08	0.60	1.68	1.82	0.98	2.80
1240	5.6	1.50	0.81	2.31	2.62	1.37	3.99
1084	3.2	0.47	0.83	1.30	0.75	1.37	2.12
1058	3.7	0.83	0.47	1.30	1.37	0.75	2.12
1068	4.9	0.83	0.66	1.49	1.37	1.08	2.45
1093	5.4	0.66	0.83	1.49	1.08	1.37	2.45
1118	5.0	1.39	0.83	2.22	2.23	1.37	3.60
1130	4.8	1.79	1.08	2.87	3.04	1.82	4.29*
1122	5.8	2.59	1.50	3.84*	4.37	2.62	5.62*
1112	3.2	0.83	0.47	1.30	1.37	0.75	2.12
1113	3.5	1.08	0.60	1.68	1.82	0.98	2.80
1115	3.8	1.50	0.81	2.31	2.62	1.37	3.87
1146	5.2	2.41	1.27	3.66*	4.36	2.23	5.61*
1199	3.8	0.83	0.47	1.30	1.37	0.75	2.12
1210	6.4	1.08	0.60	1.68	1.82	0.98	2.80
1221	6.6	1.50	0.81	2.31	2.62	1.37	3.99
1247	5.4	1.39	0.83	2.22	2.23	1.37	3.60
1243	6.7	1.79	1.08	2.87	3.04	1.82	4.86
1233	9.3	2.59	1.50	4.09	4.37	2.62	6.99
1270	3.9	0.83	0.47	1.30	1.37	0.75	2.12
1300	3.8	0.83	0.47	1.30	1.37	0.75	2.12
1289	4.6	1.39	0.47	1.86	2.23	0.75	2.98
1308	3.9	1.39	0.47	1.86	2.23	0.75	2.98
1287	2.4	1.05	0.73	1.78	1.24	0.87	2.11
1299	3.4	1.31	0.77	2.18	1.70	1.08	2.78
1279	8.0	1.74	1.14	2.88	2.46	1.51	3.71*
1357	3.8	0.83	1.89	2.08*	1.37	2.98	2.62*
1358	5.2	1.08	2.40	2.33*	1.82	3.90	3.07*
1359	6.0	1.50	3.07	2.75*	2.62	5.48	3.87*
1360	6.6	2.41	5.07	3.66*	4.36	8.91	5.61*
1406	2.0	0.83†	0.47	1.30	1.37†	0.75	2.12
1407	3.7	0.83	1.03	1.86	1.37	1.35	2.62*

* Compressive strength of wall tie governs wall strength

† Assumes loaded leaf supported at bottom and both vertical edges

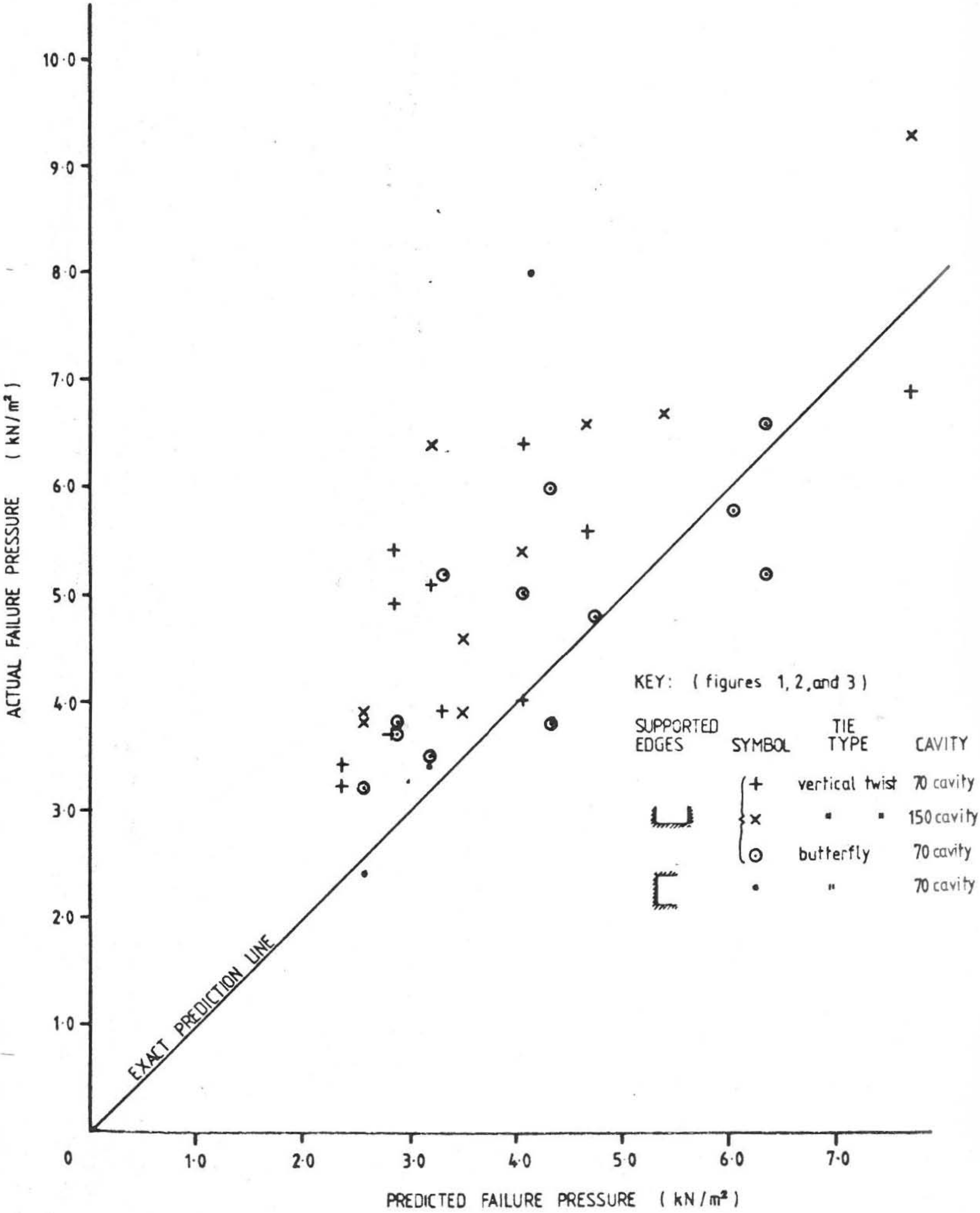

FIGURE 1 PREDICTED FAILURE PRESSURE VERSUS ACTUAL FAILURE PRESSURE

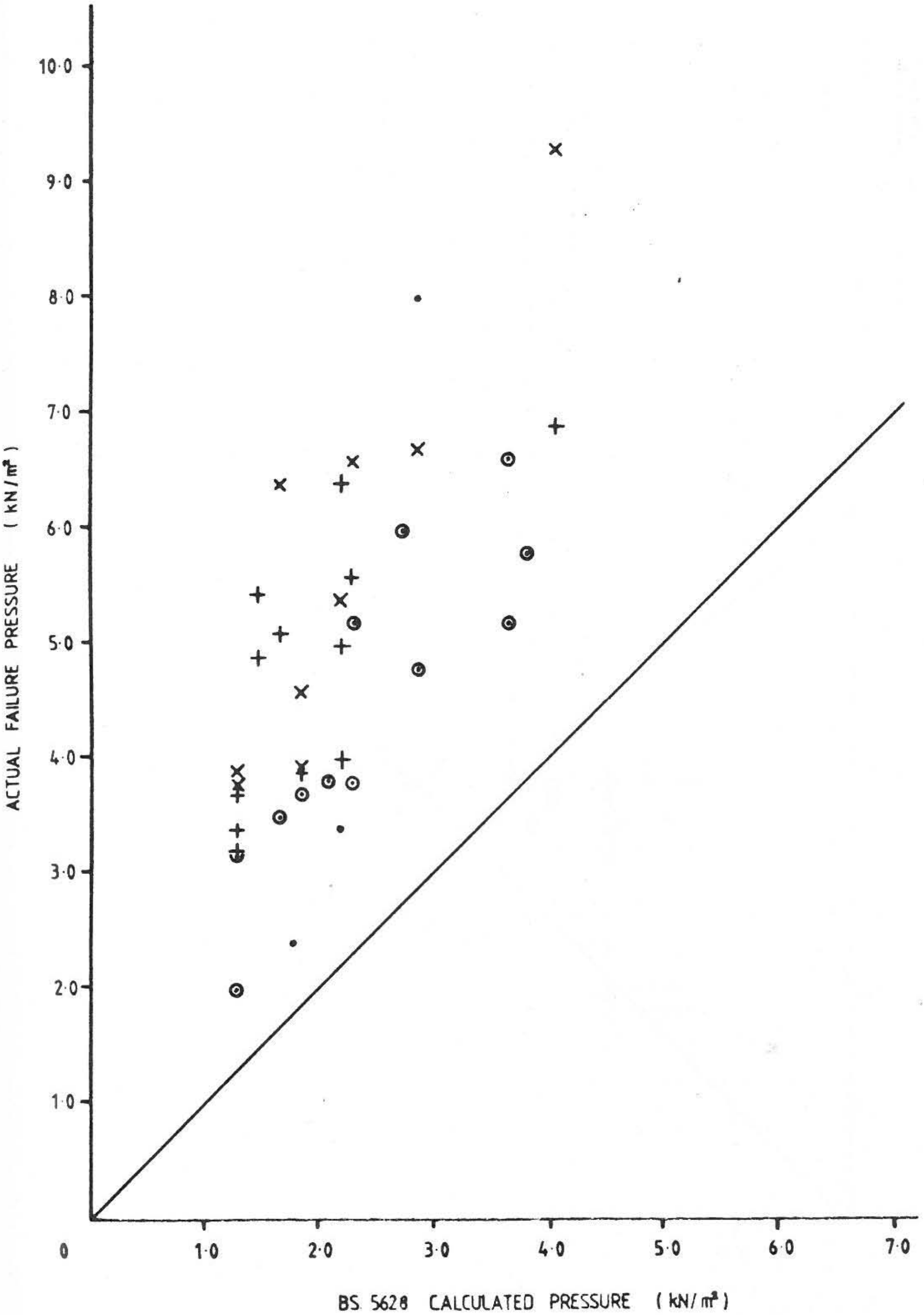

FIGURE 2. BS 5628 CALCULATED PRESSURE, SIMPLY SUPPORTED CASE, VERSUS ACTUAL FAILURE PRESSURE

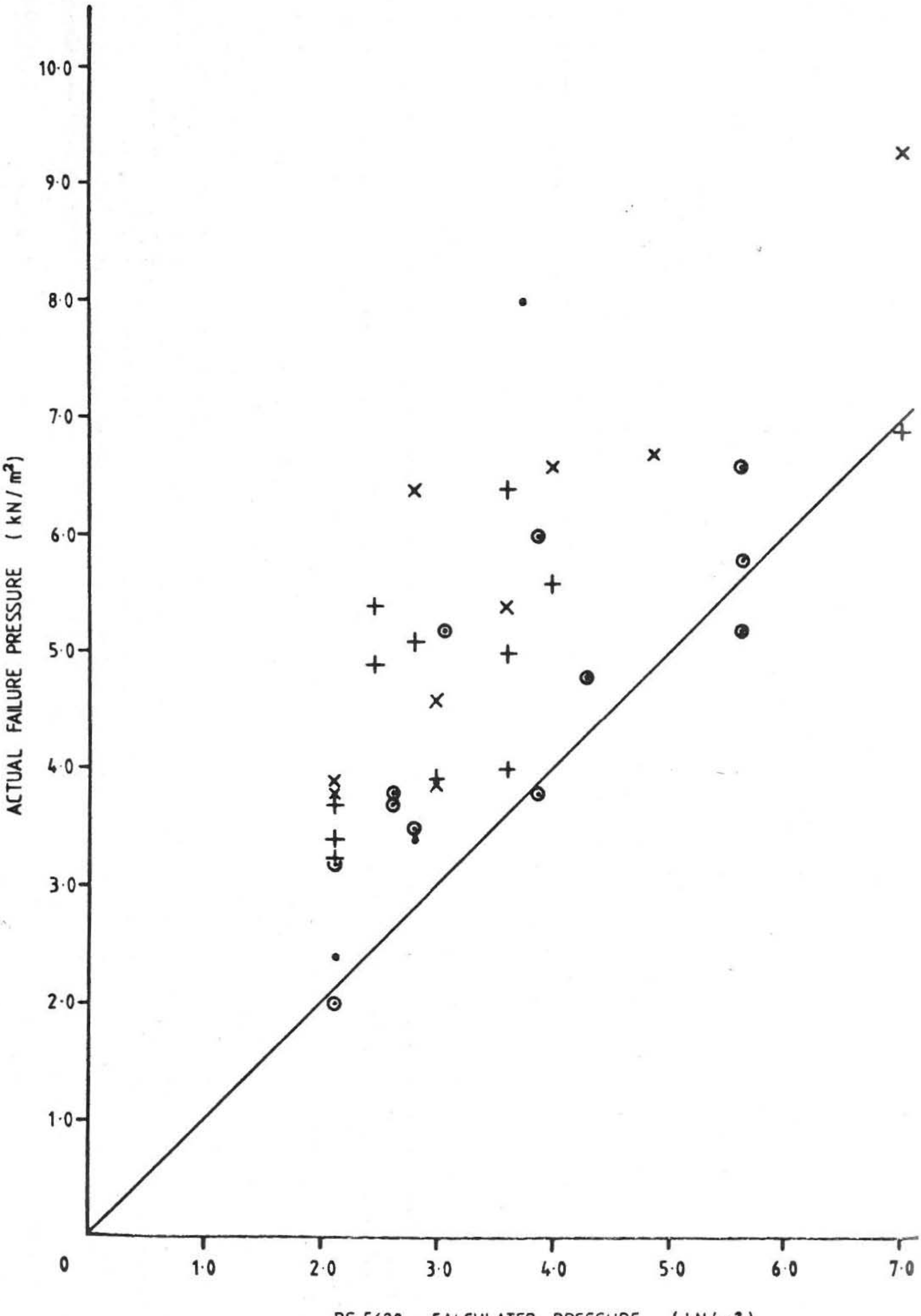

FIGURE 3. BS 5628 CALCULATED PRESSURE, FULL CONTINUITY OVER VERTICAL SUPPORTS VERSUS ACTUAL FAILURE PRESSURE