Further Compressive Loading Tests on Diaphragm Walls

Authors: K. Fisher (Redland Bricks Ltd.)

and B. A. Haseltine (Jenkins & Potter, Consulting Engineers) (England)

Abstract

Structural research carried out in recent years on the properties of diaphragm walls has included the effect of compressive loading on walls constructed of half-scale bricks. The brick unit strength used in this early work was higher than recognised by the design Codes, making extrapolation necessary for calculation. Results indicated that for practical purposes, the effective thickness may be taken as the overall thickness.

This paper reports a series of tests using a more realistic unit strength. Two diaphragm walls were constructed, 3.04 m high, 2.8 m wide with an overall wall thickness of 222 mm. Five cross ribs were incorporated (including one at each end) with their alternate headers bonded into the two leaves of the wall. Ribs at each end were separated by 726 mm and those at the centre by 674 mm. Transducers positioned on both leaves measured compressive and lateral deflections, while load was increased to ultimate failure.

In the first test, load was axially applied to both leaves. The second test was carried out with an eccentric load of t/3. Results obtained are discussed in relation to the calculated loads using the Code of Practice CP 111 and the limit state design code BS 5628.

1. Introduction

Diaphragm walls are essentially wide cavity walls connected at regular intervals across the cavity by brick cross ribs. The cavity width and rib spacing is chosen to suit the relevant structural application where tall single-storey buildings are required.

The calculation methods currently used in design are based on reasonable engineering assumptions. Although structures designed in accordance with such methods have performed successfully, diaphragm walls cannot be designed strictly in accordance with the current structural Codes of Practice, CP111 [1] and the limit state BS 5628 [2] since there is no direct guidance on the effective thickness,

and hence slenderness ratio, of the diaphragm wall. Empirical estimation is therefore necessary, although radius of gyration has been suggested by Sawko and Curtin[3] as a basis for effective thickness calculation.

Within the last few years, considerable research has been carried out on the performance of diaphragm walls, the results of which have been summarised in papers by Curtin [4] and Curtin and Sawko[5] and in published discussion of these papers by the Institution of Structural Engineers.[6]

The results of initial tests to measure the failure load of diaphragm walls built of half-scale bricks were reported by Fisher and Haseltine[7] in a paper presented to the Fifth International Brick Masonry Conference, the results of which are summarised in the above mentioned discussion paper [6]. Since the brick strength used in this initial work was higher than recognised by the design Codes, it was necessary to extrapolate for calculation purposes.

This paper reports the results of two further tests, using units of lower strength, one wall being axially loaded, and one having an eccentrically applied load.

2. Materials

2.1 Bricks

Half-scale solid wirecut bricks were used. Nominal dimensions were: length 108 mm, width 54 mm, thickness 36 mm. Unit compressive strength determined in accordance with BS 3921[8] is given in Table 1.

2.2 Mortar

Ordinary Portland cement and hydrated lime was used throughout the work. Designation (iii) mortar was used, batched 1:1:6 by volume.

3. Wall Construction

Figure 1 illustrates wall dimensions, position of cross-ribs and bonding details. Walls were constructed and tested on spreader beams, consisting of rolled steel channel infilled with concrete. Brickwork was built 24 courses per metre, using a half-scale (5 mm) mortar joint.

3.1 Wall No.1

48 hours after completion of brickwork, the cavities at the top of the wall were sealed with rigid expanded polystyrene sheet, 50 mm thick, cut to size and wedged into position with the top surfaces projecting 25 mm above the finished brickwork. The whole of the top brickwork surface was then levelled with a 1:2 cement:sand screed 25 mm thick.

75 mm mortar cubes were made during wall construction, together with brick cubes, nominally 110 x 110 mm cross-section and 120 mm high. Compressive strength results of these cubes are given in Table 1.

3.2 Wall No.2

On completion of building, a 6 mm thick steel plate, 2800 mm long and 148 mm wide, was bedded onto the top of the wall with one edge flush with the face of the front leaf.

Mortar and brick cubes were made as described in 3.1.

4. Experimental procedure

Compressive shortening and lateral deflections were measured at eight and eighteen positions respectively. Compressive shortening was measured over a gauge length of 2 m using steel rods and electrical transducers. The rods (four on each face of the wall) were supported by metal angle brackets screwed to the wall. Measurement of lateral deflection was effected using electrical transducers (nine on each face), fixed to a tubular alloy support frame. The output from all transducers was fed into a data logger. Figure 2 shows the relative positions of the measuring points across the wall face.

Walls were loaded to failure at a constant rate of 0.7 $N/mm^2/min$. Transducer readings were recorded at regular increments of load.

5. Experimental Results and Observations

5.1 Results

Table 1 summarises the compressive strength of the walls together with the brick, brick cube and mortar results.

TABLE 1.

Strength of walls, bricks, mortar and brick cubes.

Test Wall No.	Compressive strength (N/mm^2) Wall	Brick	Mortar Cube	Brick Cube	Ratio of wall strength to Brick Strength	Brick Cube Strength	Ratio of brick Cube strength to brick strength
1	5.74	24.0	2.59	10.0	0.24	0.57	0.42
2	7.79*	31.0	2.52	16.2	0.21	0.41	0.52

* based on two thirds wall thickness (see table 2)

Stress/strain curves and typical lateral deflection for wall 1 are given in Figures 3 and 4. Figures 5 and 6 give similar data for wall 2, with the

exception that on Figure 5 compressive shortening is plotted against load in view of the load being eccentric.

5.2 Observations

5.2.1 Test 1

Cracking of the wall was observed at the top right hand side of the wall at an applied load of 170 tonnes, followed by spalling, and some cracking at the left-hand base of the wall. These cracks extended further as load was increased. Failure occurred at 195 tonnes, when the upper three-quarters of the front leaf collapsed, leaving the remainder of the wall in position, with most of the cross ribs split at the face of that part of the wall remaining.

5.2.2 Test 2

Audible cracking was heard during application of the first 20 tonne increment; a vertical crack was observed at the top right hand corner of the wall, down the end rib, at a load of 55 tonnes. Localised crushing occurred in this area at 80 tonnes. Some horizontal cracking was visible, with a further extension of spalling at an applied load of 110 tonnes. The visible cracks widened until failure at 120 tonnes, when the front leaf collapsed leaving the rear leaf intact, this being the leaf carrying only a small portion of the applied load.

6. Discussion

A previous paper[7] explained that both the British Codes CP 111 and BS 5628 use a slenderness ratio approach to compressive strength design, but that there had been no guidance on the method of obtaining diaphragm wall effective thickness. Three possible effective thicknesses were given, based on an equivalent second moment of area, the actual thickness of $\sqrt{12}$ times the radius of gyration. For the present tests, the effective thickness (t_{ef}) calculated in similar manner would be 212.5 mm, 222 mm and 284.9 mm.

Table 2 compares the failure stress in the wall with the stresses derived from CP111 and BS 5628 when using their tabulated stresses, based on brick strengths and mortar type or the experimental methods.

In BS 5628, the characteristic strengths can be obtained from wall tests, and a minimum of two are recommended; to reduce the actual stress to a characteristic figure, the mean is divided by 1.2, on the basis of a "standard" coefficient of variation. The factor 1.2 has been used in arriving at the figures 4.78 and 6.49 N/mm^2 in table 2, although each is only a single test result. However when design is based on wall tests, the value of γ_m may be reduced to

0.9 of the usual value. In order to obtain a comparison with f_k from table 2(a) of BS5628, this 0.9 factor has been applied to 4.78 and 6.49 to give the bracketed figures. In examining table 2 (and subsequently table 3), it must be remembered that all figures based on CP111 are permissible, and a global safety factor is already included in them.

Table 2.

Comparison of failure stress with that obtained from BS5628 and CP111

Code	Stress (N/mm^2)		Test 1	Test 2
	In wall at failure		5.74	7.79
BS5628	Characteristic compressive strength f_k		4.78	6.49
	(using Appendix A2) +		(5.31)*	(7.21)*
	f_k from table 2 (a)		6.49	7.75
CP111	Permissible from test using Clause 502	t_{ef} 212.5 mm	1.05	1.6
		222 mm	1.05	1.59
		284.9 mm	1.09	1.56
	Permissible from table 3 (a)		1.45	1.73

+ unaffected by effective thickness

*equivalent strength to table 2 (a) allowing for permitted reduced value of γ_m when f_k based on wall tests.

For test 2, as the load was applied eccentrically, there is a variable stress distribution across the section. In analysing to CP 111 it would be normal to use $\frac{W}{A} \pm \frac{M}{Z}$ to obtain the peak fibre stress, and then to enhance the table 3(a) stress by 25%, as the stresses in table 2 derived from Clause 502 do not compare directly with those from table 3(a). However the effect of this is so artificial, it appeared inappropriate for use in this paper.

To calculate the compressive strength of a wall, BS 5628 utilises a rectangular stress block centred on the load. Since the Code does not deal with cellular

sections, it is not known whether this method is meant to be applied to such walls, but the stresses in table 2, and the wall strengths in table 3 below, have been derived on the basis of a rectangular stress block.

Test 1, being an axially loaded wall built in a brick having a strength well within the Code table, gives a good comparison of the behaviour of a diaphragm wall. It can be seen that the characteristic strength, or even the actual strength, is less than the Code table provisions, although by only a small margin. Similarly the CP111 permissible figures obtained from the test are lower than the tabulated value related to brick strength and mortar type. However the safety factor demanded by Clause 502 of CP111 is very high (approximately 6).

In test 2, the characteristic and permissible figures are again less than the relevant tabulated strengths of the Code, but the margin is less than observed in test 1. The figures given in table 2, considered in conjunction with those reported earlier [7], suggest that diaphragm walls should not be loaded in compression to their maximum based on Code tabulated strengths. This is especially true when in test 2, audible cracking was apparent before the first load increment of 20 tonnes was completed, this load being less than the permissible wall stress from table 3.

In table 3, wall strengths have been calculated from the appropriate figures in table 2 and the relevant Code provisions.

The various values of t_{ef} give different slenderness ratios, although as pointed out by Curtin [6], it is unfortunate that the walls are all stocky, whether t_{ef} is taken as 212.5 or 248.9 mm. It is thus not possible to derive a firm rule for the best method of obtaining t_{ef} for design use, but the earlier conclusion that the overall thickness is the most sensible and convenient still seems appropriate.

TABLE 3.

Comparison of wall strengths with calculated values from BS 5628 and CP 111.

Code	Wall strength (kN)		Test 1	Test 2
	Test Strength		1913	1177
BS 5628	Characteristic strength (using appendix A2)		1594 (1771)*	981 (1090)*
	Calculated using Appendix A2, f_k from table 2 above	t_{ef} = 212.5mm	1529 (1699)*	800 (889)*
		222 mm	1545 (1717)*	800 (889)*
		284.9mm	1593 (1770)*	800 (889)*
CP111	Safe strength using clause 502, permissible stress from table 2 above	t_{ef} = 212.5mm	304	186
		222 mm	308	190
		284.9mm	345	212
	Safe strength using Code table 3 (a) stress	t_{ef} = 212.5mm	420	201
		222 mm	425	207
		284.9mm	459	235

* using equivalent value from table 2.

7. Conclusions

Tests on two diaphragm walls built with bricks lying well within the range covered by both British masonry Codes confirm the effect noted in an earlier paper (7) that the compressive strength of diaphragm walls may not be as great as would be calculated from codified tabular values. The eccentrically loaded wall performed closest to the Code prediction.

It appears that the slenderness ratio of a diaphragm wall should be based on its actual thickness, but tests on more slender walls would be desirable to confirm this.

References

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2. British Standards Institution, Code of Practice for Structural Masonry:Part 1;

Unreinforced Masonry, BS5628:Part 1:1978.

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8. British Standards Institution, Bricks and Blocks of Fired Brickearth, Clay or Shale, BS 3921:Part 2:1974.

Acknowledgements

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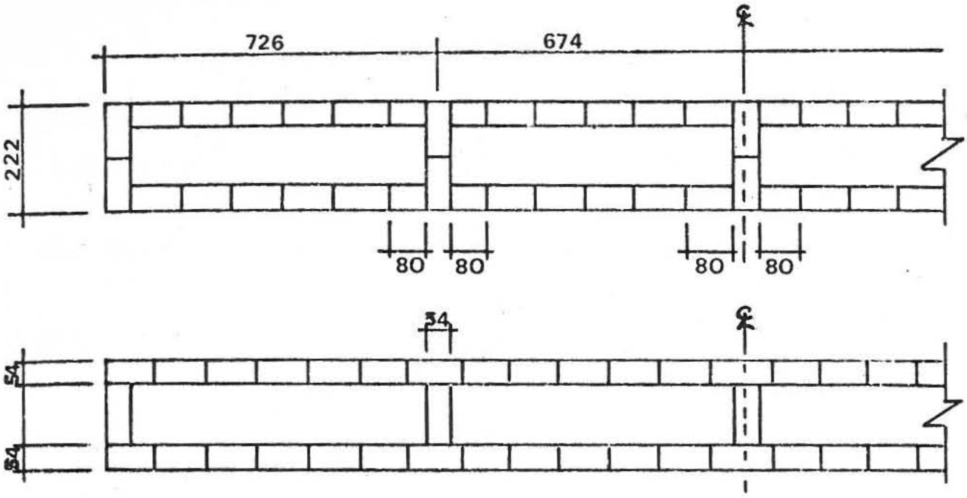

FIGURE 1. Dimensions and bonding details of half-scale walls.

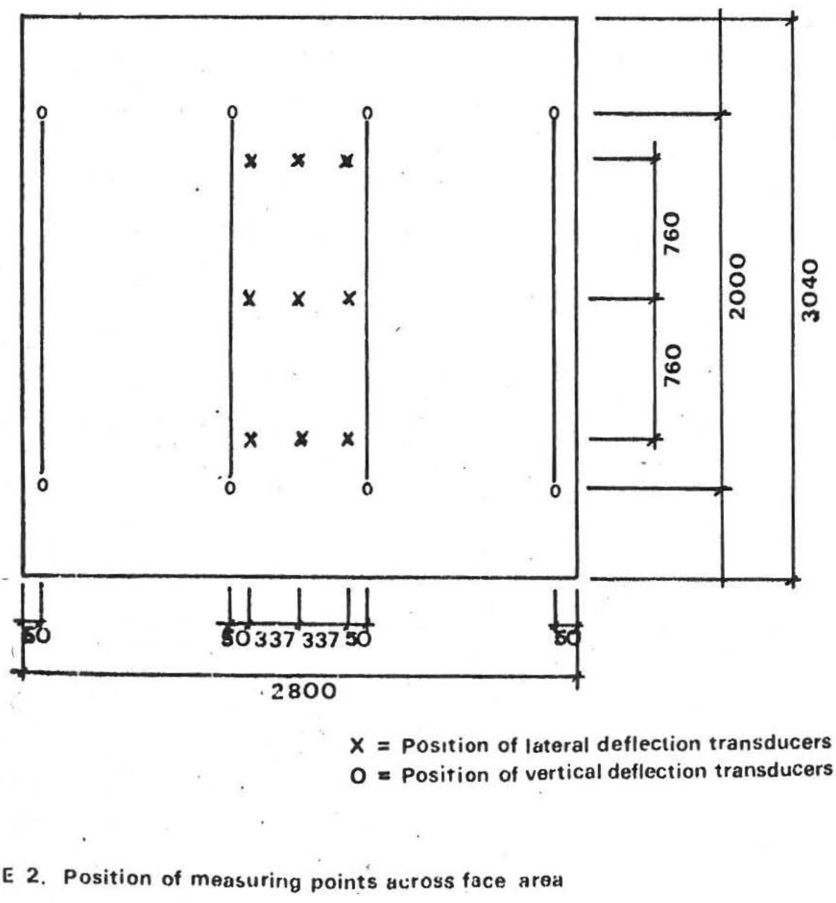

FIGURE 2. Position of measuring points across face area

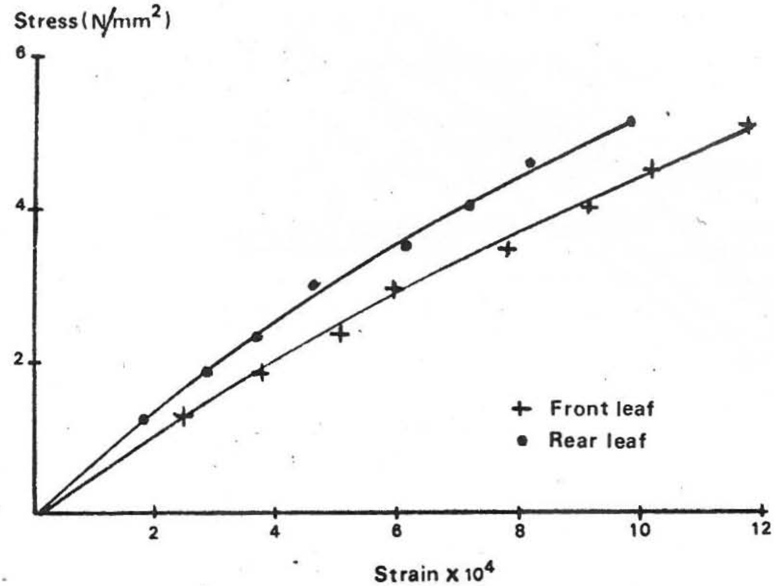

FIGURE 3. Compressive stress/strain curves for Wall 1.

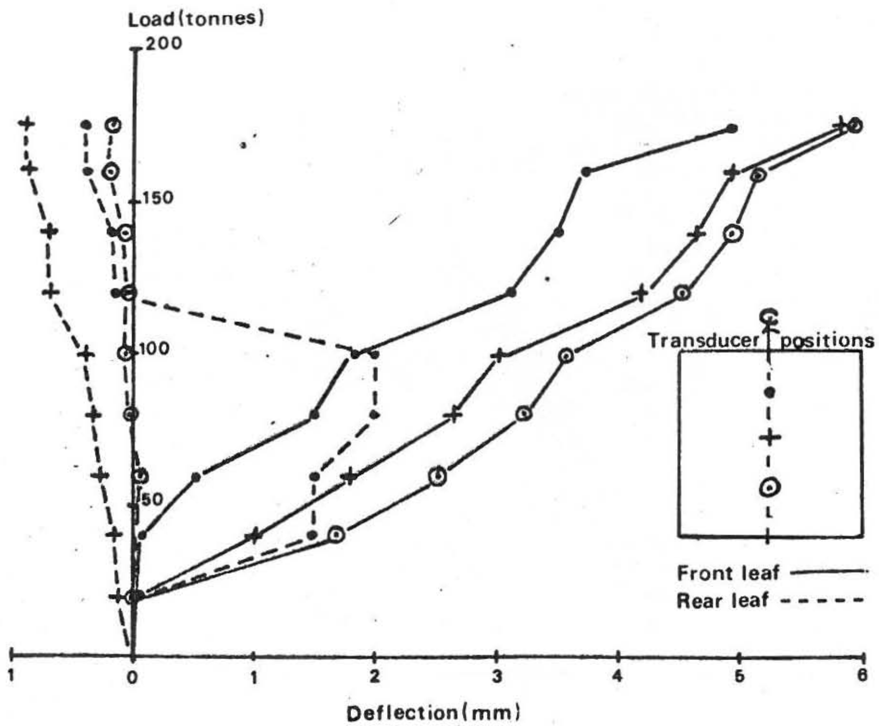

FIGURE 4. Typical lateral deflections for Wall 1.

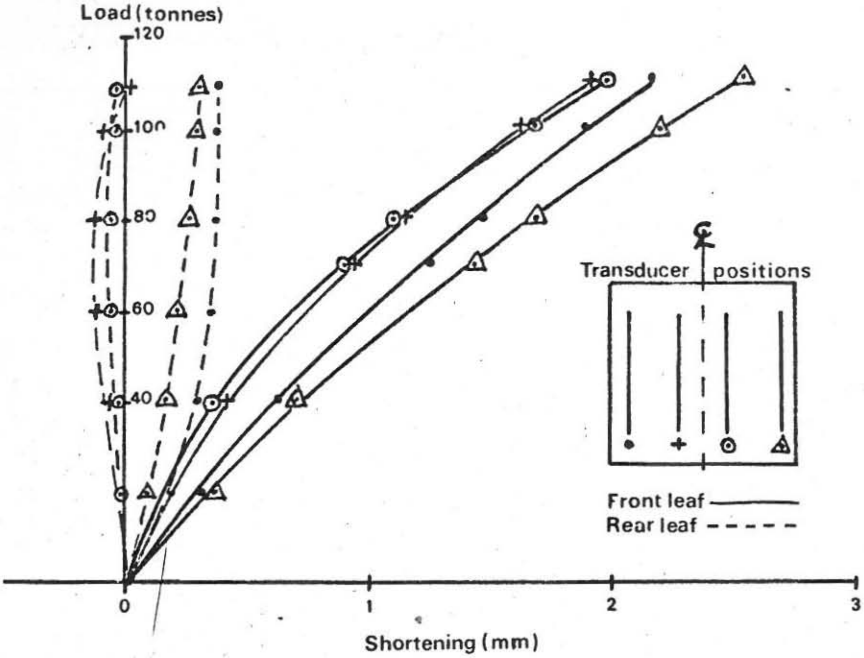

FIGURE 5. Compressive shortening under load. Wall 2.

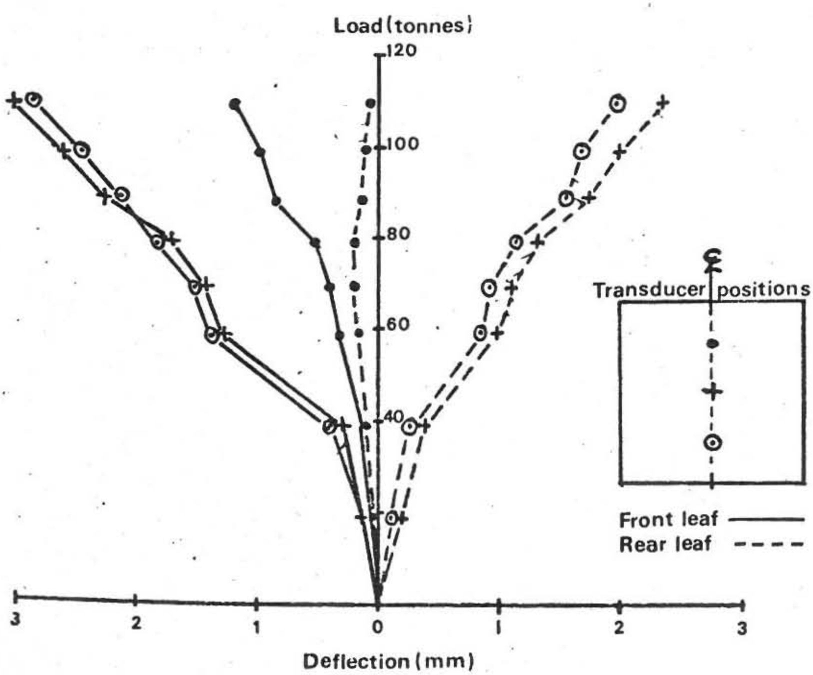

FIGURE 6. Typical lateral deflections for Wall 2.