IV–42. Compressive Loading Tests on Diaphragm Walls

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ABSTRACT

Experience has shown that diaphragm walls are well suited to tall single-storey buildings, and considerable interest has been expressed in this form of construction. In design terms, the current standards do not adequately cover such walls, the main problem being determination of the effective height and thickness of the wall and hence its slenderness ratio.

As part of a wider research programme, this paper examines the effect of compressive loading on diaphragm walls constructed of half-scale bricks. Wall dimensions were 3.04 m high, 2.8 m wide with an overall wall thickness of 219 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 in the centre by 674 mm.

Transducers positioned on both leaves measured compressive and lateral deflections of both leaves while load was increased incrementally to ultimate failure.

Results obtained are discussed in relation to the design loads applied in practice to such forms of construction, and to the calculated loads using the Codes of Practice CP 111 and the new limit state design code BS 5628.

L'expérience a démontré que les murs creux à nervures s'adaptent bien aux bâtiments hauts à un étage, et il s'est produit un vif intérêt à cette forme de construction. En ce qui concerne les calculs, les normes actuellement en vigueur ne traitent pas de tels murs dune façon suffisante, le principal problème étant celui de déterminer la hauteur et l'épaisseur de flambage du mur et ainsi son coefficient d'élancement.

Dans le cadre d'un programme de recherches de plus grande envergure, cette communication examine l'action d'un chargement compressif sur des murs creux à nervures construits de briques à dimensions réduites à moitié. Les murs avaient une hauteur de 3,04 m,une largeur de 2,8 m et une épaisseur totale de 219 mm. Cinq nervures transversales y étaient incorporées (y compris une à chaque bout), dont chaque deuxième boutisse était liaisonnée dans les deux parois du mur. Les nervures aux deux extrémités étaient séparées de 726 mm, et celles du centre de 674 mm, de la nervure voisine.

Des transducteurs installés sur les deux parois mesuraient la flèche latérale et la flèche due à la compression des deux parois pendant qu'on augmentait pas à pas le chargement jusqu'à la rupture finale.

On discute les résultats obtenus par rapport aux hypothèses de charge appliquées en pratique à de telles formes de construction, ainsi qu'aux charges calculées en utilisant les "Codes of Practice" (documents techniques unifiés) CP 111 et la nouvelle norme britannique BS 5628.

Die Erfahrung hat gezeigt, daß zweischalige Mauern mit Großhohlraum und Querrippen für hohe einstöckige Gebäude sehr gut geeignet sind und beachtliches Interesse fzuur diese Bauweise ist bisher zum Ausdruck gekommen. Hinsichtlich der Konstruktion erfassen die gegenwärtigen Normen diese Mauern nicht ausreichend, wobei das Hauptproblem die Ermittlung der wirksamen Höhe und Dicke der Mauer und somit ihres Schlankheitsgrads ist.

Als Teil eins umfangreichen Forschungsprogramms untersucht diese Arbeit die Wirkung von Druckbelastung auf mit Ziegeln halben Maßstabs gebauten Mauern. Die Ausmaße der Mauer betrugen: 3,04 m Höhe, 2,8 m Breite, Mauerdicke insgesamt 219 mm. Fünf Querrippen, einschließlich der beiden an den Enden, wurden in die Mauer eingebaut, wobei jeweils jeder zweite Kopfziegel in die beiden Schalen der Mauer eingebunden wurde. Die Endrippen waren jeweils 726 mm von den nächsten Rippen entfernt, während der Abstand zwischen den drei mittleren Rippen je 674 mm betrug.

Mit an beiden Schalen angebrachten Kraftwandlern wurden die Druck- und Seiten-durchbiegungen gemessen während die Last stufenweise bis zum endgültigen Versagen erhöht wurde.

Die Ergebnisse werden im Zusammenhang mit den für derartige Bauweisen in der Praxis angewandten Lastannahmen und mit den gemäß den Merkblättern CP 111 und der neuen britischen Norm BS 5628 berechneten Lasten erörtert.

L'esperienza ci ha dimostrato che i diaframmi dei muri sono ben situati per l'altezza di un primo piano di costruzione edile. È stato expresso un interesse considerabile per questo modo di costruzione. In termini del disegno,

nella forma corrente non copre adeguatamente tali muri; essendo che i problemi principali sono la determinazione effettiva dell'altezze a lo spessore del muro, e da qui il suo rapporto di sottilezza.

Come parte di un progamma di ricerche, questo articolo esamina l'effetto d'un carico compressivo sui diaframmi dei muri costruiti con mattoni di metà scala metrica. Le dimensioni del muro crano 3m.04. D'altezze 2m.8 di larghezza 219mm. di spessore. Cinque costole di traverso erano incorporate nel muro (includendo le due estremità) con mattoni di testa alternativamente legati ai due fogli del muro. Le costole alle estremità erano separate da 726 mm. e quelle di mezzo da 674mm.

I trasduttori situati tra i due fogli del muro, hanno misurato la deviazione compressive laterali di tutti e due i fogli del muro, mentre il carico veniva aumentato fino alla rottura finale.

I risultati ottenuti sono stati discussi in rapporto al disegno del carico applicato sulla forma practica di costruzione, e dei carichi calcolati usando i codoci di pratica cp 111 e il nuovo limite del codice del disegno dichiarato BS 5628.

INTRODUCTION

The diaphragm wall is basically a wide cavity brick wall braced by cross ribs of brickwork at regular intervals to form a series of I-sections. It is well suited for use in industrial buildings and sports halls, which require tall single-storey buildings enclosing large open areas, and it can replace the columns, cladding and internal finishes of conventional steel or concrete framed structures, providing a durable, attractive and maintenance-free structure.

A number of buildings incorporating diaphragm wall construction have been built in recent years. Several are illustrated in Brick Development Association Technical Notes[1,2] where aspects of the design principles and procedure are discussed.

The calculation methods currently used in design are based on reasonable engineering assumptions, and structures designed in accordance with such calculations have performed successfully. They cannot however be designed strictly in accordance with current structural Codes of Practice CP 111[3] and the new limit state design code BS 5628,[4] as direct guidance is not given on the effective thickness, and hence slenderness ratio of the diaphragm wall. An empirical estimation is therefore necessary. Sawko and Curtin[5] suggest the effective thickness might be based on radius of gyration.

The performance of diaphragm walls has been examined in a research programme covering axial and lateral loading, rain penetration and thermal insulation. The tests described in this paper form part of the research on behavior under axial loading. Initial axial load tests carried out at Liverpool University have been reported[6] on a wall built of half-scale bricks, representing an equivalent wall height in excess of 6 m; there was no sign of failure when a 100-ton load was applied. In order to measure the ultimate failure load of such walls, two further tests, now described, were carried out.

MATERIALS

Bricks

Half-scale solid wirecut bricks were used, being strictly selected to provide bricks having dimensions within acceptable limits. Nominal brick dimensions were: length 108 mm, width 51 mm, thickness 34 mm. Unit compressive strength was determined in accordance with BS 3921[7]. Results are summarized in Table 1.

Mortar

Ordinary Portland cement and hydrated lime was used throughout the work. Mortar was designation (iii) of BS 5628, batched 1:1:6 by volume, and used within two hours of mixing. The bricklayer adjusted workablilty to suit his requirements.

WALL CONSTRUCTION

Bonding details, position of cross-ribs and wall dimensions are illustrated in Figure 1.

Both walls were constructed and tested on a spreader beam, consisting of a rolled steel channel infilled with concrete. Brickwork was built 25 courses per metre, using a half scale (5 mm) mortar joint. Facework was completed by 'striking' the joints as work proceeded. In construction of wall 1, the mortar joint between the first course of brickwork and the building beam was omitted. Wall number 2 was bedded on the beam in the normal manner.

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 × 110 mm cross-section and 115 mm high. Compressive strength results on these cubes are given in Table 3.

EXPERIMENTAL PROCEDURE

Compressive and lateral deflections were measured at eight and thirty positions respectively. Steel rods and electrical transducers measured compressive deflections over a gauge length of 2 m. The rods (four on each face of the wall) were supported by metal angle brackets screwed to the wall. Measurement of lateral deflection was carried out using electrical transducers (fifteen 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.

Both walls were loaded to failure at a constant rate of 0.7 N/mm²/min. Transducer readings were recorded at 50 tonne increments of load.

EXPERIMENTAL RESULTS AND OBSERVATIONS

Results

Table 2 summarises the compressive strength of the two walls, together with the mortar and brick cube results.

Deflections under load have been plotted, and typical graphs for walls are given in Figures 3 and 4. Compressive deflections measured over 2 m gauge length are expressed as stress/strain curves. Lateral deflections are plotted against load.

Observations

Test 1

Visual observation indicated that the first signs of failure occurred along the base of the wall, at an applied load of 250 tonnes. Hair-line cracks, extending upwards from the base of the wall were visible on all elevations. The most likely origin of these cracks is related to the development of stress concentrations imposed by the omission of the mortar bed under the first course of brickwork.

Intermittent, loud, cracking sounds were heard coming from the inside of the wall; these were attributed to cracking of the cross-ribs. Loading was continued until failure occurred at an applied load of 485 tonnes. At failure the wall collapsed completely, but several large portions of brickwork remained intact showing splitting of the cross-webs.

Test 2

During loading of this wall, the intermittent cracking sounds, heard in the initial test, were again audible but at a higher load. No visual evidence of external cracking was observed until the load reached 500 tonnes, when vertical cracks appeared in the return ends of the wall. Loading was continued until failure occurred in an explosive manner at 670 tonnes. Sixteen courses of brickwork remained reasonably intact at the base, the remainder collapsing into relatively small fragments.

COMPARISON OF EXPERIMENTAL RESULTS WITH CALCULATED VALUES

Both the permissible stress and limit state design codes in the U.K., CP 111:1970[3] and BS 5628:Part 1:1978[4] respectively, rely on a slenderness ratio approach to design. The slenderness ratio is taken as the effective height divided by the effective thickness. which for solid walls is the actual thickness. When other types of wall are designed e.g. cavity walls and those with piers incorporated in their length, the effective thickness is based on the concept of equivalent second moment of area, unlike other codes where a radius of gyration approach is often used.

If the second moment of area basis is used for the diaphragm test walls, the effective thickness is 207.7 mm, and for the radius of gyration approach 284.7 mm, compared to an actual thickness of 219 mm.

Both BS 5628 and CP 111 give methods for obtaining a characteristic or permissible stress from wall tests. In the former, being limit state, the failure load is divided by 1.2 to allow for a reasonable variation in results, but slenderness ratio is not usually taken into account. For these two tests, the figure of 1.2 should be higher because of the high variation, but 1.2 has been used to obtain a characteristic strength as indicated in Table 3. This table also gives figures for characteristic strength from the Code Table 2(a), based on mortar and unit strength, but unfortunately extrapolated, as the unit strengths are higher than those recognized by the Code.

Clause 502 of CP 111, being in permissible stress terms, gives considerably lower figures than BS 5628 and, as the slenderness ratio is involved, a permissible stress has been calculated for effective thickness t_{ef} based on a second moment of area, actual thickness, and radius of gyration. This is compared to extrapolated values from Table 3a, CP 111 in Table 3.

It can be seen that the actual failure stress for test 1, and the characteristic values obtained from the tests are less than that obtained from simple knowledge of the brick and mortar. This applies also to the permissible values, which are considerably lower than those from table 3a of CP 111; this is independent of the basis on which t_{ef} is calculated.

If the characteristic strengths as obtained from the tests in Table 3 are used to calculate the ultimate strength of the wall, the effect of slenderness, i.e., t_{ef} as well as height, can be included. This is shown in Table 4. The permissible stress obtained from the tests, together with the Code permissible values, as given in Table 3, have been used to calculate permissible loads on the wall.

As in Table 3, it can be seen that the loads calculated from BS 5628 using the characteristic strength from the tests, give lower values than the failure load factored by 1/1.2, the reason being that a slenderness reduction factor has now been applied. It should be noted that the quite wide variations in effective thickness make only small changes in the result.

Using the CP 111 approach, the safe loads obtained from the permissible stress based on clause 502 of CP 111 are considerably less than those calculated from the permissible stresses given by the Code.

CONCLUSIONS

Comparison of experimental diaphragm wall test results with values calculated from BS 5628 and CP 111 suggests that the test results were not as high as should have been obtained if the diaphragm wall is to be treated as a normal solid wall. Three values of effective thickness were used in the calculation based respectively on the second moment of area, the radius of gyration and the actual thickness. The difference in results obtained using these three effective thicknesses is small, and for all practical purposes, the effective thickness may be taken as the overall thickness, making a simple rule for designers to use.

The unit strength used was higher than recognized by the Codes, making extrapolation necessary for calculation. A wall test using a more realistic unit strength would be of value in supporting the results reported.

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TABLE 1—Compressive Strength of Bricks

Wall Test No.	Compressive strength (N/mm^2)				No. of Samples
	Mean	Range	Standard Deviation	Coefficient of Variance (%)	
1	134	97–189	35.9	26.8	10
2	165	124–236	35.5	21.5	20

TABLE 2—Strength of Walls, Brick, Mortar and Brick Cubes

Test Wall No.	Compressive strength (N/mm^2)				Ratio of wall strengths		Ratio of brick cube strength to brick strength
	Wall	Brick	Mortar Cube	Brick Cube	Brick Strength	Brick cube Strength	
1	15.35	134	2.58	38.5	0.12	0.43	0.29
2	21.20	165	2.54	42.7	0.14	0.53	0.26

TABLE 3—Comparison of failure stress with that obtained from BS 5628 and CP 111

Code	Stress (N/mm^2)		Test 1	Test 2
	In wall at failure		15.35	21.20
BS 5628	Characteristic compressive strength f_k (using Appendix A2) +		12.79	17.67
	f_k from table 2 (a) *		18.50	19.50
CP 111	Permissible from test using clause 502	t_{ef} 207.7 mm	2.77	3.82
		219 mm	2.80	3.87
		284.7 mm	2.77	3.82
	Permissible from table 3 a *		4.60	5.40

+ unaffected by effective thickness
* unit strength exceeds maximum figure in tables—value given is extrapolated.

TABLE 4—Comparison of Wall Strengths with Calculated Values from BS 5628 and CP 111

Code	Wall stregth (kN)		Test 1	Test 2
	Test strength		4758	6572
BS	Characteristic strength (using Appendix A2)		3965	5478
5628	Calculated using Appendix A2, f_k from Table 3 above	t_{ef} = 207.7 mm	3767	5204
		219 mm	3806	5258
		284.7 mm	3965	5478
CP 111	Safe strength using Clause 502, permissible stress from table 3 above	t_{ef} = 207.7 mm	747	1030
		219 mm	764	1056
		284.7 mm	816	1125
	Safe strength using Code table 3a stress	t_{ef} = 207.7 mm	1241	1456
		219 mm	1255	1473
		284.7 mm	1355	1590

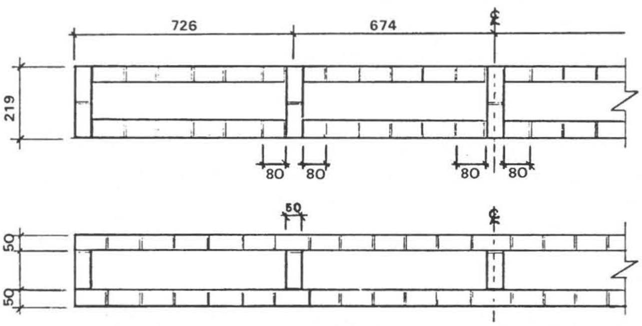

Figure 1. Dimensions and bonding details of half-scale walls.

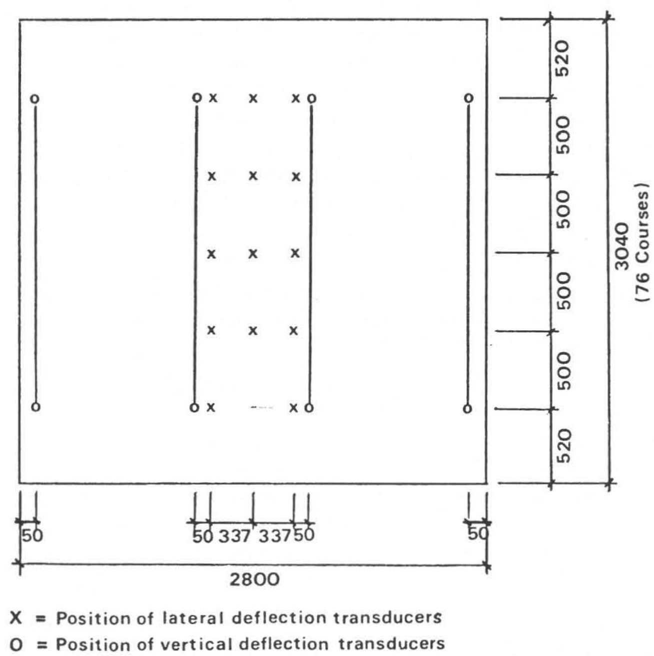

Figure 2. Position of measuring points across face area.

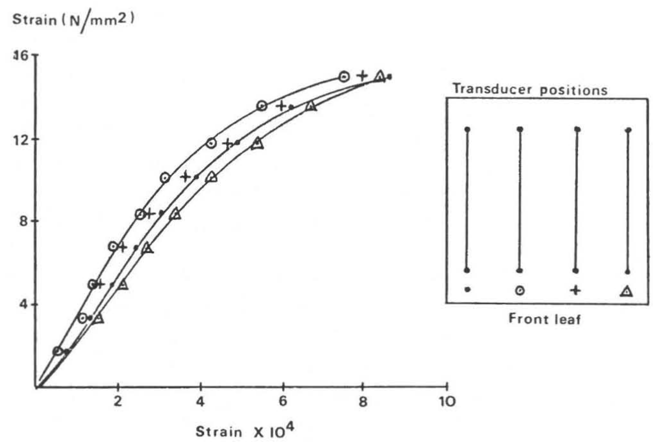

Figure 3. Typical stress/strain curve for Wall 1.

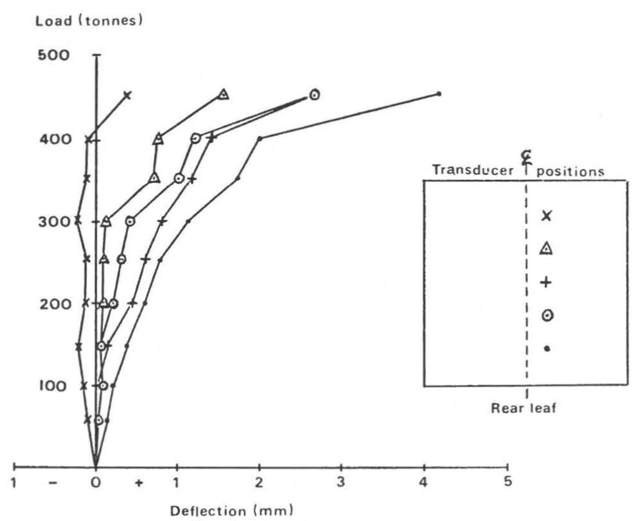

Figure 4 Typical lateral deflections for Wall 1