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FLEXURAL CAPACITIES OF CONCRETE BLOCK WALLS WITH OPENINGS

by

Andrew C. Middleton[1] and Robert G. Drysdale[2]

ABSTRACT

The test results for six full-scale concrete block walls subjected to uniformly distributed out-of-plane loading are reported. The walls had overall dimensions of 2.8 x 6.0 m. The effects of size and location of openings and of steel reinforcing were investigated. All walls were simply supported on all four sides with clear span dimensions of 2.8 x 5.8 m. Auxillary tests were performed on masonry assemblages to obtain the basic material strength characteristics. These included tests of individual joints under bending normal and parallel to the bed joint to document the respective flexural tensile strengths.

The first cracking loads and the failure loads were determined as well as the load-deflection behaviour over the full loading range. The impact of openings was relatively small and reinforcing resulted in substantial increases in failure loads. The results from yield-line analyses were compared to the failure loads and gave conservative predictions of capacities.

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[1] Engineer, Structural Headquarters, Canadian National Railway, Montreal, Quebec, Canada.

[2] Professor, Department of Civil Engineering, McMaster University, Hamilton, Ontario, L8S 4L7, Canada.

INTRODUCTION

Existing masonry design codes differ substantially in their treatment of masonry walls subjected to uniformly distributed out-of-plane loading. Particularly in North America, the lack of extensive experimental and analytical research may be partly responsible for no specific treatment of this topic in the design codes. Alternately, specification of much lower design strengths for flexural tension has created a greater incentive for codes in other countries to take advantage of inherent strengths in walls supported on 3 or 4 sides. The British Code (BSI 1978) uses a design procedure based on moment coefficients derived from yield-line analyses and experimental results (Haseltine, West and Tutt, 1977). Although the typical crack patterns for walls appear similar to yield lines and several researchers (Haseltive, West and Tutt, 1977; Hendry 1973; Hendry and Khein, 1976) have reported getting good agreement between predicted failure loads and test results, the pragmatic justification for using a theory based on ductile behaviour for a brittle material like masonry is difficult for many to accept. In addition, the results from some tests (Baker, 1973) are not conservatively predicted.

The Australian Code (SAA 1988) uses very low allowable tensile stresses comparable to those used in the British Code (BSI 1978), but it differs in the method used to calculate the wall strength. Based on work by Baker (1973, 1981), the Australian code uses an empirical strip method where the ultimate capacity of a wall is considered to be the sum of the capacities of a vertically spanning strip and a horizontally spanning strip.

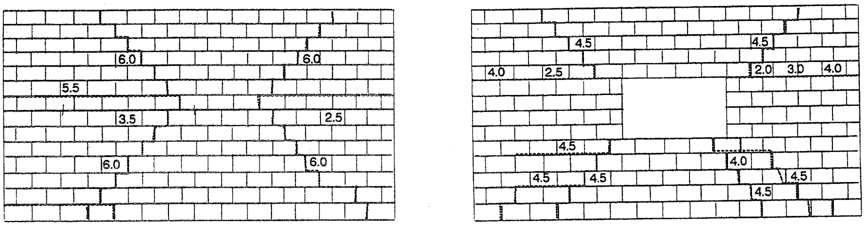
In North America (ACI 1992, CSA 1995), the design for out-of-plane bending is governed by allowable tension stresses and strengths, respectively, with the designer being responsible for performing an appropriate analysis. With the aid of computers, finite element analysis (Essawy 1986) is becoming an alternative to existing analysis methods such as elastic plate analysis or the crossed strips method.

The limited research which does exist in masonry walls subjected to out-of-plane loading deals primarily with walls without openings. Consequently, design codes and textbooks offer little advice on how to handle walls with openings.

WALL TEST PROGRAM

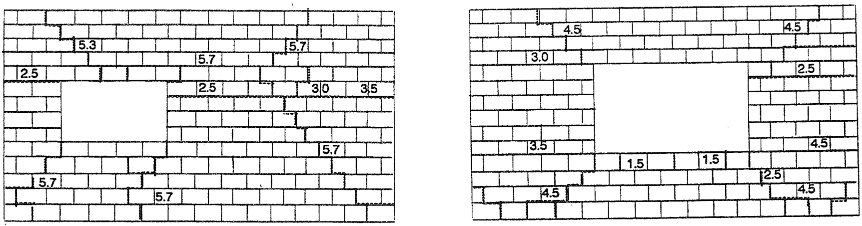
Wall Test Apparatus

Details of the wall test apparatus are shown in Fig 1. It was constructed to be able to test full size walls up to 6.0 m long by 3.6 m high. The support frame was bolted to the strong floor of the testing laboratory and was designed (Essawy and Drysdale 1983) to accommodate various locations and combinations of edge supports. The design of the heavy steel support frame was based on limiting the differential deflection between any two points on the support frame to less than 1 mm at a lateral pressure of 12.5 kPa (250 psf). A backup wall made of a plywood covering on a steel framework is tied to the support frame to enclose an air bag placed between it and the test wall. The air bag was fabricated to cover the entire area of a test wall. The air bag was inflated using a



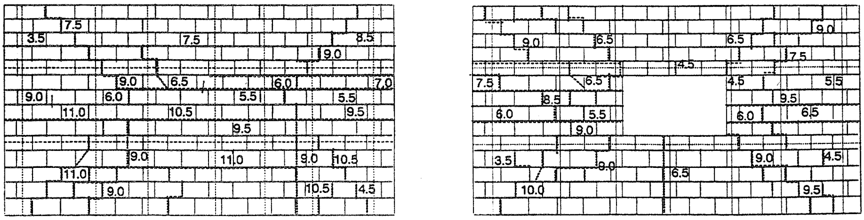
a) Wall 1N

b) Wall 2NSWC



c) Wall 3NSWOC

d) Wall 4NLWC



e) Wall 5R

f) Wall 6RSWC

Fig. 1. Details of Test Set-up.

100 psi (690 kPa) air supply incorporating a pressure reduction value and a low pressure regulator on the intake. Manometers using water columns were located at the intake and at the far end of the air bag to ensure accurate readings of the air pressure.

To provide well-defined support conditions to facilitate the development of analytical models, simple support conditions were used. At the bottom of the wall, individual steel plates for each block transferred the reaction from the wall to a 40 mm diameter roller located along the mid-depth of the wall. The individual steel plates had a 20 mm radius milled slot to permit rotation while a shear key prevented lateral displacement. The supports along the sides and top consisted of 25 mm diameter steel rods welded to the support frame. Lateral load was transferred to the steel rods through 5 mm thick, 25 mm wide steel strips, held in place against the wall and the steel rods using plaster of paris, thereby eliminating the effects of any imperfections in the alignment of either the wall or the reaction supports.

Openings in Walls

Openings in block walls usually have windows to transfer wind load to the surrounding wall through connections between the window frame and the wall. Rather than use actual windows, a simulator was used. The simulator was made up of 19 mm (3/4 inch) plywood fastened to a wood frame. The wood frame fit within the wall opening with the plywood overlapping onto the surrounding blocks by at least 50 mm (2 in.) on each side. The wood frame was used to stiffen the plywood and help distribute the load as a window frame normally would.

Fabrication of Test Specimens

The full size walls and auxillary test assemblages were built by an experienced mason using type-S mortar and standard 190 mm two-cell concrete blocks. The mortar was prepared in 60 lb (27 kg) batches, proportioned by weight for better quality control, and any mortar not used within a half hour was discarded rather than retempered. All mortar joints were tooled. The mortar flow was measured and three 2-inch (51 mm) cubes were taken for each mortar batch.

The auxillary test specimens, to determine the flexural tensile strength normal and parallel to the bed joints were constructed at the same time as the full size walls. The auxiliary specimens were made up of five block high stack bonded prisms for bond wrench tests (ASTMC 140-93 1993) and two block high beam specimens to determine the flexural strength parallel to the bed joint (ASTM E518-80(87), 1993).

Wall Test Procedure

Each full size wall was carefully picked up at four points and positioned over the individual bearing plates. The wall was then carefully lowered onto a full bed of mortar and levelled. The mortar was allowed to harden for several days prior to testing. On the day of the test, the backup wall was tied to the support frame using threaded rods and nuts. During testing, deflections were recorded using dial gauges positioned in vertical lines at the mid-length and quarter points of the wall. Deflections of the support frame were also monitored at the corners and mid-lengths of all sides of the test wall.

Mechanical strain gauge points were positioned throughout the panels. The deflection and strain readings were taken after each increment in air pressure and the wall surface was checked for cracks.

TEST RESULTS

Auxillary Tests, Block and Mortar Strengths

Using hard capping, the mean compressive strength of the block was 37.0 MPa. The splitting tensile strength of the block was 2.68 MPa. The block had an initial rate of absorption of 2.89 kg/m^2/min. The Type S mortar had proportions by weight of portland cement:lime:sand:water of 1:0.21:4.24:0.9 which resulted in a mortar flow of 127% and a cube compressive strength of 16.6 MPa.

The prism tests gave a compression strength of 32.7 MPa. The flexural tensile strength normal to the bed joint was 0.68 MPa compared to 1.38 MPa for tension parallel to the bed joint.

Full Size Wall Results

Figure 2 shows the cracking patterns for the six full size walls and Fig. 3 shows each wall's mid area deflections. The loads at first cracking and failure are listed in Table 1 along with the capacities from the yield line analyses. This information is used to discuss crack propagation and load carrying behaviour.

Table 1 Load at First Crack and Failure Load for Test Walls

Wall 5.8x2.8 m	Opening Size (m)	Opening Location	Reinforcing	First Major Crack* (kPa)	Failure Load (kPa)	Yield Line Analysis (kPa)
1N	N.A.	N.A.	No	2.5	6.0	4.8
2NSWC	0.8x1.6	Centre	No	2.0	4.5	4.15
3NSWOC	0.8x1.6	1.4m off centre	No	2.5	5.7	4.58
4NLWC	1.2x2.4	Centre	No	2.5	4.5	3.8
5R	N.A.	N.A.	Yes	3.5	11.0	12.8
6RSWC	0.8x1.6	Centre	Yes	3.5	10.0	11.7

*Last stable load before cracking

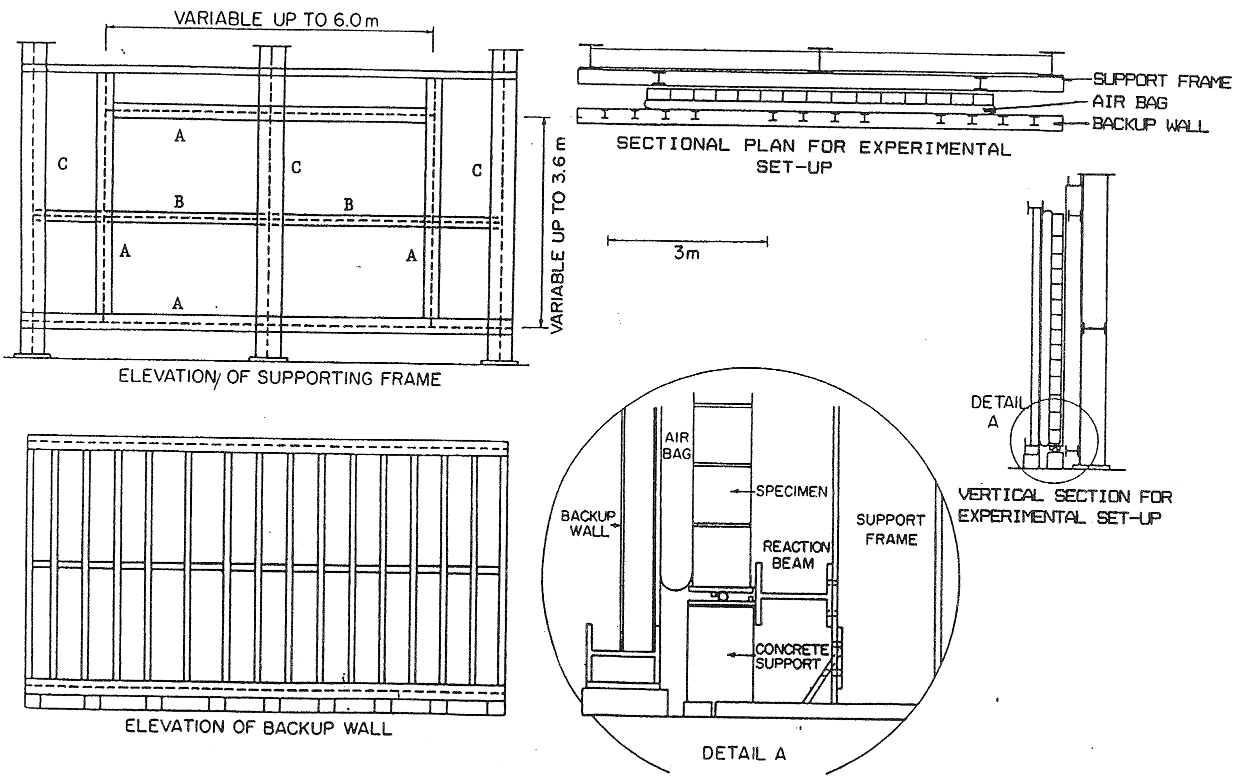


Fig. 2. Crack Patterns for Test Walls

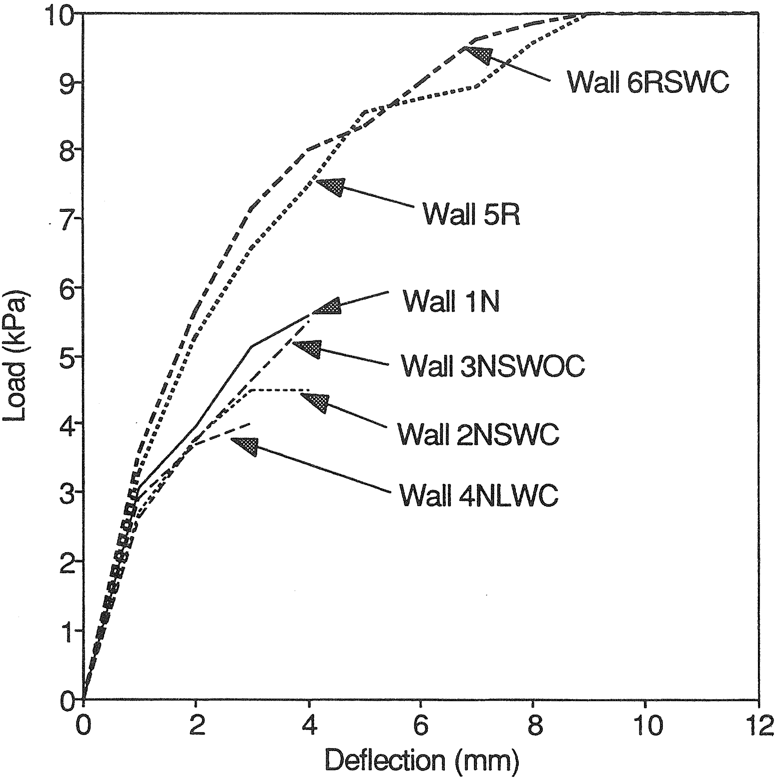


Fig. 3 Mid-Area Deflection versus Lateral Pressure

a) Wall IN: This wall did not have an opening and was not reinforced. It acts as the control wall for the test program. The crack pattern consisted of a mid-height horizontal crack which developed shortly after first cracking and diagonal cracks running to the corners formed at failure. This crack pattern resembles the yield line pattern corresponding to a predicted failure at 4.8 kPa. The Load-Deflection diagram indicates linear behaviour until the first crack forms, then there are changes with each significant new crack.

b) Wall 2NSWC: This wall differed from Wall IN by having a 0.8 m high x 1.6 m long opening in the centre. The first crack appeared at 2.0 kPa and it failed at 4.5 kPa. The wall surface area was 7.9% less than Wall IN with a 20% lower load at first cracking. The crack pattern is similar to wall IN except that the initial horizontal crack formed at the top of the opening and the diagonals formed from the corners of the opening. The load-deflection behaviour for wall 2WSWC is similar to Wall IN with initial linear behaviour until first cracking. The capacity of Wall 2NSWC was 25% lower than for Wall IN. The yield line analysis predicted a capacity of 4.15 kPa, a less conservative estimate than for Wall IN.

c) Wall 3NSWOC: This was the only nonsymmetric test wall with the 0.8 x 1.6 m opening located 1.4 m to the left of centre. It first cracked at 2.5 kPa and failed at 5.7 kPa; values very similar to Wall IN. The initial horizontal crack ran along the top of the opening, with somewhat independent cracks running from the lower corners of the opening and unequal diagonals forming at failure. The load-deflection relationship is very similar to Wall IN. The yield line predicted capacity is only slightly less than for Wall IN.

d) Wall 4NLWC: Wall 4NLWC contained a large 1.2 m high by 2.4 m long central opening removing 18% of the wall surface area. The first major crack formed at 2.5 kPa and the wall failed at 4.5 kPa. Small cracks at the bottom of the opening appeared at 1.5 kPa but they did not propagate any further.

The cracking pattern is similar to Wall 2NSWC with diagonals forming from the opening corners at failure, but this wall is unique in having horizontal cracks running at both the top and bottom of the opening.

e) Wall 5R: Like Wall IN, Wall 5R had no openings, but had two 100 mm^2 reinforcing bars running horizontally and seven 200 mm^2 vertical reinforcing bars spaced at 400 mm. Only the cells containing reinforcement were grouted. The first crack for Wall 5R was visible at 3.5 kPa, a 40% improvement over Wall IN and the failure load was nearly double the failure load for this comparable unreinforced wall. The overall crack pattern is reasonably similar to Wall IN, but the cracking is much more extensive (i.e., more spread out over the wall.) The horizontal cracks did not appear suddenly as with the unreinforced walls but propagated slowly with additional loading. Even the diagonals which tended to cause failure in the previous walls developed over several load increments.

The load-deflection behaviour is linear until first cracking and then exhibits a more elastic behaviour without the brittle failure as in Wall IN. The yield line prediction overestimated the failure load.

f) Wall 6RSWC: This wall had the same dimensions and opening as Wall 2NSWC and it also had the same reinforcing as Wall 5R. The first crack occurred at the same 3.5 kPa load but it fails at 10 kPa load. The crack pattern is more extensive than the unreinforced wall 2NSWC but it followed the same general trend. The diagonal cracks were more pronounced for Wall 6RSWC than for Wall 5R. The load deflection response is very similar to wall 5R.

CONCLUSIONS

1. The behaviour of concrete block walls subjected to lateral out-of-plane loading can be divided into three stages: pre-cracked, cracked and failure. This suggests that a multiple analysis approach, possibly including elastic and failure mechanism methods, may be required.
2. Even though the entire wall area remained under lateral load and the window openings resulted in large reductions in the areas of the vertical and horizontal cross-sections, the impacts on cracking load and failure load were less than proportional decreases. Nonetheless, the size and location of the openings did have sufficient effect to warrent consideration during design.
3. The presence of reinforcing enhances the total load carrying capacity but the wall begins to crack at nearly the same load levels as unreinforced walls. The reinforcement spreads the cracking throughout the wall to a greater degree.
4. The presence of openings and reinforcement allows more pronounced deflection of walls prior to failure. The reinforced walls exhibited considerable ductility whereas the unreinforced walls still exhibited brittle failure.
5. Although the capacities predicted using an unadjusted yield line analysis are in reasonable agreement with the test results, work continues to provide design guidance which is a rational representation of actual behaviour.

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