10th Canadian Masonry Symposium, Banff, Alberta, June 8 – 12, 2005

STRAIN GRADIENT IN MASONRY WALLS

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ABSTRACT

Strain measurements in 32 concrete block masonry walls tested under various axial loadings have shed some light on the nature of the strain variation through the wall thickness. The strain gradient profile in an eccentrically loaded specimen has been found to change noticeably as the load increases monotonically from zero to ultimate. Typically, the strain gradient is close to linear at low load levels but becomes quadratic or cubic in nature through the thickness as load levels increase. For specimens tested under eccentric compressive loading, ultimate strain and ultimate stress at the extreme compressive fibre, larger than those of concentrically loaded specimens, were observed. A parabolic stress-strain relationship for masonry in compression obtained from tests and the rectangular stress block theory were used to evaluate the strain gradient effect on ultimate load capacities. Experimental findings are presented in tabular and graphical form and their implications for analysis and design are discussed in detail.

KEYWORDS: strain gradient, concrete block masonry wall, eccentric loading, stress-strain relationship, stress-block theory

INTRODUCTION

The hypothesis of plane sections before bending remaining plane after bending, as in the traditional flexural theory, is adopted in flexural analysis and design of masonry. This implies that a linear strain distribution exists in the cross section. Application of this assumption in flexural analysis and design of concrete structures by many researchers has shown good correlation between calculated and experimental strength [1, 2]. While this assumption is widely accepted and is considered to be accurate enough for design purposes, the validity of this hypothesis has been questioned for a number of reasons [2]:

1. Most of the previous research was based on test results of concrete beams and columns with rectangular cross section, and measurements were made in a region of constant moment;
2. Strains, usually measured on the surface of the concrete members, may not be able to represent the strain conditions inside the members;
3. For laminated or composite members such as reinforced masonry, disturbance will occur at the points where material or geometric properties change abruptly.

Consequently, one may question the validity of the application of linear strain distribution assumption in masonry structural design when subjected to combined bending and axial loading. At the same time, uniaxial compression tests have traditionally been used to define the stress-strain relationship for materials loaded eccentrically, a practice which is also carried out in masonry. This assumption does not consider the strength increase for masonry at the extreme compressive fibre due to strain gradient effect. The experimental study presented herein, in which strains were measured in concrete block masonry wall specimens tested both axially and eccentrically, was conducted to investigate the strain variation within masonry wall cross-sections to assess the validity of these assumptions. Thirty-two masonry wall specimens including grouted plain masonry and reinforced masonry wall specimens were tested in this experimental program at various load eccentricities [3]. Based on a rational analysis of the test results, the applicability of predicting masonry wall strength using stress-block theory was studied.

WALL SPECIMENS

Of the thirty-two wall specimens tested, six were plain concrete masonry walls, twelve had a single layer of centrally located reinforcement and fourteen had a double layer of vertical reinforcement. All specimens were 800 mm long by 1200 mm high using standard two-core concrete masonry blocks of nominal thickness 150 mm in running half-bond pattern. Type S ready-mixed mortar was used for constructing the wall specimens and corresponding prisms. ASWG9 ladder type bed joint reinforcement was placed at 400 mm centre to centre beginning with the bottom course to control shrinkage. Grout used in the wall specimen construction was designed to have a 28 day compressive strength similar to the concrete masonry units. For each wall specimen, five companion prisms were constructed and tested at the time of the wall test. The average compressive strength of the prisms was used in the calculations in the following sections.

Plain masonry walls were constructed either fully grouted or partially grouted with only the two outer cells grouted. Reinforced masonry walls were tested with various grout and reinforcement patterns, the details of which are shown in Figure 1.

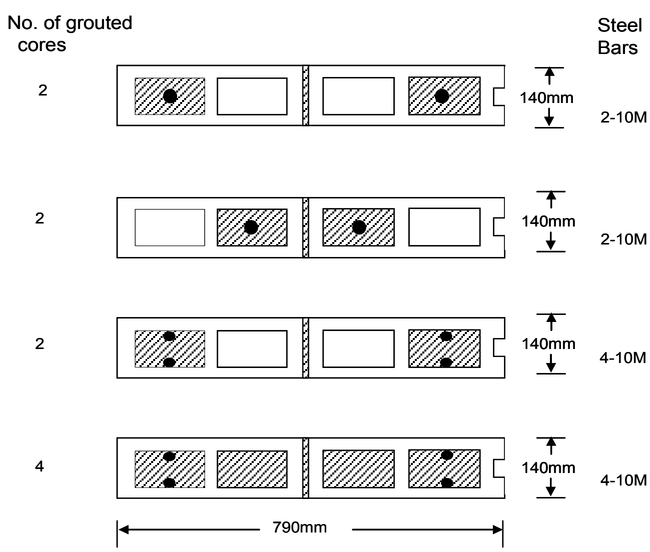


Figure 1 - Cross-Section Details of Reinforced Specimens

To differentiate specimens, a designation system such as 2S0-11 was used. The leading digit refers to the number of wall cores grouted, either 2 or 4. The letters P, S, and D refer to plain, singly reinforced, and doubly reinforced masonry walls, respectively. The digit, 0, 1, 2, and 3, immediately following the letter represents the corresponding eccentricity ratio, e/t, equal to 0, 0.18, 0.27, and 0.36, respectively. The last two digits in the specimen designation refer to the specimen number within a group and the group number, respectively. A detailed description of the specimen variables and their identifications are presented in Table 1 where P_u, Δ_u, and M_u are the ultimate load, ultimate deflection at mid-height, and ultimate moment reached during testing.

Table 1 - Specimen Description and Test Results for Wall Specimens

Wall Designation	No. of Grout Cores	e/t	Steel Bars	P_u (kN)	Δ_u (mm)	M_u (kN.m)
4P0-11	4	0	0	1348	1.3	1.75
2P0-11	2	0	0	1090	1.5	1.63
4P1-11	4	0.18	0	1140	5.8	35.34
2P1-11	2	0.18	0	936	4.5	27.80
4P3-11	4	0.36	0	670	8.0	39.13
2P3-11	2	0.36	0	657	6.5	37.38
2S0-11	2	0	2-10M	1124	1.0	1.12
2S1-11	2	0.18	2-10M	967	3.5	27.75
2S1-21	2	0.18	2-10M	1048	4.1	30.71
2S2-11	2	0.27	2-10M	802	4.4	33.84
2S2-21	2	0.27	2-10M	665	4.3	28.00
2S2-31	2	0.27	2-10M	717	4.3	30.19
2S2-12	2	0.27	2-10M	668	4.5	28.26
2S2-22	2	0.27	2-10M	580	4.6	24.59
2S3-11	2	0.36	2-10M	484	12.0	30.20
2S3-21	2	0.36	2-10M	492	10.0	29.72
2S3-12	2	0.36	2-10M	567	5.9	31.92
2S3-22	2	0.36	2-10M	669	5.8	37.60
4D2-11	4	0.27	4-10M	780	4.6	33.07
4D2-21	4	0.27	4-10M	872	4.6	36.97
4D2-31	4	0.27	4-10M	817	4.6	34.64
4D2-41	4	0.27	4-10M	914	4.5	38.66
2D2-11	2	0.27	4-10M	730	4.3	30.73
2D2-21	2	0.27	4-10M	706	4.2	29.65
4D3-11	4	0.36	4-10M	604	9.5	36.18
4D3-21	4	0.36	4-10M	607	8.5	35.75
4D3-31	4	0.36	4-10M	580	10.0	35.03
4D3-41	4	0.36	4-10M	580	8.5	34.16
2D3-11	2	0.36	4-10M	591	10.0	35.70
2D3-21	2	0.36	4-10M	598	12.0	37.32
2D3-31	2	0.36	4-10M	568	9.5	34.02
2D3-41	2	0.36	4-10M	550	9.0	32.67

TEST SETUP AND INSTRUMENTATION

A self-equilibrating steel frame as shown in Figure 2 was used for testing the larger wall specimens which were mounted in the frame under pinned support conditions. For plain masonry wall specimens, strains on both compressive and tensile surfaces were measured using Linear Strain Converters (LSCs) with travel lengths of 25.8 mm and 50.6 mm and an accuracy of 0.00001mm. LSCs were mounted across mortar joints on both the compression and tension faces. In the case of reinforced specimens, in addition to the strains measured on the compression and tension faces, strains were also measured on the vertical reinforcement instrumented with strain gauges at mid-height of the specimen. Strain gauges were water-proofed and wrapped in tape to prevent them from being accidentally damaged during grouting. Care was taken to secure the reinforcement in the intended positions during grouting using stiff wire clips. Holes were drilled in the top-most block as an outlet for electrical wires from strain gauges. Vertical compressive loading was applied using an 1800 kN hydraulic jack, which was bolted to the top reaction beam of the test frame. Compressive loading was transmitted through a load cell with a maximum capacity of 1780 kN to monitor the vertical load during the tests. Lateral mid-height deflections of wall specimens were continuously monitored using an endless dial gauge mounted on an independent frame.

EXPERIMENTAL PROCEDURES

During a typical test, axial load was gradually increased monotonically to failure. Readings from load cells, continuous dial gauges, and LSCs were taken and recorded by a computer-controlled data acquisition unit. Data acquisition and recording rates were set to occur every three seconds. At approximately 90 per cent of the expected ultimate loading, LSCs were removed to avoid damage and the wall specimen loaded to failure. In all cases, ultimate failure was deemed to have occurred when vertical cracks formed and the wall could not sustain any further vertical load, or when the specimen displayed large lateral deflection at decreasing load.

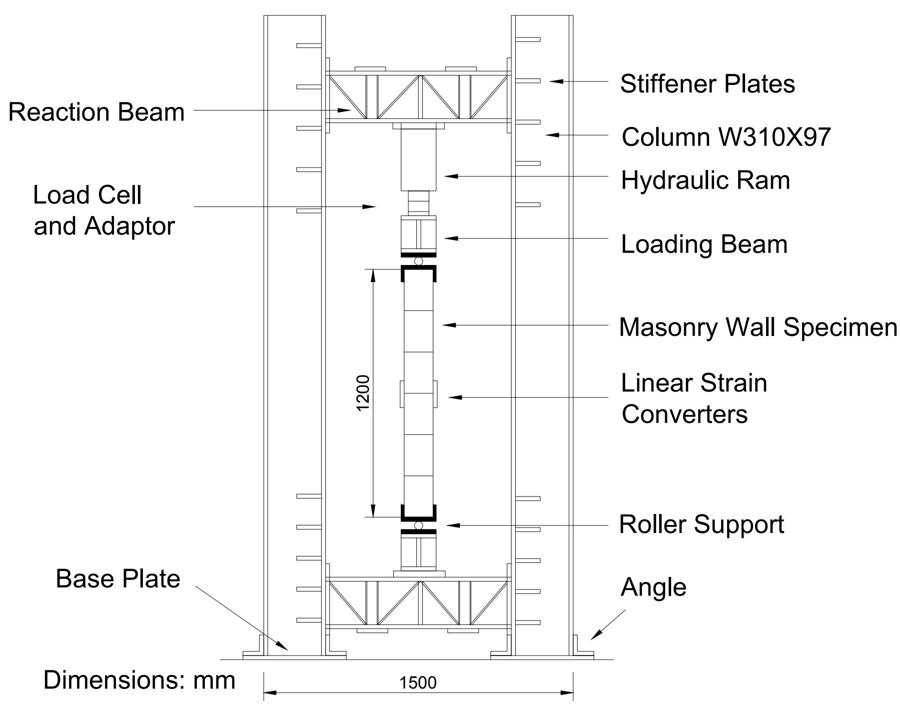


Figure 2 – Test Setup

RESULTS AND DISCUSSION

Test results are summarized in Table 1 where e/t is the ratio of eccentricity to wall thickness, P_u is the ultimate axial load, Δ_u is the deflection at mid-height at ultimate, and M_u is the maximum moment at the mid-height calculated as $P_u(e+\Delta_u)$. The stress-strain relationship for masonry in compression, strain distribution profiles, and strain gradient effect and its design implications are discussed in the following sections.

Stress-Strain Relationship

Stress-strain relationships for plain masonry walls 4P0-11, 4P1-11 and 4P3-11 are shown in Figure 3. While the compressive stress for concentrically loaded specimen 4P0-11 was determined directly by dividing the applied load by the effective cross sectional area, the compressive stresses on the extreme compressive fibre of eccentrically loaded specimens, 4P1-11 and 4P3-11, were calculated assuming an elastic stress distribution across the depth of the cross section. It is evident that the extreme fibre stresses for eccentrically loaded specimens are 2 to 2.5 times the stresses of a concentrically loaded specimen due to a strain gradient effect. The ultimate strains for eccentrically loaded specimens ranged from 0.0035 to 0.0042, which are markedly higher than that of the concentrically loaded specimen and also higher than the current Canadian design code [4] suggested value of 0.003. A similar trend was also observed in plain masonry specimens 2P0-11, 2P1-11, and 2P3-11 where only two outer cells had been grouted.

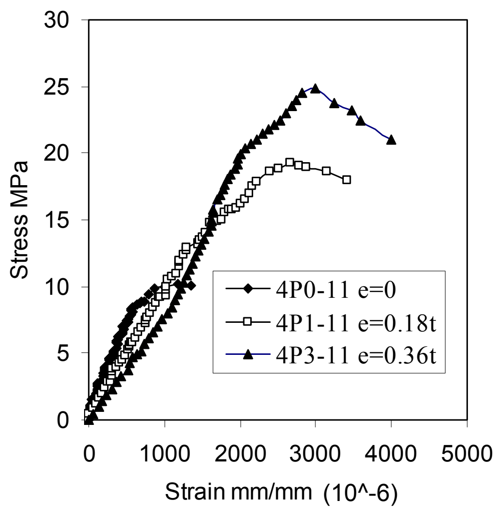
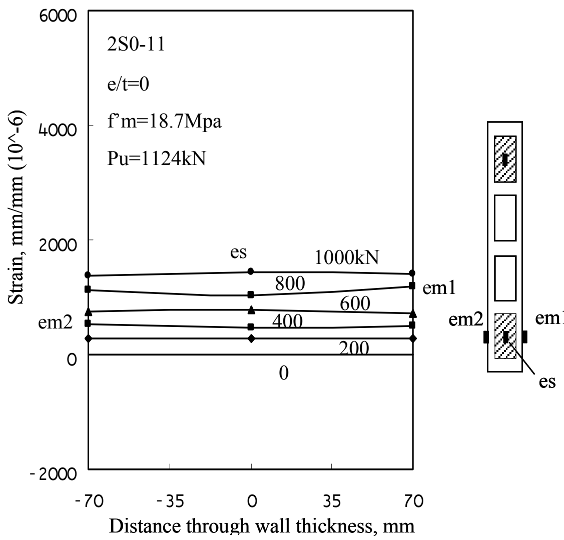


Figure 3 – Stress-Strain Curves for Concentrically and Eccentrically Loaded Plain Masonry Specimens

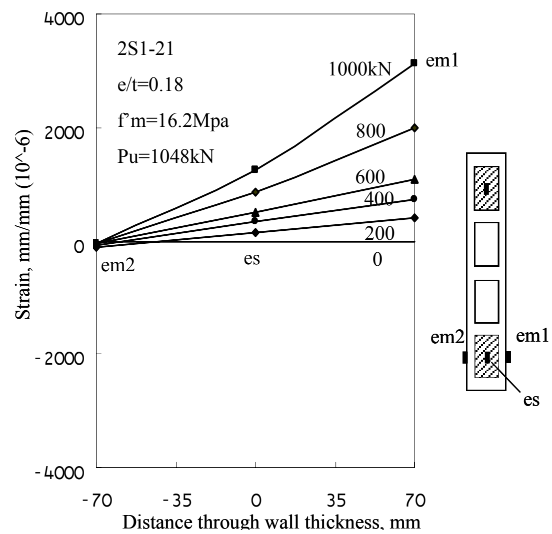
Strain Distribution Profiles

Single layer reinforced masonry walls

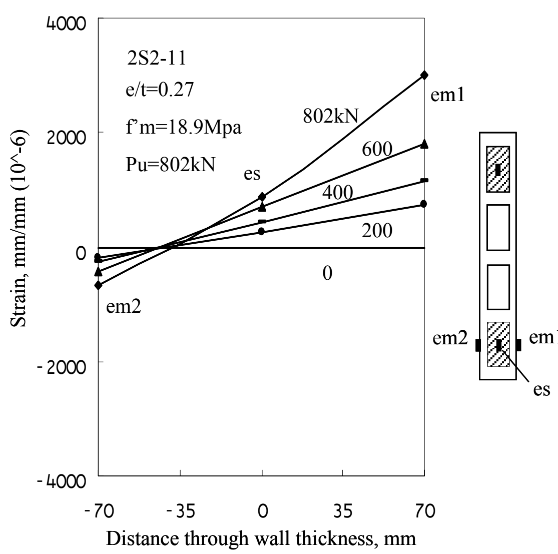
For reinforced masonry walls with a central layer of reinforcement, strain measurements were taken at the compression and tension faces as well as on the centrally located vertical steel at mid-height of the specimens. These values are respectively designated as em_1, em_2 and e_s on the strain gradient curves of Figure 4 which shows typical strain profiles for wall specimens tested at load eccentricity ratios, e/t, equal to 0.0, 0.18, 0.27 and 0.36. For concentrically loaded specimens (Figure 4-a), strains remain linear with zero gradient through the thickness as load is incremented to ultimate. For eccentrically loaded specimens (Figures 4-b, 4-c, and 4-d), strain gradients, which appear to be more or less linear at low load levels, become noticeably non-linear at about 60 per cent of the ultimate wall capacity. This non-linear strain distribution can be approximated by quadratic functions. As is evident in Figure 4-b, the wall specimen experienced very low tension with almost the entire masonry wall cross section under compression.



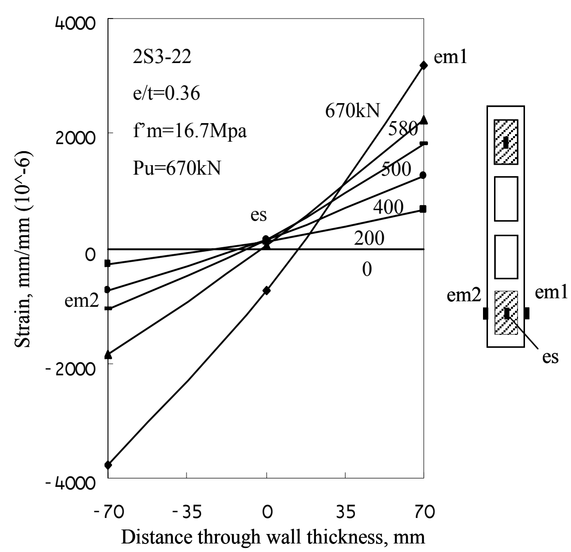
(a) e/t = 0



(b) e/t = 0.18



(c) e/t = 0.27



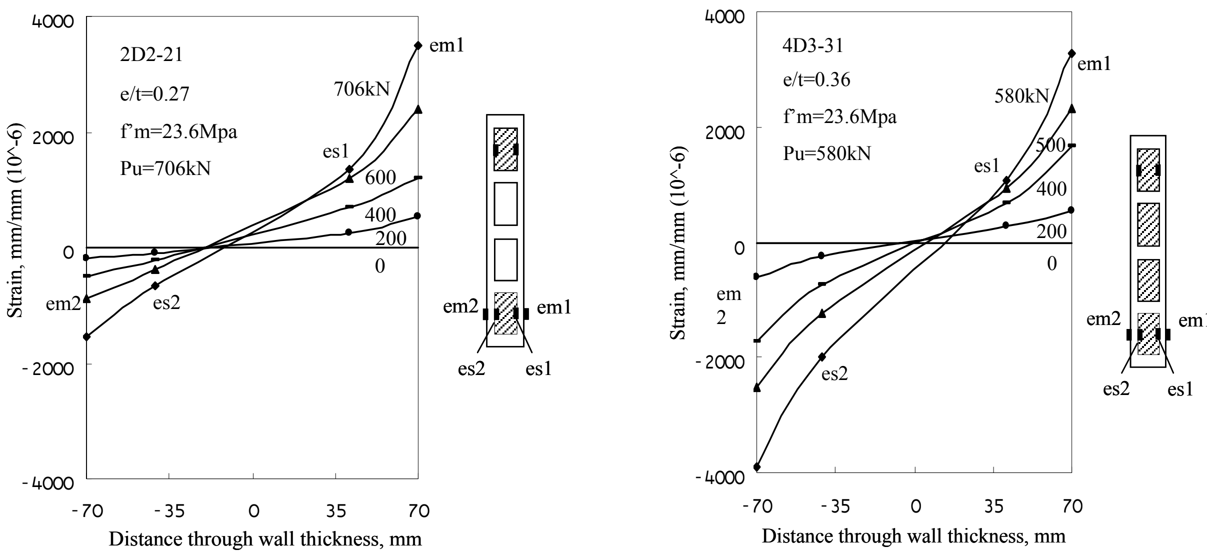
(d) e/t = 0.36

Figure 4 – Strain Gradient Profile for Single Layer Reinforced Specimens with Various Eccentricities

Referring to Figure 4-c, wall specimens tested at a load eccentricity ratio of e/t equal to 0.27 developed some tension, but the crack depth did not reach the central vertical rebar. Wall specimens tested at a larger load eccentricity ratio of e/t equal to 0.36 (as shown in Figure 4-d) exhibited cracks going beyond the vertical steel bars at mid-depth of the wall thickness while the strains in the steel bars remained below the yield strain of 0.002.

Double layer reinforced masonry walls

Figure 5 shows strain variations for double layer reinforced wall specimens tested with eccentricity ratios of 0.27 and 0.36, respectively. Strain measurements were monitored at four different locations through their wall thickness. Strains em_1 and es_1 represent the compressive strain at the face of a masonry wall and the strain in the adjacent vertical steel reinforcement, respectively. Strains em_2 and es_2 represent the strains in masonry and reinforcement in the tension zone. It is evident that strain distributions through the thickness are approximately cubic



(a) e/t = 0.27

(b) e/t = 0.36

Figure 5 – Strain Gradient Profile for Double Layer Reinforced Specimens with Various Eccentricities

throughout the loading sequence up to wall ultimate capacity. The vertical steel adjacent to the tension face of the wall specimen tested at a load eccentricity ratio of e/t equal to 0.27 did not reach the yield strain of 0.002. On the other hand, the vertical steel adjacent to the tension face of the wall specimens tested at e/t equal to 0.36 developed strains greater than or equal to the steel yield strain.

From the above observations of the strain gradient for reinforced masonry walls, it is evident that the reinforcement affects the strain variation through the thickness. Referring to Figure 4-c (2S2-11), a single layer reinforced specimen and Figure 5-a (2D2-21), a double layer reinforced specimen, both were partially grouted walls with the two outer cells reinforced. These walls were tested at a load eccentricity of 0.27 of the wall thickness. Noticeably different, the strain gradient for 2S2-11 is quadratic while that for 2D2-21 has a cubic strain distribution. This suggests that the nature of the strain gradient is affected by the reinforcement pattern through the wall thickness. On the other hand, Figure 6 shows the strain gradient profile for a singly reinforced wall, 2S3-21, with reinforcement placed in the inner cells which is similar to the gradient shown in Figure 4-d for 2S3-22, in which the two vertical reinforcing bars are placed in the two outer cells.

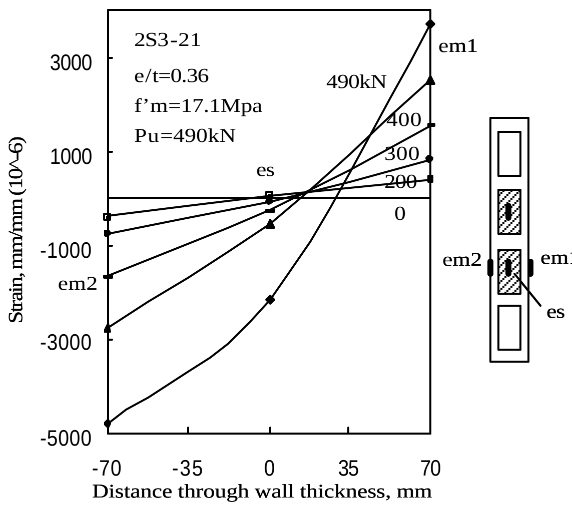


Figure 6 – Strain Gradient Profile for Single Layer Reinforced Specimen with Different Grouting Pattern

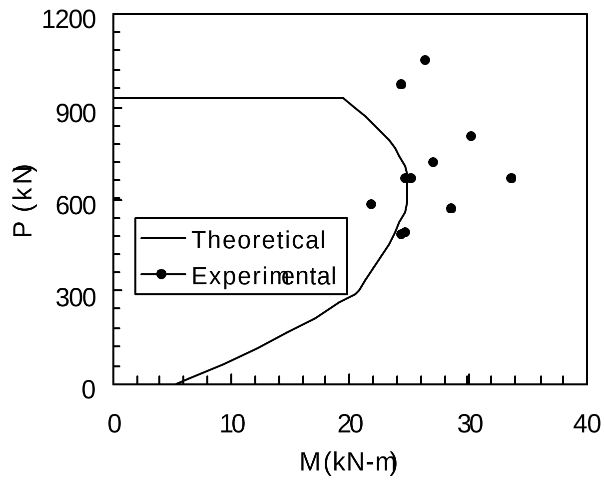


Figure 7 – Comparison of P-M Interaction Diagram and Test Results

Strain Gradient Effect

Concentrically loaded uniaxial prism compression tests have traditionally been used to define the stress-strain relationship for masonry loaded under strain gradient. The implicit assumption is that there is no effect of strain gradient on the shape of the stress-stain curve [5]. The current Canadian masonry design code [4] assumes a linear strain distribution across the section and adopts the rectangular stress block theory to calculate the actual stress distribution in masonry. To evaluate the effect of non-linear strain distribution observed from tests and the effectiveness of rectangular stress block theory, the experimental compressive depths, C_{exp}, obtained from strain distribution profiles were compared with C_{cal}, the theoretical compressive depths calculated using rectangular stress block theory under the ultimate load. The results are presented in Table 2. The ratios of C_{exp}/C_{cal} ranged from 0.59 to 1.48 with the majority of cases being less than 1.0. This indicates that, for a constant ultimate load, the rectangular stress block theory requires a deeper compressive depth than that measured from the tests to maintain the equilibrium. The implication of this discrepancy can also be viewed in Figure 7, in which the P-M interaction diagram is plotted for single-layer reinforced specimens using rectangular stress block theory together with experimental results. Experimental moments excluded the portion caused by deflection at the mid-height of specimens. It is noted that in general, the P-M interaction diagram based on rectangular stress block theory somewhat underestimates the wall load capacity. This underestimation is more pronounced in the region of compression-controlled failure. This observation is in line with the research work conducted by Liu [6]. A similar comparison between the P-M interaction diagram and tested load capacities was also made for specimens with a double layer of reinforcement. It was found that, while similar conclusions can be drawn, test results for double layer reinforced specimens are less scattered and agree well with rectangular stress block theory as seen in Table 2.

It is believed that the discrepancy between test load results and predicted values using rectangular stress block theory is attributable to: (a) higher stresses than f'_m on the extreme compressive fibre due to strain gradient effect; and (b) higher ultimate strain than 0.003 for masonry under eccentric loading.

Table 2 – Comparison of Experimental and Theoretical Compressive Depth, C.

Specimen	P_{uexp} (kN)	C_{exp} (mm)	C_{cal}(mm)	C_{exp}/C_{cal}
4P1-11	1140	132.9	116.6	1.14
2P1-11	936	114.9	153.8	0.74
4P3-11	670	64.6	93.8	0.69
2P3-11	657	70.0	97.4	0.72
2S1-11	967	140.0	147.3	0.95
2S1-21	1048	140.0	162.6	0.86
2S2-11	802	108.6	117.0	0.93
2S2-21	665	125.0	93.0	1.34
2S2-31	717	127.5	102.0	1.25
2S2-12	668	88.3	93.5	0.94
2S2-22	580	116.7	79.0	1.48
2S3-11	484	50.4	64.5	0.78
2S3-21	492	51.3	65.7	0.78
2S3-12	567	84.0	77.0	1.09
2S3-22	669	56.6	93.5	0.61
4D2-11	780	78.8	77.5	1.02
4D2-21	872	79.7	84.9	0.94
4D2-31	817	71.7	80.4	0.89
4D2-41	914	52.6	88.5	0.59
2D2-11	730	89.5	99.0	0.90
2D2-21	706	82.9	95.2	0.87
4D3-11	604	66.8	63.4	1.05
4D3-21	607	69.0	63.6	1.08
4D3-31	580	59.8	61.1	0.98
4D3-41	580	61.2	61.0	1.00
2D3-11	591	72.4	78.8	0.92
2D3-21	598	70.8	79.6	0.89
2D3-31	568	74.6	75.8	0.98
2D3-41	550	79.7	73.5	1.08

CONCLUSIONS

The experimental program investigated strain distributions across the thickness of concrete masonry wall specimens with different reinforcement patterns and grouting patterns and tested under eccentric compressive loading. The following conclusions may be drawn:

1. Reinforcement pattern has an influence on the strain gradient for eccentrically loaded wall specimens. In singly reinforced specimens, the strain gradient becomes quadratically distributed through the thickness as ultimate is approached, while for walls with a double layer of reinforcement the strain gradient is predominantly cubically distributed through the thickness for the greater part of the loading history.
2. Stress-strain relationships for plain wall specimens loaded concentrically and eccentrically were found to differ noticeably in both ultimate strength and ultimate strain values. The compressive stress at the extreme compressive fibre for eccentrically loaded specimens ranged from 2 to 2.5 times the stress for concentrically loaded specimens. The ultimate strain of the former was found to be between 0.0035 and 0.0042.
3. A comparison of load capacities obtained from tests and rectangular stress block theory suggests that rectangular stress block theory gives a lower bound estimation in predicting masonry wall capacity for plain and singly reinforced wall specimens, while it agrees reasonably well with results for double layer reinforced specimens. The discrepancy between test results and results using rectangular stress block theory seem to become more pronounced when compression failure is predominant.

Due to the random nature of the masonry materials, the test results show noticeable scatter. More testing is needed to draw confident conclusions on strain gradient effects and the effectiveness of using rectangular stress block theory in masonry.

ACKNOWLEDGEMENTS

The contribution of materials and labour for test specimens by the Shaw group is greatly appreciated.

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