IN-PLANE SHEAR RESISTANCE OF PARTIALLY GROUTED REINFORCED CONCRETE MASONRY SHEAR WALLS

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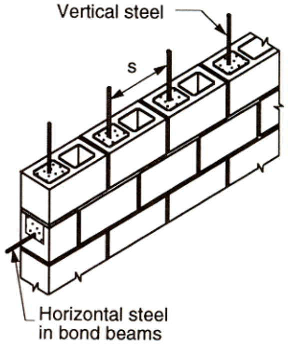
ABSTRACT

The objective of this paper is to establish the accuracy of the existing shear expression for reinforced masonry shear walls when applied to partially grouted (PG) masonry shear walls. To accomplish this objective 60 PG masonry shear wall specimens tested in the past have been located, and seven existing shear expressions adopted by current codes, such as MSJC 2008, and developed in the past research were employed. Most of these expressions are developed based on the research on fully grouted (FG) masonry shear walls. The reported experimental shear resistance of the walls were compared with the predicted values by existing shear expressions. The results of this study indicate that the shear strength expression for reinforced masonry shear walls provided by MSJC (along with others) appears unconservative for PG masonry shear walls. The lack of conservatism may result from the empirical development of this expression based exclusively on fully-grouted shear wall tests, which display failure modes distinctly different than their PG counterparts.

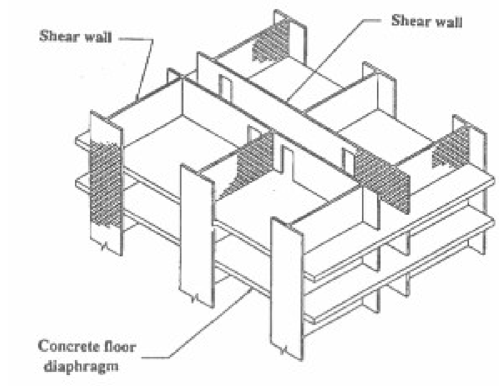
KEYWORDS: concrete masonry, reinforced masonry, shear walls, partially grouted, shear strength, experimental research.

INTRODUCTION

Partially-grouted (PG) reinforced masonry (Figure 1(a)) with concrete units is a common type of construction throughout many moderate to high seismic regions of the United States, such as mid-western, eastern and north-western U.S. Considerable number of fire stations, police stations, schools and warehouses in these regions have PG reinforced masonry shear walls as their lateral load resisting system. Figure 1(b) shows a typical multi-story building in which the masonry shear walls are the only lateral load resisting system. However, the shear strength expression for reinforced masonry shear walls adopted by the Masonry Standards Joint Committee (MSJC) (2008) [2] is empirically based on the behaviour of fully-grouted (FG) masonry shear walls; it is also applicable to the design of PG masonry shear walls. Research into the behaviour of PG masonry shear walls is limited compared to studies of FG masonry shear walls.



(a)



(b)

Figure 1: (a) Partially-Grouted Reinforced Masonry, (b) A Typical Multi-story Building with Reinforced Masonry Shear Walls as Lateral Force Resisting System [1]

The primary objective of this study is to establish if current shear strength expressions for reinforced masonry shear walls accurately reflect the behaviour of PG masonry shear walls. Specifically, the objectives are to investigate the accuracy of the empirically derived shear strength expressions provided by current codes and previous studies. To accomplish this objective, 60 PG masonry shear wall specimens tested in previous researches were identified and their reported experimental shear strengths were compared with the shear resistance predicted by seven existing shear expressions for masonry shear walls.

PAST RESEARCH TEST SPECIMENS

Over the past years some experimental studies have been carried out to study the shear strength of PG masonry shear walls. In all, 60 PG masonry shear wall tests in which the walls displayed shear failures were found in the literature (Ghanem et al. [3 and 4], Schultz [5 and 6], Voon and Ingham [7], Matsumura [8 and 9], Chen et al. [10] and Hidalgo et al [11]. To facilitate comparison, these 60 walls were grouped into eight sets, which are summarized in Table 1. Based on the data provided by past researchers these walls comply with the requirements of reinforced masonry. However, in some cases walls without horizontal reinforcement have been tested to assess the contribution from shear reinforcement.

SHEAR EXPRESSIONS

Some of the past studies have empirically developed expressions for shear strength of reinforced masonry shear walls. To facilitate a comparison of both past experiments and shear strength expressions the following seven expressions are considered. These include those adopted by the MSJC (2008) [2], CSA S304.1-04 [12] and NZS 4230 [13] (see the notation section for complete definitions of all terms). It is important to note that all of these expressions, except Matsumura [9], were initially derived from fully grouted (FG) masonry shear walls tests. The only distinction between PG and FG masonry shear walls in these equations is either the use of net area (A_n) instead of gross area (A_g) in Eqs. 1, 2, 5, and 6 or coefficients to account for partial grouting in Eqs. 4 and 7. Reference [14] provides more detailed information about the origins of these expressions and description of the terms and coefficients used in these equations.

Table 1: Summary of the Test Specimens from Previous Studies

Wall Group	No. of Walls	Wall No.	H mm (in)	L mm (in)	ρ_h (%)	ρ_v (%)	Vertical Rebar Spacing s_v mm (in)	Horizontal Rebar Spacing s_h mm (in)	Axial stress level MPa (psi)	Location of the Inflection Point
Ghanem et al. [3 and 4] ‡										
G1	**2**	**1-2**	2845 (112)	2845 (112)	0.12	0.12	1220-2640 (48-104)	1220-2640 (48-104)	0.3 (43)	top†
G2	**2**	**3-4**	2845 (112)	2845 (112)	0.12	0.12	1220 (48)	1220 (48)	0.3-0.6 (43-86)	top
Schultz [5 and 6]										
S	**6**	**5-10**	1422 (56)	1422-2845 (56-112)	0.05- 0.12	0.03- 0.06	1220-2640 (48-104)	One bond beam at mid-height	0.6 (86)	Mid-height††
Voon and Ingham [7]										
V	**2**	**11-12**	1800 (71)	1800 (71)	0	0.87-1.45	405-810 (16-32)	0	0	top
Matsumura [8 and 9]										
M1	**29**	**13-41**	1800 (71)	970-1970 (38-78)	0-0.222	0.19-0.664	400-910 (16-36)	One bond beam at mid-height	0-1.47 (214)	Mid-height
M2	**10**	**42-51**	590-1800 (23-71)	520 (20.5)	0- 0.071	1.02	400 (16)	One bond beam at mid-height	0	Mid-height
Berkeley [9 and 11]										
B1	**6**	**52-57**	1422 (56)	1220 (48)	0-0.15	0.17-0.45	1016 (40)	711-1422 (28-56)	0.52-1.50 (75-216)	Mid-height
B2	**3**	**58-60**	2032 (80)	1067 (42)	0-0.21	0.51	810 (32)	500-711 (20-28)	0.74- 1.20 (107-173)	Mid-height

‡ Scaled up from 1/3 scale to the prototype size
† Single curvature bending
†† Double curvature bending

- **MSJC 2008 (Reinforced Masonry) (RM):**

$$V_{n1} = 0.083\left[4.0 - 1.75\left(\frac{M}{Vd_v}\right)\right]A_n\sqrt{f'_m} + 0.25\sigma_n A_n + 0.5 A_h f_{yh}\, d_v / s_h \qquad (1)$$

- **MSJC 2008 (Unreinforced Masonry) (URM):**
  Nominal shear strength for unreinforced masonry shall be the smallest of the following:

$$V_{n2} \le \begin{cases} 0.33 A_n\sqrt{f'_m} \\ 0.83 A_n \\ 0.26 A_n + 0.45 N_u \end{cases} \qquad (2)$$

- **NZS 4230:2004 (SANZ 2004):**

$$V_{n3} = \left[(C_1 + C_2)v_{bm} + 0.9\frac{N^*}{b_w d}\tan\alpha + C_3\frac{A_v f_y}{b_w s}\right] \times b_w d \qquad (3)$$

- **CSA S304.1-04:**

$$V_{n4} = \left[\left[0.16\left(2-\frac{M_f}{V_f d_v}\right)\sqrt{f'_m}\right]b_w d + 0.25P_d\right]\gamma_g + \left(0.6A_v f_y \frac{d_v}{s}\right) \quad (4)$$

- **Anderson and Priestley (1992):**

$$V_{n5} = C_{ap}kA_n\sqrt{f'_m} + 0.25\sigma_n A_n + 0.5A_h f_{yh}\, d/s_h \quad (5)$$

Where the C_{ap} term is to account for the type of masonry used in construction, and shall be taken as 0.24 and 0.12 for concrete and clay brick masonry, respectively.

- **Shing et al. (1990):**

$$V_{n6} = (0.166 + 0.0217\rho_v f_{yv})\sqrt{f'_m}A_n + (0.0217\sigma_n A_n)\sqrt{f'_m} + \left(\frac{L-2d'}{s_h}-1\right)A_h f_{yh} \quad (6)$$

- **Matsumura (1988):**

$$V_{n7} = \left[k_u k_p\left(\frac{0.76}{(h/d)+0.7}+0.012\right)\sqrt{f'_m} + 0.2\sigma_n + 0.18\gamma\delta\sqrt{\rho_h f_{yh} f'_m}\right]\times(0.875td) \quad (7)$$

where k_u=1.0 for fully grouted masonry, k_u=0.64 for partially grouted masonry; k_p=1.16$\rho^{0.3}_{ve}$; γ =1.0 for fully grouted masonry, γ =0.6 for partially grouted masonry; and δ=1.0 for loading resulting in inflection point at mid-height of wall, δ=0.6 for loading with cantilever boundary condition. Ratios of experimentally observed to calculated shear strength for the eight sets of shear wall tests described above, as well as the average and standard deviation (σ) for each set, are presented in Table 2. As shown in the last five rows of Table 2, which summarizes all data available, all strength expressions except for V_{n2} (MSJC URM), V_{n3} (NZS 4230:2004) and V_{n4} (CSA S304.1-04) were unconservative with mean strength ratios ranging from 0.84 to 0.94. Although V_{n2}, V_{n3} and V_{n4} expressions did prove to be conservative, their standard deviations were quite large at 0.6, 1.11 and 0.72, respectively. Within the abovementioned equations V_{n3} (NZS 4230:2004) seems to have the most conservative prediction for the shear resistance of these PG shear walls. This can be due to the fact that in this equation net area of PG shear walls is assumed to be the thickness of the face-shells times %80 of the length of the wall, while in other equations the net area includes the grouted cells as well.

To establish the effect of key parameters, Figure 1 provides a plot of these ratios versus (a) wall size (area), and (b) aspect ratio. For the sake of conciseness, only the ratios associated with the MSJC (2008) [2] RM and CSA S304.1-04 strength expressions were used to generate these plots. However, the general trends that are apparent in Figure 1 and 2 were consistent across all of the RM strength expressions included in this study. These trends are discussed in the following.

SPECIMEN SIZE

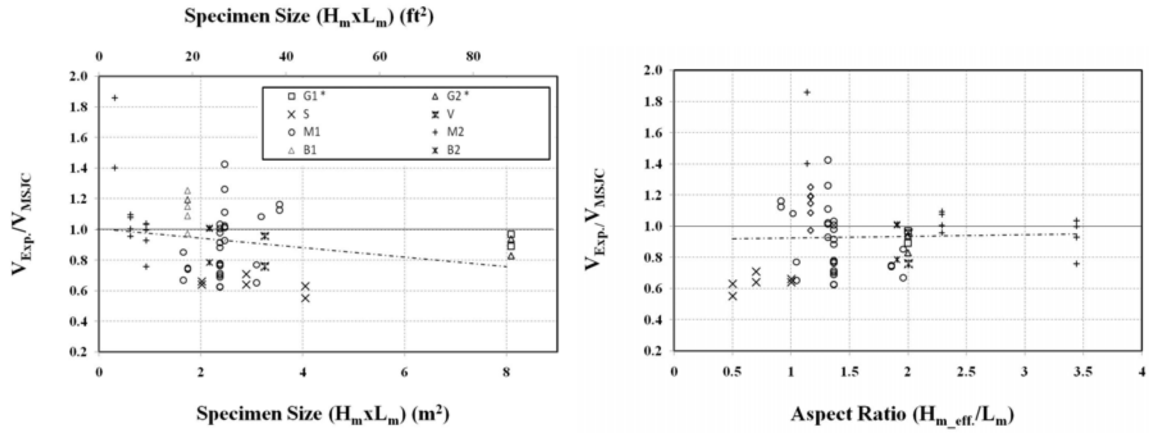
Figure 2(a) and 3(a) show that as the size of the wall specimens increase (based on wall area), the MSJC RM and CSA strength expressions become more unconservative. The only specimens tested with sizes larger than 4 m^2 (43 $ft.^2$) were the 1/3-scale walls tested by Ghanem et al. [3 and 4], and these walls had an actual area of less than 1 m^2 (with a prototype or equivalent full-scale wall area of around 8 m^2). The size of these test specimens are not representatives of realistic shear walls. The lack of data on PG masonry shear walls of realistic size represents a continued gap in the literature. Although there is insufficient evidence to discount all tests of smaller walls due to the apparent size-effect, it is important to note that the unconservatism displayed by all strength expressions was largest for the walls most representative of typical masonry shear walls. One possible reason for this apparent size effect is the anomalies associated with load introduction, which are exacerbated as the specimens get smaller. For example, a common loading technique is to have large reinforced concrete loading beams at the top and bottom of the walls, which provide significant confinement that is not realistic, especially for small walls [5 and 15].

Table 2: A Summary of Experimental over Predicted Shear Strengths for Walls 1 through 60 for Different Shear Expressions (V_{exp}/V_{ni})

Wall No.	Wall Set	Term	Predicted						
			V_{exp}/V_{n1} RM †	V_{exp}/V_{n2} URM ‡	V_{exp}/V_{n3}	V_{exp}/V_{n4}	V_{exp}/V_{n5}	V_{exp}/V_{n6}	V_{exp}/V_{n7}
Ghanem et al. (1992, 1993)									
1-2	**G1**	**Avg.**	0.93	1.71	2.39	0.86	0.78	1.16	1.27
		σ	0.06	0.15	0.31	0.05	0.05	0.10	0.36
3-4	**G2**	**Avg.**	0.89	1.49	2.47	0.83	0.75	1.05	1.27
		σ	0.08	0.08	0.31	0.09	0.08	0.16	0.05
Schultz (1996, 1997)									
5-10	**S**	**Avg.**	0.64	1.04	1.69	0.59	0.69	0.73	0.74
		σ	0.05	0.11	0.26	0.09	0.05	0.18	0.11
Voon and Ingham (2007)									
11-12	**V**	**Avg.**	0.86	3.71	4.73	0.8	0.67	0.72	2.76
		σ	0.14	0.71	2.24	0.13	0.11	0.11	0.91
Matsumura (1986, 1988)									
13-41	**M1**	**Avg.**	0.89	1.63	1.75	0.97	0.65	0.82	0.81
		σ	0.21	0.48	0.52	0.32	0.13	0.18	0.16
42-51	**M2**	**Avg.**	1.11	1.92	3.66	2.29	0.87	0.87	1.07
		σ	0.31	0.53	1.34	1.03	0.27	0.46	0.17
Berkeley (Chen et al. 1978, and Hidalgo et al. 1978)									
52-57	**B1**	**Avg.**	1.14	1.84	2.58	1.57	1.07	1.70	1.01
		σ	0.10	0.23	0.41	0.28	0.11	0.67	0.11
58-60	**B2**	**Avg.**	0.93	1.31	2.12	1.33	0.74	0.98	0.73
		σ	0.13	0.18	0.14	0.07	0.09	0.22	0.03
Total (Walls 1-60)		**Min**	0.34	0.79	0.83	0.32	0.33	0.34	0.56
		Max	1.86	4.21	6.86	4.53	1.52	2.80	3.40
		Avg.	0.90	1.67	2.23	1.17	0.72	0.90	0.94
		σ	0.26	0.60	1.11	0.72	0.21	0.41	0.41
		COV	0.29	0.36	0.5	0.62	0.29	0.46	0.44

† Reinforced Masonry

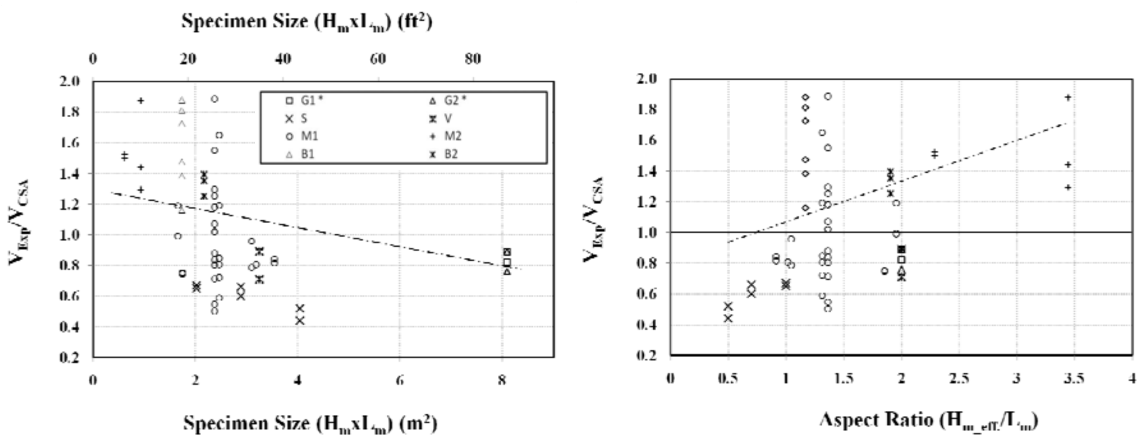
‡ Unreinforced Masonry



(a) (b)

* Specimens Set G1 and G2 are 1/3 scale specimens which are scaled up to the prototype size.

Figure 2: (a) Effect of Size of Specimen, (b) Effect of Aspect Ratio (For MSJC 2008 RM Shear Equation)



(a) (b)

* Specimens Set G1 and G2 are 1/3 scale specimens which are scaled up to the prototype size.

Figure 3: (a) Effect of Size of Specimen, (b) Effect of Aspect Ratio (For CSA S304.1-04 Shear Equation)

ASPECT RATIO

Figures 2(b) and 3(b) illustrate that the influence of aspect ratio, taken as whole, appears to be fairly minor for MSJC RM shear expression, but this influence is more considerable for CSA shear expression. However, all walls with an aspect ratio less than 1.0 displayed strength ratios less than 0.75. While there have been relatively few walls tested in this range of aspect ratios, the available data does suggest that for low aspect ratios the shear strength expressions provided by MSJC and CSA are unconservative for PG walls.

CONCLUSIONS

60 partially grouted reinforced concrete masonry shear walls were located in this study and their shear resistance were compared to the predicted shear strength by existing shear expressions for

reinforced masonry shear walls. The following conclusions are drawn based on the results of this study:

- The shear strength expression for reinforced masonry shear walls provided by MSJC (along with others) appears unconservative for PG masonry shear walls. This may be due to the reason that these expressions are empirically derived based on the behaviour of fully-grouted reinforced masonry shear walls, which display failure modes distinctly different than their PG counterparts.
- Shear expression provided by MSJC for unreinforced masonry appears to give more conservative results for the shear resistance of partially grouted walls. One possible explanation for this fact is the lack of coupling between vertical reinforcements. In the case of partially grouted walls, after the hollow panels are cracked these walls lose their capacity and reach their failure point.
- Based on the available experimental data, it appears that the MSJC (2008) RM and CSA S304.1-04 shear strength expressions become more unconservative as (a) the shear wall area increases, and (b) the aspect ratio of the shear wall decreases below 1.0.
- Based on the results presented in this paper, it is apparent that the shear resistance of PG shear walls cannot be predicted conservatively by the equation adopted by MSJC 2008. To resolve this problem the authors suggest that special reinforced masonry shear walls be fully grouted in mid to high seismic regions in the United States. Since the use of area of the face-shells instead of net area has shown to give more conservative results in NZS 4230:2004 shear expression, it is suggested that the net area term (A_n) in MSJC shear expression be replaced by the area of the face-shells for PG shear walls wherever design of PG shear walls is needed. However, the reader should be cautioned that applying any modifications such as this suggested change or any other modifications needs to be investigated through comprehensive experimental tests.
- There is a gap in the literature related to the response of PG masonry shear walls with sizes more than 4 m^2 (43 ft^2).

NOTATION

A_h	Area of single horizontal reinforcing steel bar, (mm^2)
A_n	Net cross-sectional area, (mm^2)
A_g	Gross cross-sectional area, (mm^2)
A_v	Area of longitudinal reinforcement, (mm^2)
b_w	Wall width, (mm)
C_{ap}	Coefficient to account the type of masonry used in construction
C_1, C_2, C_3	Shear strength coefficients
d	Distance from extreme compression fiber to Centerior of longitudinal tension reinforcement or 0.8 L for walls, (mm)
d'	Distance between wall edge and outermost wall vertical reinforcing steel, (mm)
d_u	Drift index at the ultimate failure, (%)
d_v	Actual depth of a member in direction of shear considered (mm)
d_y	Drift index at yielding on the bilinear (Elasto-plastic) plot, (%)
f'_m	Masonry compressive strength, (MPa)

f_{yh}	Yield strength of horizontal reinforcing steel, (MPa)
f_{yv}	Yield strength of vertical reinforcing steel, (MPa)
F_{ndt}	Diagonal tension strength of masonry assemblages, kN
H_m	Height of the wall, (mm)
$H_{m\_eff.}$	Effective height of the wall based on fixed-fixed boundary condition, (mm)
k	Ductility reduction factor
k_p	Coefficient of the effect of flexural reinforcement
k_u	Reduction factor
L_m	Length of the wall, (mm)
N^*	Factored axial compression load, (kN)
N_u	Compression axial force on the wall, (kN)
s_h	Spacing of horizontal shear reinforcement, (mm)
t	Effective wall thickness, (mm)
$V_{\exp}$	Experimentally measured shear strength, (kN)
V_n	Nominal shear strength, (kN)
α	Angle formed between centers of load application and reaction
γ	Factor concerning the type of grouting
δ	Factor concerning loading method
μ_Δ	Ductility level, displacement ductility
ρ_h	Ratio of shear reinforcing steel
ρ_v	Ratio of vertical reinforcing steel
ρ_{ve}	Ratio of outermost wall vertical reinforcing steel
σ	Standard Deviation
σ_n	Axial stress, (MPa)

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