THE ACCURACY OF IN-PLANE SHEAR STRENGTH OF PGM WALLS IN DIFFERENT INTERNATIONAL STANDARDS

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ABSTRACT
The purpose of this paper is to evaluate the accuracy of standards in predicting the in-plane shear strength of partially grouted reinforced masonry (PGM) walls based on available experimental results. The shear equations selected herein are code's provisions from United States (MSJC 2011), New Zealand (NZS4230 2004), Canada (S304.1-04) and Australia (AS3700-2011). The experimental results were selected from a large data base including more than one-hundred specimens and only walls that displayed shear failure were selected for the comparisons. The ability of selected equations in predicting shear strength is compared with test results. Moreover, the weight of different parameters contributing to the shear strength, including: masonry compressive strength, level of axial compressive stress, wall aspect ratio, amount and spacing of vertical and horizontal reinforcement are investigated and compared with test results in detail. This study illustrates poor correlation between code predictions and test results. As a general result, the current standards are unable to predict the shear strength of PGM walls effectively. Interestingly, for some test specimens the codes prediction reaches up to even three times of the real value for shear strength. Consequently, based on the results presented herein, a new design equation or a modification of current provisions is required for PGM walls.

KEYWORDS: partially grouted masonry, in-plane, shear strength, masonry standards

INTRODUCTION
Poor behaviour of unreinforced masonry (URM) walls in past earthquakes, steer the direction of researches to develop application of reinforced masonry (RM) walls. RM Walls are either partially grouted or fully grouted (Figure 1). A RM wall consists of heterogeneous material including masonry blocks, reinforcement, grout, and mortar. Hence, its failure is attributed to combination of different factors. As the nonlinear behaviour of RM is complicated, semi-empirical expressions have been adopted by international codes. The accuracy of semi-empirical expressions depends on the quality and quantity of existing experimental work. Significant research related to masonry shear walls were conducted in United States, Japan, and New Zealand since 1980 [1-11]. However, portion of this database is not well documented and some test specimens were not conformed to current codes.

From a construction viewpoint, partially grouted masonry (PGM) walls are more efficient than fully grouted walls since service installation and construction are easier and faster. Reduction in weight of the structure and saving material are other advantages of PGM walls over fully grouted walls [8,12].

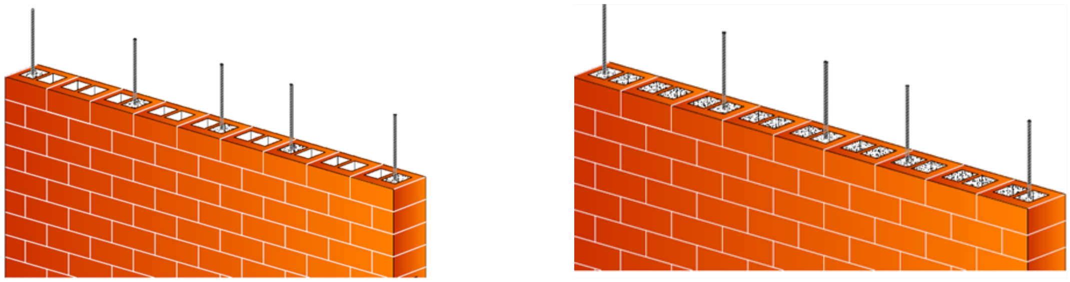


Figure 1: Reinforced masonry shear wall

The resisting mechanism of a PGM wall is different from that of fully grouted reinforced masonry walls [5,13]. Shear failure mechanism of PGM wall is characterized by diagonal tension and cracking leading to rapid stiffness degradation and brittle failure. If adequate shear reinforcement is provided, diagonal cracks do not open up excessively and they are able to distribute evenly across the wall. [14]

This manuscript focuses on the in-plane shear strength of PGM walls. The effects of different parameters including reinforcement ratio, aspect ratio, and level of axial stress on shear strength of PGM wall in different codes are investigated and compared with the test results.

SHEAR EQUATION IN DIFFERENT CODES

In this paper, four international standards, namely MSJC-2011 (standard of United States) [15], AS3700-2011 (standard of Australia) [16], NZS4230-2004 (standard of New Zealand) [17] and S304.1-2004 (standard of Canada) [18] were selected to be evaluated based on existing test results.

In a generic form, the nominal shear strength of reinforced masonry walls V_n is determined by the sum up of masonry component (V_m) reinforcement component (V_s) and the effect of axial stress (V_p)

$$V_n = V_m + V_s + V_p \tag{1}$$

Shear strength equations in each code are summarized in Table 1.

EXPERIMENTAL DATABASE

An extensive literature review has been done and the experimental results of 89 partially grouted walls were selected for comparison with the different codes presented in this manuscript. All selected walls were subjected to either monotonic or cyclic lateral displacement until failure occurred. These walls were built using concrete masonry units (CMUs) and failed in shear. The database has been assembled from 9 resources; includes 89 tests carried out by Matsumura (1988), four by Chen (1987), 10 by Yency et al.(1989), 4 by Ghanem (1992), 12 by Shultz (1996), six by Elmapruk (2009), four by Minaie (2009), five by Maleki (2008) and five by Nolph (2011). One drawback of the available database is that it is not well documented. For example for some specimens the complete information about wall's detail, material properties and test set-up is not provided. The authors of this manuscript used engineering judgment and common values for some parameters.

CODE COMPARISONS

The ability of different codes in predicting the shear strength achieved in tests is compared here via Table 2 and Figures 3 to 9. A statistical comparison for V_{test}/V_{calc} for the compiled test data is summarized in Table 2 in terms of maximum, minimum, average, standard deviation, range, and variance. In addition, the percentage of the number of specimens that were over-predicted using each code is presented. A value of one for V_{test}/V_{calc} indicates that the equation correctly predicted the shear strength of the specimens. A value greater than one for V_{test}/V_{calc} indicates that the equation is conservative, while values smaller than one show un-conservative estimation of the nominal shear strength. As shown in Table 2, the minimum value for V_{test}/V_{calc} ratio is between 0.28 and 0.5 for all standards. It means that for some test results the shear strength prediction is more than three times of the tested value, implying that the current codes yield an unsafe prediction of shear strength of PGM walls.

Table 1: In-plane shear strength equations

Equation	V_m	V_p	V_s	$V_{n\,max}$
MSJC-2011	$0.083\left[4.0-1.75\left(\frac{M}{V\,l_w}\right)\right]A_n\sqrt{f'_m}$	$0.25P_u$	$0.5\left(\frac{A_v}{s_h}\right)f_{yh}l_w$	$0.50\,A_n\sqrt{f'_m}$ for $M/Vl_w \le 0.25$ $0.33\,A_n\sqrt{f'_m}$ for $M/Vl_w \ge 1.00$ *
AS3700-2011	$f_{vr}\,A_d$	-	$0.8f_{yh}A_s$	-
NZS 4230-2004	$(c_1+c_2)\,v_{bm}\,b_{we}d_v\sqrt{f'_m}$	$0.9P_u\tan\alpha$	$0.8\left(\frac{A_v}{s_h}\right)f_{yh}\,d_v$	$0.45\sqrt{f'_m}b_{we}dv$ **
S304.1-2004	$0.16\left[2.0-\left(\frac{M}{Vd_v}\right)\right]b_wd_v\sqrt{f'_m}\gamma_g$	$0.25\,P_u\gamma_g$	$0.6\left(\frac{A_v}{s_h}\right)f_{yh}d_v$	$0.4b_wd_v\sqrt{f'_m}\gamma_g$ for $h_w/l_w > 1$ $0.4b_wd_v\sqrt{f'_m}\gamma_g\,[2.0-h_w/l_w]$ for $h_w/l_w \le 1$

* $V_{n\,max}$ should be interpolated for $0.25 \le M/Vl_w \le 1.0$
** For good quality masonry walls

The average values of V_{test}/V_{calc} for MSJC 2011, AS3700-2011 are 0.86, 0.79 respectively both below the value of one and thus indicating un-conservative predictions. The average values of V_{test}/V_{calc} are 1.49 and 1.36 for NZS4230-2004 and S304.1-2004, respectively. The most conservative codes are the NZS4230-2004 and S304.1-2004 where they over-predicted the shear strength of 17% and 24% of the tested specimens compared with 71% and 76% for MSJC-2011 and AS3700-2011, respectively. However, the value of the calculated V_{test}/V_{calc} using NZS4230-2004 and S304.1-2004 are highly scattered compared to the other codes. As shown in Table 2, NZS4230-2004 has the highest standard deviation of 0.54, variance of 0.29, and range of 2.75.

The MSJC-2011 has the smallest standard deviation of 0.25, variance of 0.06, and range of 1.3. This is followed by AS3700-2011 and S304.1-2004.

Table 2: Statistical comparison of V_{test}/V_{calc}

	MSJC-2011	AS 3700-2011	NZS 4230-2004	CSA S304.1-04
Min	0.35	0.28	0.50	0.40
Max	1.65	1.83	3.25	3.75
Average	0.86	0.79	1.49	1.36
Std Dev.	0.25	0.30	0.54	0.55
Var.	0.06	0.09	0.29	0.31
Range	1.3	1.54	2.75	3.35
Percentage of Over-predicted specimens	71%	76%	17%	24%

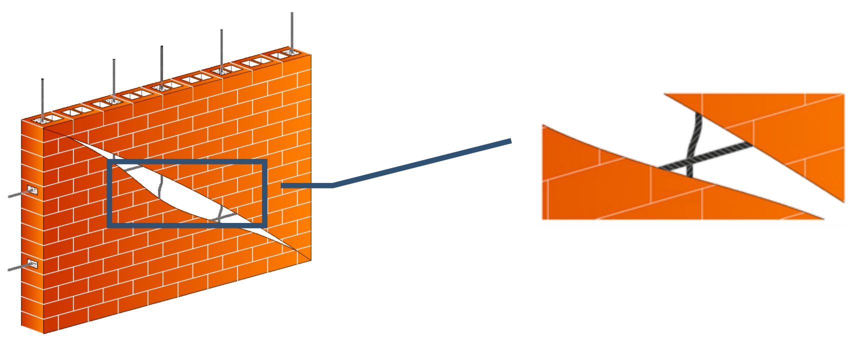
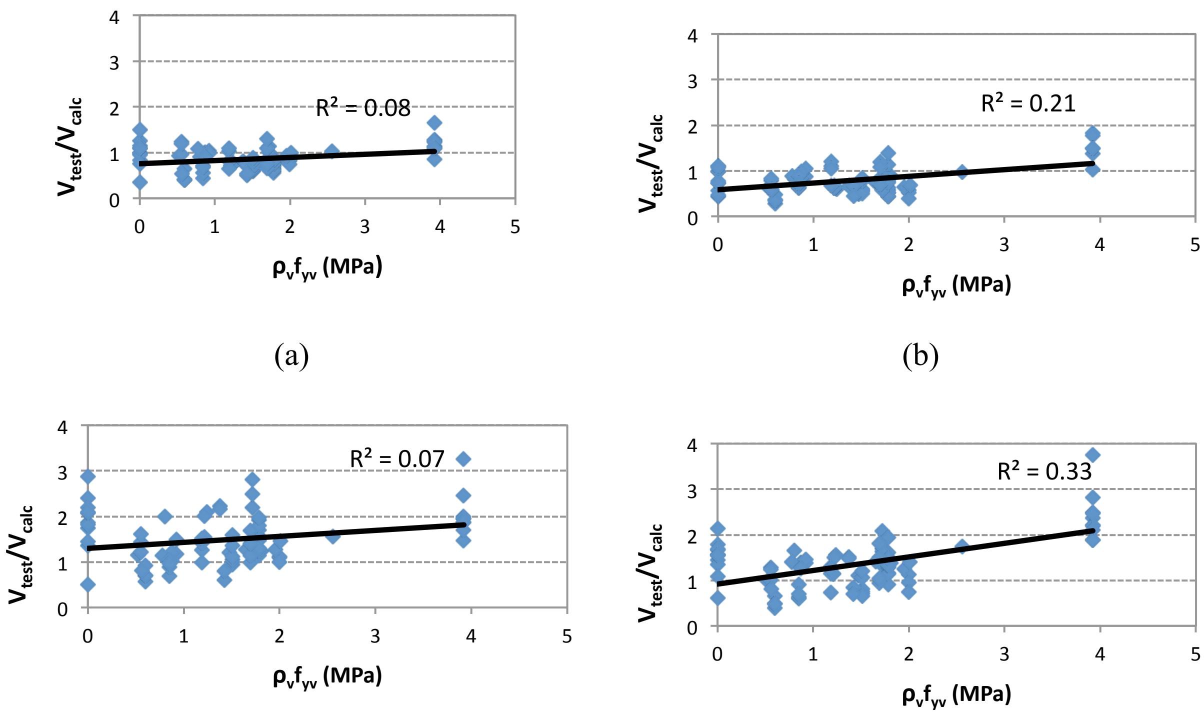


Figure 2. Dowel action of vertical reinforcement

PARAMETRIC EVALUATIONS

In Figures 3 to 9, the values of V_{test}/V_{calc} for each specimen were plotted versus different parameters to isolate the effects of these parameters on the accuracy of the predictions by the different codes. The parameters evaluated are the horizontal and vertical reinforcement percentages, axial stress, aspect ratio, masonry compressive strength, net to gross area ratio and distance between vertical reinforcement. The points on the line of unity show that the prediction values are equal to the test results i.e. perfect correlation. Bias, measured through the slope of the trend line and the R^2 of the data points, is another measure of the accuracy of the predicting equations. A negative trend line indicates that as the parameter on x-axis increases, the equation tends to over-predict the effects of that parameter on the strength of the specimens and since lead to more un-conservative prediction and vice versa.

- Vertical Reinforcement Percentage: It has been reported that vertical bars provide post-cracking resistance mainly through dowel action (Figure 2) [1,4]. The small R^2 in Figures 3(a) and 3(c) show that in terms of dowel effect, the MSJC-2011 and NZS4230-2004 are less biased compared with AS3700-2011 and S304.1-2004. The positive slope of regression line in Figure 3 reveals that all codes underestimate the effect of the dowel action on the shear strength. Although NZS4230-2004 considers the effect of vertical reinforcement by incorporating factor C_1, its effect seems to be not reflected efficiently in the equation.



(a) (b)

(c) (d)

Figure 3: Effect of vertical reinforcement (a)MSJC2011, (b)AS3700-2011, (c)NZS4230 2004, and (d)S304.1-2004

- Horizontal Reinforcement Percentage (ρ_h): Figure 4 shows the horizontal reinforcement ratio versus V_{test}/V_{calc} ratio. It can be seen that there is a correlation between the $\rho_h f_{yh}$ and the error in predicting the shear strength of PGM walls in AS3700-2011 and S304.1-04. Both codes over-predict the effects of horizontal reinforcement. Both the MSJC-2011 and NZS4230-2004 are not biased in this regard with $R^2 \approx 0$.

- Axial Stress: It has been reported that applying high axial compressive load up to a certain level, increases the masonry shear strength by enhancing the aggregate interlocking friction and decreasing the width of the cracks. This mechanism is reflected in all above-mentioned codes, through the V_p term, except for AS3700-2011. The accuracy of the weight placed on this parameter in different standards is demonstrated in Figure 5. As shown , MSJC-2011 and NZS4230-2004 have small R2 i.e. these codes are not biased with respect to the applied axial load. The negative and small positive slop of the regression lines of S304.1-2004 and AS3700-2011 illustrate that the prediction become unconservative and slightly conservative respectively as the axial stress increases.

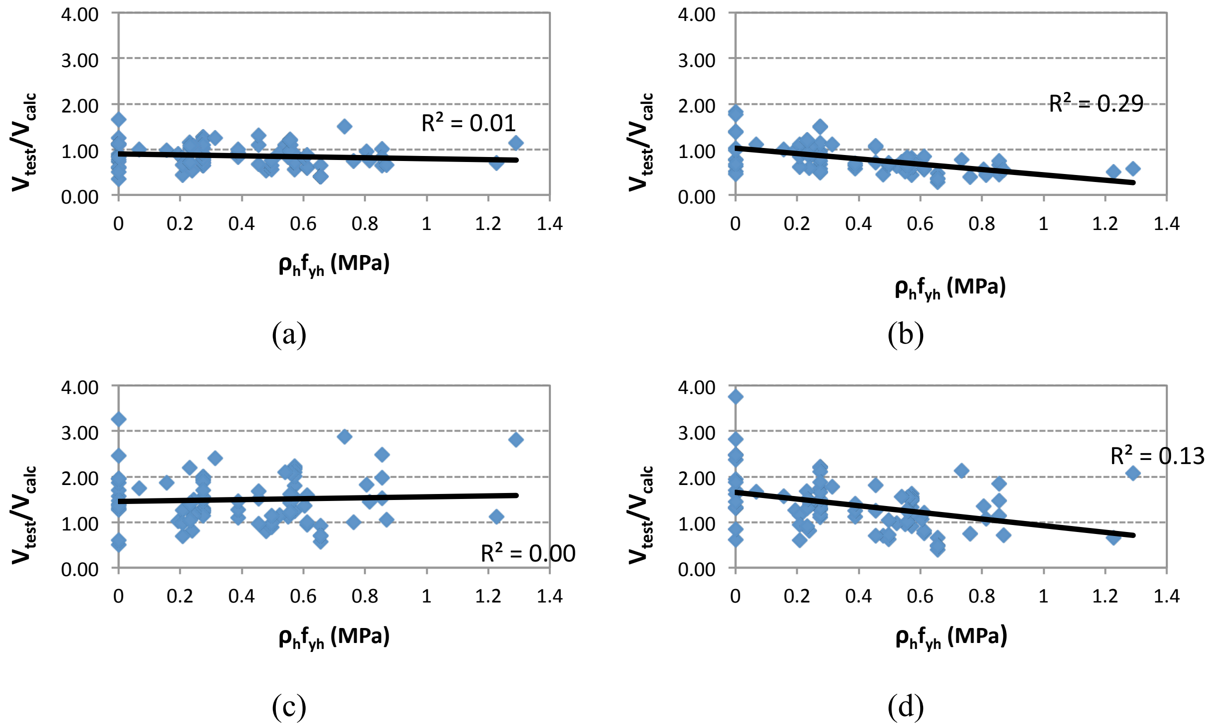


Figure 4: Effect of horizontal reinforcement (a)MSJC-2011, (b)AS3700-2011, (c)NZS4230-2004, and (d)S304.1-2004

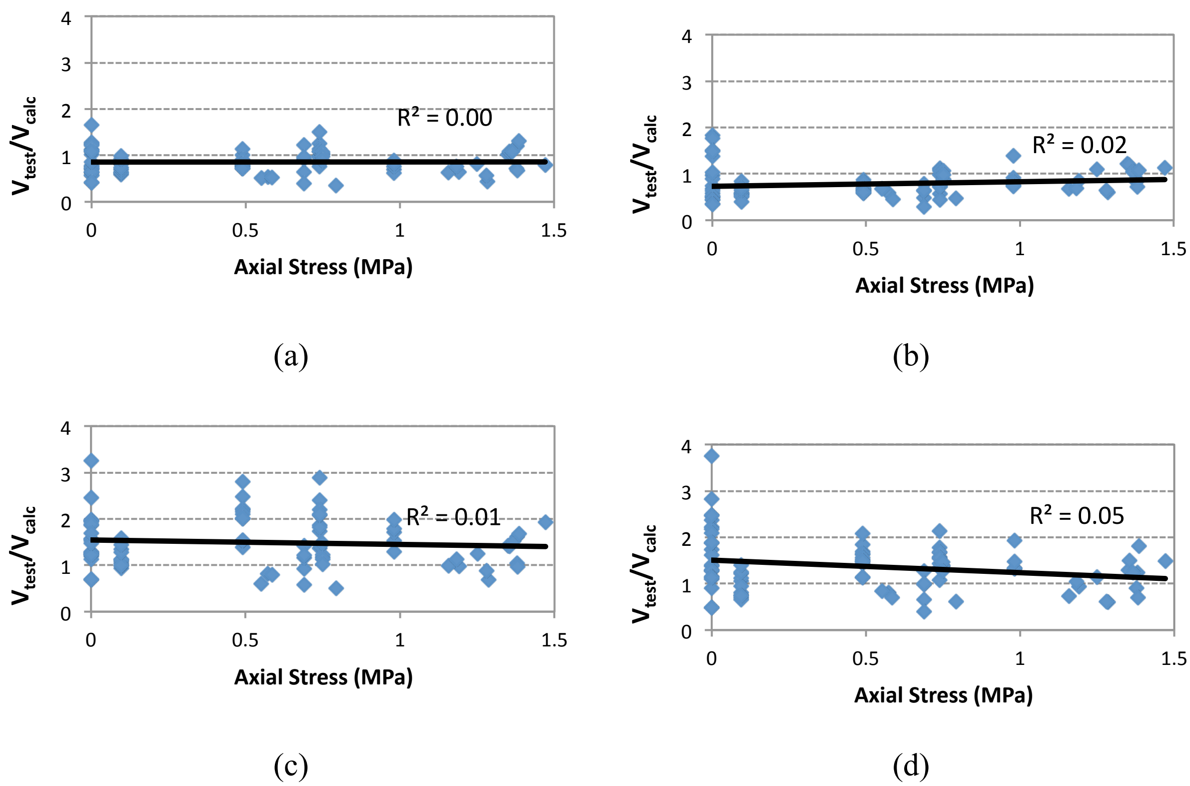
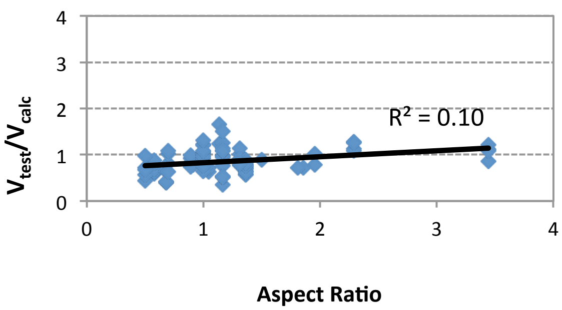


Figure 5: Effect of axial stress (a)MSJC-2011, (b)AS3700-2011, (c)NZS4230 2004, and (d)S304.1-2004

- Aspect Ratio: According to the equations in Table 1, all standards assume that the walls having smaller aspect ratios i.e. squat walls, exhibit higher shear strength than those having larger aspect ratios i.e. slender walls. The reason is attributed to the role of arching action in squat walls, in which a considerable portion of the shear force is resisted by compact zones which conveys large compressive stresses. [6]

Figure 6 shows the effect of aspect ratio on V_{test}/V_{calc} ratio. Apparently, all standards are unable to account for the effect of aspect ratio accurately. As the aspect ratio decreases the prediction become more unconservative. For squat walls with small value of aspect ratio (less than unity), the value of V_{test}/V_{calc} is less than one in all standards and hence yielding an unsafe predication, an indication of excessive weight placed on aspect ratio in standards. The equations of MSJC-2011 and NZS4230-2004 are less biased compared to other codes, as indicated by smaller R^2 values. These two codes' approach better described the effect of aspect ratio (Figures 6(a) and 6(c)). The bias is significant for AS3700-2011 and S304.1-2004.



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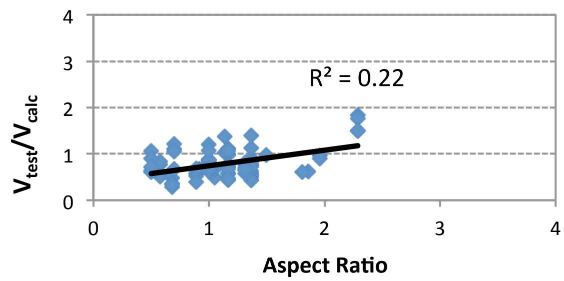

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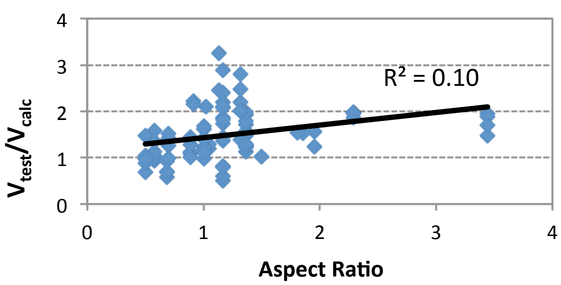

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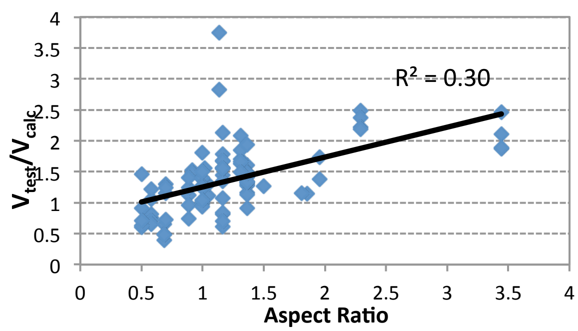

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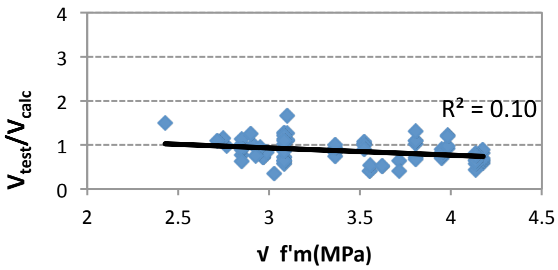
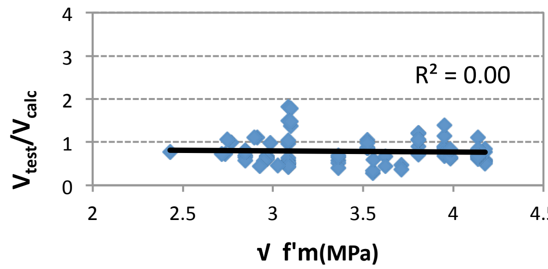
Figure 6: Effect of aspect ratio (a)MSJC-2011, (b)AS3700-2011, (c)NZS4230-2004, and (d)S304.1-2004

- Masonry Compressive Strength (f'_m): Figure 7 shows the effect of masonry tensile strength on the values of V_{test}/V_{calc}. Masonry tensile strength is represented in MSJC-2011, NZS4230-2004 and S304.1-2004 via parameter $\sqrt{f'_m}$. As shown in the figure, MSJC-2011, NZS4230-2004 and S304.1-2004 have higher R^2 indicating bias of the equations. All these codes overestimate the effect of $\sqrt{f'_m}$. For high range of f'_m the values of V_{test}/V_{calc} decrease and hence the prediction becomes unconservative.





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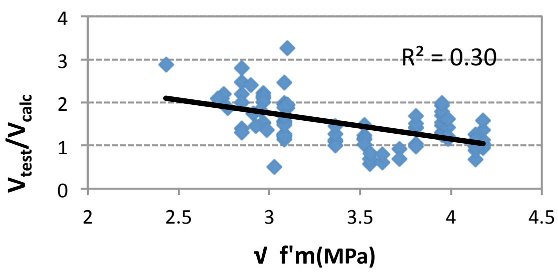
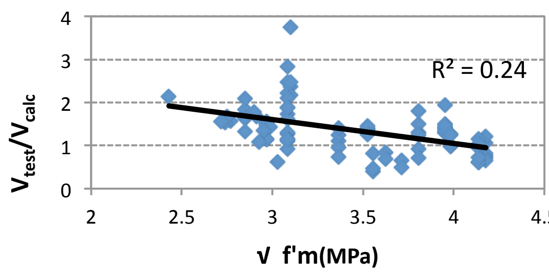
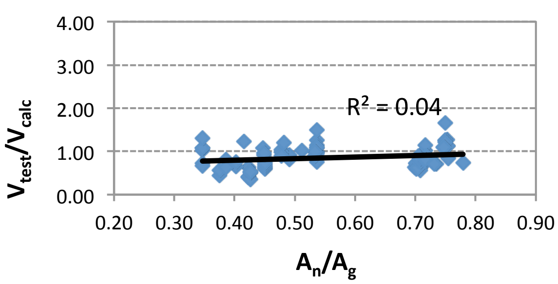
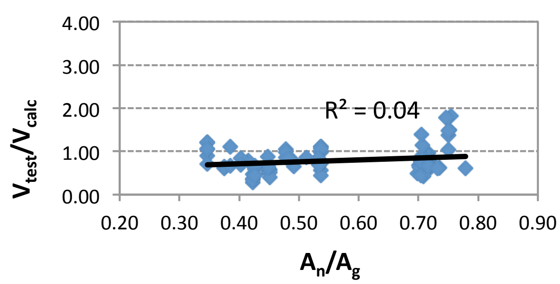




(c) (d)

Figure 7: Effect of masonry Compressive Strength (a)MSJC-2011, (b)AS3700-2011, (c)NZS4230-2004, and (d)S304.1-2004





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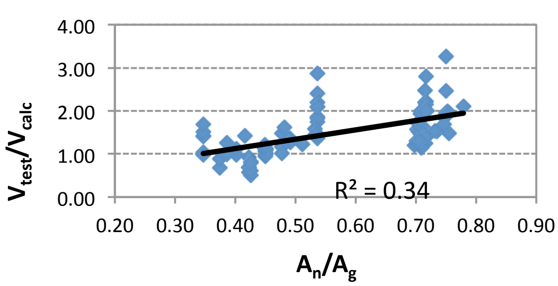
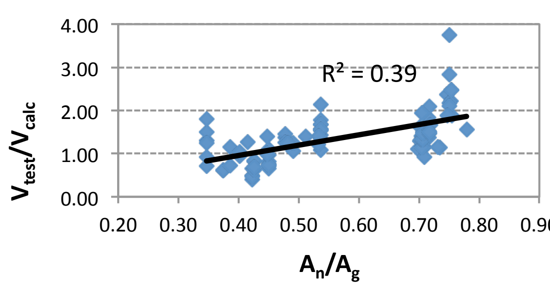


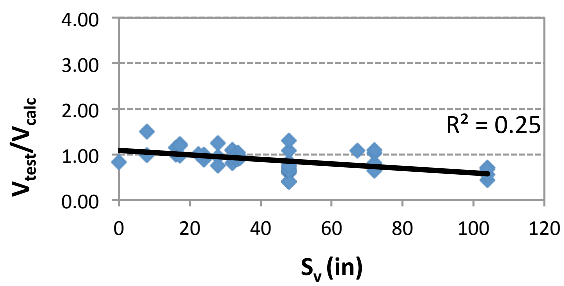


(c) (d)

Figure 8: Effect of A_n/A_g (a)MSJC-2011, (b)AS3700-2011, (c)NZS4230-2004, and (d)S304.1-2004

-Effect of net to gross area ratio (A_n/A_g): Figure 8 shows the effect of net to gross ratio on the value of $V_{test}/V_{calc.}$ (A_n and A_g are the net and gross cross sectional area of the masonry, respectively). As the net to gross area ratio decreases all standards more or less overestimate the shear strength of PGM walls. In this regard, MSJC-2011 shows less bias compared with the other codes, as indicated by R^2 values. In an extreme case for the maximum value of net area (A_n=A_g), i.e. for FGM walls, predictions from all standard become safe, confirming the well agreement between test results and standard provisions for FGM walls. For small values of A_n/A_g the prediction is unconservative. A smaller value of A_n/A_g is corresponding to a lesser number of vertical reinforced grouted cores, which usually means greater spacing of vertical reinforcement. Unconservative prediction of standards for walls having low value of A_n/A_g can be attributed to the lack of enough weight placed on vertical reinforcement spacing in the current provisions.

- Vertical Reinforcement Spacing: Figure 9 presents the effect of spacing between vertical reinforcement on the shear strength of PGM walls. The downward trend of regression lines show that all standards tend to overestimate the shear strength as the spacing between vertical reinforcement increases. Of all standard AS3700-2011 is the less biased one. The reason can be explained as the shear strength in AS3700-2011 is limited by vertical reinforcement rather than horizontal reinforcement. Usually, the vertical reinforcement is correspondent to spacing. In most of the experiments from data base less vertical reinforcement ratio generally resulted in a greater spacing. Consequently, the effect of spacing of vertical reinforcement is indirectly reflected in AS3700-2011 leading to a less biased prediction compared with other codes.



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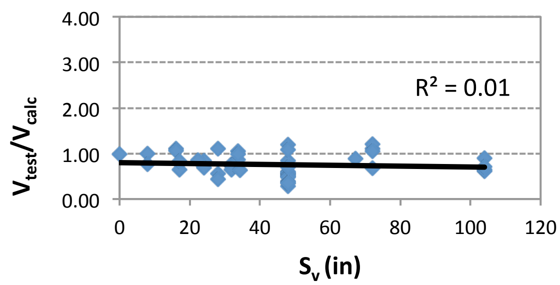

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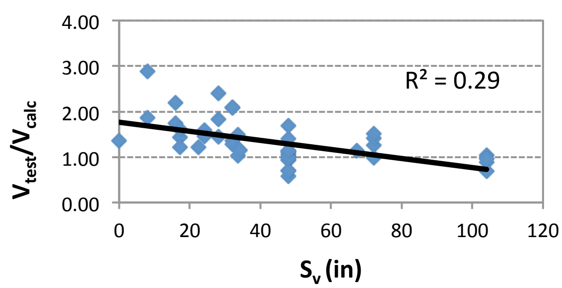

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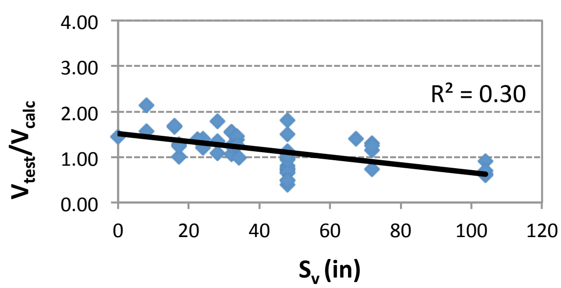

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Figure 9: Effect of Vertical Reinforcement Spacing (a)MSJC-2011, (b)AS3700-2011, (c)NZS4230-2004, and (d)S304.1-2004

CONCLUSIONS

-This paper examined the effectiveness of four prominent masonry building codes, namely, MSJC-2011, AS3700-2011, NZS4230-2004 and S304.1-2004 in predicting the shear strength of PGM walls based on the results of 89 test specimens.
-The main conclusion of this research is that all standards provisions are highly unsafe in predicting the shear strength of PGM walls. Consequently, the relevant codes' provisions need to be revised immediately as it poses a potentially life threatening problem
-The minimum value for V_{test}/V_{calc} was between 0.28 and 0.5 for all standards. It means that for some test results the shear strength prediction is more than three times of the tested value.
-The MSJC 2011 and AS3700-2011 over predicted the shear strength of more than 70% of the specimens.
- Narrower scatter and smaller standard deviation of V_{test}/V_{calc} in MSCJ-2011 show that this standard is less biased toward most of the parameters included in the shear strength equation, but at the same time considerably unconservative.
- The available data suggests that by decreasing the aspect ratio, percentage of vertical reinforcement or A_n/A_g ratio or by increasing the vertical reinforcement spacing, the value of V_{test}/V_{calc} reduces and the perdition become more unsafe.
- Although the term f'_m is not directly reflected in the provision of AS3700-2011, the AS3700-2011 is the least biassed code in considering the effect of f'_m. The other codes placed excessive weight on f'_m.
- The spacing between vertical reinforcement seems to be an important contributing factor in shear strength of PGM is not considered in the shear equation of selected standards.

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List of Symbols

Symbols which are not addressed below are explained in the text.

A_n	Net wall cross-sectional area	M	Maximum moment at the section under consideration
A_v	Cross-sectional area of shear reinforcement	P_u	Axial compressive load
A_{st}	The cross sectional area of the reinforcement in tension zone or $0.02b_{we}d_v$ whichever is less	P_u	Axial compressive load
b_w	Thickness of the wall	s_h	Spacing of horizontal reinforcement
b_{we}	Effective thickness of the wall (sum of face shells thickness)	V	Max. shear force at the section under consideration
d_v	Effective depth of the wall (need not to be taken less than $0.8l_w$)	υ_g	Maximum total shear stress
f_m	Masonry compressive strength	V_m	Shear strength provided by masonry
f_{yh}	Horizontal steel yield strength	V_n	Nominal shear strength
f_{vr}	Effective shear strength	V_p	Shear strength provided by axial stress
f_{yv}	Vertical steel yield strength	V_s	Shear strength provided by reinforcement
h_w	Height of the wall	$V_{n\,max}$	Maximum nominal shear strength
l_w	Length of the wall		