13TH CANADIAN MASONRY SYMPOSIUM
HALIFAX, CANADA
JUNE 4TH – JUNE 7TH 2017

COMPARISON OF AVAILABLE EXPRESSIONS IN PREDICTING THE FLEXURAL STRENGTH OF SELF-CENTRING MASONRY WALLS

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ABSTRACT

The restoring nature of the post-tensioning (PT) force in self-centring masonry walls (SMWs) returns the wall to its original vertical position and minimizes the residual displacement. While strain compatibility equations can be used to determine strains in structural elements having bonded reinforcement, it cannot be applied to SMWs. The current approach of the Masonry Standards Joint Committee (MSJC 2013) ignores the stress increase in PT bars beyond initial post-tensioning. However, several experimental and finite element studies have shown that under lateral loads the post-tensioning force increased, and the stress in the PT bars is a function of wall rotation and neutral axis depth. In this study, the accuracy of different expressions to predict the flexural strength of SMWs is investigated using experimental results of 18 SMWs tested under in-plane loading as well as finite element analysis results. The walls of the experimental database were all fully grouted and had heights ranging from 2800 mm to 5250 mm, lengths ranging from 1000 mm to 3000 mm, compressive strengths ranging from 13.3 MPa to 20.6 MPa and axial stress ratios ranging from 0.04 to 0.2. In this study four different available methods are considered to predict the in-plane flexural strength of SMWs, including MSJC 2013 (no PT bar elongation) and methods A, B and C proposed in other studies. Comparing the prediction obtained from MSJC 2013 and other available methods, with experimental results and finite element analysis result revealed that ignoring the elongation of PT bars in strength prediction resulted in a considerable underestimation of the flexural strength of SMWs. Using other methods, such as Method C, could significantly improve the prediction.

KEYWORDS: *self-centering walls, flexural strength, unbonded, in-plane, rocking*

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INTRODUCTION

Self-centring concept was first developed for moment resisting frames [15] using unbonded post-tensioning (PT) steel. In self-centering systems, the restoring nature of force in unbonded PT steel returns the system back to its original position. Self-centering behavior reduces residual drifts and structural damage during earthquake ground motion, and is specifically favorable for structures which are designed for immediate occupancy performance levels. Due to its unique behaviour, the self-centering concept has been applied to various types of structures such as steel moment resisting frames, timber structures, and precast concrete systems [3; 4; 14; 16]. When a self-centering masonry wall (SMW) is subjected to a lateral in-plane load and the cracking moment is exceeded at the base of the wall, a single horizontal crack forms at the wall-foundation interface. The self-centering behavior is specifically favorable for structures which are designed for immediate occupancy performance levels. The rocking mechanism of SMWs (Figure 1) results in plastic deformation concentrated at the toe of the wall which can be repaired with minimal cost [2; 5; 9; 18; 19].

To calculate the in-plane strength of self-centering masonry walls, the stress developed in PT bars at the wall peak strength is required. The stress developed in a PT bar depends on the bar strain and hence the elongation of the bars. In bonded masonry walls the strain compatibility concept can be considered to determine the stress in the bars. For SMWs, the strain in the PT bar remains approximately constant along the length of the bar. Therefore, displacement compatibility criteria need to be considered rather than strain compatibility (Figure 1). While the current approach of the Masonry Standards Joint Committee (MSJC 2013) [13] considers the stress increase in PT bars beyond initial post-tensioning to predict the out-of-plane flexural strength, it is not considered for in-plane flexural strength prediction. Recently, expressions have been proposed by different researchers for evaluating such post-tensioning force [1; 19]. The accuracy of the available expressions in predicting the in-plane strength of SMWs is evaluated in this study.

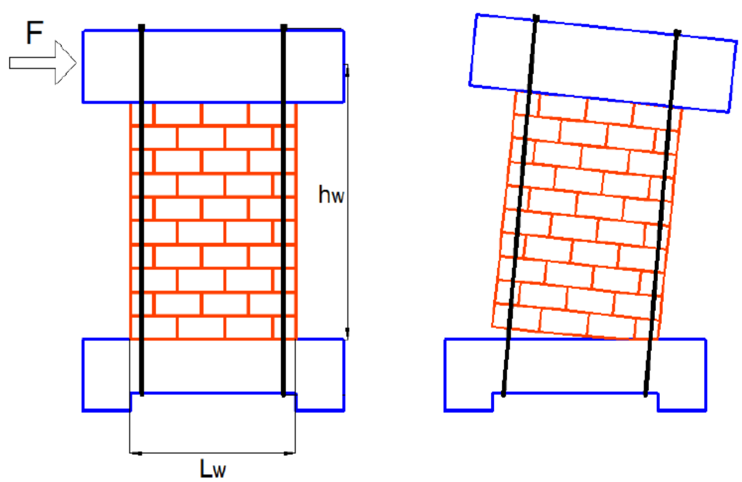


Figure 1: Rocking in self-centering masonry walls

PREDICTION OF NOMINAL FLEXURAL STRENGTH

Four different available equations are considered here to predict the in-plane flexural strength of SMWs. These expressions include no PT bar elongation (Adopted by MSJC 2013 [13] and methods A, B and C which are presented in the following.

Masonry Standard Joint Committee (MSJC 2013)

MSJC 2013 uses Eq. 1 and Eq. 2 to predict the flexural strength of SMWs,

$$M_n = (f_{se}A_{ps} + f_yA_s + N)(d - \frac{a}{2}) \tag{1}$$

$$a = \frac{f_{se}A_{ps} + f_yA_s + N}{0.8f'_m b} \tag{2}$$

where a is the depth of the equivalent compression zone, A_s is the area of conventional flexural reinforcement, f_y is the yield strength, f_{se} is the effective stress in the PT bar after immediate and long term stress losses, A_{ps} is the area of the PT bar, N is the gravity load including the self-weight of the wall, f'_m is the compressive strength of masonry, b is the cross section width and d is the effective depth of the wall. The predicted lateral strength of SMWs using this flexural expression is equal to the nominal moment capacity, M_n, divided by the wall height, h_w.

In the flexural expression presented by MSJC 2013 (Eq. 1), the distributions of tendons along the length of the wall are not considered. The reason is that the equation was originally developed for out-of-plane loading where the tendons are usually located at the center of the wall. This results in a single value for effective depth. As for in-plane loading the equation needs to consider the location of multiple PT bars along the wall length, the Eq. 3 and Eq. 4 should be used in lieu of Eq. 1 and Eq. 2,

$$M_n = \sum f_{ps\,i}\,A_{ps\,i}\left(d_i - \frac{a}{2}\right) + \sum f_y\,A_{sj}\left(d_j - \frac{a}{2}\right) + N(\frac{L_w}{2} - \frac{a}{2}) \tag{3}$$

$$a = \frac{\sum f_{ps\,i}\,A_{ps\,i} \ + \sum f_y\,A_{s\,i} + N}{0.8f'_m b} \tag{4}$$

where L_w is the length of the wall, A_{sj}, d_j and f_y are the cross sectional area, the distance from the extreme compression fiber to the ith vertical bar, and the yield strength of conventional flexural reinforcement, respectively.

As mentioned, MSJC 2013 conservatively ignores the effect of the stress increment due to the elongation of PT bars, hence, $f_{ps} = f_{se}$. However, for out-of-plane bending of SMWs, Eq. 5 is considered by the MSJC 2013 to evaluate f_{ps},

$$f_{ps} = f_{se} + 0.03(\frac{E_{ps}d}{L_{ps}})(1 - 1.56\frac{A_{ps}f_{ps} + N}{f'_m L_w d}) \quad \text{(Out-of-plane bending)} \tag{5}$$

where L_{ps} is the unbonded length and E_{ps} is the elastic modulus of PT bar.

Method A: Out of plane expression

Ryu et al.[18] indicated that the out-of-plane expression of MSJC 2008 [12] can be also used to determine the flexural strength of walls loaded in-plane. The equation was proposed by Bean Popehn et al. [1] as a result of a series of test results and finite element models of SMWs loaded out-of-plane. However, the equation has been updated in the latest version of MSJC [13] (Eq. 5). Moreover, to determine the in-plane flexural strength of SMWs having multiple post-tensioning bars, the ultimate stress in each PT bar needs to be calculated. Hence, to account for different locations of PT bars along the length of the wall, Eq. 5 can be re-written as,

$$f_{ps\,i} = f_{se} + 0.03(\frac{E_{ps}d_i}{L_{ps}})(1 - 1.56\frac{\sum A_{ps\,i}\,f_{ps\,i} + N}{f'_m L_w d_i}) \tag{6}$$

Method B: Wight and Ingham's Approach

Eq. 6 assumed constant rotation of SMWs of 0.03 rad (or drift of 0.03). However, it has been shown that rotations of walls at the peak strength is not constant and is a function of the configuration of the wall, aspect ratio, and axial stress ratio, f_m/f'_m, where f_m is defined using Eq. 8. [7]Using experimental results and finite element models, Wight and Ingham [19] proposed Eq. 7 to estimate the peak tendon force:

$$f_{ps} = f_{se} + \frac{E_{ps}}{L_{ps}}\theta(d_i - \frac{f_m L_w}{\alpha\beta f'_m}) \tag{7}$$

$$f_m = \frac{f_{se}A_{ps} + N}{L_w b} \tag{8}$$

$$\theta = [\left(\frac{h_w}{L_w}\right)\varepsilon_{mu}]\Big/[30\left(\frac{f_m}{f'_m}\right)] \tag{9}$$

α and β are the stress block parameters, h_w is the height of the wall and ε_{mu} is the ultimate masonry strain, which are provided by different building codes (e.g. in MSJC 2013: α=β=0.8, ε_{mu}= 0.0035 and 0.0025 for clay and concrete masonry, respectively). Note that in spite of Eq. 6, Eq. 7 does not require iterations as the compression zone length is not a function of f_{ps} [10].

Method C: Hassanli et al.'s Approach

Hassanli et al. [7] developed Eq. 10 to predict the PT bar ultimate stress of SMWs,

$$f_{ps\,i} = f_{se\,i} + (\theta_m c - \theta_0 c)\,\frac{E_{ps}}{L_{ps}}\left(\frac{d_i}{c} - 1\right) \tag{10}$$

where,

$$\theta_m c = (0.55L_w + 17.375\frac{f_m}{f'_m}) \quad (11)$$

$$\theta_0 = \begin{cases} (f_m h_w)/(1350 f'_m L_w) & \text{Concrete masonry} \\ (f_m h_w)/(900 f'_m L_w) & \text{Clay masonry} \end{cases} \quad (12)$$

$$c = (\sum f_{ps\,i} A_{ps\,i} + N)/(\alpha\beta f'_m\, b) \quad (13)$$

where c is the length of the compression zone, θ_m is the wall rotation at peak strength and θ_0 is the rotation corresponding to the decompression point, and f_m can be calculated using Eq. 8. Note that L_w in Eq. 11 is in meters.

Table 1: Post-Tensioned Masonry Wall Database

Ref.	Wall Designation	Original designation	Material
Laursen [11]	L1-Wall1	FG:L3.0-W20-P3	CMU
	L1-Wall2	FG:L3.0-W15-P3	CMU
	L1-Wall3	FG:L3.0-W15-P2C	CMU
	L1-Wall4	FG:L3.0-W15-P2E	CMU
	L1-Wall5	FG:L1.8-W15-P2	CMU
	L1-Wall6	FG:L1.8-W15-P3	CMU
	L3- Wall1	S3-1	CMU
	L3-Wall2	S3-2	CMU
	L2-Wall1	FG:L3.0-W15-P1-CP	CMU
	L2-Wall2	FG:L3.0-W15-P2-CP	CMU
	L2-Wall5	FG:L3.0-W15-P2-HB	CMU
Rosenboom [17]	R-Wall1	Test1	CBM
	R-Wall2	Test3	CBM
	R-Wall3	Test2	CBM
Hassanli [6]	W1	W1	CMU
	W2	W2	CMU
	W3	W3	CMU
	W4	W4	CMU

FG = fully grouted, CMU = concrete masonry unit, CBM= clay brick masonry

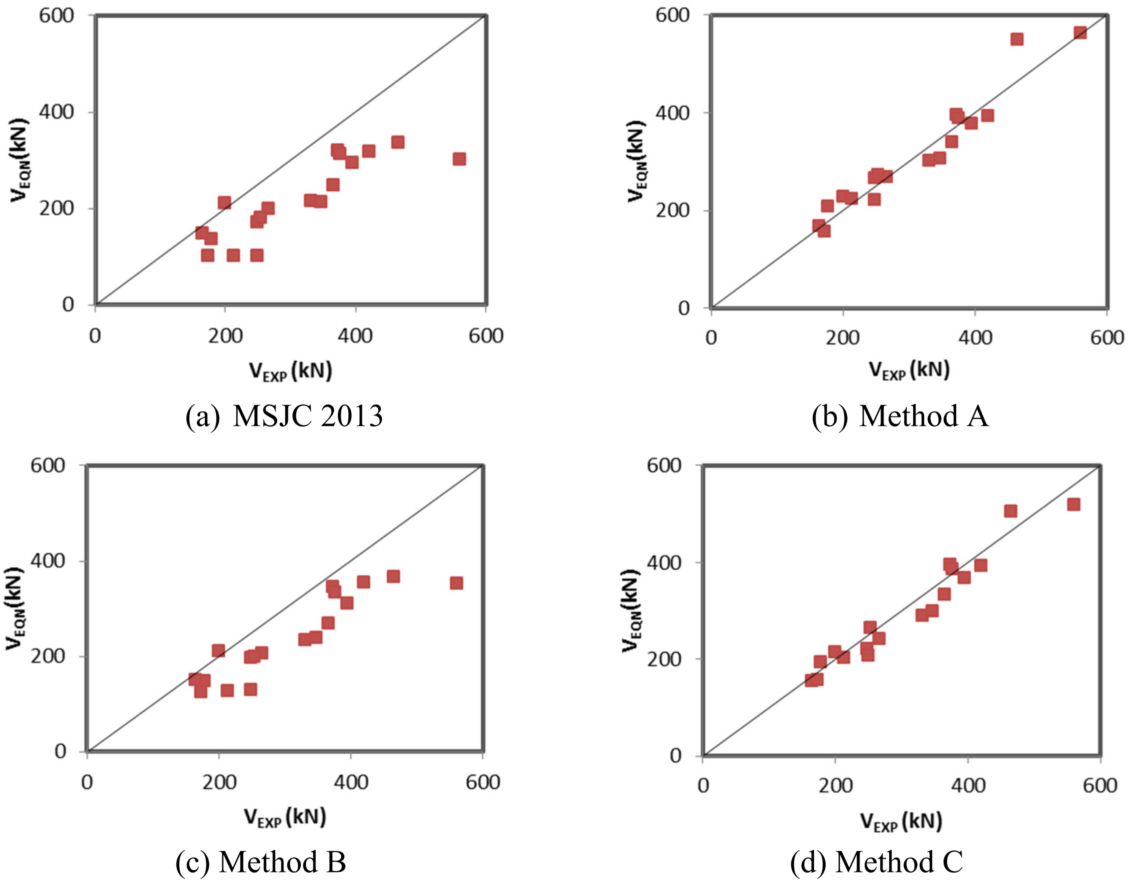
COMPARISON OF FLEXURAL EXPRESSIONS WITH EXPERIMENTAL RESULTS

Table 1 summarizes a database of 18 SMWs. The strength obtained from flexural strength expressions of MSJC 2013 and Methods A, B and C is calculated as V_{EQN}. V_{EXP} is the maximum lateral load obtained from the experimental work. The values of V_{EQN}/V_{EXP} are presented in Table 2.

Table 2: Strength Prediction Using Different Approaches

Wall	MSJC 2013	Method A	Method B	Method C
L1-Wall1	0.54	1.00	0.63	0.93
L1-Wall2	0.72	1.18	0.79	1.09
L1-Wall3	0.86	1.06	0.93	1.06
L1-Wall4	0.76	0.94	0.85	0.93
L1-Wall5	0.76	1.17	0.84	1.09
L1-Wall6	0.75	1.01	0.77	0.91
L3- Wall1	0.65	0.91	0.71	0.88
L3-Wall2	1.05	1.14	1.05	1.07
L2-Wall1	0.90	1.02	0.91	0.94
L2-Wall2	0.62	0.88	0.68	0.86
L2-Wall5	0.68	0.93	0.73	0.91
R-Wall1	0.69	0.89	0.79	0.89
R- Wall2	0.74	0.96	0.79	0.93
R- Wall3	0.83	1.04	0.89	1.02
W1	0.58	0.91	0.70	0.91
W2	0.47	1.05	0.58	0.96
W3	0.41	1.07	0.52	0.84
W4	0.72	1.08	0.79	1.04
Max	1.05	1.18	1.05	1.09
Min	0.41	0.88	0.52	0.84
Average	0.71	1.01	0.77	0.96
Std Dev.	0.15	0.09	0.13	0.08
Var.	0.02	0.01	0.02	0.01
Range	0.64	0.30	0.54	0.25

Figure 2 shows the relationship between V_{EQN} and V_{EXP}. As shown, the MSJC 2013 method underestimates the strength of almost all of the test specimens. The value of V_{EQN}/V_{EXP} based on MSJC 2013 varies from 0.41 to 1.05 with an average of 0.71, and *Method A* predicts V_{EQN}/V_{EXP} values varying from 0.88 to 1.18 with an average of 1.01. However, *Method A* overpredicted the strength of 55% of the specimens. Using *Method B,* V_{EQN}/V_{EXP} varies from 0.52 to 1.05 with an average of 0.77. As shown, *Method C* has a better average and narrower range compared to the MSJC 2013 results. *Method C* presents the lowest range and most accurate conservative average of V_{EQN}/V_{EXP}. Using *Method C*, V_{EQN}/V_{EXP} varies from 0.84 to 1.09 with an average of 0.96. However, *Method C* over-predicted the strength of 27% of the test specimens.



(a) MSJC 2013

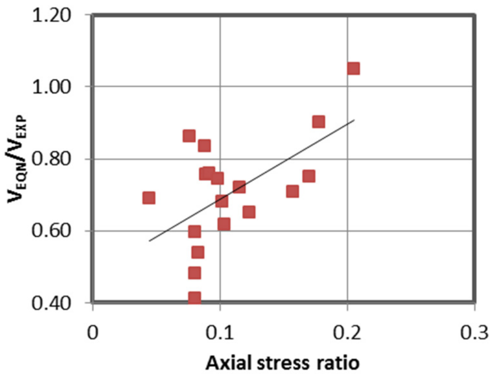
(b) Method A

(c) Method B

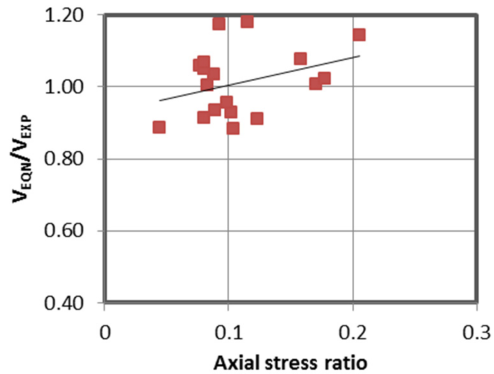
(d) Method C

Figure 2: Accuracy of Different Expressions Based on Experimental Results

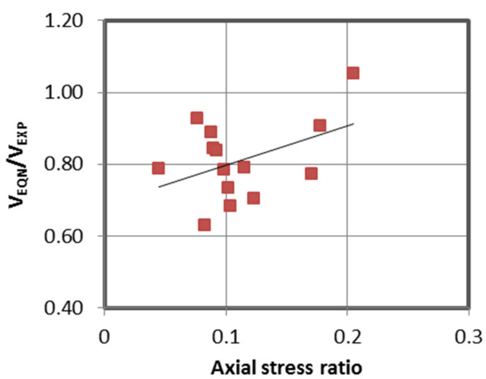
Figure 3 presents the values of V_{EQN}/V_{EXP} versus the axial stress ratio. As the scatter of the data is reduced in *Method A* and *Method C* compared with the other two methods. Among the different methods, *Method C* showed the smallest slope of the regression lines, indicating that this method is the least biased toward the level of axial stress ratio compared to the other approaches.



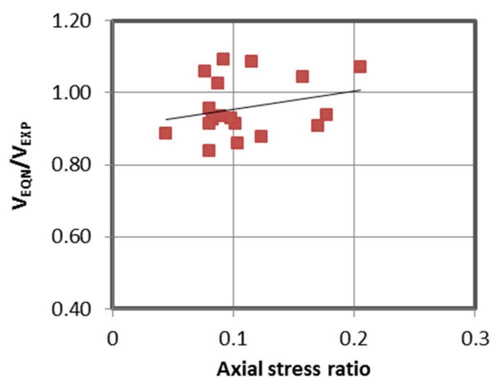
(a) MSJC 2013



(b) Method A



(c) Method B

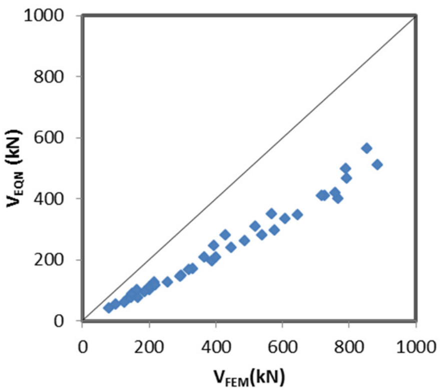


(d) Method C

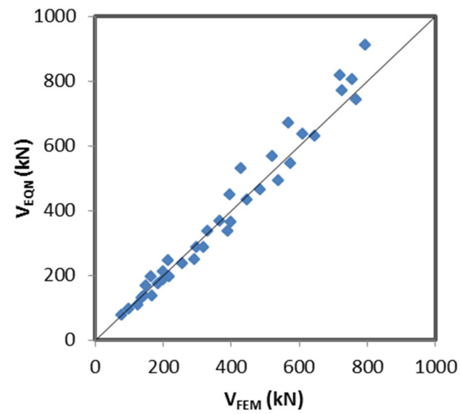
Figure 3: Comparison of VEQN/VFEM Based on Experimental Results

COMPARISON OF FLEXURAL EXPRESSIONS WITH FINITE ELEMENT MODEL RESULTS

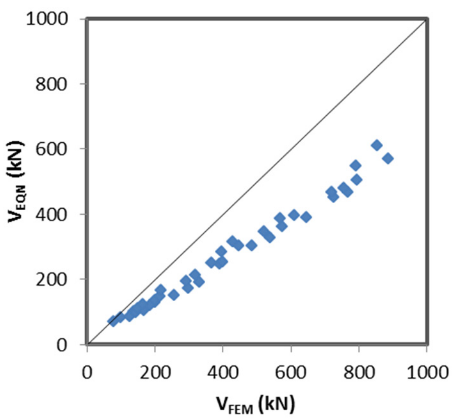
The results of parametric study conducted by Hassanli et al. [7] were adopted here to evaluate the adequacy of the available methods in flexural strength prediction of SMWs. More information about the material model and finite element analysis can be found in [7; 8]. Figure 4 shows the predicted lateral strength obtained using the FE analysis, V_{FEM}, against that calculated using the different approaches. Figure 5 presents the values of V_{EQN}/V_{FEM} of different methods. As shown, MSJC 2013 is the most conservative approach, since the MSJC 2013 ignores the post-tensioning bar elongation. *Method A* overestimated the strength of 45% of the investigated walls. For 27% of the specimens the overprediction was more than 10%. *Method B* provides a very conservative estimation. The strength of almost all of the specimens were underpredicted using *Method B*. *Method C* followed very closely the FE results with an average of V_{EQN}/V_{FEM} of 0.9 and overestimated the strength of 7% of the FE walls.



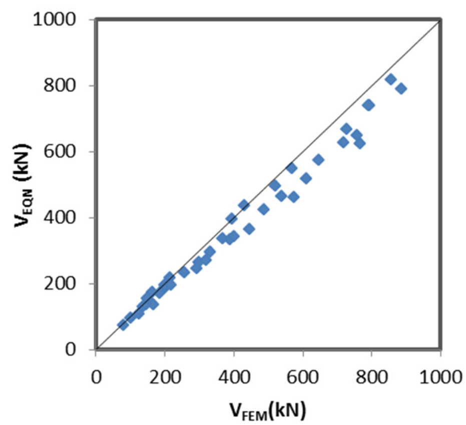
(a) MSJC 2013



(b) Method A

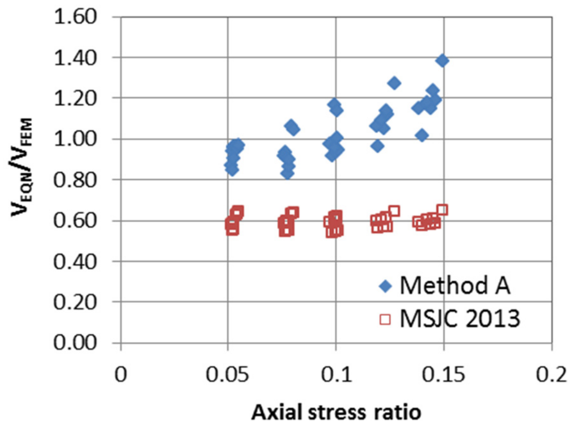


(c) Method B



(d) Method C

Figure 4: Comparison of VEQN/VFEM Based on FEM Results



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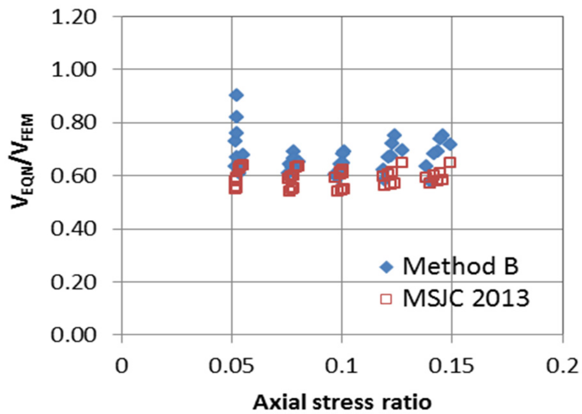

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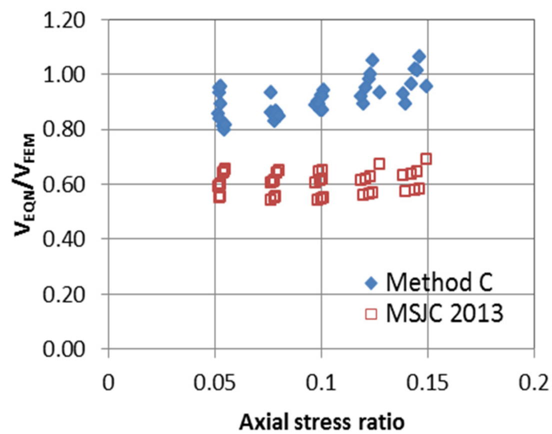

(c)

Figure 5: Comparison of MSJC 2013 with Other Expressions Based on FEM Results

CONCLUSIONS

This manuscript compared the accuracy of different expressions in predicting the flexural strength of self-centering masonry walls (SMWs). The strength of 18 tested SWMs was compared with the values calculated using the MSJC 2013 approach as well as three available methods. According to the results, disregarding the elongation of the PT bars in self-centering masonry walls, as is adopted by the MSJC 2013, results in a highly conservative strength prediction, and using other methods, such as *Method C* presented in this paper, could significantly improve the prediction.

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