Tenth U.S. National Conference on Earthquake Engineering
Frontiers of Earthquake Engineering
July 21-25, 2014
Anchorage, Alaska

A NEW SHEAR STRENGTH DESIGN FORMULA FOR CONFINED MASONRY WALLS: PROPOSAL TO THE MEXICAN CODE

J. J. Perez-Gavilan[1], L.E. Flores[2] and A. Manzano[3]

ABSTRACT

Based on new experimental evidence a new formula to estimate the cracking due to tension shear strength of confined masonry walls is proposed. The new expression includes the influence of aspect ratio and the bending moment on top of the wall in the shear resistance of a wall. A recent experimental study showed a considerable increase in the cracking shear force for reducing aspect ratios. The effect is taken into account with a factor that is applied to the nominal shear strength which was calibrated for square walls. A second set of tests conducted with walls with only lateral load and lateral load and moment on top of the wall, have shown, especially for slender walls, a reduction of the cracking strength with the increase of flexural moment. The format of the new formula separates the effect of aspect ratio and moment, which are taken as independent variables. The new expression is compared to the current formula of de Mexican code.

---

[1] Applied mechanics, Instituto de Ingeniería de la UNAM, Av. Universidad 3000, CU, CP 04510, Mexico D.F., jjpge@pumas.iingen.unam.mx
[2] Centro Nacional de Prevención de Desastres, (CENPARED), Av. Delfín Madrigal No. 665, Col. Pedregal de Santo Domíngo, México D. F. CP 04360
[3] Ph.D. Student, Instituto de Ingeniería de la UNAM

DOI: 10.4231/D39G5GF1R

Tenth U.S. National Conference on Earthquake Engineering
Frontiers of Earthquake Engineering
July 21-25, 2014
Anchorage, Alaska

A New Shear Strength Design Formula for Confined Masonry Walls: Proposal to the Mexican Code

J. J. Perez-Gavilan[1], L. E. Flores[2] and A. Manzano[3]

ABSTRACT

Based on new experimental evidence a new formula to estimate the cracking due to tension shear strength of confined masonry walls is proposed. The new expression includes the influence of aspect ratio and the bending moment on top of the wall in the shear resistance of a wall. A recent experimental study showed a considerable increase in the cracking shear force for reducing aspect ratios. The effect is taken into account with a factor that is applied to the nominal shear strength which was calibrated for square walls. A second set of tests conducted with walls with only lateral load and lateral load and moment on top of the wall, have shown, especially for slender walls, a reduction of the cracking strength with the increase of flexural moment. The format of the new formula separates the effect of aspect ratio and moment, which are taken as independent variables. The new expression is compared to the current formula of de Mexican code.

Introduction

The Mexican masonry code [1] shear strength formula for confined masonry walls, without horizontal reinforcement is given by Eq. 1

$$V_{mR} = F_R(0.5v^*A_T + 0.3P) \leq F_R 1.5v^*A_T \tag{1}$$

where v^* is the shear strength of the masonry as obtained from diagonal compression tests, A_T is the untransformed cross sectional area of the wall including tie columns, P is the axial force on the wall and F_R is the strength reduction factor. The rightmost term limits the amount of axial load that may increase the wall strength. The formula was calibrated with many full scaled tests of walls, usually with a height to length aspect ratio equal to one and with different types of masonry units and mortar [2,3]. The effect of aspect ratio and the flexural moment on top of the wall are neglected.

---

[1] Applied mechanics, Instituto de Ingeniería de la UNAM, Av. Universidad 3000, CU, CP 04510, Mexico D.F., jjpge@pumas.iingen.unam.mx
[2] Centro Nacional de Prevención de Desastres, (CENPARED), Av. Delfín Madrigal No. 665, Col. Pedregal de Santo Domíngo, México D. F. CP 04360
[3] Ph.D. Student, Instituto de Ingeniería de la UNAM

J. J. Perez-Gavilan, L. E. Flores, A. Manzano. A new shear strength design formula for confined masonry walls: proposal to the Mexican code. *Proceedings of the 10th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK, 2014.

Many important codes recognize the effect of aspect ratio on the shear strength of reinforced masonry [4]. Often, the effect of aspect ratio, is included with a factor, function of M/VL, the shear span ratio, that affects the basic masonry strength of the wall. In the shear span ratio M and V are the flexural moment and the shear force at the base of the wall, respectively, and L the wall's length. This parameter may be understood as an effective aspect ratio if $M = VH_e$ where H_e is the effective height of the wall, then $M/VL = H_e/L$. This interpretation is important as it explains how the presence of moment is taken into account, i.e., as a change of aspect ratio.

The effect of aspect ratio in confined masonry shear strength was studied by Alvarez [5]. He analyzed many experimental results of walls with different aspect ratios and concluded that shear strength increases with deceasing aspect ratio. A recent experimental study [6], confirmed Alvarez results.

As mentioned above, the effect of flexural moment, in the shear strength of reinforced masonry with a given aspect ratio is estimated indirectly as the strength of a wall with an effective aspect ratio. The effect is limited to walls with effective aspect ratio less than or equal to one ($M/VL \leq 1$), i.e. for squat walls [7,8]. In an analytical investigation conducted by Zeballos [9], where walls were modelled with finite elements not including tie-columns, it is shown that the shear strength of slender walls should be reduced as the effective aspect ratio is increased.

The effect of the moment on top of the wall was recently studied by means of explicit application of cyclic loads, flexural moment and shear on full scale confined masonry walls [10,11]. The results show that the presence of flexural moment reduces the cracking shear strength due to tension of confined masonry walls, especially of slender walls.

In next sections the main results that show the effect of aspect ratio and flexural moment on the cracking shear strength of confined masonry are presented. Later those results are integrated into a new shear strength formula; its values are compared with current code's formula given by Eq. 1.

Effect of Aspect Ratio

In [6] seven full scaled confined masonry walls with aspect ratios form 0.27 up to 2.2 were tested with constant vertical load and cyclic lateral loads. The results show that the cracking strength observed in the laboratory consistently exceeded the cracking strength predicted by Eq. 1, and that the difference increases with reducing aspect ratios. In Figure 1, the quotient of the cracking strength observed in the laboratory and the strength predicted with Eq. 1 using a unit strength factor and average shear strength v_m instead of the design strength value v^*, is shown. The authors argued that because the code's formula was calibrated with walls tested that had a unit aspect ratio, the difference between the observed cracking strength the code's estimation, may be attributed to differences in flexural deformations of walls with different aspect ratio. Using this idea they obtained the factor in Eq. 2, where V_c is the cracking strength and V_n the nominal

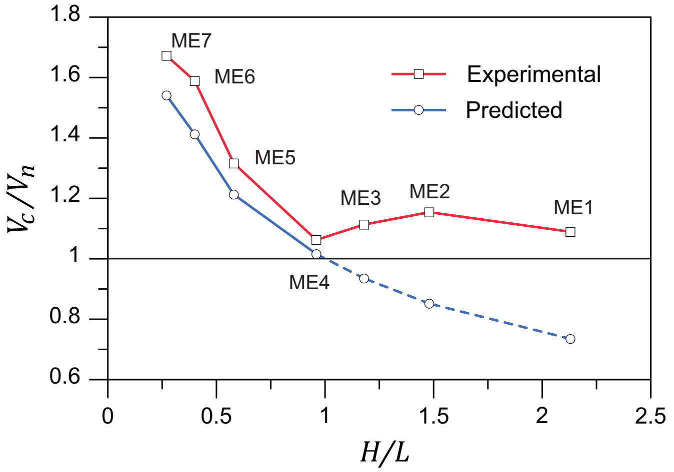


Figure 1 Experimental (red) and predicted (blue) cracking strengths over the nominal Mexican code cracking strength.

$$\frac{V_c}{V_n} = f = \frac{(10\eta + 3)(10w^2\eta + 3)}{100w^2\eta^2 + 60w^2\eta + 9} \tag{2}$$

cracking strength given by Eq. 1 with units strength reduction factor, $w = H/L$ is the aspect ratio and $\eta = G/E$ is the quotient of masonry's shear and elastic modulus. The prediction given by Eq. 2 is presented in Figure 1. There is a good agreement with the experimental results for walls with $H/L \leq 1$. Eq. 2 predicts a reduction of the cracking strength for slender walls, however that reduction was not observed. This discrepancy was attributed to the distance between the tie columns that for slender walls may increase confinement and was not considered in Eq. 2. Eq. 2 was linearized to ease its application and instead of the aspect ratio the effective aspect ratio was used, leading to Eq. 3

$$\begin{aligned} f &= 1.55 && H/L < 0.2 \\ f &= 1.69 - 0.69\frac{H_e}{L} && 0.2 \leq H/L \leq 1 \\ f &= 1 && H/L > 1 \end{aligned} \tag{3}$$

To take into account the aspect ratio in the wall's shear strength Eq. 4 was proposed

$$V_c = V_n \cdot f = (0.5v^* A_T + 0.3P) \cdot f \tag{4}$$

Unlike the codes for reinforced masonry, the factor to take into account the aspect ratio is applied to both components of strength: the basic shear strength of masonry and the axial stress contribution. As the factor was deduced using the differences in flexural deformations of walls with different aspect ratios and the lateral deformations at cracking are affected by the axial load it was considered theoretically more appropriate to apply the factor to both components [6]. Other variables such as the horizontal reinforcement do not affect the cracking strength.

Effect of flexural moment

To estimate the reduction of the cracking shear strength due to the flexural moment on top of the wall M_a, it was assumed *a priori* [10,11] that the lateral displacements at cracking is fixed, not depending on which force may produce the lateral displacements: flexural moment on the top of the wall, shear or a combination of those forces. If there is a flexural moment on top of the wall, it produces a lateral displacement that cannot be generated through lateral force anymore. Consequently, the cracking shear force is reduced. Using these ideas the cracking strength may be computed using Eq. 5

$$V_c = V_n - \frac{M_a}{H_k} \tag{5}$$

where M_a is the flexural moment on top of the wall, being positive if in the same direction of the moment produced by the shear force and negative otherwise, and H_k is a constant defined by Eq. 6

$$H_k = \frac{2}{3}\frac{k_f + k_v}{k_v}H \tag{6}$$

where $k_f = 3EI/H^3$ and $k_v = GA/\kappa H$, A and I are the cross sectional area and moment of inertia, H is the height of the wall, considered to be the distance between the adjacent floors of the wall and κ the shear factor. The quotient between the reduced and nominal shear strength may be written as in Eq. 7

$$\frac{V_c}{V_n} = \frac{1}{1 + \frac{15\beta\eta w^2}{20\eta w^2 + 6}} \tag{7}$$

where $\beta = 2M_a/VH$ is the normalized moment on top of the wall. If $\beta = 0$, there is no moment, in that case $V_c/V_n = 1$, regardless of the aspect ratio. In case $\beta = -1$, the wall has its top end fixed, no rotation can be generated. In that case the moment reduces the lateral displacement produced by the lateral force; consequently, at least theoretically, the shear strength should increase. In the left of Figure 2 the quotient in Eq. 7 is plotted against aspect ratio for different levels of normalized moment; to the right the same quotient is plotted against normalized moment for different values of aspect ratio. It can be observed that the effect is larger for increasing aspect ratio but is asymptotic. For very long walls the effect is null.

The effect of η is considerable. For $\eta = 0.4$ flexural deformations are larger than for $\eta = 0.2$, clearly the effect of the flexural moment increases with η. Results presented in [10,11] show a good agreement between the predicted reduction of shear strength with flexural moment and experiment.

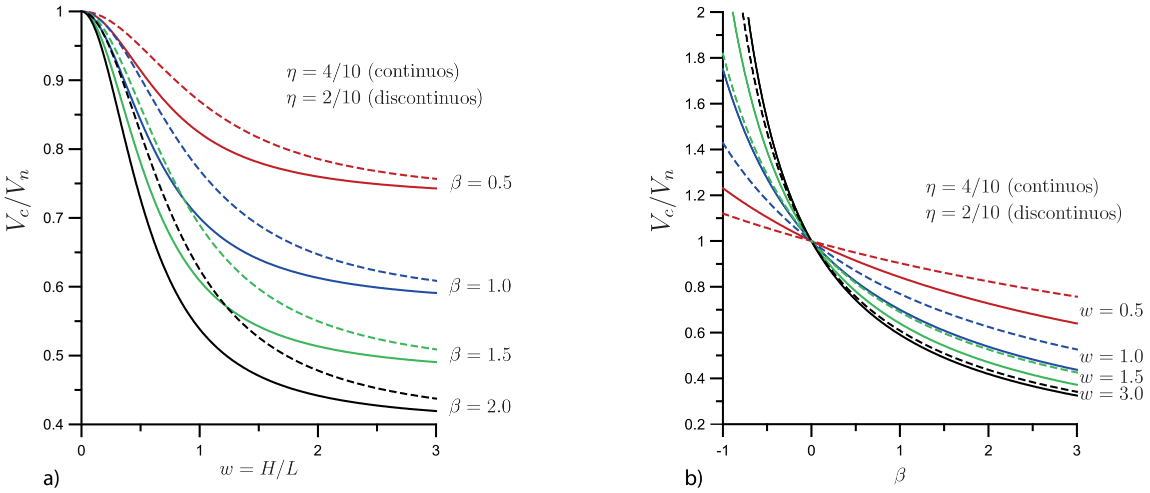


Figure 2 a) Normalized cracking strength *vs* aspect ratio, and b) *vs* normalized moment

It can be observed that the effect of moment is larger for slender walls but the reduction

A new formula for shear strength

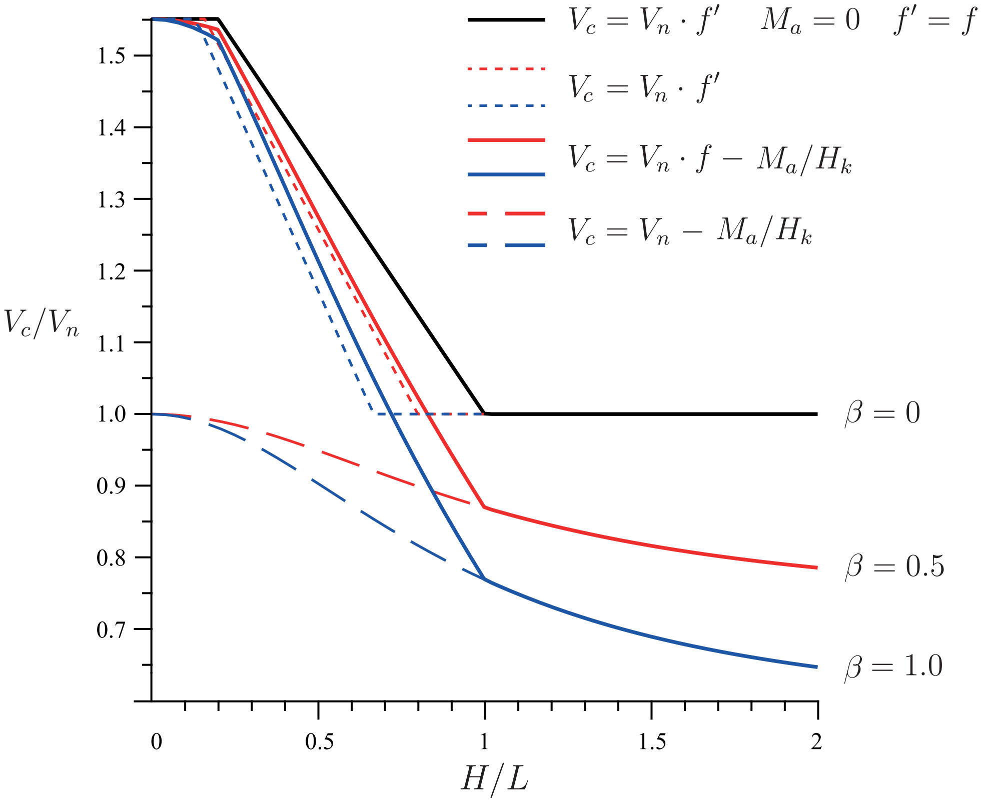
The results presented in the previous sections may be integrated into one formula to consider both the effect of aspect ratio and flexural moment on top of the wall in the strength of confined masonry walls. The proposed formula is presented in Eq. 8

$$V_{mR} = F_R\left\{(0.5v^*A_T + 0.3P)\cdot f - \frac{M_a}{H_k}\right\} < 1.5F_R v^* A_T \cdot f \tag{8}$$

where the first term in parenthesis is the nominal strength from Eq. 1, where f is the factor given by Eq. 3 using the height instead of the effective height of the wall; this change needs a careful explanation and will be given below. M_a/H_k is the effect of the flexural moment on top of the wall as discussed in the previous section.

One important aspect of the design of the formula was how to include the effect of flexural moment. As stated before, it is generally accepted to take the effect of flexural moment with an effective aspect ratio for squat walls. If that nation should be kept, the result is that two different formulas need to be considered, one for $M/VL < 1$ including only the f factor, and one for $M/VL \geq 1$ with $f = 1$ and the term M_a/H_k, with a possible discontinuity at $M/VL = 1$. By taking the aspect ratio instead of the effective aspect ratio in f in Eq. 8, the second term in the formula should have the same effect in the shear strength as having the effective aspect ratio for squat walls. Let us check that out.

In Figure 3, it is shown the quotient of nominal shear strength evaluated with the new formula in Eq. 8, denoted by V_c, and nominal strength using Eq. 1, denoted by V_n. The continuous curves in red and blue show the quotient using the new formula as in Eq 8, for two values of the normalized moment $\beta = 0.5$ and $\beta = 1.0$, respectively. The case for $\beta = 0$ is shown with a continuous black line. The dotted lines correspond to the value of the quotient



$$f' = \begin{cases} 1.55 & H_e/L \le 0.2 \\ 1.69 - 0.69 H_e/L & 0.2 < H_e/L \le 1 \\ 1.0 & 1 < H_e/L \end{cases} \qquad f = \begin{cases} 1.55 & H/L \le 0.2 \\ 1.69 - 0.69 H/L & 0.2 < H_e/L \le 1 \\ 1.0 & 1 < H/L \end{cases}$$

Figure 3 Comparison of shear strength with new formula and current code's

evaluated using the effective aspect ratio and not considering the term with M_a in it. It can be observed that both quotients are similar as it was needed to show. The dashed lines represent the effect of the second term only, with $f = 1$ for squat walls, they show that as the walls get squat the effect of the flexural moment decreases. The result concedes with intuition as for squat walls the lateral displacement do to flexural moment tend to zero due to their large flexural rigidity.

Conclusions and final remarks

A new design shear strength formula for confined masonry walls was proposed, that take into account two new parameters: 1) the aspect ratio and 2) the flexural moment on top of the wall.

The shear strength compared with the current Mexican code's formula, increases for walls with decreasing aspect ratio while the strength is reduced for slender walls. The proposed flexural new term may be used for all aspect ratios; it was shown that it produces a similar effect for squat walls than using an effective aspect ratio as is used in many codes for reinforced masonry.

The proposed formula takes as independent variables the aspect ratio and the flexural moment on top of the wall. The height of the wall is always the distance between wall's adjacent building floors, there is no need of the effective height concept. The flexural term takes into account the shear strength-moment interaction; it is not just an artifact to transform a wall with a given aspect ratio with a moment on top of the wall into an equivalent, fictitious, wall with a larger aspect ratio and no moment on top.

The normalized moment β is the main parameter to reduce the shear strength of the wall; however, the variation of this parameter is not clearly understood. It should increase with the number of floors in the structure, but many other variables may affect its value, for example the boundary conditions and the aspect ratio of the wall should affect it. There is an analytical study currently under way to try answering some of these questions. In theory, β may be less than cero, which produce an increase in shear strength. However, there is limited experimental evidence of this so in the proposal when the wall is in double curvature, the flexural term is ignored.

Acknowledgments

This work was funded by the National Council of Science and Technology of México (CONACYT) through grant No 133225 and partially by the Mexico City Government through grant No. CT/04/10.

References

1. NTCM 2004, Normas Técnicas Complementarias para el Diseño y Construcción de Estructuras de Mampostería, *Gobierno del DF*, México 2004.
2. Alcocer, S. y Meli. R. Test program on the seismic behaviour of confined masonry walls, The masonry Soc. J. (Boulder) 12 (2) 68-76, 1995.
3. Meli, R. Behaviour of Masonry Walls Under Lateral Loads, Fifth World Conference on Earthquake Engineering, Rome, 1973
4. Davis, C. L. Evaluation of design provisions for in-plane shear in masonry walls (Master of Science Thesis), Washington State University, Civil Engineering, 2008.
5. Alvarez, J. J., *Some topics of the seismic behavior of confined masonry structures*. Eleventh World Conference on Earthquake Engineering, paper No 180; Elsevier Science Ltd., 1996.
6. Pérez Gavilán, J. J., L. E. Flores, S. M. Alcocer, *An experimental study of confined masonry walls with varying aspect ratio*, Earthquake Spectra, in press, 2013.
7. Matsumura, A. *Shear Strength of reinforced masonry walls*, Proceedings of Ninth World Conference on Earthquake Engineering VI, 121-126; Tokyo-Kyoto, Japan., 1998.
8. Voon, K. C., e Ingham, J. M., *Experimental in-plane shear strength investigation of reinforced concrete masonry walls*, Journal of Structural Engineering, 132:3, 400-408., 2006.
9. Zeballos, A., A. San Bartolomé y A. Muñoz, *Efectos de la esbeltez sobre la resistencia a fuerza cortante de los muros de albañilería confinada. Analisis por elementos finitos*, Blog de Angel San Bartolomé, Pontificia Universidad Católica de Perú, http://blog.pucp.edu.pe/media/688/20070504-Esbeltez%20-

%20Elementos%20finitos.pdf., 1992.

10. Manzano A., J. J., Pérez Gavilán, *Shear moment interaction in confined Masonry walls*, 12th Canadian Masonry Symposium, Vacouver Canada, paper 323., 2013a.
11. Pérez Gavilán, J. J., A. Manzano, *Efecto del momento flexionante en la fuerza cortante que produce el agrietamiento por tensión diagonal en muros de mampostería confinada*. Revista de Ingeniería Sísmica, 88 1-22., 2013b