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VERTICAL REINFORCEMENT REQUIRED IN SQUAT CONCRETE SHEAR WALLS

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ABSTRACT

A method to determine the strength of squat shear walls accounting for the complex flexure–shear interaction is proposed. The method accounts for the effect of wall height-to-length ratio and suggests the full contribution of vertical distributed shear reinforcement to the flexural resistance of walls with height-to-length ratios greater than 0.8. The proposed method was verified against nonlinear finite element analysis predictions for 42 shear-dominated squat walls where the capacity was limited by yielding of vertical reinforcement at the base of the wall. The walls had height-to-length ratios from 0.3 to 2.0 and had varying amounts of distributed horizontal reinforcement, distributed vertical reinforcement, and concentrated vertical reinforcement at the ends of the wall. As a result of the current study, the August 2009 addendum of the 2004 Canadian concrete code included a change to Clause 21.7.4.7 consistent with what is proposed here for the vertical reinforcement required in squat shear walls.

Introduction

The 2004 Canadian concrete code (CSA A23.3) contains new provisions for the design of squat shear walls, which are defined as shear walls with height-to-length ratios of 2.0 or less. The provisions are based on a uniform shear element (often called membrane element) model, which assumes that all vertical distributed reinforcement needed for shear resistance must be provided in addition to any distributed vertical reinforcement considered to resist flexure at the base of the wall. When the new provisions were implemented into the Canadian code, it was known the vertical reinforcement requirements were conservative, especially for walls with a height-to-length ratio close to 2.0; but it was not known how conservative. A number of Canadian designers noted that the amount of vertical reinforcement required by the new provisions in squat walls had increased significantly from what they had traditionally provided.

The current study was undertaken to determine whether the 2004 Canadian code requirements could be modified so as to require less vertical reinforcement in squat walls. As a result of the current study, the August 2009 addendum of CSA A23.3 2004 did include a change to the squat wall design requirements (Clause 21.7.4.7). The previous requirements were that for all squat walls (height-to-length ratio equal to or less than 2.0), the vertical tension force required to

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resist flexure at the base of the wall shall be provided by vertical reinforcement in addition to the distributed reinforcement required to resist the shear. According to the addendum, this requirement no longer has to be satisfied for walls with a height-to-length ratio greater than 0.8. That is, when the height-to-length ratio of a squat wall is greater than 0.8, all the distributed vertical reinforcement required for shear can be used to resist flexure at the base of the wall. This change will significantly reduce the required vertical reinforcement in such squat walls. The current paper presents the background to this change.

The requirements for vertical reinforcement in squat walls are of course much more complex than the simplified building code requirement described above where above a certain height-to-length ratio all of the vertical reinforcement contributes to resisting flexure; but below that ratio, none of the distributed vertical reinforcement required for shear contributes to resisting flexure. In reality there is a complex transition. The current paper also presents more complex procedures for determining the vertical reinforcement required in squat shear walls.

NLFE Analysis of Squat Walls

Program VecTor2 (Wong and Vecchio, 2002) was used to conduct the nonlinear finite element analyses of squat walls. The program employs state-of-the-art material models (Vecchio 2000) to relate biaxial strains to biaxial stresses. Palermo and Vecchio (2004) verified VecTor2 for squat shear walls, and additional verification was conducted as part of the current study (Esfandiari, 2009).

A total of 42 walls in four groups with aspect ratios of h_w/l_w=0.3, 0.5, 1.0, and 2.0 were analyzed. The concrete cylinder compressive strength was assumed to be 40 MPa and the steel yield stress was assumed to be 400 MPa. Strain hardening was ignored. The walls were designed to fail due to yielding of vertical reinforcement at the base of the wall according to the 2004 CSA A23.3 procedure. Wall cross-sections were uniform along the wall height and no top loading beam was included. Further details are provided by Esfandiari (2009).

All walls were monotonically loaded along the top edge and the load was applied from left-to-right uniformly over the length of the wall. To achieve a lower-bound solution, the contribution of the compression zone was minimized by placing the minimum amount of concentrated reinforcement permitted by the 2004 CSA A23.3 in 10% of the wall length on the compression side. In order to increase the flexural capacity of the walls, a large amount of concentrated vertical reinforcement was placed on the tension side of the wall. Horizontal reinforcement ratios were varied from 0.25% to 1.0% for every combination of aspect ratio and amount of concentrated vertical reinforcement except for a few. For walls with height-to-length ratio of 2.0, distributed vertical reinforcement ratios were assumed to be either equal to the distributed horizontal reinforcement ratio or 3 times this amount. For all other walls, the amount of distributed vertical reinforcement was equal to the amount of distributed horizontal reinforcement as higher amounts of vertical reinforcement resulted in shear failures.

Analysis Results

The shear stress distributions at the base of four walls are examined in Fig. 1. The walls all had a same cross-section with horizontal and vertical reinforcement ratio of 0.5% and had different aspect ratios h_w/l_w = 0.3, 0.5, 1.0, and 2.0. The results shown are for the load level immediately prior to flexural failure. As the height-to-length ratio decreases, shear is carried by a larger portion of wall length at the base. For example, for the wall with h_w/l_w=0.3, about 60% of the wall length is subjected to significant shear, while for the wall with h_w/l_w=0.5, shear is resisted over about 40% of the wall length. For walls with height-to-length ratios of 1.0 and 2.0, almost all shear force is resisted in the compression zone. In this case, the demand on distributed vertical reinforcement due to shear is not significant and thus the reduction in flexural capacity due to shear is not significant.

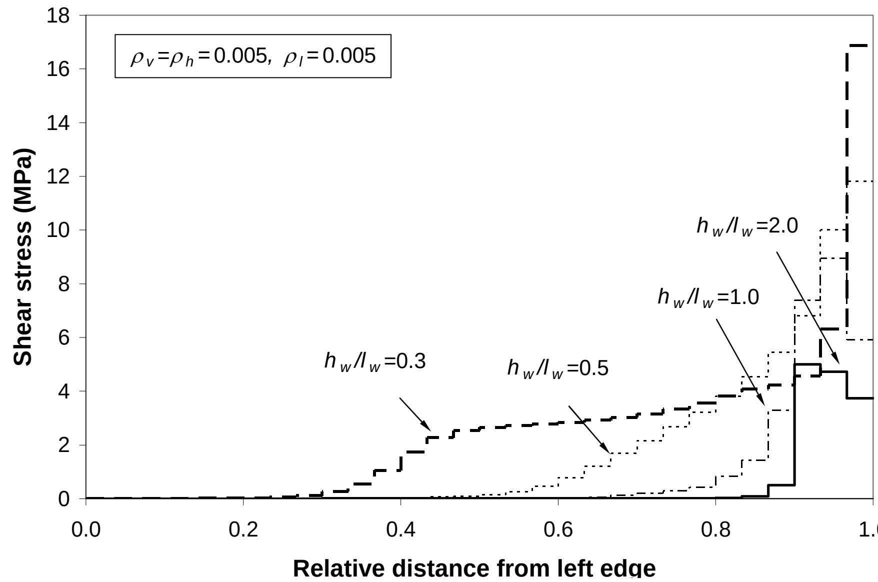

Fig. 1 NLFE predictions for shear stress distributions at base of four squat shear walls immediately prior to flexural failure.

Figure 2 shows the total normal stress (vertical force per unit length divided by thickness of wall) distributions for the same walls at the base. The total normal stress is equal to the vertical compression stress in concrete n_v (negative for compression) plus the steel force per unit area $\rho_v f_s$ determined from the stress f_s in the vertical distributed reinforcement. When vertical reinforcement is yielding and there is no vertical compression stress due to shear, the total normal stress is equal to $\rho_v f_y$. As the vertical reinforcement ratio is 0.5% $(\rho_v = 0.005)$ and the yield strength of the reinforcement f_y = 400 MPa, a total normal stress of $\rho_v f_y$ = 2.0 MPa is the maximum tensile stress which corresponds to yielding of all distributed vertical reinforcement. For walls with height-to-length ratios of 1.0 and 2.0, the total normal stress in a significant portion of the wall from the tension face to the flexural compression zone reaches the maximum value of 2.0 MPa. In the wall with height-to-length ratio of 0.3, the total normal stress $\rho_v f_y$ = 2.0 MPa extends up to about $0.4l_w$ from the tension face, while for the wall with h_w/l_w = 0.5, the total normal stress of 2.0 MPa extends to about $0.6l_w$ from the tension face.

The predicted flexural capacities of sixteen walls are presented in Fig. 3. The NLFE predictions are shown as solid lines with markers, while the plane section analysis (Response 2000) predictions are shown as a dotted line. The amount of distributed vertical reinforcement in these walls was equal to the amount of distributed horizontal reinforcement and ranged from 0.25% to 1.0%. The predicted flexural capacity from a plane sections analysis was found to be proportional to the amount of distributed vertical reinforcement, which was equal to the amount of distributed horizontal reinforcement. The NLFE predicted flexural resistances of walls with height-to-length ratios of 1.0 and 2.0 were almost the same as predicted by plane sections analysis. In contrast, walls with h_w/l_w of 0.3 and 0.5 have much less flexural capacity due to the influence of shear, and the strength reduction is more significant as h_w/l_w decreases.

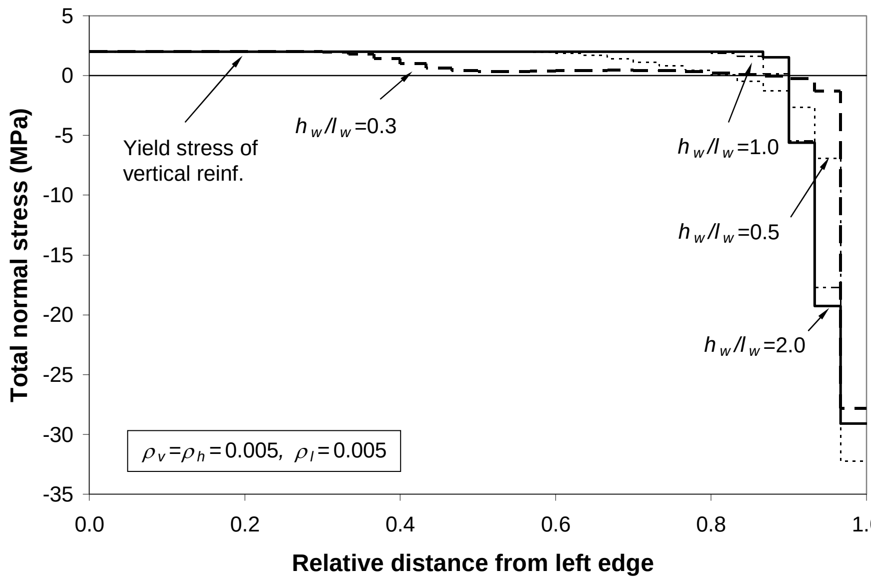

Fig. 2 Finite element predictions for total normal stress distributions at base of four squat shear walls immediately prior to flexural failure.

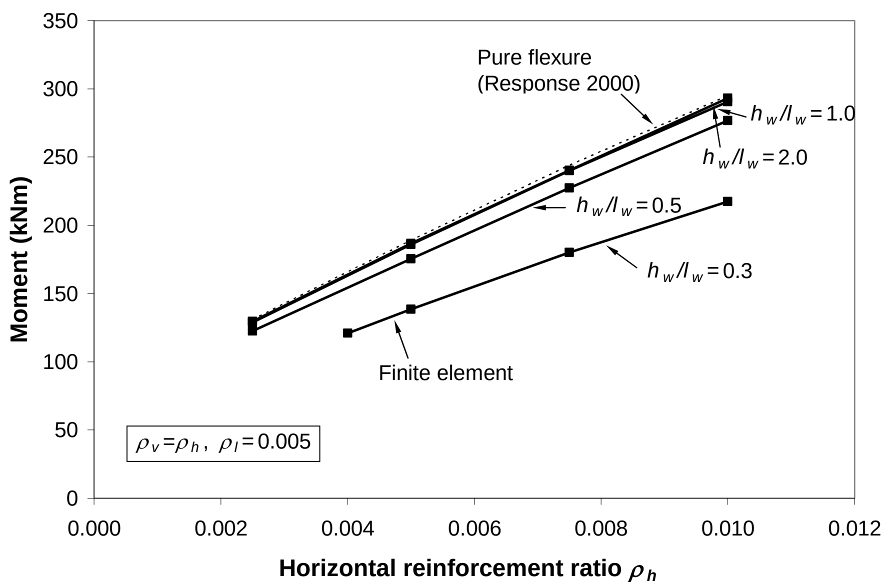

Fig. 3 Predicted overturning (flexural) capacities of sixteen squat shear walls.

Truss Model for Force Flow in Squat Walls

The force flow in squat shear walls determined from NLFE can be presented using a truss model in which reinforcing steel is assumed to resist all tension and concrete resists diagonal compression. The forces in a wall with height-to-length ratio of 0.5 are presented in Fig. 4. Note that uniformly distributed shear force is applied over the effective shear length $d_v = 0.8l_w$ along the top. A unit horizontal force is applied on each node of the truss along the top. All forces in truss members relate to this unit force, which represents shear resisted by each member if the shear is uniformly distributed. The forces carried by horizontal reinforcement in the truss model are anchored in the diagonal struts and are not transferred to the concentrated vertical tension reinforcement. This is possible because the direction of diagonal struts change to balance the horizontal force that is carried by the horizontal reinforcement. As the diagonal struts change direction to balance the horizontal forces, the diagonal strut force increase due to the increase in horizontal component of force. Note that of the 6 vertical elements in the wall web representing distributed vertical reinforcement, 4.8 of them (80%) contribute to the flexural capacity of the wall as was seen in the NLFE results, and shear at the base of the wall is resisted by a short length of the wall on the compression side.

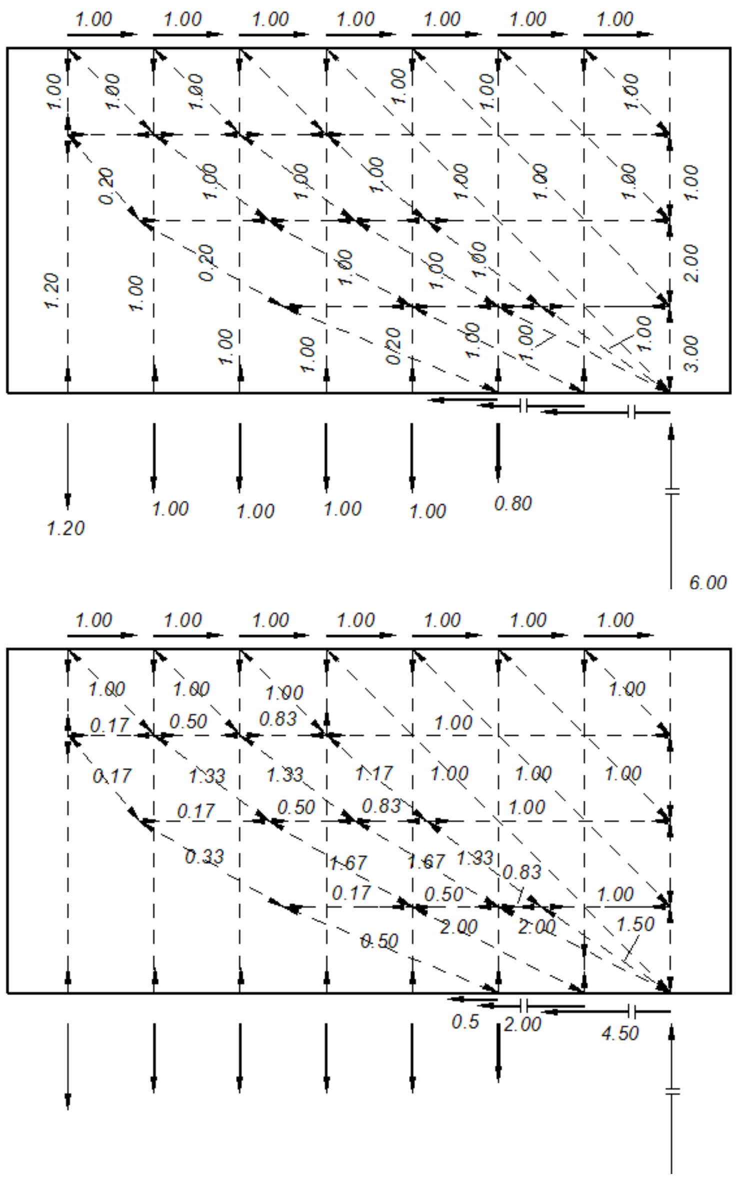

Fig. 4 Truss model for squat wall with height-to-length ratio of 0.5. Numbers shown in figure are vertical components of forces (top) and horizontal components of forces (bottom).

Proposed Model for Flexural Capacity

As was seen in the NLFE results and in the truss model, distribution of normal compression stress at the base of a squat shear wall is over a longer length than predicted by pure flexure (plane sections) analysis. This reduction in over-turning capacity due to shear is more significant when the wall height-to-length ratio is small, and becomes insignificant for walls with height-to-length ratios close to 1.0 or greater. The proposed model can capture this behaviour by including an axial force N_v in addition to the other forces that act at the wall base as shown in Fig. 5. N_v is the compression force needed for the shear to be resisted by concrete. It is zero for slender walls and increases as the wall height-to-length ratio reduces. When N_v equals zero, the model gives the same result as sectional analysis under pure flexure, i.e., there is no reduction due to shear.

T in Fig. 3 is the force in the concentrated vertical reinforcement and T_d is the resultant force in the distributed vertical reinforcement. At flexural capacity, T is equal to the area of concentrated reinforcement times the steel yield stress. Assuming that most of the distributed reinforcement yields over the wall length, T_d can also be reasonably approximated by total area of distributed vertical reinforcement times steel yield stress.

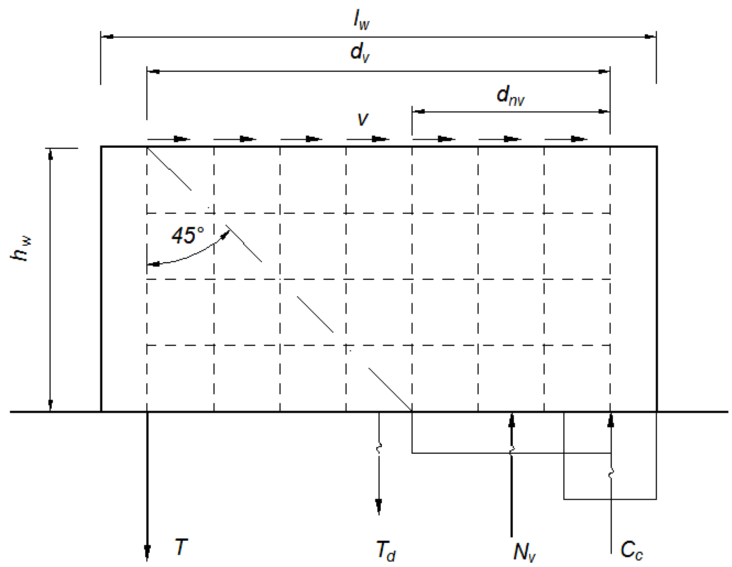

Fig. 5 Proposed model for estimating flexural capacity of squat shear walls.

The axial compression force N_v is the resultant of the normal (compression) stress in concrete only acting over a portion of wall length d_{nv}. As was presented by the truss model in Fig. 4, rotation of diagonal struts that go directly to the wall base do not affect the magnitude of N_v per unit length. A simple expression for the normal stress needed to resist shear is $v\cot\theta$ and thus $N_v = v\cot\theta(b_w d_{nv})$ where θ is the angle of diagonal compression and $v = V / b_w d_v$ is the average shear stress in the wall. The angle θ can be determined from simple equilibrium requirements depending on the relative amounts of distributed vertical and horizontal reinforcement and wall axial compression force. Note that the model would give the same result as 2004 CSA A23.3 when d_{nv}=d_v and it gives the same result as a flexural analysis when d_{nv}=0. Based on the NLFE results, d_{nv} needs to be a function of wall aspect ratio. It is proposed that

$d_{nv} = d_v - h_w \geq 0$ and this is shown in Fig. 5.

In the proposed model shown in Fig. 5, the magnitude and location of C_c is determined from equilibrium in the vertical direction using the equivalent stress block for concrete compression stress in the flexural compression zone. Moment capacity is then determined from moment equilibrium at the base. This is an iterative procedure for a given wall with a given amount of distributed reinforcement because the wall flexural capacity as well as the shear force corresponding to the wall flexural capacity is unknown. Note the flexural capacity is a function of shear force at flexural capacity in the proposed model. For design, however, the procedure is not iterative as the applied bending moment and shear force are known.

Fig. 6 compares the finite element predictions for the flexural capacity of squat walls failing in flexure with the predictions of the 2004 CSA A23.3, as well as the proposed method

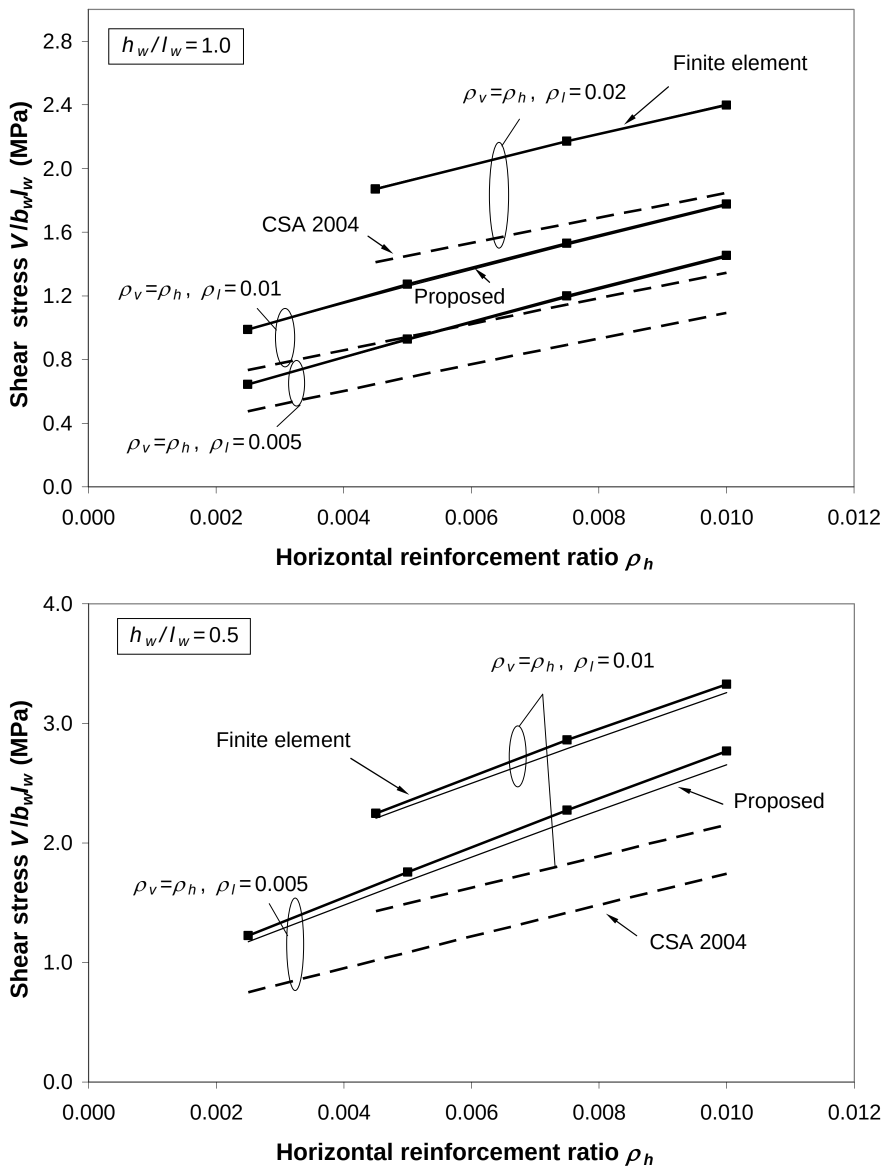

Fig. 6 Comparison of NLFE predictions for shear at flexural capacity of squat walls with 2004 CSA A23.3 and proposed method for a wall with $h_w/l_w = 1.0$ (top) and 0.5 (bot.).

predictions. The relationship between average shear stress over the full wall length immediately prior to flexural failure and the horizontal reinforcement ratio is presented. NLFE predictions are shown with thick solid lines with markers, while the proposed method predictions are presented by the thinner solid lines. The predictions of the 2004 CSA A23.3 method are shown by dashed lines. To determine the flexural capacity of the walls according to the 2004 CSA A23.3 method, only the portion of distributed vertical reinforcement that is not needed for shear was included in the sectional analysis. This was an iterative procedure because the wall flexural capacity was not known and therefore shear at flexural capacity was also unknown.

Proposed Simplified Method

A simpler model that can be used to estimate the flexural capacity of squat walls is to assume the flexural compression stresses are as predicted by a flexural (plane sections) analysis but only a portion of the distributed vertical reinforcement is available to resist flexural tension. In Fig. 5 N_v is assumed to be zero, and T_d is reduced to αT_d. α =1.0 means that all of the distributed vertical reinforcement contributes to the flexural capacity, while $\alpha = 0$ means none of the distributed vertical reinforcement contributes to the flexural capacity as was assumed in CSA A23.3 for $h_w/l_w \leq 2.0$.

In order to get the same flexural capacity, the moment about the point of application of the compression force C_c in both models must be equal: $\alpha T_d(0.5d_v) = T_d(0.5d_v) - N_v(0.5d_{nv})$. Assuming all vertical distributed reinforcement is yielding: $T_d = \rho_v f_y b_w d_v$, $N_v = v\cot\theta(b_w d_{nv})$ and $v = \rho_v f_y \tan\theta$ results in the following equation for the portion of the distributed vertical reinforcement that contributes to the flexural resistance at the base of a squat wall:

$$\alpha = 1 - \left(d_{nv} / d_v\right)^2 \tag{1}$$

in which $d_{nv} = d_v - h_w \geq 0$ and d_v= $0.8l_w$. Thus Eq. (1) can be expressed entirely in terms of the wall height-to-length ratio as follows:

$$\alpha = h_w / l_w \left(2.5 - 1.56 h_w / l_w\right) \leq 1.0 \tag{2}$$

This function is plotted in Fig. 7 as a solid line. As shown, about 80% and 40% of distributed vertical reinforcement contributes to the flexural capacity for squat walls with h_w/l_w = 0.5 and 0.2, respectively. All of the distributed vertical reinforcement contributes to the flexural capacity of squat walls with h_w/l_w > 0.8. As shown in Fig. 7, a simple conservative lower-bound to Eq. (2) is given by:

$$\alpha = 1.5 h_w / l_w \leq 1.0 \tag{3}$$

Finally, an even simpler approach would be to use all of the distributed vertical reinforcement in squat walls to calculate the flexural resistance at the base when $h_w/l_w \geq 0.8$ and use none of the distributed vertical reinforcement for the flexural resistance at the base when $h_w/l_w < 0.8$. This last approach was adopted in the August 2009 addendum to the Canadian concrete code CSA A23.3-2004.

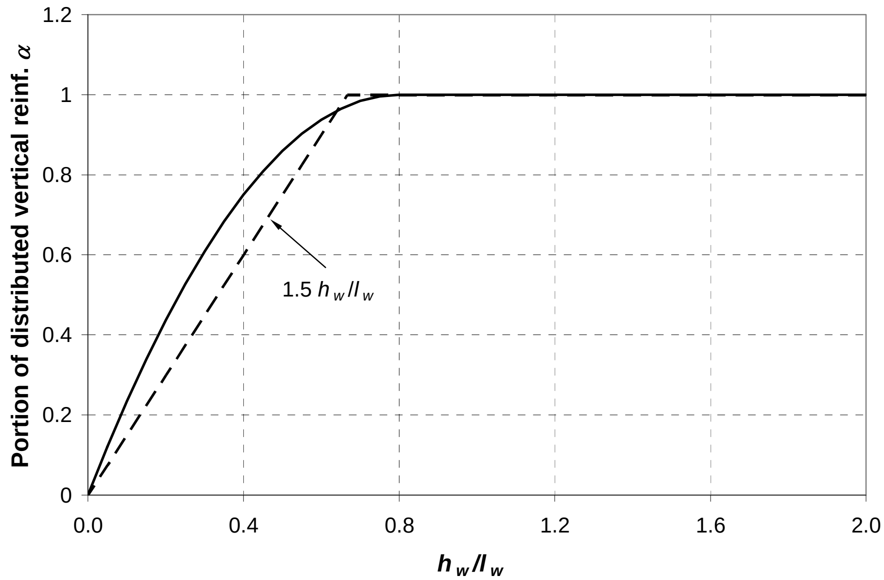

Fig. 7 Portion of distributed vertical reinforcement available to resist overturning (flexure) at the base of a squat shear wall.

Conclusions

A method to determine flexural strength of squat shear walls accounting for flexure–shear interaction at the base of the wall was developed. The method accounts for the effect of wall height-to-length ratio and allows full contribution of vertical distributed shear reinforcement in flexure for walls with height-to-length ratios of equal to or greater than 0.8. The proposed method was verified against NLFE predictions for 42 shear dominated walls where the capacity was limited by yielding of vertical reinforcement. The walls had height-to-length ratios of 2.0, 1.0, 0.5 and 0.3 and had varying amounts of distributed horizontal reinforcement, distributed vertical reinforcement, and concentrated vertical reinforcement.

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