UNCERTAINTY IN PARTIALLY GROUTED MASONRY SHEAR STRENGTH PREDICTIONS

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ABSTRACT

A dataset of 167 fully and 205 partially grouted masonry shear wall specimens was recently assembled. The combined dataset of 372 masonry shear wall test results has been used to perform regression analysis to determine the accuracy and precision of the TMS masonry shear strength equations. The analysis confirmed previous observations that the TMS shear equation is unconservative for partially grouted shear walls. Additional analysis was conducted to investigate the effectiveness of the grouted wall factor recently introduced into the TMS shear equation. The analysis also indicated that the shear equation demonstrates more variability for partially grouted walls than for fully grouted walls, and it appears that the increased variability has gone unnoticed when considering the shear strength of partially grouted masonry. This article presents a statistical analysis of the modeling uncertainties for fully and partially grouted masonry shear walls. The analysis shows that the current shear strength equations in TMS and CSA predict design strengths that are more variable for partially grouted walls than for fully grouted walls. The increase in variability is due to a bias in the current equations toward fully grouted walls because they were developed using fully grouted wall data. Corrections are recommended for the TMS and CSA shear strength equations to reduce the difference in accuracy and uncertainty between partially grouted and fully grouted masonry.

KEYWORDS: *partial grouting, regression, reinforced masonry, shear equation, shear strength*

INTRODUCTION

Partial grouting is a practice in which "designated cells or spaces are grouted, leaving the remaining cells and spaces ungrouted" [1]. In some cases, partial grouting may provide economic benefits by reducing labor, materials, and weight compared to fully grouted walls. Research has shown that partially grouted masonry shear walls can be an effective part of the lateral force-resisting system [2].

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While a large number of projects has been conducted related to many aspects of shear strength of masonry walls [3]-[9], evaluation of the TMS or CSA shear equations has typically been ancillary to the main research focus and has generally been limited to a relatively small subset of the available data.

Most of the partially grouted shear wall research has been conducted after the TMS 402-16 [1] and CSA S304-14 [10] shear strength equations were developed. Development of the shear strength equations resulted primarily from efforts by the Technical Coordinating Committee on Masonry Research (TCCMaR) [11] and adapted to US or Canadian practice. The TCCMaR equation was assembled from earlier equations proposed by Blondet et al. [12] and by Anderson and Priestley [13], both of whom developed their respective equations solely using fully grouted data. The development of the TMS equation can be traced through several sources in the masonry literature, but a complete description of the development of the CSA equation does not appear to be available.

Both shear equations include provisions to account for the reduction in nominal strength for partially grouted shear walls. At its inception in the TCCMaR study, the masonry component of the TMS shear equation was based on the net cross-sectional area of the masonry A_n, which reduced the area for partially grouted walls [11]. The TCCMaR equation was incorporated into the original strength design provisions first adopted into the 2002 revision of TMS 402 [14]. The definition for shear reinforcement contribution was modified in TMS 402-02 to replace the $\rho_h A_n$ term with $A_v d_v / s$. The net area definition was replaced in TMS 402-11 [16] by the net shear area A_{nv}, which excludes the areas of webs which are not adjacent to a grouted cell. The changed area definition further decreased the cross-section area resisting the shear force used in calculating the shear strength for partially grouted walls. The TMS 402-13 [17] code introduced a grouted wall factor γ_g with a set value of 0.75 to further reduce the nominal shear strength of partially grouted shear walls in addition to the reduction for shear area. The grouted wall factor is applied to the masonry, axial, and reinforcement terms in the shear equation. A summary of the changes made to the TMS shear design strength equation is presented in Table 1.

Table 1: Evolution of the TMS Shear Design Strength Equation (SI Version)

NEHRP 1994 [11]	$V_n = 0.083\left[4.0 - 1.75\left(\frac{M}{Vd}\right)\right] A_n\sqrt{f'_m} + 0.25P + 0.5\rho_h f_y A_n$
TMS 402-02 [14]	$V_n = 0.083\left[4.0 - 1.75\left(\frac{M}{Vd_v}\right)\right] A_n\sqrt{f'_m} + 0.25P + 0.5\left(\frac{A_v}{s}\right) f_y d_v$
TMS 402-05 [15]	$V_n = 0.083\left[4.0 - 1.75\left(\frac{M_u}{V_u d_v}\right)\right] A_n\sqrt{f'_m} + 0.25P_u + 0.5\left(\frac{A_v}{s}\right) f_y d_v$
TMS 402-11 [16]	$V_n = 0.083\left[4.0 - 1.75\left(\frac{M_u}{V_u d_v}\right)\right] A_{nv}\sqrt{f'_m} + 0.25P_u + 0.5\left(\frac{A_v}{s}\right) f_y d_v$
TMS 402-13 [17]	$V_n = \left[0.083\left[4.0 - 1.75\left(\frac{M_u}{V_u d_v}\right)\right] A_{nv}\sqrt{f'_m} + 0.25P_u + 0.5\left(\frac{A_v}{s}\right) f_y d_v\right]\gamma_g$
A_n = net cross-sectional area of masonry (mm^2); A_{nv} = net shear area (mm^2); A_v = area of shear reinforcement (mm^2); d_v = length of the shear wall in the direction of shear (mm); f'_m =specificed compressive strength of masonry (MPa); f_y = specified yield strength of shear reinforcement (MPa); $M/(Vd) = M_u/(V_u d_v)$ = shear span ratio, which needs not be taken greater than 1.0; P = unfactored axial load (N); P_u = factored axial load (N); s = spacing of shear reinforcement (mm); V_n = nominal shear strength (N); γ_g = grouted wall factor, which is 0.75 for partially grouted shear walls and 1.0 otherwise; and ρ_h = ratio of shear reinforcement area.	

The current CSA shear strength equation, presented in Table 2, was introduced in CSA S304.1-94 [18] and was unchanged in CSA S304.1-04 [19] and CSA S304-14 [10]. The CSA shear design strength equation is similar, in overall form, to the TMS equation but contains several notable differences. Some differences are readily visible, such as different coefficient values, separate strength reduction factors for the masonry and reinforcement components, and application of the γ_g term to only the masonry and axial components. Some subtle differences include several equation terms which are defined differently between the two codes, viz.: d_v, which is used to represent the effective depth, and γ_g, which is defined as the ratio of effective and gross cross-sectional areas. For partially grouted masonry that is face-shell bedded, effective area is equivalent to the net shear area in TMS 402. CSA S304 limits the effective area of partially grouted masonry to be not greater than half the gross area of the wall.

Table 2: Equivalent Forms of the CSA Shear Strength Equation

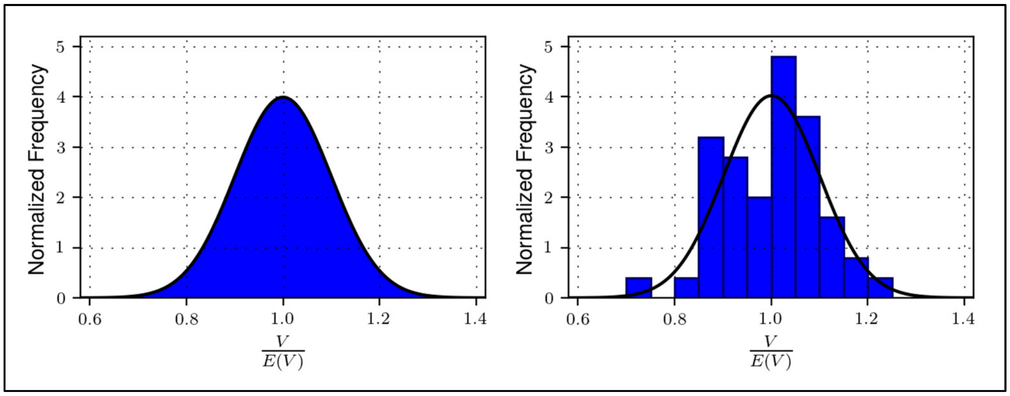
Original	$V_r = \phi_m[v_m\, b_w d_v + P_d]\gamma_g + 0.6\phi_s A_v f_y \dfrac{d_v}{s}$ where $v_m = 0.16\left(2 - \frac{M_f}{V_f d_v}\right)\sqrt{f'_m}$
Simplified	$V_r = \phi_m\left[0.16\left(2 - \dfrac{M_f}{V_f d_v}\right)\sqrt{f'_m}\, b_w d_v + P_d\right]\gamma_g + 0.6\phi_s A_v f_y \dfrac{d_v}{s}$
In terms of cross-sectional area	$V_r = \phi_m\left[0.16\left(2 - \dfrac{M_f}{V_f d_v}\right)\sqrt{f'_m}\, A_e\left(\dfrac{d_v}{l_w}\right) + P_d\left(\dfrac{A_e}{A_g}\right)\right] + 0.6\phi_s A_v f_y \dfrac{d_v}{s}$ where $A_e \leq 0.5A_g$ for partially grouted masonry

A_e = effective cross-sectional area of masonry, which is the mortar-bedded area plus the area of the grouted cells (mm^2); A_g = gross cross-sectional area of masonry (mm^2); A_v = area of shear reinforcement (mm^2); b_w = width of wall (mm); d_v = effective depth, which needs not be taken less than $0.8l_w$ for walls with flexural reinforcement distributed along the length (mm); f'_m =specificed compressive strength of masonry (MPa); f_y = specified yield strength of shear reinforcement (MPa); l_w = length of wall (mm); $M_f/(V_f d_v)$ = shear span ratio, which is taken between 0.25 and 1.0; P_d = factored axial compressive load, which is based on 0.9 time dead load plus any axial load arising from bending in coupling beams (N); s = spacing of shear reinforcement (mm); V_r = factored in-plane shear resistance (N); $\gamma_g = 1.0$ for fully grouted and solid masonry or $= A_e/A_g \leq 0.5$ for partially grouted masonry; ϕ_m = strength reduction factor for masonry; and ϕ_s = strength reduction factor for reinforcement.

BACKGROUND

Experimental shear wall data represent a subset of the population of masonry shear walls. If it were possible to determine the shear strengths of all masonry shear walls, the strength values would vary widely, even amongst walls with the same geometric and material properties. If all the values for a given type of wall were collected, the plot of the relative strength frequencies versus the strength values would represent the distribution of the strength values, as shown in Figure 1a. The frequency of the strengths would be greatest around the mean strength and would taper off at higher and lower strengths. The distribution of masonry shear strength is typically assumed to follow a Normal distribution, which can be described with only two parameters, the mean and the variance.

It is not possible or feasible to test the entire population of masonry shear walls, so the true mean and variance of the population can never be known precisely, but they can be estimated through experimentation. Researchers perform experiments by constructing and testing a relatively small subset of the population, called a sample. When all specimens in the sample are tested and the relative frequency of the strengths are plotted, the distribution varies from the theoretical population distribution. The mean and variance of the sample distribution also vary from the true population parameters. An example sample distribution is shown in Figure 1b.



(a) Population **(b) Sample taken from the population**

Figure 1: Histograms and fitted probability distributions for a hypothetical population

The variance of the population distribution is caused by the natural variability that is present in the masonry materials. The variance in the sample distribution has two components, natural variation and sampling error, so it will always be larger than the true variance. Since the contribution from sampling error cannot be segregated from the contribution due to natural variation, the true variance cannot be determined explicitly from experimentation; it can only be estimated. Reliable estimates of the true variance can be achieved by decreasing the sampling error to an amount that is small relative to the material variability. Sampling error can be decreased through exercising care in constructing and testing specimens and by increasing the sample size. The sampling error is inversely proportional to the number of Error Degrees of Freedom

$$EDOF = n - p. \tag{1}$$

where n is the sample size, and p is the number of variables investigated. The influence of the *EDOF* on the confidence of a sample is demonstrated in Figure 2. As the number of samples increases, the trendline of the sample more closely approximates the population trend and the width of the confidence interval narrows.

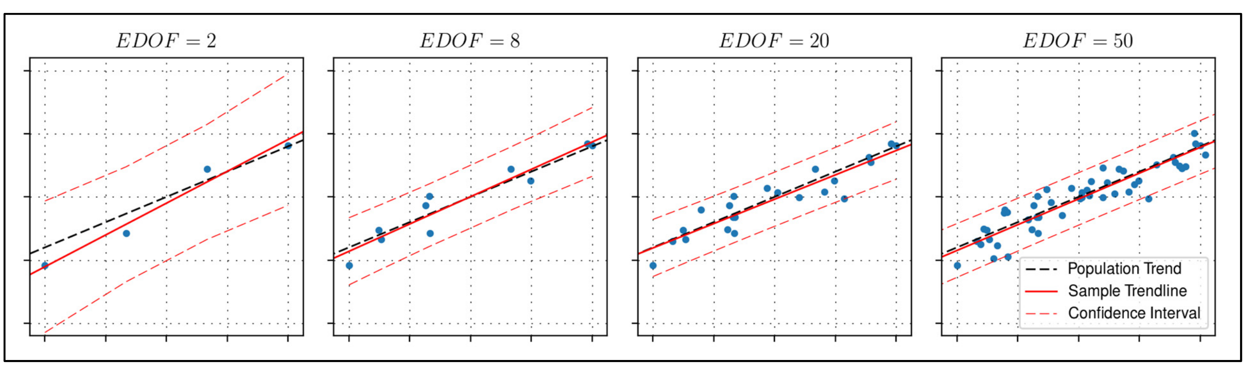


Figure 2: Influence of EDOF on modelling uncertainty

Due to the expense inherent with masonry shear wall testing, the number of samples typically included in any study is relatively small while the number of variables is relatively high. The lack of duplicates in many masonry shear wall studies dramatically increases the influence of the sampling error on the results. A recent study by Oan and Shrive [20] included duplicate specimens for each combination of parameters. The authors observed that one of their conclusions would have been notably different if they had not included duplicate specimens in their study. Unfortunately, many other masonry studies have not considered the potential influence of sampling error on the results nor have considered whether their conclusions are statistically significant.

Two independent analyses of the TMS equation were conducted by Davis [21] and Minaie [22]. These studies computed averaged experimental-to-predicted strength ratios for a small sample of masonry shear wall specimens extracted from the literature. The calculated mean ratio values were 1.16 and 0.90 for fully and partially grouted walls, respectively. The quotient of these two ratios was the basis for the grouted wall factor introduced into the 2013 edition of TMS 402 for partially grouted masonry.

A detailed study of the TMS shear equation was previously conducted to evaluate the current grouted wall factor [23]. The study improved upon the previous studies conducted by Davis and Minaie by incorporating several mechanisms to minimize the sampling error and its influence on the results. The study assembled a larger dataset of both fully and partially grouted shear walls specimens from the literature, determined potential differences between studies in the literature, and used correction factors to standardize the data. The previous study concluded that the TMS 402-13 grouted wall factor value of 0.75 was not low enough to entirely account for the reduction in nominal shear strength for partially grouted walls. In addition, the study concluded that the COV for partially grouted shear walls was higher than that for fully grouted walls.

CURRENT STUDY

The aforementioned study [23] has been expanded to investigate the difference in variability between shear strength predictions for fully and partially grouted masonry shear walls. The dataset from the previous study has been supplemented with data from 37 specimen tests [24]-[26]. The supplemental data were scrutinized and standardized using the same methodology used in the previous study; details of the methodology have been published previously [23][27]. The augmented dataset consisted of 167 fully grouted and 205 partially grouted masonry shear wall specimens.

The TMS shear equation applies the grouted wall factor and a single strength reduction factor to both the masonry and reinforcement components. The CSA equation applies the grouted wall factor only to the masonry and axial components and specifies separate strength factors for the masonry and reinforcement components. Since the format of the TMS equation is more readily adapted to linear statistical analysis, the analysis was limited to the TMS shear equation. Based on the similarities between the two equations, however, the results of the analysis can be generalized to the CSA equation.

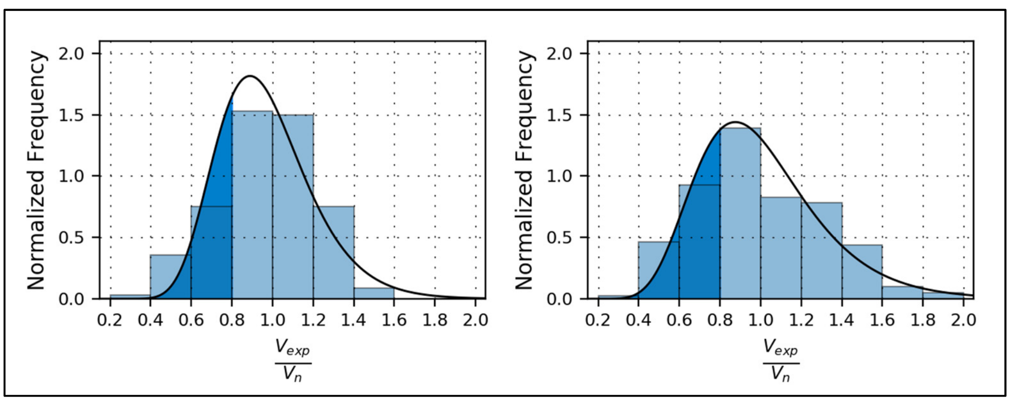
The calculated strength ratios were grouped together by grouting type. A lognormal distribution was fitted to each group and the distribution statistics were determined. The lognormal distribution was appropriate to this case for several reasons: (1) each ratio is computed from two values, both of which are normally distributed; (2) the normal distribution would theoretically include values less than zero, which is not possible; (3) the lognormal distribution visually matches the data distributions better than the normal distribution; and (4) the lognormal distribution has a constant coefficient of variation (COV), which is more typically used by researchers than the standard deviation.

The median was used to represent the nominal strength ratio of each group in lieu of the arithmetic mean since it is a more representative statistic for data with a skewed distribution. The median represents the 50th percentile point of the distribution, where half of the distribution is above and half is below. For a lognormal distribution, the median is equivalent to the geometric mean of the distribution.

RESULTS

The fitted distributions for the fully and partially grouted walls including the grouted wall factor are shown in Figure 3, and the distribution statistics are presented in Table 3. The median shear strength of fully grouted walls is slightly unconservative, but the median shear strength of partially grouted walls is more unconservative by approximately 5% compared to that of the fully grouted walls. The result confirms the conclusion from the previous study [23] that the value of 0.75 for the grouted wall factor γ_g is not sufficiently low to fully account for the reduction in nominal strength for partially grouted walls.

The COV of the partially grouted group is higher than that of the fully grouted group by approximately 27%. Such a difference indicates that there is more uncertainty and variability in the design strength of partially grouted walls than that of fully grouted walls.



(a) Fully grouted **(b) Partially grouted**

Figure 3: Histograms and fitted lognormal distributions for TMS shear equation

Table 3: Fitted Distribution Parameters

	Fully Grouted	**Partially Grouted**	$\boldsymbol{\frac{PG}{FG}}$
Median	0.942	0.896	0.951
COV	0.224	0.309	1.27
Relative P_f	0.248	0.354	1.43

To investigate the effect that the increased uncertainty in the design strength of partially grouted walls has on the probability of failure, the distribution statistics for each group were used to calculate the probability of obtaining a strength ratio less than the strength reduction factor ϕ. These values represent the probability of failure given the case where the load equals the design capacity:

$$P\left[V_{capacity} \leq \phi V_n \middle| V_{demand} = \phi V_n\right] \tag{2}$$

The results are also presented in Table 3. The probability value does not equate to the probability of failure in all cases since the load also has a stochastic distribution, but it provides an objective value by which to compare the groups. Since the distribution of the load is theoretically the same for all groups, the probability value in Equation (**2**) is assumed to be proportional to the actual probability of failure for the entire distribution of possible shear loads:

$$P\left[V_{capacity} \leq V_{demand} \middle| V_{demand}\right]. \tag{3}$$

DISCUSSION

Based on the grouted wall factor of 0.75 used in TMS 402, the nominal shear strength of partially grouted masonry is approximately 5% more unconservative than that of fully grouted masonry. To predict nominal strengths that maintain a similar level of conservativeness between the two, the grouted wall factor would need to be 0.713. In practice, this value would likely be rounded to 0.70 for simplicity, which would make the nominal strength of partially grouted masonry slightly less unconservative than that of fully grouted masonry and would result in approximately a 7% decrease in design strength.

TMS 402-16 prescribes the same strength reduction factor to be used for both fully and partially grouted walls. Using the same strength reduction factor value for both cases implicitly assumes that the variances of the fully and partially grouted walls are the same. Based on the current values for the grouted wall factor, γ_g, and strength reduction factor, ϕ, specified in TMS 402, the relative probability of failure of partially grouted walls is computed to be approximately 43% higher than that of fully grouted walls. The lower median and higher COV for partially grouted walls produce a probability distribution curve that is centered at a lower value and is wider than the fully grouted curve, as shown in Figure 4. The wider distribution has greater area under its tail, particularly the lower tail. Below the shear reduction factor of $\phi = 0.8$, the partially grouted curve encloses a larger area of probability than that of the fully grouted curve.

Since the lognormal distribution maintains a constant COV, decreasing the grouted wall factor will not affect the COV of the partially grouted distribution, but will shift the center of the curve to the right and reduce the area under the lower tail. By changing the grouted wall factor to 0.70 and maintaining the strength reduction factor of 0.8, the relative probability of failure for partially grouted masonry will decrease to 0.274, which is still approximately 10% higher than that for fully grouted masonry. If the shear strength reduction factor decreased to 0.75 in addition to reducing the grouted wall factor to 0.70 for partially grouted masonry, then the relative probability of failure for partially grouted masonry will decrease to 0.208, which is approximately 16% lower than that for fully grouted masonry.

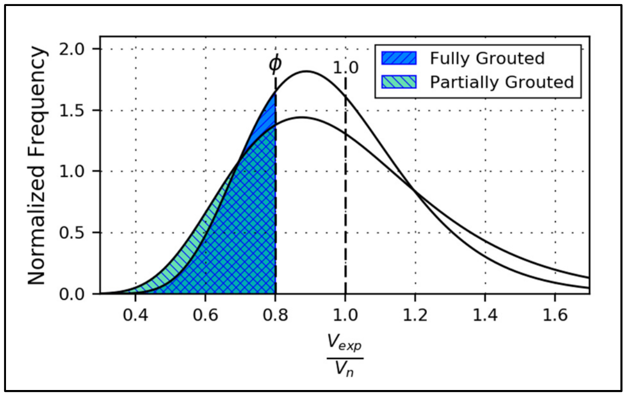


Figure 4: Comparison of relative failure probabilities for fully and partially grouted masonry

Changing the grouted wall factor to 0.70 for partially grouted walls is justifiable and arguably necessary from a life safety standpoint. Changing the shear reduction factor is logical from a theoretical standpoint because it would represent the higher uncertainty and COV of partially grouted masonry shear strength. From a practical standpoint, however, changing the strength reduction factor will add complexity to the code and decrease the design strength by an additional 6% while widening the disparity in failure probabilities between partially and fully grouted masonry from +10% to -16%. Given the prevalent use of partially grouted masonry in design, reducing both the grouted wall and strength reduction factors will result in a net reduction of 13% in design shear strength, which could impact the competiveness of masonry as a building material.

The exact correlation between the CSA and TMS equations is complicated by different definitions for terms common to both equations. As noted earlier, the γ_g term in the TMS code and CSA standard do not serve the same purpose. In the CSA standard, the grouted wall factor is a reduction from gross area to effective area. In the TMS code, the grouted wall factor is a supplemental reduction applied in addition to the reduction for net shear area. Based on the results of the study presented herein, the shear strength predictions made with the CSA shear equation could be approximately 30% less conservative for partially grouted walls than for fully grouted walls.

Another difference that is not readily apparent is the definition for specified compressive strength, f'_m. In ASTM C1314 [28], f'_m is the average strength of three prisms tests, but in the CSA S304 [10], f'_m is the lower bound of a 95% confidence interval determined from at least five prisms tests. CSA specifies that the COV of prism tests used in determining f'_m cannot be less than 10%. Additionally, ASTM C1314 prism strengths are corrected to represent a standard h/t ratio of 2 whereas CSA prism strengths are corrected to represent a h/t ratio of 5. If specified compressive strengths were calculated for both standards using the same masonry prisms, the f'_m value used in the CSA equation would be no greater than 71% of the f'_m value used in the TMS equation. After applying the square root term, the $\sqrt{f'_m}$ strength term in the CSA equation would be no greater than 84% the $\sqrt{f'_m}$ term in the TMS equation.

A comparison of the design strength components for the TMS 402 and CSA S304 equations is provided in Table 4. The vertical reinforcement was assumed to be distributed throughout the length of the wall to allow the term d_v to be replaced by l_w in the TMS equation and by $0.8l_w$ in the CSA equation. The partially grouted walls were assumed to be face shell bedded to allow the effective area A_e to equal the net shear area A_{nv}. The f'^{*}_{m} term used in Table 4 is based on the ASTM C1314 definition and the correction factor 0.84 has been incorporated into the coefficient values for the CSA equations.

Experimental research has observed that the CSA shear equation is very conservative [29]. Based on the comparison shown in Table 4, the CSA equation will always result in lower design shear strengths than that of the TMS equation, which is partly due to the reduction in the f'_m definition. If the CSA used the same definition for f'_m as that of the TMS, the leading coefficient in the masonry component would only increase to 0.019 and 0.038 for when the ratio of the areas is less or equal to and greater than 0.5, respectively. The lower design shear strength from the CSA equation is mostly due to the lower strength reduction factor of 0.6, as opposed to 0.8 in the TMS equation.

Several studies have concluded that using the net shear area alone does not fully account for the reduced shear strength of partially grouted walls relative to fully grouted walls [22][30][31]. While TMS 402 has implemented an additional reduction when it adopted the grouted wall factor of 0.75 for partially grouted walls, CSA S304 has yet to implement a similar reduction for partially grouted walls. Given the highly conservative nature of the current CSA equation, it would be more appropriate to leave the current equation unchanged for partially grouted masonry and to incorporate a factor of 1.40 into the equation to increase the design shear strength of fully grouted masonry. The 1.40 factor was computed from the reciprocal of the 0.713 grouted wall factor described in the previous section.

Table 4: Comparison of TMS and CSA Shear Design Strengths Using Similar Terms

<table>
<tr><th colspan="3"></th><th>Masonry Component</th><th>Axial Component</th><th>Reinforcement Component</th></tr>
<tr><td rowspan="2">TMS 402</td><td colspan="2">FG</td><td>$0.066\left(4-1.75\frac{M_u}{V_u l_w}\right)\sqrt{f'^{*}_{m}}A_g$</td><td>$+0.20\ P_u$</td><td>$+0.40\ A_v f_y \frac{l_w}{s}$</td></tr>
<tr><td colspan="2">PG</td><td>$0.050\left(4-1.75\frac{M_u}{V_u l_w}\right)\sqrt{f'^{*}_{m}}A_{nv}$</td><td>$+0.20\ P_u$</td><td>$+0.40\ A_v f_y \frac{l_w}{s}$</td></tr>
<tr><td rowspan="3">CSA S304</td><td colspan="2">FG</td><td>$0.032\left(4-2.5\frac{M_f}{V_f l_w}\right)\sqrt{f'^{*}_{m}}A_g$</td><td>$+0.15\ P_u$</td><td>$+0.41\ A_v f_y \frac{l_w}{s}$</td></tr>
<tr><td rowspan="2">PG</td><td>$\frac{A_{nv}}{A_g} > 0.5$</td><td>$0.016\left(4-2.5\frac{M_f}{V_f l_w}\right)\sqrt{f'^{*}_{m}}A_g$</td><td>$+0.075\ P_u$</td><td>$+0.41\ A_v f_y \frac{l_w}{s}$</td></tr>
<tr><td>$\frac{A_{nv}}{A_g} \leq 0.5$</td><td>$0.032\left(4-2.5\frac{M_f}{V_f l_w}\right)\sqrt{f'^{*}_{m}}A_{nv}$</td><td>$+0.15\ P_u \frac{A_{nv}}{A_g}$</td><td>$+0.41\ A_v f_y \frac{l_w}{s}$</td></tr>
</table>

CONCLUSIONS

The grouted wall factor included in the TMS equation is not sufficiently low to account for the difference in nominal shear strength between partially grouted masonry and fully grouted masonry. The research presented herein determined that a grouted wall factor of 0.70 is more appropriate for partially grouted masonry in the TMS equation because it maintains a similar degree of conservativeness between partially grouted and fully grouted masonry shear strength. The TMS shear strength equation produces predictions with higher variability and uncertainty for partially grouted walls than fully grouted walls. As presently constituted, TMS design shear strengths have a 43% greater probability of exceedance for partially grouted walls. By adopting the recommended change to the grouted wall factor, this discrepancy decreases to 10%.

The CSA equation was confirmed to be very conservative, particularly for fully grouted masonry walls. To maintain a similar degree of conservativeness between fully and partially grouted masonry, the CSA equation should be multiplied by factor of 1.4 when used to determine the shear strength of fully grouted masonry.

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