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Shear Design Provisions for Reinforced Concrete Masonry Beams in the TMS 402 Code: Is it Time for Change?

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ABSTRACT

Shear failures of reinforced concrete masonry (RCM) beams without stirrups can be brittle and sudden, with little to no warning of impending failure. Since it is difficult to provide web reinforcement in masonry, RCM beams are often constructed without stirrups. As such, the design provisions used to determine shear strength of RCM beams without web reinforcement must be accurate, safe, and rational. The objective of this paper is to assess the reliability and predictive capability of the shear design provisions of RCM beams in the TMS 402 code. A database of 133 shear tests reported in the literature on RCM beams without stirrups was used to conduct the evaluation process. The failure shear stresses of the beams covered in the assembled database were predicted using two North American masonry design standards (i.e. TMS 402-2022 and CSA S304-2024) and one reinforced concrete code (ACI 318-2019). The study showed that the TMS 402 predictions were associated with the highest coefficient of variation of the three analyzed codes along with the larger number of unsafe predictions. Although the recently revised shear design provisions of ACI 318-2019 produced a smaller number of unsafe predictions and smaller ratios of experimental to predicted shear strengths, there was only marginal improvement in the coefficient of variation. The CSA S304, on the other hand, had the lowest coefficient of variation with a small number of unsafe predictions. Further analysis indicated that CSA S304 can account accurately for all factors affecting the shear strength of RCM beams. These results highlight the need to revise the shear design provisions for RCM beams in the TMS 402 code and suggest that CSA S304-2024 provisions serve as a base for the needed revisions.

KEYWORDS

Beams, reinforced concrete masonry, size effect, shear strength, design codes.

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INTRODUCTION

Reinforced concrete masonry (RCM) beams are essential structural elements in any masonry building. RCM beams are used to span doors, windows and passages. They are also used as connections between shear walls or piers, forming coupling beams [1]. Since it is challenging to place web reinforcement in masonry, RCM beams are often constructed without shear reinforcement [2]. RCM beams without web reinforcement can experience brittle failure with minimal deformation to warn of impending failure [3]. The shear strength may determine the ultimate load-carrying capacity of a masonry beam, and thus, shear strength is a critical property of masonry. To avoid brittle shear failures, the design provisions of RCM beams without web reinforcement must be accurate, safe, and rational.

Multiple experimental investigations dedicated to studying the shear performance of RCM beams [4-8] have shown many similarities in behaviour between reinforced concrete and fully grouted RCM beams. These studies have also shown that the main factors affecting the failure shear stress of RCM beams are the size effect, the main reinforcement ratio, the compressive strength of masonry, the shear span-to-depth ratio, and the maximum aggregate size of the grout (fine or course grout). Given the wide variety of variables affecting shear strength, it is not surprising that there are discrepancies between design provisions in reinforced masonry design codes of different countries. Most of these design methods in current masonry building codes are empirically based on limited experimental data of RCM beams compared to reinforced concrete (RC) beams [9]. The TMS 402-2022 code (USA) [10] does not account for most of the basic factors affecting the shear capacity of masonry members. The Canadian masonry design standard, CSA S304, on the other hand, witnessed a significant change in its shear design provisions of RCM beams through replacing empirical design expressions adopted in older versions with the rational approach of the Simplified Modified Compression Field Theory (SMCFT) [12]. The CSA S304-2024 [11] accounts for all major factors affecting the shear strength of RCM beams.

In North American Universities, the masonry design course is taught after the reinforced concrete design course, and, commonly, the instructors of masonry design courses highlight the similarity in behaviour between RCM beams and reinforced concrete beams. Instructors usually compare the design provisions of fully grouted masonry beams to those of reinforced concrete beams. The recently revised shear design provisions of ACI 318-2019 [13] capture most of the factors affecting the shear strength of reinforced concrete beams (beam depth "size effect", the tensile reinforcement ratio, and the presence of axial loads). The significant differences between the shear provisions in ACI 318-2019 [13] and TMS 402-22 [10] highlight the need to revise the shear design provisions in TMS 402. Furthermore, improving design provisions for beams will improve shear design provisions for other structural elements such as walls, pilasters and columns.

This paper aims to evaluate the shear design provisions of TMS 402-2022 to assess their safety and predictive capabilities. The evaluation was conducted using shear strength results for 133 RCM beams without shear reinforcement collected from previous studies reported in the literature. Shear design provisions in CSA S304-2024 and ACI 318-2019 were also evaluated to justify the need to revise TMS 402-2022.

SHEAR DESIGN PROVISIONS FOR RCM BEAMS

TMS 402-2022

The nominal shear strength provided by masonry is computed using Equation 1 (in psi units):

(1) $V_m = [4.0 - 1.75(M_u/V_u\, d_v)]\, A_n\sqrt{f'_m}$

Where:

M_u/V_ud_v = a/d for point-loaded beams, and need not be greater than 1.0,

A_n = net cross-sectional area of beam (taken as b_w d),

For slender beams with a/d > 1.0 the formula can be simplified to the following (in MPa units):

$$(2)\ v_m = V_m / b_w d_v = 0.187\sqrt{f'_m}$$

CSA S304-2024

The shear design provisions for reinforced masonry beams in the Canadian code (CSA S304-2024 [11]) are based on the Simplified Modified Compression Field Theory (SMCFT), initially developed for reinforced concrete as described by Bentz et al. [12]. The SMCFT assumes that aggregate interlock, formed across cracks in the concrete below the neutral axis, is the primary shear transfer mechanism in reinforced concrete beams without web reinforcement. The SMCFT adopts the experimental observations of Walraven [14], who has shown that the aggregate interlock capacity of a crack is inversely related to the width of that crack. In SMCFT, the width of a crack, w, can be calculated as the product of the average strain normal to the crack, ε, and the spacing of the cracks, s, in the normal direction (i.e. w = ε . s). According to SMCFT, any action that increases the longitudinal strain in a member or increases the crack spacing will reduce the aggregate interlock and, hence, the shear strength due to the resulting wider cracks. The CSA S304-2024 [11] code is the only masonry design code that accounts for the size effect, wherein the failure shear stress decreases as the effective depth increases due to reduced aggregate interlock capacity. Similarly, the design provisions of CSA S304 account for the strain effect, wherein the increased longitudinal strains result in lower failure shear stresses due to reduced aggregate interlock capacity.

The CSA S304-2024 general shear design method uses the following basic equation to calculate the shear strength of reinforced masonry beams without stirrups: -

$$(3)\ V_m = K_b\, \beta\, \sqrt{f'_m}\ b_w\, d_v$$

Where:

b_w = Overall web width of the beam (mm)

K_b = a factor that accounts for the type of masonry and is equal to 1.0 for grouted hollow masonry

β = a factor that describes the ability of cracked masonry to transfer shear stress by aggregate interlock

f'_m = masonry compressive strength

d_v = effective depth for shear calculations, taken as the greater of 0.9d or 0.72h, mm

h= overall height of the beam, mm

The term β is calculated as the product of a strain effect term and a size effect term:

$$(4)\ \beta = \frac{0.4}{(1+1500\varepsilon_x)} . \frac{1300}{(1000+z_e)} = (Strain\ effect\ term).(Size\ effect\ term)$$

For longitudinal strain at the mid-depth of reinforced masonry sections that are neither prestressed nor subjected to axial loads, ε_x, is a function of the factored applied moment, M_f , shear V_f at the section, the stiffness (E_s) and area (A_s) of the longitudinal flexural steel. The equation for calculating ε_x is as follow:

(5) $\varepsilon_x = \frac{M_f/d_v+V_f}{2E_sA_s}$

The term z_e is an "equivalent crack spacing factor" that models the effects of different maximum aggregate size (a_g):

(6) $z_e = g_a\, z_s$

g_a =1.4 for course grout and 1.7 for fine grout

z_s = the lesser of d_v or the vertical spacing between layers of intermediate reinforcement

To use the CSA S304 general method to calculate shear strengths of experimental specimens, Equations (3) through (6) must be applied at the critical section by solving a quadratic equation or using an iterative approach [12].

ACI 318–2019

Shear strength, V_c, of non-prestressed reinforced concrete beams without stirrups or reinforced with less than the minimum shear reinforcement can be calculated as follows:

(7) $V_C = \left[0.66\,\lambda_s\,\lambda(\rho_w)^{\frac{1}{3}}\sqrt{f'_c} + 0.037\,\frac{N_u}{A_g}\right] b_w\, d$

Where:

V_C = Nominal shear strength provided by concrete

A_g = Gross area of concrete section

d = effective shear depth of the member

f'_c = specified compressive strength of concrete

ρ_w = Longitudinal tensile (flexural) steel ration

N_u= Axial load acting on critical section

λ= concrete density factor, equal to 1.0 for normal concrete density

λ_s = Size effect modification factor, need not to be greater than 1.0, and shall be determined from

(8) $\lambda_s = \sqrt{\frac{2}{\left(1+\frac{d}{254}\right)}}$

In applying the ACI equations to predicts the shear strength of RCM beams, V_m and f'_m will directly replace V_C and f'_c, respectively.

Table 1 summarizes the factors affecting shear strength of RCM beams accounted for in each design code considered in this paper. The TMS 402-2022 accounts for f'_m and ignores the rest of the factors. The ACI 318-2019 accounts for f'_m, ρ, and the size effect. CSA S304-2024, on the other hand, considers all the influential factors. It accounts for the strain effect (a/d, E_s and ρ) through formulation in terms of the longitudinal strain at the mid-depth of a beam web, ε_x. It is also accounts for size effect and the aggregate interlock effects through the crack spacing parameter (z_s) and the maximum coarse aggregate size (a_g).

Table 1: Predictive Abilities of Shear Design Provisions in Reinforced Masonry Codes

Design Methods	Intended Use	Key Parameters					Predictive Ability			
		f'_m	Strain Effect			Size Effect (d)	Average (v_{Exp}/v_{Pred})	STDV	COV (%)	1st Percentile
			M/V (a/d)	ρ	E					
TMS 402- 2022	Reinforced Masonry	X					1.24	0.37	30	0.38
ACI 318-2019	Reinforced Concrete	X		X		X	1.66	0.43	26	0.66
CSA S304-2024 General Method	Reinforced Masonry	X	X	X	X	X	1.30	0.27	21	0.67

EXPERIMENTAL DATABASE

To evaluate the predictive abilities of the masonry design codes considered in this paper, 133 shear strength test results were collected from published literature [4-8]. The database covers fully grouted steel-reinforced concrete masonry beams having f'_m ranging from 8.6 to 32.6 MPa, block strength ranging from 9.6 to 45 MPa, different mortar types (N and S) with mortar strength ranging from 5 to 20 MPa, fine and coarse grout strength ranging from 12.8 to 45 MPa, a/d ranging from 2.5 to 6.7, flexural reinforcement ratio ranging from 0.33% to 2.5%, and effective depth ranging 109 to 1450 mm. Only slender beams (with a/d ratio of 2.5 and greater) were included in the database.

DISCUSSION OF RESULTS

The failure shear stresses of the assembled database were predicted using each of the codes considered in this paper. Table 1 summarizes the average ratios of experimental to predicted strengths, the standard deviations and the coefficient of variation values (COV) for each of the design codes. It can be seen in Table 1 that the ACI 318-2019 code had the highest average (v_{Exp}/v_{Pred}) ratio and is associated with the second largest variation. Although the TMS 402 -2022 exhibits the lowest (v_{Exp}/v_{Pred}) ratio, it produced the highest variation of 30 %, devaluing the importance of this lowest average (v_{Exp}/v_{Pred}). The CSA S304-2024, on the other hand, produced the smallest COV of 21% and the second lowest average (v_{Exp}/v_{Pred}) ratio.

Figure 1 shows that TMS 402 predictions follow a horizontal distribution disengaging from the diagonal line of unity. The ACI 318-2019 show a slight improvement in following the line of unity for low shear strength predictions. CSA S304 2024 predictions follow a diagonal distribution along the line of unity with most of the predictions located to right side of the line of unity, indicating a reasonable margin of safe prediction.

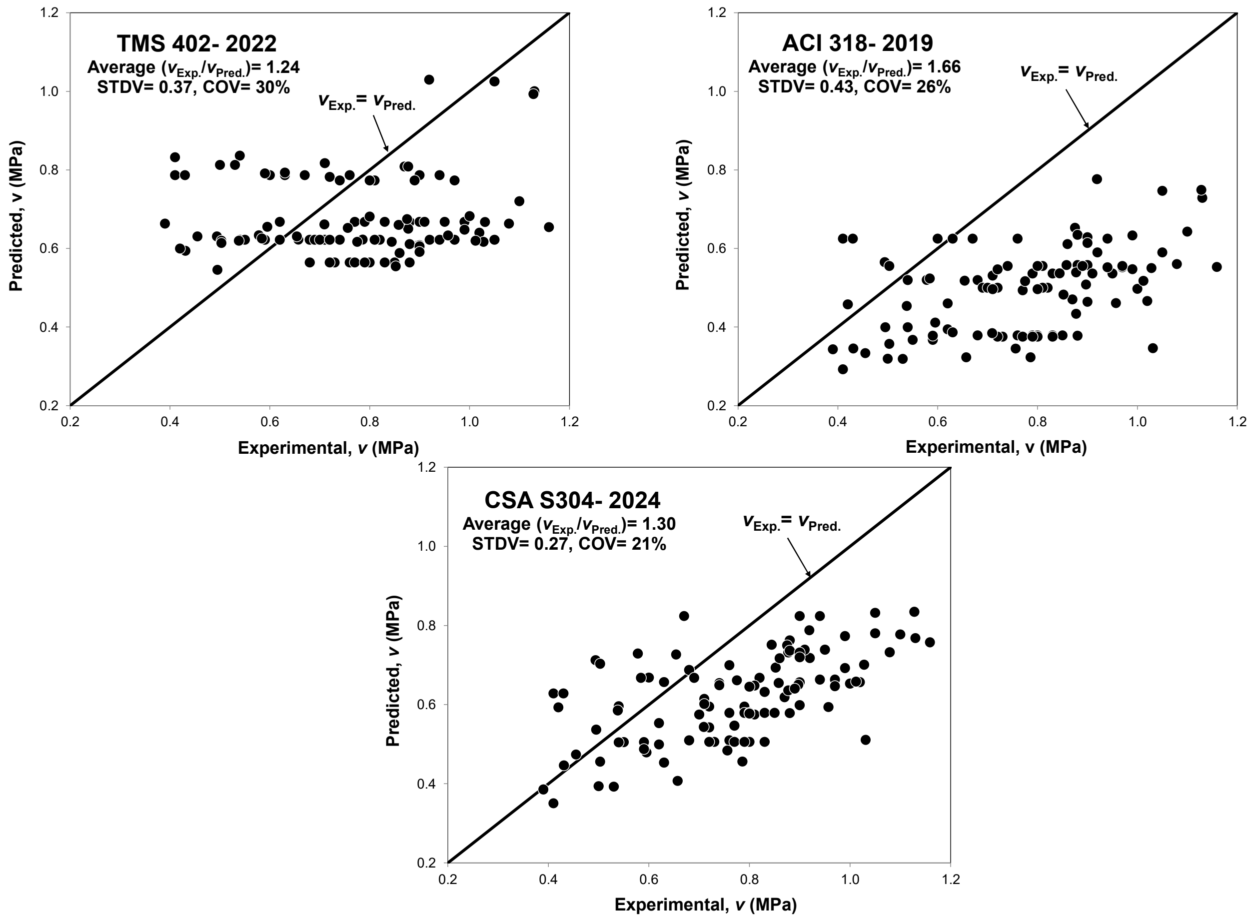

Figure 1: Comparison of TMS 402-2022, ACI 318-2019, and CSA S304-2024 Shear Strength Predictions

Another critical and well-known parameter summarized in Table 1 is the "1st-percentile value,". This value has traditionally been used as an estimate of the required shear strength reduction factor [15] to achieve an appropriately safe design equation. For a design equation to be considered to have sufficient safety, the shear strength reduction factor should be equal to or less than the 1st percentile value. Assuming a normal distribution, the first percentile value equals 2.33 standard deviations from the mean.

In the case of the TMS 402 -2022 Code, the first percentile value equals 1.24-2.33(0.37) = 0.38. As such, 99% of the tested shear strengths are expected to exceed 0.38 times the strength calculated by Equation (1). Although the TMS 402 -2022 accurately predict RCM beam shear strength (due to its low average v_{Exp}/v_{Pred} ratio), its high variation requires a very low strength reduction factor to apply the code safely. This factor of 0.38 is well below the reduction factor of 0.75, as suggested by TMS 402 -2022. This can raise serious concerns about the safety of this code when designing RCM beams. As the 0.67 1st percentile value calculated above is greater than the reduction factor in CSA S304-2024, the CSA S304 general method would provide the safest and most accurate shear designs of RCM beams. It can be seen in Figure 1c that the slope of a straight regression line through the experimental test results would be less than the unity slope, indicating the need for improvement in the prediction ability of CSA S304. The CSA S304 formulation is based on SMCFT [12], which considers the maximum aggregate size and shear crack spacing as the main factors influencing the shear strength of RCM. As such, it is recommended that experimental and analytical studies be conducted to evaluate the effect of different types of grouts (made with different aggregate sizes) on the shear strength of reinforced masonry. The suggested studies account for the fact that shear cracks in RCM beams pass through three regions: diagonally through the grouted units, the mortar bed joints, and the mortar head joints. The other factor worthy of study is the shear crack spacing, as the distance between the RCM head joints governs these cracks.

It is worthwhile to compare the predictions of the design standards considered in this paper to determine their predictive abilities for specific influence factors that control the shear resistance of RCM beams.

Effect of RCM Beam Depth (Size Effect)

The failure shear stress of RCM beams without shear reinforcement decreases as the effective depth increases. This phenomenon is known as the “size effect”. Experimental investigation conducted at Carleton University [8] showed that the size effect in reinforced masonry is real and very significant. Shear tests are normally conducted on relatively small beams and most code design equations were developed statistically based on experimental databases consisting primarily of these small beams. However, these design provisions are often used to design beams much larger than the specimens tested in laboratories. The effective depths of these large masonry beams range from 1.5 to 5 times beyond the size of typical laboratory shear tests, and at that range of depth, the size effect can be expected to dominate shear response. As such, design code equations should accurately account for the size effect in shear. it is expected the TMS 402 code will be non-conservative at large effective depths. This is a very worthwhile and important aspect for further study.

Figure 2 presents the failure shear stresses of a series of RCM beams tested by Sarhat 2016 [8] in which the beam effective depth (d) was varied along with the predicted failure shear stresses of the TMS 402, ACI 318-2019, and CSA S304 standards. Figure 2 shows significant reduction in failure shear stress with the increase in effective depth. Beam SL1 (d=1420mm), for example, failed at a shear stress of 67% of beam SS1 (d=300mm). It can also be seen that the TMS 402 code extremely overestimates the shear strength of the RCM beams. This overestimation can be attributed to the fact that it does not account for size effect in shear. The inability of TMS 402 to account for the size effect could lead to a high risk of sudden failure of large masonry beams and girders at lower loads than they designed for by these codes.

Although the ACI 318 code (intended to be used for reinforced concrete) can capture the variation in failure shear stresses of the RCM beams with increase in size, it produced extremely conservative predictions, casting doubts on the suitability of ACI 318 to directly replace the TMS 402 shear design provisions without modifications. The size effect factor in ACI 318 is grounded in the principles of fracture mechanics and statistical analysis and does not relate to the resistance mechanism components across shear cracks in RCM beams. The CSA S304 could accurately and safely predict the variation in failure shear stresses of the RCM beams with the change in the beam depth. The accuracy of CSA S304 predictions can be related to the rational explanations of the size effect on shear strength of RCM beams. According to the CSA S304 general method, deeper beams have larger spacings between cracks, and hence wider cracks. Wider cracks lead to less shear resistance by aggregate interlock and thus lower shear failure stresses. The increase in crack spacing and widths with the increase in RCM beam depth was experimentally observed in Sarhat’s investigation [8]. Sarhat [8] observed that the horizontal crack spacing at mid-height in the small beams (effective depth, d of 300mm) was governed by the distance between the head joints (400mm in this case) as these joints offer predefined paths for cracks to propagate through. In the medium (d= 885 mm) and large beams (d =1420mm), on the other hand, the crack spacings at mid-height were proportional to the effective depth (i.e., a function of d). These increases in crack spacings were associated with a significant increase in crack widths. As such, the reduced failure shear stress as the depth increases can be explained by reduced aggregate interlock capacity caused by increasing crack widths. Thus, wider cracks precipitate shear failure at a lower shear stress due to reduced aggregate interlock capacity. Reflecting the lower failure shears, the peak measured shear strain at failure exhibited average decreases of 55% and of 80% in SL1 and SL2 compared to that of the SS1 beam.

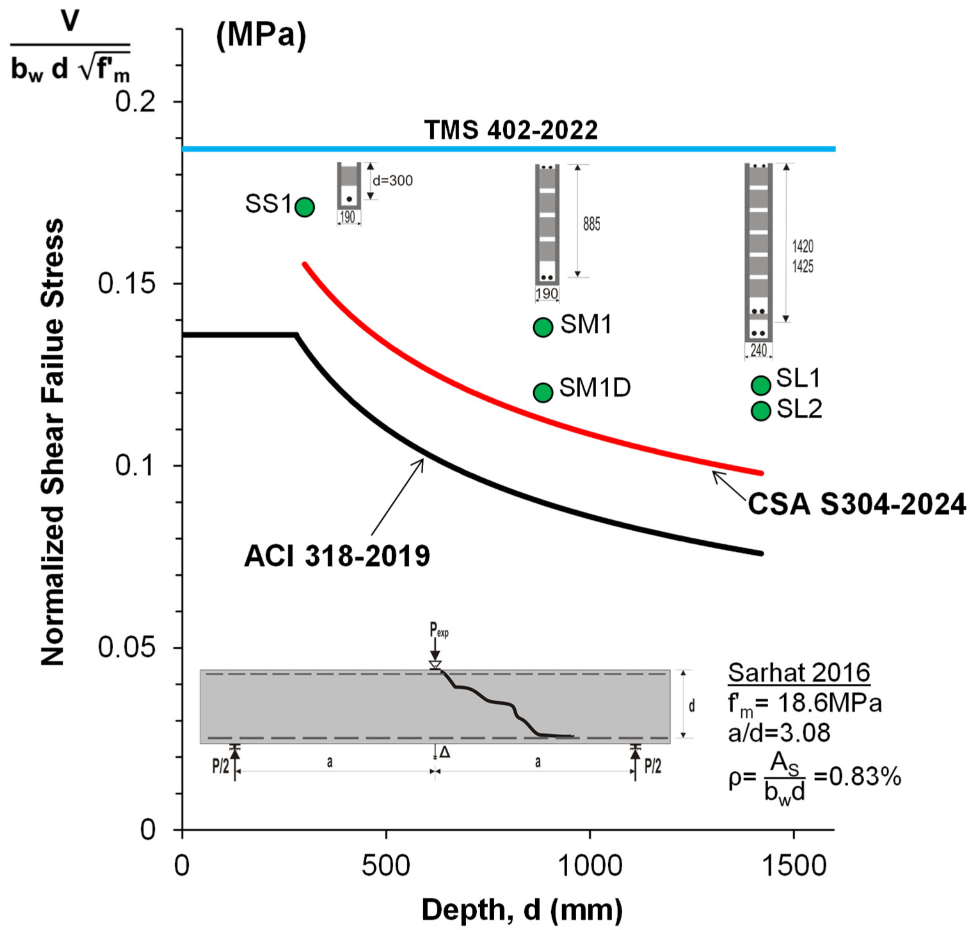

Figure 2: Size Effect on Shear Strength of RCM Beams

Effect of shear span to depth ratio (a/d)

Suter and Keller [4] studied the effect of a/d on the shear strength of RCM beams. Figure 3 indicates a significant decrease in ultimate shear stress observed with increasing a/d in the range of 3 to 6. It can be seen in Figure 3 that TMS 402-2022 and ACI 318-2019 are not sensitive to the change in a/d as both predict constant values of normalized failure shear stress. In contrast, CSA S304-2024 accurately captures the decrease in shear strength with an increase in a/d. The CSA S304 general method suggests that increasing a/d leads to greater longitudinal strain in the RCM beam's mid-depth. The increased strain causes shear cracks to develop at larger spacings and widths, resulting in lower shear resistance due to reduced aggregate interlock capacities.

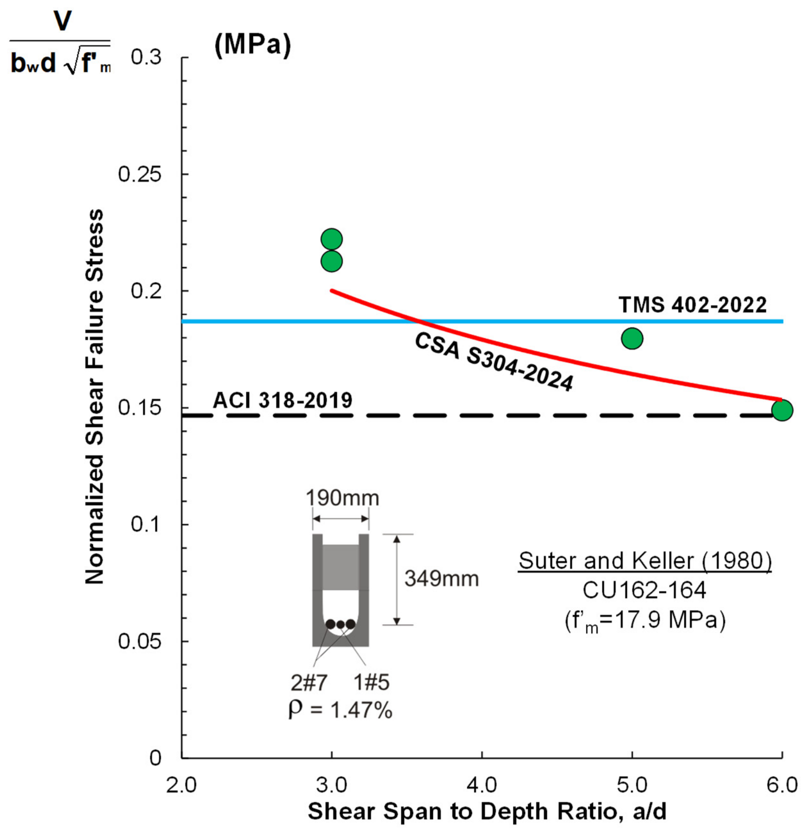

Figure 3: Effect of Span to Depth Ratio (a/d) on Shear Strength of RCM Beams

Effect of Flexural reinforcement Ratio (ρ_w)

Figure 4 presents the normalized failure shear stresses of a series of RCM beams tested by Sarhat [8], in which the flexural reinforcement ratio varied between 0.33% and 1.68%. It is evident from Figure 4 that a larger flexural reinforcement ratio enhances the shear strength of RCM beams. The predicted failure shear stresses by TMS 402, CSA S304 and the ACI 318 codes are also presented. Notably, the ACI 318 code, specifically intended for reinforced concrete, offers accurate predictions for the effect of flexural reinforcement ratio on RCM beams. The CSA S304 code was able to capture the experimental behaviour of the series of beams quite effectively and far better than the TMS 402 and ACI 318 codes. The CSA S304 is formulated based on the premise that the aggregate interlock capacity of concrete masonry at cracks governs shear strength. Larger flexural reinforcement ratios tend to decrease the longitudinal strains in the mid-depth of the RCM beam, which results in narrower shear crack widths. This reduction in crack widths enhances the aggregate interlock capacity across shear cracks. The capability of the CSA S304 to account for other influential factors affecting RCM has been proven experimentally [8,9,16]. Examples of these factors include the use of FRP reinforcement, the use of high- strength steel, the use of longitudinal bed joint reinforcement, and grout type (fine versus coarse). It should be noted that TMS 402 shear provisions restrict reinforcing bars to conventional steel reinforcing with yield strengths that do not exceed 60 ksi (414 MPa). Additionally, the TMS 402 shear expression is not intended to be used to design masonry members that are reinforced with high-strength steel or FRP rebars. TMS 402 does not account for the effect of grout type or the presence of joint reinforcement

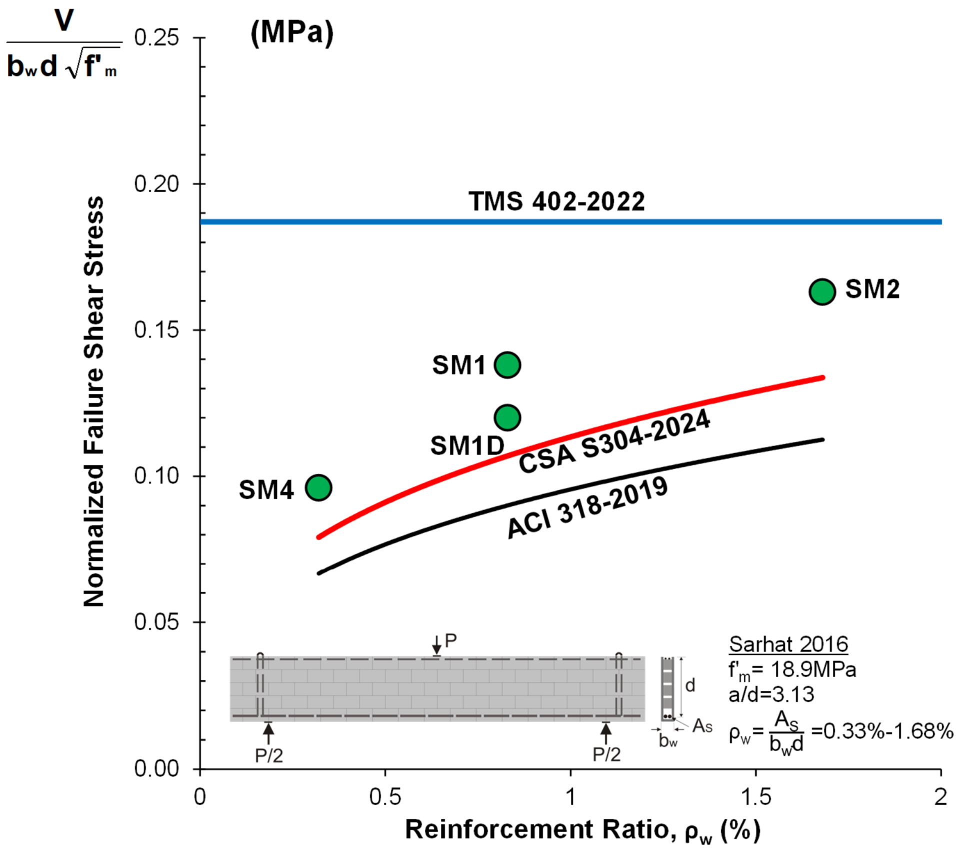

Figure 4: Effect of Flexural Reinforcement Ratio on Shear Strength of RCM Beams

CONCLUDING REMARKS

Based on the collected database of RCM beams in this study, it was found that the shear design provisions in TMS 402-2022 do not account for most of the factors affecting the shear design of RCM beams. The need to revise the TMS provision is substantial. The predictive ability evaluation conducted in the paper showed that the ACI 318 provisions intended for reinforced concrete provide more accurate predictions for RCM beams than TMS 402. However, the ACI provisions produce extremely conservative predictions associated with high variation. The ACI 318 provisions could be used as a basis for revising the TMS 402 code, but modifications would be needed. This paper presents clear evidence that the strength of RCM beams can be more accurately and safely calculated using the CSA S304 masonry code. This accuracy justifies using the CSA S304 as a base for revising the shear provision in TMS 402 masonry codes in its upcoming version.

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