14TH CANADIAN MASONRY SYMPOSIUM
MONTREAL, CANADA
MAY 16TH – MAY 20TH, 2021

Comparison of Selected CSA S304-14 and TMS 402-16 Reinforced Masonry Design Provisions and Material Properties

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ABSTRACT

A Canada-U.S. collaborative project titled "*CANUS: Harmonization of Canadian and American Masonry Structures Design Standards Project*" was established in 2019 to highlight key similarities and differences with the design of reinforced masonry between the two countries. The initiative was funded jointly by the National Concrete Masonry Association (NCMA) foundation, Canadian Concrete Masonry Producers Association (CCMPA), Canada Masonry Design Centre (CMDC), and Canadian Standards Association (CSA). The overarching goal of the CANUS research program is to improve and harmonize, to the extent possible, masonry design provisions in both countries as well as to identify future research needs towards that goal. This paper is one of five companion papers and provides a comparison of selected key design provisions and material properties, while other papers quantify the differences between the two standards through parametric studies or design examples. While the comparison revealed similar design equations and approaches in the two standards, significant differences in specified masonry compressive strength, cross-sectional properties, and reduction factors (strength and material) were noted. Given similarly constructed masonry structures have performed well in the U.S. for many years, opportunities to relax some of the more stringent requirements in the future editions of CSA S304 have been identified. In contrast, gaps that need to be covered in future editions of the TMS 402 standard have been identified in light of the more comprehensively addressed design topics in CSA S304-14.

KEYWORDS: *reinforced masonry design, masonry codes, limit state design, strength design, CSA S304, TMS 402*

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INTRODUCTION

As part of a larger research program titled *"CANUS: Harmonization of Canadian and American Masonry Structures Design Standards Project" (CANUS-2019),* this paper presents a discussion on the key similarities and differences of selected provisions in CSA S304-14 [1] and TMS 402-16 [2] as well as a comparison of the typical masonry material properties used in Canada and the U.S. CANUS-2019 is sponsored jointly by the National Concrete Masonry Association (NCMA) foundation, Canadian Concrete Masonry Producers Association (CCMPA), Canada Masonry Design Centre (CMDC), and Canadian Standards Association (CSA). CANUS-2019 is an extensive collaborative work of a team of practicing engineers and academics from the U.S. and Canada. This paper is one of five companion papers presented at this conference.

The primary objective of the CANUS project is to conduct a comprehensive comparison of the design requirements of TMS 402-16 and CSA S304-14 for specific limit states and parameters. The expected outcomes of the project are potential revision proposals to one or both standards and a list of short- and long-term research needs. Because concrete masonry as a material and an assembly is not fundamentally different in each market, the long-term goal of the project is to achieve better harmonization between the two standards.

Scope

The review presented in this paper is limited to the limit state design and strength design methodologies of CSA S304-14 and TMS 402-16, respectively. Structural elements constructed of reinforced concrete masonry are addressed; whereas unreinforced masonry, clay masonry, autoclaved aerated concrete (AAC), and glass block masonry are left out of the scope.

The side-by-side comparison of the key sections and design equations in TMS 402-16 and CSA S304-14, as well as their impact on individual elements or overall building design, is a large undertaking in itself. As such, this first-phase project focuses solely on identifying the similarities and fundamental differences between these two standards. The project's scope excludes evaluation of experimental and analytical research that provides the background to either standard's equations as well as any experimental or analytical work to prove/disprove the design outcomes from either standard.

COMPARISON OF MATERIAL PROPERTIES

In this section, material properties for the structural design of masonry elements will be presented in the form of a comparison of most commonly used material properties in Canada and the U.S.

Masonry Compressive Strength (f'_m)

Table 1 presents the correlation between unit strength and assembly strength (f'_m) in Canada and the U.S. using the unit strength method (as termed in the U.S.) and linear interpolation (which is permitted by each standard) based on type S mortar only. Both CSA S304-14 and TMS 402-16 also allow determination of f'_m by prism testing but use of this method is rare in both countries.

Table 1 presents the linear interpolation of masonry strengths for both country's block strengths to permit a direct comparison.

Table 1: Comparison of Masonry Compressive Strength (Type S Mortar) and Concrete Masonry Block Unit Strength Values

Specified Block Strength (MPa)		f'_m per CSA S304-14 (MPa)		f'_m per TMS 602-16 (MPa)
CSA S304-14	**TMS 602-16**	**Hollow**	**Grouted**	**Hollow or Grouted**
10		6.5	5.0	-
	13.8[a]	9.2[b]	6.9[b]	**13.8***
15[a]		**10.0***	**7.5***	14.4[b]
	17.3	11.4[b]	8.7[b]	15.5
20		13.0	10.0	16.4[b]
	22.4	14.1[b]	10.8[b]	17.2
	26.9	16.1[b]	12.4[b]	19.0
30		17.5	13.5	-

[a]Most common block strength used in design; *Most common f'_m value used in design

[b]Linearly interpolated strength

In Canada, most designers use a specified block strength of 15 MPa, which is similar to the most common unit used in the U.S. of 13.8 MPa (2,000 psi). Although there is an 8% difference in the specified block strength in favor of CSA S304-14, the masonry assemblage strength used in design calculations vary significantly. CSA S304-14 specifies two different assembly strengths depending on whether the cell of the unit is grouted or not, a distinction that is not made in TMS 602-16. Also, notably for the most common block strength used, TMS 602-16 specifies a masonry strength of f'_m equal to the block strength of 13.8 MPa. By contrast the most common unit used in Canadian design adopts a masonry strength of 10.0 MPa for hollow masonry and 7.5 MPa for grouted masonry. As indicated in Table 1, a 15 MPa specified unit strength would correspond to a masonry strength of 14.4 MPa by linear interpolation, which is an increase of 44% and 92% from the hollow and grouted strengths in the CSA S304-14, respectively. However, for comparison purposes, a 15 MPa concrete block and resulting masonry strengths, according to the CSA S304-14, will be compared directly to a 13.8 MPa (2,000 psi) concrete masonry unit and resulting masonry strengths, according to the TMS 602-16.

Modulus of Elasticity (E_m)

A single modulus of elasticity value for all masonry of $E_m = 850f'_m$ is used in Canada, with an upper bound of 20,000 MPa. The upper bound would only control for f'_m greater than 23.5 MPa, which is not currently possible for concrete block designed using the strength values in the CSA S304-14. TMS 402-16 varies the value slightly based on the type of masonry, with $E_m = 900f'_m$ used for concrete masonry, with no upper bound. This results in a CSA modulus to be approximately 5% lower for concrete masonry units, before the compounding difference due to the lower f'_m values. Comparing the most common masonry units used in each respective country, the grouted Young's modulus for masonry used in Canadian design is approximately half the value used in the U.S., as indicated in Eq. 1.

$$\frac{E_{m_{S304}}}{E_{m_{402}}} = \frac{(850)(7.5)}{(900)(13.8)} = \frac{6,375}{12,420} = 0.51 \tag{1}$$

Maximum Compression Strain (ε_{mu})

CSA S304-14 states that the maximum usable strain at the extreme masonry compression fiber is 0.003 (unless otherwise noted in some seismic provisions), while TMS 402-16 limits the maximum usable strain, ε_{mu}, at the extreme masonry compression fiber to 0.0025 for concrete masonry. This difference can cause a disadvantage for U.S. designs that relate to moment envelopes and maximum reinforcement considerations.

Grade of Reinforcement (f_y)

The specified yield strength of reinforcing bars used in CSA S304-14 designs is not to exceed 400 MPa. TMS 402-16 design provisions state that masonry design shall be based on a reinforcement strength equal to the specified yield strength of reinforcement, f_y, which is not allowed to exceed 414 MPa. As such, there is a 14 MPa (3.4%) difference in the permitted values for steel strength in reinforced masonry.

Modulus of Rupture/Flexural Tensile Strength (f_r/f_t)

CSA S304-14 refers to the tensile bond strength between units and mortar, as flexural tensile strength, f_t and TMS 402-16 refers to it as modulus of rupture, f_r. While they are essentially the same material property, there is a large discrepancy in the assumed values between Canada and the U.S. Table 2 summarizes the most common combination of materials used in each country.

Table 2: Specified Flexural Tensile Strength/Modulus of Rupture

	f_t per CSA S304-14 (MPa)		**f_r per TMS 402-16 (MPa)**	
	Mortar type		**Mortar Type**	
	S	**N**	**M or S**	**N**
Fully grouted hollow units Parallel to bed joints	0.85	0.55	1.84	1.38
Fully grouted hollow units Normal to bed joints	0.65	0.50	1.12	1.09

As can be seen, the differences in this material property are in the range of 54% to 60%, which can result in significant differences in the estimated cracking moment as well as the cracked or effective moment of inertia values that affect beam deflection calculations for reinforced masonry beams. It should also be noted that the source data for both codes' modulus of rupture/tensile strength values are wallette tests [3] and further research that is more inclusive of different types of masonry elements and design variables (e.g., bond pattern and material variations) is needed.

MATERIAL AND STRENGTH REDUCTION FACTORS

The approach used for reliability-based reduction factors is different between Canada and the U.S. In Canada, material-based reduction factors are applied to each individual material resistance used to determine total element (e.g., wall, beam, column) resistance. In the U.S. a single behavior-based reduction factor is applied to the total resistance calculated for a particular element. As a result, for strength design in the U.S. a nominal value, denoted by subscript "n" is first calculated and then the nominal resistance is multiplied by the appropriate ϕ factor depending on the behavior (e.g., flexure, shear, axial compression).

- $\phi_{m_{S304}}$ = 0.60 material-based reduction factor for masonry
- $\phi_{s_{S304}}$ = 0.85 material-based reduction factor for steel reinforcement
- $\phi_{402\text{-}f/a}$ = 0.90 strength-reduction factor for combinations of flexure and axial loading
- $\phi_{402\text{-}s}$ = 0.80 strength-reduction factor for shear and shear friction

COMPARISON OF KEY DESIGN EQUATIONS

In this section, provisions related to the calculation of the capacity of beams, shear walls subject to in-plane loading, and external walls subject to out-of-plane bending are compared.

Flexural Capacity of Reinforced Masonry Beams

The factored moment resistance equations and notations for CSA S304-14 and TMS 402-16 are presented in Eqs. 2 and 3, while the assumptions for the compression block depth for each are presented in Eqs. 4 and 5, respectively.

$$M_r = \phi_s A_s f_y \left(d - \frac{a}{2} \right) \tag{2}$$

$$\phi M_n = \phi A_s f_y \left(d - \frac{a}{2} \right) \tag{3}$$

$$a_{S304} = \frac{\phi_s A_s f_y}{0.85 \phi_m \chi f'_m b} \tag{4}$$

$$a_{402} = \frac{A_s f_y}{0.80 f'_m b} \tag{5}$$

Where, M_r = factored moment resistance per CSA S304-14, A_s = area of nonprestressed tension reinforcement, d = distance from extreme compression fiber to centroid of tension reinforcement, a = depth of the equivalent rectangular stress block, χ = factor used to account for direction of compressive stress in a masonry member relative to the direction used for the determination of f'_m, b = effective thickness of webs, M_n = nominal moment strength.

Despite the similarity in moment resistance equations, the resultant factored moment resistance differs considerably between CSA S304-14 and TMS 402-16 due to nuances in the compression block depth, "a", as a result of differences in f'_m values and the χ factor. Numerical differences are highlighted in the companion paper on beam parametric studies [4].

Shear Resistance of Reinforced Masonry Beams

Both standards consider the contribution of masonry and steel reinforcement in the computation of shear resistance. The shear resistance equations specified in CSA S304-14 and TMS 402-16 are given in Eqs. 6 and 7, respectively. It is important to note that the TMS 402-16 standard imposes an overall limit on the combined shear resistance of the masonry and the reinforcement as a function of the $M_u/(V_u d_v)$ ratio whereas CSA S304-14 imposes a limit on the shear contribution of only the reinforcement. Where the $M_u/(V_u d_v)$ ratio is between 0.25 and 1.0, the maximum value of V_n is to be interpolated. For the version of both standards considered (2014 for CSA S304 and 2016 for TMS 402), they both require the masonry beams to be fully grouted; therefore, the partial grouting factor (γ_g) that would be otherwise used for TMS 402-16 defaults to 1.0 here.

$$V_r = V_m + V_s \tag{6}$$

$$\begin{aligned} \phi V_n &= \phi\left(V_{nm} + V_{ns}\right)\gamma_g \\ &\le \phi\left(0.498 A_{nv}\sqrt{f'_m}\right)\gamma_g \text{ where } M_u/\left(V_u d_v\right) \le 0.25 \\ &\le \phi\left(0.332 A_{nv}\sqrt{f'_m}\right)\gamma_g \text{ where } M_u/\left(V_u d_v\right) \ge 1.0 \end{aligned} \tag{7}$$

Where, V_r = factored shear resistance per CSA S304-14, V_m = factored shear resistance of masonry members provided by the masonry, V_s = factored shear resistance provided by shear reinforcement; V_n = nominal shear strength per TMS 402-16, V_{nm} = nominal shear provided by masonry, A_{nv} = net shear area, d_v = actual depth of a member in direction of shear considered, M_u = strength level moment, V_u = strength level shear load.

The contribution of masonry to shear strength (V_m and V_{nm} for CSA S304-14 and TMS 402-16, respectively) are given by Eqs. 8 and 9.

$$V_m = \phi_m \lambda K_b \beta \sqrt{f'_m} b_w d_v \tag{8}$$

Where, λ = factor to account for the density of concrete masonry units when calculating shear capacity of beams, K_b = coefficient for shear calculations, b_w = overall web width of the beam, β = shear coefficient.

$$V_{nm} = 0.083\left[4.0 - 1.75\left(\frac{M_u}{V_u d_v}\right)\right] A_{nv}\sqrt{f'_m} \tag{9}$$

For most Canadian masonry beam designs, K_b and λ in Eq. 8 can be taken as 1.0 for reinforced grouted hollow concrete masonry and normal weight masonry units, respectively. Further, when beams contain the minimum amount of shear reinforcing in accordance with Clause 11.3.4.8.2 and the simplified method of shear analysis, CSA S304-14 permits the use of $\beta = 0.18$ and Eq. 8 reduces to:

$$V_m = 0.18\phi_m \sqrt{f'_m} b_w d_v \tag{10}$$

Similarly, for TMS 402-16 (Eq. 9), for beams dominated by flexure, taking the ratio $M_u/(V_u d_v)$ as 1.0, substituting $A_{nv} = bd_v$ and applying the strength-reduction factor Eq. 9 reduces it to:

$$\phi V_{nm} = 0.187\phi \sqrt{f'_m} b d_v \tag{11}$$

While Equations 10 and 11 look similar, it is anticipated the resulting shear resistance attributed to masonry may be vastly different due to three variances in values/approach:

1) ϕ_m in CSA S304-14 is 0.6 versus ϕ per TMS 402-16 for shear resistance is 0.8.
2) The d_v term is defined differently in the two standards. TMS 402-16 defines d_v as the depth of beam in the direction of the shear, whereas CSA S304-14 defines d_v as the effective shear depth taken as the greater of $0.9d$ and $0.72h_b$.
3) As discussed before, f'_m values are not equivalent. Quantified impact of these differences on the shear resistance of beams is presented in the companion paper "*Parametric Studies on Reinforced Masonry Beams: A Comparison of CSA S304-14 and TMS 402-16*" [4].
4) This analysis only shows the simplified method of the CSA S304-14 for beam design. It is likely that a greater shear strength can be obtained using the general method; however, due to the complexity of the equation, it does not permit direct comparison to TMS 402-16 equations.

Axial Load Resistance of Reinforced Masonry Shear Walls Subjected to In-Plane Loads

Both standards provide an upper limit to the permitted level of factored axial load resistance that a wall can provide, which are shown in Equations 12 for CSA S304-14 and Equations 13 -14 for TMS 402-16.

$$P_{r(\max)} = 0.80\left(0.85\phi_m f'_m A_e\right) \tag{12}$$

Where, P_r = factored axial load resistance, A_e = effective cross-sectional area of masonry.

If $h/r \leq 99$
$$\phi P_n = 0.80\phi\left[0.80 f'_m\left(A_n - A_{st}\right) + f_y A_{st}\right]\left[1 - \left(\frac{h}{140r}\right)^2\right] \tag{13}$$

If $h/r > 99$
$$\phi P_n = 0.80\phi\left[0.80 f'_m\left(A_n - A_{st}\right) + f_y A_{st}\right]\left[\left(\frac{70r}{h}\right)^2\right] \tag{14}$$

Where, h = effective height of column, wall, or pilaster, A_n= net cross-sectional area of a member A_{st} = total area of laterally tied longitudinal reinforcing steel, r = radius of gyration.

As can be seen in TMS 402-16, the axial load capacity varies based on the slenderness ratio defined by h/r. Once again, while the baseline equations appear similar, differences in the reduction factors and f'_m values are likely to create variances in capacities in favor of TMS 402-16 values. In contrast, there are stringent maximum reinforcement limitations as the wall heights increase in

TMS 402-16, which reduces the upper limit to the permitted factored axial loads. Quantified comparisons of the application of these provisions are provided in the two companion papers presenting parametric studies for walls subjected to in-plane loads [5] and out-of-plane loads [6].

Moment Capacity of Reinforced Masonry Shear Walls Subjected to In-Plane Loads

Moment capacity in shear walls is determined in a similar manner as with beams, with the exception of the following:

- the χ factor in the CSA S304-14 is taken as 1.0 as walls are loaded perpendicular to bed joints,
- walls are subjected to an axial load that must be accounted for in moment calculations,
- walls are permitted to be partially-grouted.

The last of these can create a significant deviation between calculations in the two countries because, in CSA S304-14, the compressive strength values vary between hollow and grouted sections and must be calculated more precisely.

Squat Walls. A key difference between the standards is the specific inclusion of provisions for squat walls in Canada. CSA S304-14 defines squat walls as having a height-to-length ratio less than 1 (i.e., $h_w/\ell_w<1$). Consequently, for bending moment calculations, CSA S304-14 adopts a reduced moment arm for those walls designated as squat, whereby squat walls must be designed with an effective depth, d, equal to $0.67\ell_w$ but not greater than $0.7h_w$. TMS 402-16 does not have equivalent considerations for squat walls. Furthermore, squat walls are defined in the TMS 402-16, not by their apparent wall dimensions, but rather by the ratio of M_u/V_ud_v being larger and smaller than 1, suggesting different considerations for shear-controlled versus flexure-controlled shear walls. A discussion on the impact of the squat wall reduced moment arm provisions in CSA S304-14 can be found in the companion paper on parametric studies on shear walls [5].

Shear Resistance of Reinforced Masonry Shear Walls Subjected to In-Plane Loads

Both standards include provisions for diagonal shear resistance as well as sliding shear/shear friction resistance calculations.

Diagonal Shear. TMS 402-16 has a single shear resistance equation, which is provided in Eqs. 7 and 9 for masonry beams. In contrast, CSA S304-14 uses a different set of shear equations for shear walls than for beams. Eqs. 15 and 16 are provided for diagonal shear resistance of masonry walls in CSA S304-14.

$$V_r = \phi_m \left(v_m b_w d_v + 0.25 P_d \right) \gamma_g + \left(0.60 \phi_s A_v f_y \frac{d_v}{s} \right) \tag{15}$$

Where, P_d = axial compressive load on the section under consideration, based on 0.9 times dead load plus any factored axial load arising from bending in coupling beams where applicable; γ_g = factor to account for extent of grouting in walls that are constructed of hollow or semi-solid units,

A_v = cross-sectional area of shear reinforcement, s = vertical spacing of horizontal shear reinforcement.

$$v_m = 0.16\left(2 - \frac{M_f}{V_f d_v}\right)\sqrt{f'_m} \tag{16}$$

Where, M_f = factored moment, V_f = shear under factored loads, and $0.25 < M_f/V_f d_v < 1.0$. Further, this shear resistance is limited to a value not greater than shown in Eq. 17:

$$V_r \le 0.4\phi_m\sqrt{f'_m}\left(b_w d_v \gamma_g\right) \tag{17}$$

In TMS 402-16, while the shear resistance equation for beams and walls is essentially the same, for walls an axial load component is typically considered (Eq. 18).

$$V_{nm} = 0.083\left[4.0 - 1.75\left(\frac{M_u}{V_u d_v}\right)\right]A_{nv}\sqrt{f'_m} + 0.25P_u \tag{18}$$

Where, P_u = strength level axial load.

Sliding Shear/Shear Friction. Eqs. 19 and 20-21 show the approach to sliding shear/shear friction for CSA S304-14 and TMS 402-16, respectively.

$$V_r = \phi_m \mu C \tag{19}$$

where, μ = coefficient of friction, C = compressive force in the masonry acting normal to the sliding plane, usually taken as P_d plus the factored tensile resistance at yield of the vertical reinforcing.

$$\text{If } \frac{M_u}{V_u d_v} \le 0.5 \text{ then } V_{nf} = \mu\left(A_{sp} f_y + P_u\right) \ge 0 \tag{20}$$

$$\text{If } \frac{M_u}{V_u d_v} \ge 1.0 \text{ then } V_{nf} = 0.42 f'_m A_{nc} \tag{21}$$

Linear interpolation is used between $\frac{M_u}{V_u d_v} \le 0.5$ and $\frac{M_u}{V_u d_v} \ge 1.0$.

Where, A_{sp} = cross-sectional area of reinforcement within the net shear area, perpendicular to and crossing the horizontal shear plane; A_{nc} = net cross-sectional area between the neutral axis of bending and the fiber of maximum compressive strain calculated at the nominal moment capacity of the section.

A few observations are made when these approaches are compared.

1. The CSA S304-14 value of "*C*" is similar to the value of $A_{sp} f_y + P_u$ in TMS 402-16; however, in TMS 402-16 the axial load, P_u, is not from a particular load case.

2. TMS 402-16 does not include the material reduction factor in its reinforcement force.
3. TMS 402-16 only permits reinforcement and axial load to aid in shear friction when shear governed walls are considered.
4. Both standards adopt a similar interpretation of the frictional coefficient, μ, taken as 1.0 for masonry-on-masonry or masonry on roughened concrete and taken as 0.7 for masonry on other surfaces.
5. Parametric studies show that this behaviour rarely controls in shear walls [5].

Flexural Resistance of Reinforced Masonry Walls Subjected to Out-of-Plane Loads

Beyond the considerations of effective compression zone width, geometrical and material differences, and slenderness/second-order effects, the approach to calculation of moments in reinforced masonry walls subjected to out-of-plane loads (*henceforth referred to as OOP walls*) are similar and based on mechanics in both countries.

A major difference between the two standards is the effective compression zone width. CSA S304-14 limits the effective compression zone width for walls laid in running bond to the lesser of 4 times the *actual* wall thickness and the spacing between bars, while TMS 402-16 sets this limit at the minimum of 6 times the *nominal* wall thickness, the spacing between bars, or 1,829 mm. For OOP wall behavior where section depth is minimal, limiting the compression zone width has a significant impact on flexural capacity. It is common for OOP wall designs in the U.S. and Canada to have a maximum vertical reinforcing spacing of 1,219 mm or 1,200 mm, respectively. As a result, the effective compression zone width limit of 6 times the *nominal* thickness in TMS 402-16 typically does not govern for commonly used nominal block sizes of 30 cm, 25 cm and 20 cm. In CSA S304-14, however, the effective compression zone width limit of 4 times the *actual* thickness is expected to create major differences in flexural capacity for vertical reinforcing spacings exceeding 600 mm for nominal 20 cm (actual 19 cm) blocks. For further discussions on this topic and its quantified impact on behavior, the reader is directed to the companion paper by Sustersic et al. [6].

Slenderness and Second-Order Effects in Walls Subjected to Out-of-Plane Loads

In the consideration of the second-order effects and allowed axial stresses with respect to the slenderness of the walls, both standards consider an effective height-to-thickness ratio of 30 to be a defining threshold value. In both countries, designers may use either the P-delta method or the moment magnification method, per code. In Canada, the use of the P-delta method is not common. In the U.S., the opposite tends to be true, as the moment magnifier method is newer (starting with the 2013 edition of TMS 402) and is not yet widely adopted.

Shear Resistance of Reinforced Masonry Shear Walls Subjected to Out-of-Plane Loads

While the shear equations adopted by TMS 402-16 for OOP walls are the same as that used for shear wall design (Eq. 7 and 18), CSA S304-14 provides specific clauses that reference out-of-plane shear (Eq. 22), as well as requiring a check for sliding shear (Eq. 19).

$$V_r = \phi_m(v_m b_w d_v + 0.25P_d) \tag{22}$$

The OOP wall shear is also subject to a maximum limit given in Eq. 17. It should be noted that in this case, b_w, is the width of grouted cells and masonry unit webs within a length not greater than 4t around each vertical bar for running bond.

CONCLUDING REMARKS AND AREAS FOR FUTURE RESEARCH

The following conclusions are derived from the side-by-side comparison of material properties, material and strength reduction factors, and design equations between CSA S304-14 and TMS 402-16:

- Despite starting from nearly identical block strength values, f'_m values differ significantly between Canada and the U.S. There is a 46% difference (13.8 MPa versus 7.5 MPa) between the most commonly used f'_m values in Canada and the U.S., in favor of the U.S. properties. This can result in significant capacity estimate differences whenever f'_m or a function of f'_m are included in design equations. A comprehensive experimental research work should be conducted, and coordinated between U.S. and Canada, using both countries' materials and prism testing standards. This in turn will lead to better alignment of the f'_m values for materials that are likely to be found very close in strength and behavior.
- The most typically used modulus of elasticity values for concrete masonry in Canada are roughly half of those that are commonly used in the U.S. due to the compounded effect of the standard equation and the masonry compressive strength. This in turn can result in significant differences in member deflection estimations. The research work mentioned above would also naturally lead to an evaluation of the moduli of elasticity values.
- Maximum strain value assumed for concrete masonry in the U.S. is 0.0005 lower than that used in Canada, which negatively impacts the already stringent maximum reinforcement limits in the U.S. A detailed parametric research study backed up by experimental work should be conducted to evaluate if a single maximum strain value for concrete and clay masonry that matches that used in Canada (i.e. 0.003) would have any detrimental impact on the designs in the U.S. If not, a code change would be warranted.
- A discrepancy up to 60% is apparent in the masonry tensile strength/modulus of rupture values between the two standards. This large discrepancy, in addition to the fact that data for these values are relatively dated and limited, highlights a research need in this area.
- In Canada, reduction factors are material based and are typically incorporated into equations next to steel and masonry strength values. In the TMS 402-16 edition, there is single reduction factor for combinations of axial load and flexure, which results in much larger moment-axial interaction diagrams than those based on CSA S304-14. It should be noted, however, at the time of writing of this paper, that the TMS 402 committee is already working on adopting reduction factors based on tension- and compression-controlled behavior for the 2022 code. This change will reduce the discrepancy between the two codes.

- In comparison of beam design provisions, the largest difference is in the use of χ factor. This coefficient, combined with lower f'_m values, is expected to create large discrepancies between possible reinforced concrete masonry beam designs in the two countries. Another coordinated experimental and analytical research program can determine if the χ factor requirements of CSA S304 could be relaxed.
- Approach to shear resistance for all member types is simplified into a single equation in TMS 402-16, while it is much more nuanced in CSA S304. There are pros and cons to both approaches. Quantified impact of the differences can be found in companion parametric study papers [4-6].
- A noteworthy difference in the approach to design of shear walls is the specific description of squat walls in CSA S304-14 and the consequent provision on reduced moment arms for squat walls. The impact of the reduced moment arm provisions is further discussed in the companion paper [5].
- In the approach to OOP walls, a noteworthy difference is the assumed effective compression zone width, which is – for most cases – $4t$ in Canada and $6t$ in the U.S. Depending on the spacing of vertical reinforcement, this can create large discrepancies in moment calculations for OOP walls. This highlights another potential experimental and analytical research area.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the valuable interactions and discussions with the participants of the CANUS Masonry Standard Harmonization Project and the sponsorship by the National Concrete Masonry Association (NCMA) foundation, Canadian Concrete Masonry Producers Association (CCMPA), Canada Masonry Design Centre (CMDC) and Canadian Standards Association (CSA).

The body of work generated through this summit could not have been possible without the efforts of the following participants and the support of their companies:

Team Canada	**Team USA**
Bennett Banting, Canada Masonry Design Centre	Richard Bennett, University of Tennessee
Hélène Dutrisac, Canada Masonry Design Centre	Lane Jobe, Miller Consulting Engineers
Bart Flisak, Crosier, Kilgour & Partners Ltd.	Phillippe LeDent, Masonry Institute of Michigan, formerly Fishbeck, Thompson, Carr & Huber Inc.
Kevin Hughes, Renoasis Engineering, formerly Tacoma Engineers	Russ Peterson, Ensoltech
Carlos Cruz-Noguez, University of Alberta	Ece Erdogmus, University of Nebraska-Lincoln
Clayton Petit, University of Alberta	Heather Sustersic, Colby Company Engineering, formerly Providence Engineering Corp.
David Stubbs, Canada Masonry Design Centre	Jason Thompson, National Concrete Masonry Association

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