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

COMPARISON OF CSA S304-14 LIMIT STATES AND TMS 402-16 STRENGTH DESIGN PROVISIONS FOR THE DESIGN OF REINFORCED MASONRY BEAMS

Erdogmus, Ece[1]; Bennett, Richard[2]; Thompson, Jason[3] and Banting, Bennett[4]

ABSTRACT

This paper is one of the five companion papers from the project "*CANUS: Harmonization of Canadian and American Masonry Structures Design Standards Project"* and it focuses particularly on the comparison of reinforced masonry beam design provisions and approaches in Canada and in the U.S. The scope is limited to concrete masonry, limit states/strength design approaches, and reinforced masonry beams. After a brief comparison of key equations, the differences are quantified through parametric studies. The difference between f'_m values typically used in Canada (7.5 MPa) and the U.S. (13.8 MPa) results in Canadian beam strength nearly half that of U.S. beams. Further, the χ factor utilized in CSA S304-14 amplifies the divergence between the standards to the point where most masonry beam designs common in the U.S. are not possible in Canada. Future research should be conducted to recalibrate and/or eliminate the χ factor to allow for a wider range of masonry beams to be specified in Canada. In contrast, TMS 402 is silent on deflection limits, distributed reinforcement, and cantilevered beams (lateral support, deep beam designation limits, etc…). Future research should be conducted to add related clarifications to future editions of TMS 402.

KEYWORDS: *reinforced masonry beams, TMS 402, CSA S304, flexural design, deflections*

---

[1] Professor, Durham School of Architectural Engineering and Construction, University of Nebraska-Lincoln, 1110 S. 67th Street, Omaha, NE 68182, eerdogmus2@unl.edu

[2] Professor, Department of Civil and Environmental Engineering, University of Tennessee, 1506 Middle Drive, Knoxville, TN, 37996, rmbennett@utk.edu

[3] Vice President of Engineering, National Concrete Masonry Association, 13750 Sunrise Valley Drive, Herndon, VA, U.S.A, jthompson@ncma.org

[4] Director of Technical Services, Canada Masonry Design Centre, 360 Superior Blvd., Mississauga, ON, Canada, Bbanting@canadamasonrycentre.com

INTRODUCTION

The *"CANUS: Harmonization of Canadian and American Masonry Structures Design Standards Project,"* 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), is an extensive collaborative work by a team of practicing engineers and academics from the U.S. and Canada. This is one of the five companion papers authored for this conference under the *CANUS* program that studies the similarities and differences in design provisions for reinforced concrete masonry structures with the ultimate goals of striving for better harmonization between CSA S304-14 [1] and TMS 402-16 [2], improving the masonry design provision in each, and identifying future research needs towards these goals.

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 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.

This paper presents the key differences and similarities between the design provisions for masonry beams between CSA S304-14 and TMS 402-16. 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 review and analyses presented in this paper is limited to the limit state design and strength design methodologies of CSA S304-14 and TMS 402-16, respectively. Investigation is also limited to reinforced concrete masonry beams without shear or compression reinforcement. Further, the comparisons in this paper are limited to flexure and shear strength. The *CANUS* group will be publishing additional papers that will provide results too extensive to include in this paper, including deep beams, lateral support of beams, and deflections.

KEY MATERIAL AND ANALYSIS DIFFERENCES

Typical values of the design compressive strength of masonry, including the area of grout, range from $f'_{m,eff}$ (commonly used in Canadian design practice) of 7.5 to 10 MPa (1,090 to 1,450 psi) with 15 MPa (2,180 psi) block strength while the companion single typical f'_m of 13.8 MPa (2,000 psi) is used in the U.S. Even though CSA S304-14 uses a 9% higher value for minimum unit strength, the specified prism strengths in the U.S. are from 38% to 100% greater. CSA S304-14 uses the χ factor to account for the direction of compressive stress in a masonry member relative to the direction used in the determination of f'_m, with the value being $\chi = 0.5$ where the force is normal to the head face and grout is not horizontally continuous in the compression zone and $\chi = 0.7$ where the force is normal to the head face and grout is continuous horizontally in the compression zone. The specified flexural tension strength/modulus of rupture for Type S mortar is 0.85 MPa (124 psi) in CSA S304-14, while the value is 1.10 MPa (160 psi) for Type S masonry cement mortar and 1.84 MPa (267 psi) for Type S Portland cement-lime mortar in TMS 402-16.

The masonry stress of the equivalent rectangular stress block is taken as 0.85 and 0.80 times f'_m in CSA S304-14 and TMS 402-16, respectively (the depth of the stress block, $0.8c$, is the same for both), while the maximum useable compressive strain of concrete masonry is 0.003 in CSA S304-14 and 0.0025 in TMS 402-16. Slightly different specified yield strengths are used for reinforcement with 400 MPa (58,000 psi) being used in Canada and 414 MPa (60,000 psi) being used in the U.S. Resistance, or strength-reduction, factors are applied to the individual material properties in CSA S304-14, with a value of 0.60 for masonry and 0.85 for reinforcement. TMS 402-16 uses a single strength-reduction applied to the nominal strength, with the value of 0.90 for flexure and 0.80 for shear. A companion paper [3] provides a more in-depth comparison of material differences in masonry design and construction between the two countries.

MAXIMUM AND MINIMUM REINFORCEMENT

The maximum reinforcement in CSA S304-14 is limited to balanced conditions, or the strain in the masonry being the maximum useable compressive strain, ε_{mu}, and the steel strain being the yield strain, ε_y. TMS 402-16 requires the strain in the steel to be $1.5\varepsilon_y$, which, for concrete masonry, is equivalent to 82% of the balanced reinforcement ratio. When the CSA S304-14 resistance factors are applied and the difference in the equivalent rectangular stress block is accounted for, the maximum reinforcement ratio, ρ_{max}, per CSA S304-14 is given in Equation 1 and for TMS 402-16 in Equation 2.

$$\rho_{max} = 0.288\chi \frac{f'_m}{f_y} \tag{1}$$

$$\rho_{max} = 0.291 \frac{f'_m}{f_y} \tag{2}$$

Thus, the two codes have approximately the same allowed maximum reinforcement ratio. However, when considering the difference in material properties and the χ factor, the maximum reinforcement per CSA S304-14 is 25-50% of that allowed by TMS 402-16. The minimum reinforcement in CSA S304-14 is given by Eq. 3.

$$\rho_{min} = \frac{0.8}{f_y} \tag{3}$$

TMS 402 has an entirely different approach to establishing a minimum reinforcement ratio, requiring that the nominal moment be at least 1.3 times the cracking moment. It is difficult to compare the two provisions in a general sense, but, if a modulus of rupture of 1.5 MPa (218 psi) is assumed, the TMS 402-16 criterion is approximately equal to that given in Equation 4. In general, CSA S304-14 minimum reinforcement requirements result in more reinforcement, but varies based on the particular beam design parameters.

$$\rho_{min} = \frac{0.5}{f_y} \tag{4}$$

FLEXURAL STRENGTH

The ratio of factored, or design, moments between CSA S304-14 and TMS 402-16, respectively, is obtained from Equation 5.

$$\frac{M_{402}}{M_{S304}} = \left({}^{\phi}\!/_{\phi_s} \right) \left(\frac{d - {}^{a_{402}}\!/_{2}}{d - {}^{a_{S304}}\!/_{2}} \right) \tag{5}$$

Figure 1 shows a comparison of the flexural strength for the same value of f'_m of 13.8 MPa (2,000 psi) for both design standards. The graphs are truncated at the maximum reinforcement for CSA S304-14, although TMS 402-16 would allow a maximum reinforcement ratio of 0.0095. From Fig. 1, even with the masonry strength values set equal, the flexural capacity of the beams per TMS 402-16 are 5-25% larger than those calculated per CSA S304-14. The most significant contributor to this divergence is the χ factor.

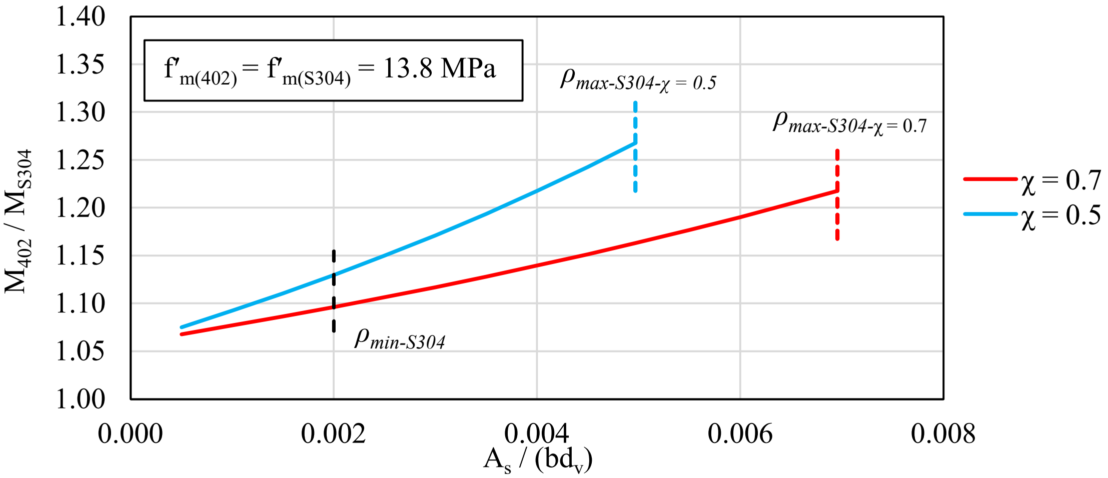

Figure 1: Comparison of Masonry Flexural Capacity when f'_m Values are Equal

Figure 2 shows the same comparison except that country-specific f'_m values, 7.5 MPa (1,090 psi) and 13.8 MPa (2,000 psi) for CSA S304-14 and TMS 402-16, respectively, are used. The combination of the penalty from the χ factor and the 46% reduction in the masonry compressive strength assigned to similarly manufactured products causes a significant difference of up to 70%

between the moment capacities and further reduces the maximum reinforcement ratio for beams designed according to the CSA S304-14.

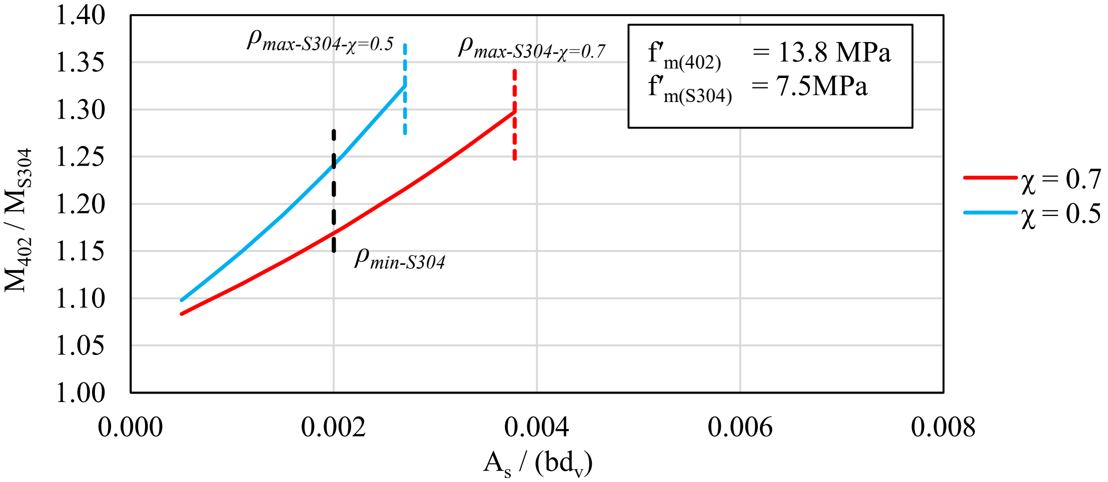

Figure 2: Relative Masonry Flexural Strength when f'_m Values are Country-specific Values

SHEAR STRENGTH

Only the shear strength due to the masonry is considered as beams are typically designed to avoid shear reinforcement if possible. The design shear strength from TMS 402-16 is provided in Equation 6.

$$\phi V_{nm} = 0.15 A_{nv} \sqrt{f'_m} \tag{6}$$

Where, f'_m is in MPa. TMS 402-16 currently does not give guidance on the “depth” to be used in calculation of A_{nv}, and, given the definition of d_v in TMS 402-16, is “the actual depth of member in direction of shear considered,” it could be interpreted as allowing the calculation of A_{nv} using the full depth of the beam. However, most American engineers use d in shear area calculations instead of d_v. The TMS 402/602 committee is working on clarifying the definition of A_{nv} for various scenarios. For the purposes of this paper, the shear area is taken as the same in CSA S304-14 and TMS 402-16.

CSA S304-14 calculates the shear resistance of the masonry as given in Eq. 7. This equation is based on the Modified Compression Field Theory, with details on its basis in [4].

$$V_m = \phi_m \lambda K_b \beta \sqrt{f'_m} b_w d_{v(S304)} \tag{7}$$

The effective depth, $d_{v(S304)}$ is the greater of 0.9 times the depth to the centroid of the tension reinforcement or 0.72 times the height of the beam. K_b is dependent on the type of masonry construction and is taken as 1.0 for grouted hollow masonry. λ accounts for the density of the masonry and is 1.00 for a density of 2,000 kg/m^2 (125 pcf), 0.85 for a density of 1,800 kg/m^3 (112 pcf), and 0.75 for a density of 1,700 kg/m^3 (106 pcf) and β is a shear coefficient. There is a simplified method for determining β as well as a general method. Typically, Canadian designers use the general method within design software for shear design which relies on a more detailed analysis method but can yield higher values of β, up to a maximum value of $\beta = 0.4$.

Figure 3 shows the ratio of the factored masonry shear strength values for masonry beams (without stirrups) plotted against the height of the beam (h) for equal f'_m values. Fig. 4 is a similar plot but with country-specific f'_m values. Whereas the normalized shear strength calculated under TMS 402-16 is a fixed value for a given specified compressive strength, the shear strength determined under CSA S304-14 varies with density of masonry (through the factor λ), beam depth, and the shear analysis method used. The jump in the graph at $h = 600$ mm is due to the requirement of intermediate reinforcement at values of $h > 600$ mm in CSA S304-14, which affects the calculation of β. The coefficient β is dependent on the minimum of the d_v and the spacing of intermediate reinforcement.

Several things are important to note from Figs. 3 and 4. The simplified method for determining β results in a masonry shear strength of approximately half that using the general method. When the values of f'_m are equal, the calculated shear strength from CSA S304-14 is always higher than the shear strength from TMS 402-16. When the country-specific values of f'_m are used, the shear strength from CSA S304-14 is approximately the same as the TMS 402-16. Because the shear strength is proportional to $\sqrt{f'_m}$, the differences in f'_m have less of an effect on shear than on flexure. Given the simplicity of the TMS 402-16 shear strength provisions, there is merit in that approach.

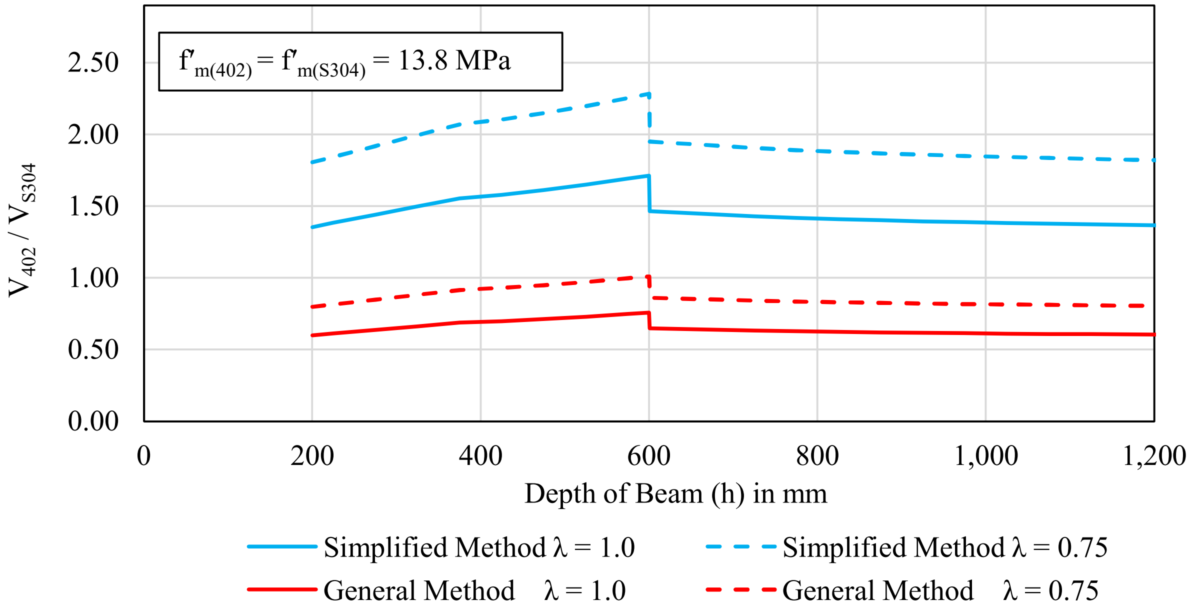

Figure 3: Shear Capacity Ratio Versus Depth of Beam when f'_m is Equal

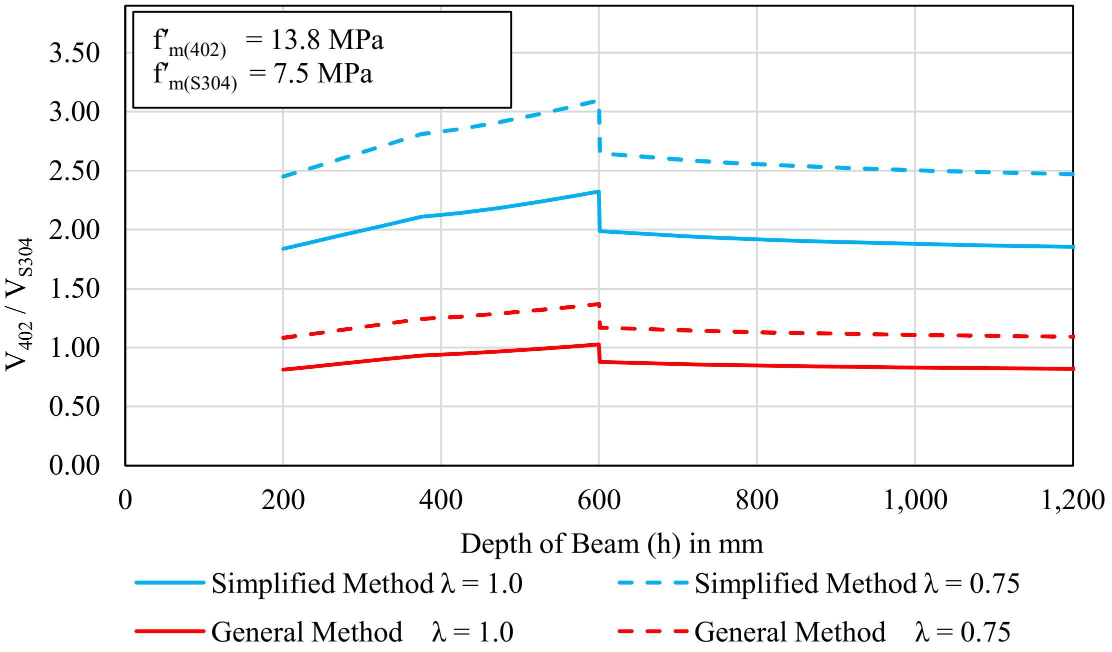

Figure 4: The Shear Capacity Ratio Versus Depth of Beam using country-specific f'_m

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are offered for flexural strength, shear strength, and other factors related to beam design that were not specifically discussed in this paper due to space limitations.

Flexure

The χ factor and lower specified value of f'_m resulted in lower moment strengths in CSA S304-14 than TMS 402-16. The largest impact of the differences was in maximum reinforcement, with these factors resulting in much smaller maximum reinforcement ratios than TMS 402-16. The need for the χ factor should be explored, and possibly it could be eliminated, at least for determining maximum reinforcement. This is consistent with the results of Samy et al [5], who recommended that CSA S304-14 could be improved by eliminating the χ factor, and that CSA S304-14 classified many beams as over-reinforced when the failure was reinforcement yielding. Others [6 and 7] have also recommended either the elimination or an increase in the χ factor. The differences in values of f'_m is a global issue that is bigger than just flexure but should be carefully examined.

The minimum reinforcement in TMS 402-16 is a function of the modulus of rupture. The value of the modulus of rupture varies over 2.5 times depending on the mortar. These values were based on wallette tests and not beam tests. We conjecture that the modulus of rupture for beams is relatively independent of mortar type and much more dependent on grout strength. The TMS 402-16 minimum reinforcement provisions could be simplified by using an approach like CSA S304-14, which would eliminate the need to know the modulus of rupture. However, the modulus of rupture would still be needed for determining the effective moment of inertia for deflection calculations.

Shear

The general method for determining the shear strength in CSA S304-14 results in approximately the same shear strength as TMS 402-16 when country-specific values of f'_m are used and greater shear strengths when the same f'_m value is used. Given the simplicity of the TMS 402-16 shear strength equation and its adequate performance, there is no compelling reason for TMS 402-16 to modify their provisions.

An area for improvement in TMS 402 is to define the shear area, A_{nv}. A change has been approved for the 2022 version of TMS 402, which defines the shear area as *bd* for fully grouted beams.

Other factors

Stack bond is not allowed in reinforced masonry beams in CSA S304-14 while TMS 402-16 does not have any limitations on stack bond. It is recommended that the work of Zohrehheydariha et al. [8] be expanded, and its repeatability is ensured followed by a code provision recommendation regarding reinforced beams with stack-bond pattern. Single course beams, including beams made of 400 mm (16 in) high U-shaped units should also be considered.

CSA S304-14 has requirements for crack control, as well as a requirement for intermediate reinforcement when the depth of the beam exceeds 600 mm (24 inch), while TMS 402-16 does not have this requirement. The need for intermediate reinforcement should be explored. Several U.S. designers have indicated intermediate reinforcement could complicate construction. If intermediate reinforcement is determined to be sufficiently beneficial to warrant it being included in TMS 402-16, the use of joint reinforcement as an alternative to bond beam reinforcing should be considered.

There is a need for development of torsional design provisions for masonry beams and subsequent research to support these design models in both standards.

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

REFERENCES

[1] Canadian Standards Association (CSA) (2014). *CSA S304 Design of Masonry Structures*, Canadian Standards Association, Mississauga, ON, Canada.

[2] The Masonry Society (TMS) (2016). *TMS 402/602 Building Code Requirements and Specification for Masonry Structures*, The Masonry Society, Longmont, CO, U.S.

[3] Erdogmus, E.; Dutrisac, H.; Thompson, J.; and Banting, B. (2021). "Comparison of Selected CSA S304-14 and TMS 402-16 Reinforced Masonry Design Provisions and Material Properties." *Proc., 14th Canadian Masonry Symposium,* Montreal, QC, Canada.

[4] Sarhat, S. R., and E. G. Sherwood. (2010). "Effective shear design of reinforced masonry beams." The Masonry Society Journal, 28(2): 27–39.

[5] Samy, B.S.A., Sarhat, S.R., and Sherwood, E.G. (2015). "Comparing Flexural Capacity of Reinforced Masonry Beams Using Different Codes," 12th North American Masonry Conference, Denver, CO, The Masonry Society.

[6] Ring, T., Das, S., and Stubbs, D. (2012). "Compressive Strength of Concrete Masonry Beams," ACI Structural Journal, 109(3), 369-376.

[7] Penales, J., Zohrehheydariha, J., and Banting, B. (2021). "Structural Behavior of Masonry Beams with Alternative Shear Reinforcement," J. Struct. Eng., 147(3), DOI: 10.1061/(ASCE)ST.1943-541X.0002940.

[8] Zohrehheydariha, J; Das, S; and Banting, B. (2018). "Effect of Unit Bonding Patterns on the Structural Performance of Loadbearing Concrete Block Masonry Beams," J. Struct. Eng., 2019, 145(1): 04018233, DOI: 10.1061/(ASCE)ST.1943-541X.0002234.