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PARAMETRIC STUDIES ON REINFORCED MASONRY SHEAR WALLS RESISTING IN-PLANE LOADS: A COMPARISON OF CSA S304-14 AND TMS 402-16

Erdogmus, Ece[1]; Cruz-Noguez, Carlos[2]; Ledent, Philippe[3]; Jobe, Lane[4]; Hughes, Kevin[5]; Banting, Bennett[6] and Thompson, Jason[7]

ABSTRACT

As one of the five companion papers from the project, "*CANUS: Harmonization of Canadian and American Masonry Structures Design Standards Project",* this paper focuses on the comparison of CSA S304-14 and TMS 402-16 design provisions related to in-plane load resistance of reinforced masonry shear walls. Seismic design provisions for masonry walls are included in the discussions, as they pertain to the resistance of the reinforced masonry shear walls, specifically for in-plane behavior. The parametric studies are mainly based on wall height-to-length aspect ratio to address both flexure-controlled and shear-controlled walls. The main differences identified include the limitations posed by the maximum reinforcement provisions in the U.S., reduced moment arm provisions in Canada, and the overall approach to designing masonry shear walls as the seismic risk at a geographical location increases. It is noted that at the *h/l* aspect ratio of 1, the reduced moment arm provisions (CSA S304-14) may not be serving the intended purposes. Further, the U.S. provisions significantly limit the height of masonry shear walls in highly seismic areas, whereas Canadian provisions render some walls infeasible due to significantly lower compressive strength (f'_m) values combined with a lower material reduction factor.

KEYWORDS: *reinforced masonry shear walls, in-plane resistance, limit state design, strength design, CSA S304, TMS 402*

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

[2] Associate Professor, Department of Civil and Environmental Engineering, 7-306 Donadeo Innovation Centre for Engineering, University of Alberta, Canada, cruznogu@ualberta.ca

[3] Executive Director, Masonry Institute of Michigan, 24725 W 12 Mile Rd, Suite 388, Southfield, MI, U.S.A., phil@masonryinfo.org

[4] Principal Engineer, Miller Consulting Engineers, Inc. Portland, Oregon, lane@miller-se.com

[5] Structural Consulting Engineer, Renoasis Engineering, Aurora, ON, Canada, kevin@renoasis.ca

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

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

INTRODUCTION

This paper presents parametric studies on the design provisions in CSA S304-14 [1] and TMS 402-16 [2] related to reinforced concrete masonry shear walls subject to in-plane forces, and it is a part of five companion papers related to the CANUS 2019 Project. *CANUS 2019 - Harmonization of Canadian and American Masonry Structures Design Standards Project* 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). It is an extensive collaborative work by a team of practicing engineers and academics from the U.S. and Canada. 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

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. The review and analyses presented in this report is limited to the limit state design (CSA S304-14) and strength design (TMS 402-16) methodologies related to reinforced concrete masonry shear walls. The comparisons in this paper are limited to axial-flexural capacity and shear capacity, as well as a study of how each standard addresses the impact of moment arms on assessing in-plane strength. The *CANUS* team will be publishing additional papers and reports that will provide additional results too extensive to include in this paper, including a deeper look into the impact of the maximum reinforcement ratio and maximum compressive strain provisions of TMS 402, consideration of CSA S304-14 ductility checks, as well as single and multi-story shear wall design case studies. Finally, to avoid repetition among companion papers, design equations for shear, moment, and axial capacity are provided in the CANUS project overview paper by Erdogmus et. al [3].

KEY DIFFERENCES IN MASONRY DESIGN

There are some key differences in masonry design between the two countries that affect all capacity calculations. These are briefly listed here, but more information is also provided in a companion paper [3].

- f'_m: The typical value used in Canada is 7.5 MPa, while it is 13.8 MPa in the U.S. This results in a baseline of 54% difference in all design capacity estimates related to f'_m.

- Maximum useable compressive strain of concrete masonry: 0.003 in Canada versus 0.0025 in the U.S.
- Nominal yield strength of reinforcement: 400 MPa in Canada versus 414 MPa in the U.S.
- Material and Strength Reduction Factors:
    - CSA S304-14 incorporates material reduction factors:
        - $\phi_m = 0.60$
        - $\phi_s = 0.85$
    - TMS 402-16 applies strength reduction factors to the nominal strength values based on behavior:
        - ϕ =0.80 for shear
        - ϕ = 0.90 for compression and flexure

SEISMIC SHEAR WALL CATEGORIES

The 2015 National Building Code of Canada (NBCC 2015) [4] and the 2016 American Society of Civil Engineering Standard 7 (ASCE 7-16) [5] provide the loading and risk criteria that determine the classification of masonry walls that are part of the seismic force resistance systems in buildings. While there are similar shear wall types in these codes/standards, their restrictions and how often they are used in practice vary between the two countries. In the U.S., once the seismic design category (SDC) is determined based on the geographical location, soil properties, and the risk category of a building in accordance with ASCE 7-16, the design professional is *required* to select specific masonry shear wall categories that are permitted in that SDC. While there is a similar approach to wall designations in Canada, the moderately ductile and ductile shear walls have been introduced relatively recently and are only typically used when required for post-disaster structures. In contrast to ASCE 7-16 provisions, buildings constructed in a higher seismic designation under the Canadian code are *not necessarily required* to use a high ductility wall category unless height limits are an issue. As such, a specific category of Seismic Force Resisting System (SFRS) is only mandated for certain types of structures designated post-disaster and when heights of the building exceed a specified limit.

Table 1 provides the shear wall categories and respective response modification factors (R, R_d, *and* R_o) prescribed in the U.S. and Canadian codes. The Canadian provisions use an over-strength related force modification factor (R_o) together with a ductility-related force modification factor (R_d), and this is applied to each wall type in determining the static base shear. In the U.S., a single response modification coefficient (R) is used. As can be seen in Table 1, the combined factor of R_dR_o in Canada correlate closely to the R factor in the U.S.

Table 1: Comparison of Different Shear Wall Categories and Response Modification Factors

CSA S304-14 (NBC-2015)				TMS 402-16 (ASCE 7-16)	
Type of SFRS	R_d	R_o	R_dR_o	**Seismic Force-Resisting System**	R
Ductile shear walls	3	1.5	4.5	Special reinforced masonry shear walls (SRMSW)	5.0
Moderately ductile shear walls	2	1.5	3.0	Intermediate reinforced masonry shear walls (IRMSW)	3.5
Conventional construction shear walls	1.5	1.5	2.25	Ordinary reinforced masonry shear walls (ORMSW)	2.0
Unreinforced masonry	1.0	1.0	1.0	Detailed plain masonry shear walls	2.0
				Ordinary plain masonry shear walls	1.5

Design Provisions Related to Ductility

Both TMS 402-16 and CSA S304-14 incorporate increased ductility requirements for masonry walls designed for higher seismic risk areas; however, the approach followed in both codes is different. TMS 402-16 achieves higher ductility using a maximum reinforcement limit and detailing requirements that get increasingly more stringent as the seismic design category increases from *A* to *F*. TMS 402-16 limitations on the maximum area of flexural reinforcement per Section 9.3.3.2 are shown in Table 2 and expressed in Equation US-1 for fully grouted shear walls subjected to in-plane loads with uniformly distributed reinforcement. In contrast, CSA S304-14 requires ductility verification for moderately ductile and ductile walls per Clauses 16.8.7 and 16.9.7 for moderately ductile and ductile walls, respectively (Table 3).

Table 2: TMS 402-16 Summary of Provisions for Maximum Area of Flexural Reinforcement

TMS 402-16 Provision	Aspect Ratio	Seismic Wall Category	Tensile Strain Factor (α)	Maximum Reinforcement Ratio (ρ_{max})
9.3.3.2.1	$M_u/V_ud_v \geq 1$	ORMSW	1.5	Equation US-1
9.3.3.2.2		IRMSW	3*	Equation US-1
9.3.3.2.3		SRMSW	4*	Equation US-1
9.3.3.2.4	$M_u/V_ud_v \leq 1$ and $R \leq 1.5$	All reinforced categories	N/A	No upper limit
	$M_u/V_ud_v \leq 1$ and $R \geq 1.5$	All reinforced categories	1.5	Equation US-1

*This is for in-plane loads. For walls subject to out-of-plane loads, use 9.3.3.2.1.

$$\rho_{max} = \frac{A_s}{d_v} = \frac{0.64\, f'_m b \left(\frac{\varepsilon_{mu}}{\varepsilon_{mu}+\alpha\varepsilon_y}\right) - \frac{P}{d_v}}{f_y\left(\frac{\alpha\varepsilon_y-\varepsilon_{mu}}{\varepsilon_{mu}+\alpha\varepsilon_y}\right)} \qquad \textbf{[US-1]}$$

*Where; P is the axial load and shall be taken from the loading combinations given by D+ 0.75L+ 0.525*Q_E.

Table 3: CSA S304-14 Summary of Provisions Related to Ductility Verification

Wall Category	CSA S304-14 Clause	Ductility Verification and Calculations
Moderately Ductile Shear Walls	16.8.7 Ductility Verification	In lieu of satisfying the requirements of Clause 16.8.8, walls having a height-to-length ratio, h_w/ℓ_w, equal to or greater than 5, reinforcement with f_y = 400 MPa, and $\frac{\Delta_{f1}R_dR_0}{h_w} \leq 0.01$, shall be deemed to satisfy the requirements of 16.8.8 when c is less than $0.15\ell_w$.
	16.8.8 Ductility Calculations	$\theta_{ic} > \theta_{id}$ **[CAN- 1]**
	16.8.8.2 Inelastic rotational demand	$\theta_{id} = \frac{(\Delta_{f1}R_dR_0 - \Delta_{f1}\gamma_w)}{h_w - \frac{\ell_w}{2}} \geq \theta_{min}$ **[CAN- 2]** Where, θ_{min} = the minimum inelastic rotational demand, $\theta_{min} = 0.003$ for Rd = 2.0, and $\theta_{min} = 0.004$ for Rd = 3.0
	16.8.8.3 Inelastic rotational capacity	$\theta_{ic} = \left(\frac{\varepsilon_{mu}\ell_w}{2c} - 0.002\right) \leq 0.025$ **[CAN- 3]**
	16.8.8.4	A rearrangement of Equations **CAN-2** and **CAN-3** may be used to ensure adequate ductility of the masonry shear wall: $c/\ell_w \leq \frac{\varepsilon_{mu}}{\frac{4A_r}{(2A_r-1)}\left(\frac{\Delta_{f1}R_dR_0}{h_w}\right)\left(1-\gamma_w/R_dR_0\right)+2\varepsilon_y}$ **[CAN- 4]**
Ductile Shear Walls	16.9.7	Ductile shear walls shall meet the ductility condition requirement of 16.8.8. For walls having a height-to-length ratio, h_w/ℓ_w, equal to or greater than 5, reinforcement with f_y = 400 MPa, and $\frac{\Delta_{f1}R_dR_0}{h_w} \leq 0.01$, the requirements of Clause 16.8.8 shall be deemed to be satisfied when c is less than $0.125\ell_w$.

PARAMETRIC STUDIES

Several parametric studies are carried out to quantify the differences in design provisions, material properties, and material/strength reduction factors. To allow for the isolation of certain factors in the parametric studies, the input parameters will vary between "equivalent" values and country-specific values. Country-specific properties are given in the Key Differences section. Further details and discussions on these key differences can be found in the companion paper by Erdogmus et al. [3]. The nominal block width used in the analyses is 8 in. (203 mm).

Comparison of Axial-Flexural Capacity of Shear Walls

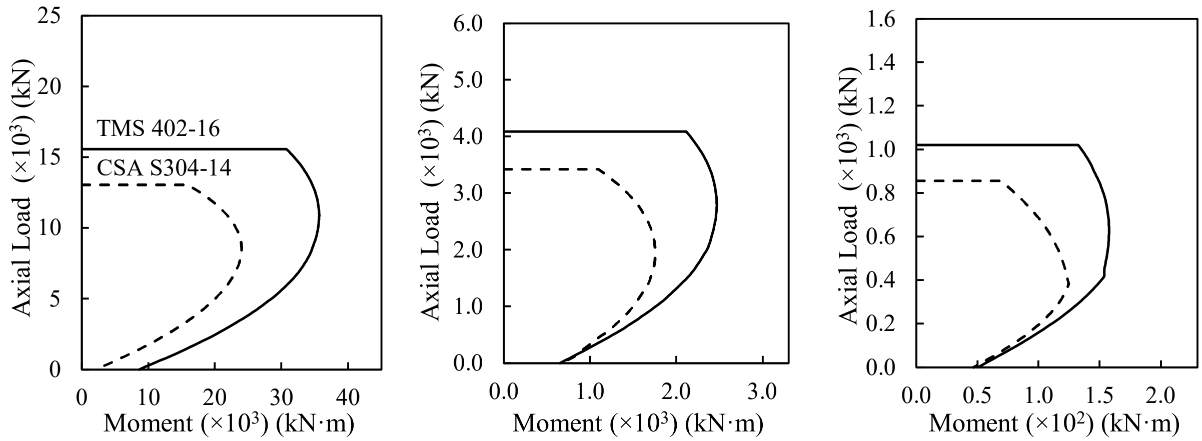
The design equations for axial and flexural capacity calculations in CSA S304-14 and TMS 402-16 are provided in the companion paper by Erdogmus et al. [3]. The design equations themselves and the theory behind them are similar. In fact, a baseline comparison of design equations without the addition of reduction factors and country specific values showed that the design envelopes are very similar in the tension-controlled area and slightly larger for the compression-controlled area. For brevity, these design envelopes (both with equivalent material properties and not considering reduction factors) are not presented here but can be found in the complete CANUS report [6] and upcoming extended journal papers. Here, only the comparison of factored design envelopes with equivalent and country-specific values are presented, which ultimately showcases the major impact from the lower f'_m values specified in CSA S304-14.

In CSA S304-14, h_w/ℓ_w ratios less than 1.0 are considered to be squat, and a reduced moment arm needs to be considered for these walls. Such a provision does not exist in TMS 402-16. To evaluate the impact of this provision, along with other differences between the two standards, the wall lengths are varied to establish a range of wall aspect ratios as shown in Table 4.

Table 4: Description of the Parametric Study Variables

Height of wall (h_w)	Length of Wall (ℓ_w)	Aspect Ratio (h_w/ℓ_w)	Squat per CSA S304-14?
118 in. (3,000 mm)	31.5 in. (800 mm)	3.75	No
	126 in. (3,200 mm)	0.94	Yes: Consider Clause 10.10.2.2 and use reduced moment arm
	480 in. (12,200 mm)	0.25	

The axial-flexural capacity envelopes for when the material properties are set equal are shown in Figure 1. In Figures 1(b) and (c), the impact of the differences in the tension-controlled area of the interaction diagrams is less dramatic as the material resistance factor for steel reinforcement in CSA S304-14 is similar to that of TMS 402-16 for flexure (CSA S304-14 $\phi_s = 0.85$, TMS 402-16 $\phi = 0.90$).



(a) $h_w/\ell_w = 0.25$ (b) $h_w/\ell_w = 0.94$ (c) $h_w/\ell_w = 3.75$

Figure 1: *Factored* Capacity Interaction Diagrams Comparing Design Equations with Equivalent Material Properties (TMS 402-16 = solid lines, CSA S304-14 = dashed lines)

Figure 2 presents the results for the same three walls with country-specific material properties. It can be seen that the lower values of masonry strength in the CSA S304-14 result in a dramatic difference between interaction diagrams.

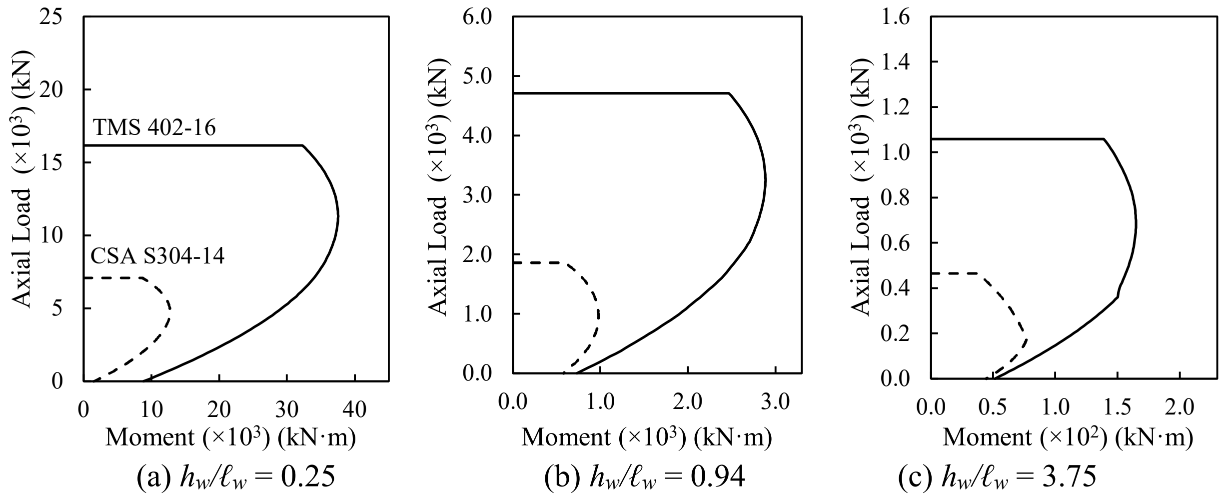
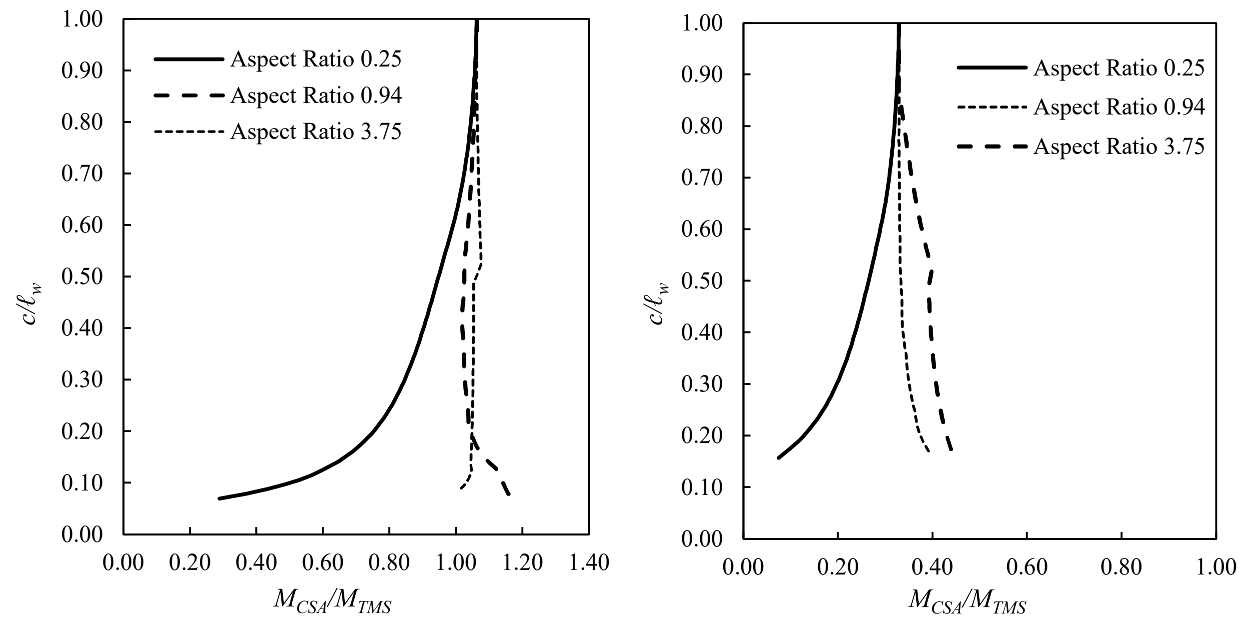


Figure 2: *Factored* Capacity Interaction Diagrams Comparing Typical Country-Specific Materials and Equations (TMS 402-16 = solid lines, CSA S304-14 = dashed lines)

A few caveats should be noted here: 1) Combinations of large axial load acting concurrent with large bending moment (*i.e.,* the upper right-hand side of the interaction envelopes per TMS 402-16) are not commonly encountered in practice. Considering an average f'_m (7.5+13.8)/2 = 10.6 MPa and a typical axial load index value for the walls, say, 10% of the gross section capacity ($0.10A_gf'_m$), this leads to limiting values of axial load of 2.65x10^3 kN, 0.69x10^3 kN, and 0.17x10^3 kN for the walls with h_w/l_w=0.25, 0.94 and 3.75, respectively. Considering these axial load limits, the differences in the size of the interaction diagrams of Figure 2 are less consequential. 2) If the TMS 402-16 maximum reinforcement limits were to be considered, the difference is expected to be much smaller between the two codes, especially for axial capacity. However, it is difficult to show the impact of maximum reinforcement limits in a parametric study, as the applied loads on the walls are a factor in the determination of the maximum reinforcement (Equation 1). 3) At the time of writing of this paper, the TMS 402 code committee is considering changing the combined axial and moment reduction factor to have different values for tension-controlled and compression-controlled zones *along with* a potential relaxation of the maximum reinforcement limits. If adopted, these changes would bring the moment capacities between the countries closer.

Impact of CSA S304-14 Squat Wall Reduced Moment Arm Requirements on Moment Capacity

To further study the impact of the reduced moment arm provisions for different wall aspect ratios, normalized interaction diagrams are plotted for three aspect ratios (Figure 3).



(a) Identical Material Properties and Nominal (unfactored) Moment Strengths

(b) Country-Specific Material Properties and Design (factored) Moment Strengths

Figure 3: Ratio of Moment Resistances Using the CSA S304-14 and the TMS 402

In these normalized plots, the vertical axis represents the c/ℓ_w ratio (neutral axis depth/wall length), and the horizontal axis provides the ratio of moment resistance derived from the CSA S304-14 (M_{CSA}) to that of TMS 402-16 (M_{TMS}). Variation in material properties and reduction factors are first left out (Figure 3(a)), then are both considered (Figure 3(b)) to showcase their impact.

When the material properties are kept equal and the reduction factors are ignored (Figure 3(a)):

- The wall with an aspect ratio of 0.25 demonstrates that the use of the reduced moment arm provision in the CSA S304-14 leads to a significant reduction to the moment resistance.
- For the wall with an aspect ratio of 3.75, the moment ratio (M_{CSA}/M_{TMS}) is close to 1.0.
- For the wall with an aspect ratio of 0.94, the use of the reduced moment arm provision actually results in an amplification of the moment resistance. This has to do with the fact that when the aspect ratio is this close to 1, the reduced moment arm requirement inadvertently *extends* the resultant moment arm, and, as a result, the intermediate reinforcing bars in the wall are at or close to yielding.

When country-specific material properties and reduction factors are considered (Figure 3(b)):

- Even though there is an unexpected and unintended increase in the moment resistance of walls with an aspect ratio just under 1, the effects are still significantly lower than those of the TMS 402-16.
- As shown in Figure 3(b), for the same neutral axis depth (c) to wall length (ℓ_w) ratio, the factored resistance determined using the Canadian design provisions is consistently less than 50% that of U.S. design. As such, even with a potentially unconservative approach around the aspect ratio of 1, CSA values are much lower.

In summary, the authors suggest that, at a minimum, a reconsideration of the wording of CSA S304-14 Clause 10.2.8 is necessary, where it should state that the provision *need not be applied* if it causes an increase in the moment arm inadvertently. Conversely, when other limitations are considered, the impact of the reduced moment arm may not be as significant. For instance, for walls with an aspect ratio that is well below 1, the impacts of these flexural provisions are somewhat tempered by the fact that shear, and notably maximum shear, may govern the design.

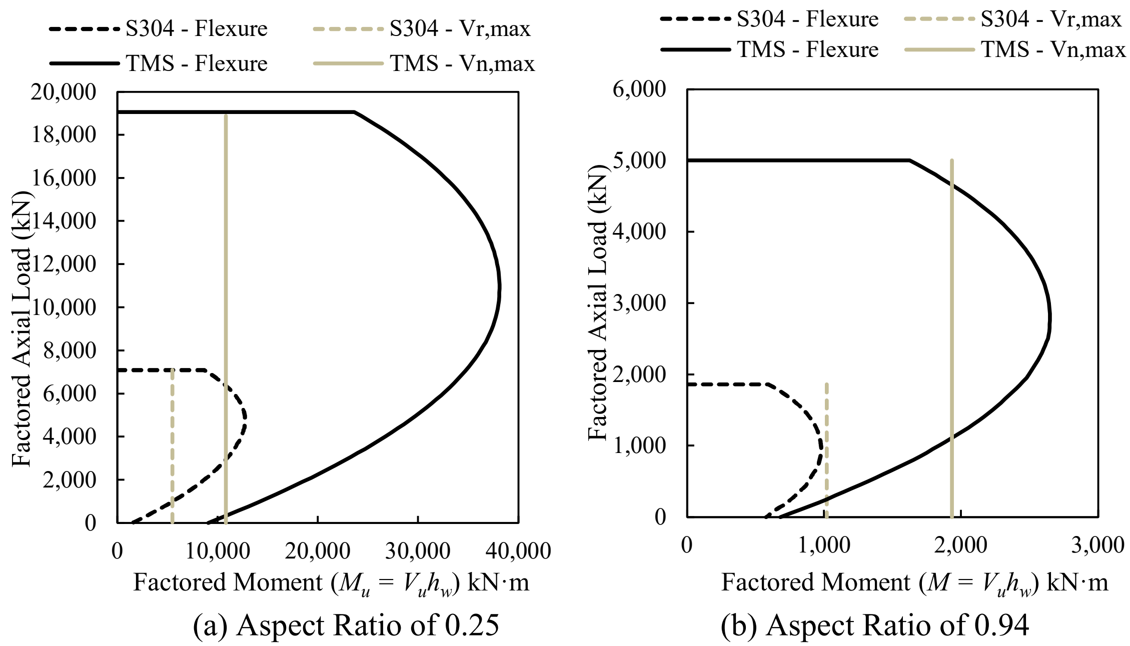


Figure 4: Maximum Shear Resistance Overlayed with Interaction Diagrams Assuming Cantilever Walls with a Single Point Load

In addition to the three caveats to the comparisons presented in Figures 1 and 2 above, the design shear capacities of the walls may impose further limitations to the moment that can be resisted by the walls. Figure 4 shows the moment-axial interaction diagrams overlayed with a vertical line that indicates the upper limit to shear resistance using both CSA S304-14 and TMS 402-16. Figure 4 is plotted for a cantilever wall subject to a single point load at the top such that the maximum moment, M, is equal to the shear, V, mulitplied by the wall height, h_w.

It can be seen that the maximum shear severely limits the maximum permissible moment for walls with an aspect ratio of 0.25. This reduction brings the two standards closer together than that implied by moment resistance calculations alone. In other words, athough TMS 402-16 does not have a reduced moment arm provision, designs are realistically limited by an upper boundary to the shear resistance.

Comparison of the Shear Capacities and Seismic Design Provisions

In this parametric study, a single-story wall scenario is examined for various vertical rebar size and spacings, wall heights, axial loads, and seismic wall designations (Table 5). This time, the wall length is kept constant at 5.08 m, while the height is varied to address various aspect ratios.

Table 5: Design Variables for Shear Capacity Comparison

Variable	Canadian units and designations	U.S. units and designations
Wall length	5.08 m	200 in.
Wall height	3, 4.57, 7.62, 10.16 m	10 ft. (120 in.), 15 ft. (180 in.), 25 ft. (300 in.), 33.33 ft. (399.96 in.)
Vertical rebar size and spacing	15M@203.2 mm, 15M@406.4 mm, 15M@609.6 mm	#5@8 in., #5@16 in., and #5@24 in.
Axial load (% $A_g f'_m$)	0 (0%), 44 (0.6%), 445 (5.7%), 890 (11.4%), 2224 (28.6%) kN	0 (0%), 10 (0.3%), 100 (3.1%), 200 (6.2%), 500 (15.6%) kips
Shear wall category based on country-specific seismic designations	Conventional Construction Moderately Ductile Walls Ductile Walls	ORMSW IRMSW SRMSW

For the combinations given in Table 5, the shear capacity is calculated as the lesser of: (i) the actual shear resistance and (ii) or shear capacity associated with the development of the flexural capacity of the walls based on a cantilevered wall with a single point load. The shear capacity ratio between country-specific designs are represented by the shear capacity determined from the CSA S304-14 provisions (V_{S304}) divided by the shear capacity determined from the TMS 402-16 provisions (V_{TMS}). Strength and material reduction factors are used for all capacity calculations. For CSA S304-14 calculations, the ductility checks for ductile and moderately ductile walls were not performed because the check requires knowledge of the applied loads.

Figure 5 shows the results in terms of the ratio of *controlling* shear resistance between the two codes in the vertical axis, plotted against the types of walls in the horizontal axis, where each dot corresponds to a combination of the parameters given in Table 5. The shaded scales at the bottom of each graph show the change in that parameter from lower (lighter shade) to higher values (darker shade).

This comparative parametric study shows that TMS402-16 can allow as much as 4.5 times the strength in extreme cases. The percentage of walls with $V_{r,S304}/\phi V_{n,TMS}$ smaller than 1 is 93%, with a mean of 0.63. It is noted that the differences between the two codes would further increase if the ductility checks from the CSA S304-14 were also implemented because only lightly reinforced walls or walls with small axial loads would meet the requirement. Also, several wall details, which pass the TMS 402-16 requirements for IRMSW and SRMSW categories, do not pass the requirements of moderately ductile or ductile shear walls in the CSA S304-14. Finally, it is observed that the capacities from the two country's provisions begin to converge as the wall height grows, even with country-specific properties.

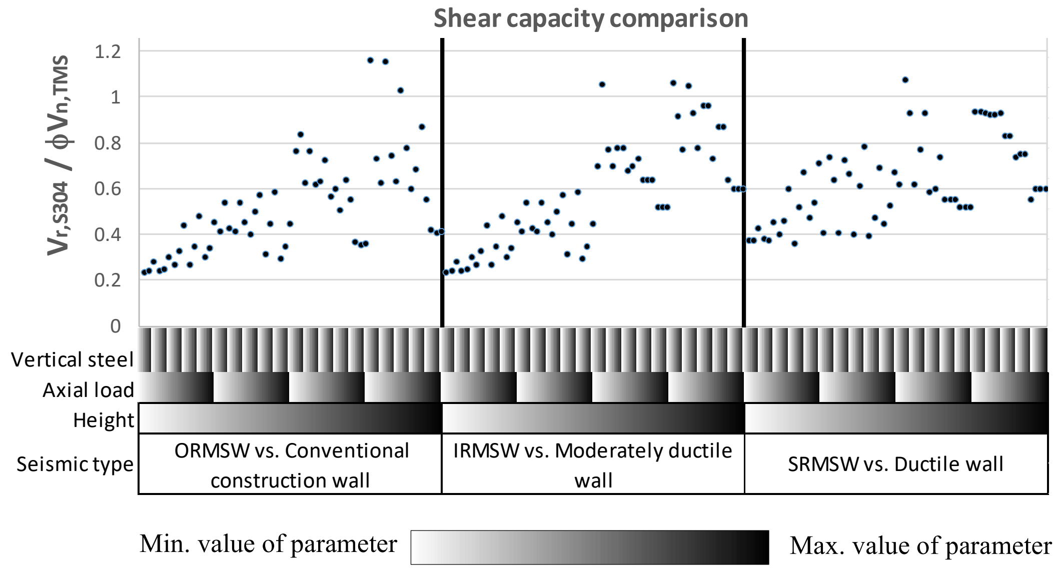


Figure 5: Factored Shear Capacity Comparison between TMS 402-16 and CSA S304-14 – Country-Specific Properties

Because the choice of lateral resisting system is left to the designer in Canada, as long as they meet the limits in height provided by the NBCC-15, the conventional construction typology is widely used for low-rise masonry structures that are not designated as post-disaster. In contrast, the choice of wall system in the U.S. is limited in regions of high seismic risk to only one category of wall (specially reinforced masonry shear walls, SRMSW). To compare the performance of the conventional construction typology in CSA S304-14 versus the ORSMW, IRSMW, and SRSMW typologies in TMS 402-16, the reader is referred to the leftmost part of Figure 5, in which ORSMW is compared to the conventional wall construction. This comparison is the same for all other U.S. wall typologies because the shear strength does not depend on the ductility level. It can be seen from this comparison that the designs, according to TMS 402-16, will also lead to consistent larger shear capacities compared to walls designed according to CSA S304-14.

CONCLUSIONS

The following conclusions are drawn from the parametric studies on shear walls considering axial-flexural capacity, reduced moment arm provisions in CSA S304-14, and shear capacities for various seismic wall designations:

- Combination of the differences in material properties and different approach/values to reduction factors results in a significant difference between interaction diagrams. However, the additional limitations from maximum reinforcement requirements in TMS 402-16, as well as an impending change to reduction factors in the next TMS 402 edition (2022), are expected to bring the two sets of design envelopes closer.
- In CSA S304-14, h_w/ℓ_w ratios less than 1.0 are considered to be squat, and a reduced moment arm needs to be considered for these walls. Such a provision does not exist in TMS 402-16.

The parametric study in this comparison highlighted that this provision has an inadvertent amplification effect when the aspect ratio is very close to 1. However, even with this amplification, when country specific values and reduction factors are considered, the factored resistance determined using the Canadian design provisions is consistently less than 50% that of U.S. design. The authors suggest that, at a minimum, a reconsideration of the CSA S304-14 wording to avoid the inadvertent amplification effect near the aspect ratio close to 1, is needed. Further, both standards may consider further investigations on squat shear wall behavior: TMS 402 could evaluate whether adding a related reduced moment arm provision for squat shear walls is warranted and CSA S304 could evaluate if the additional reduction in capacity on top of more conservative values of reduction factors and f'_m values is warranted.

- When a single-story wall scenario is examined for shear capacity considering various vertical rebar size and spacings, wall heights, axial loads, and seismic wall designations, in 93% of the cases, the TMS402-16 controlling shear capacities were higher. In fact, it was shown that TMS402-16 can allow as much as 4.5 times the strength in extreme cases compared to CSA S304-14. However, it was also observed that the capacities from the two country's provisions begin to converge as the wall height grows, even with country-specific properties.

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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 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] National Building Code of Canada (NBCC) (2015). *National Building Code of Canada*. Canadian Commission on Building and Fire Codes and National Research Council of Canada, Ottawa, ON, Canada.
[5] American Society of Civil Engineers (ASCE) (2016). *ASCE – 7 Minimum Design Loads for Buildings and Other Structures*, American Society of Civil Engineers, Reston, VA, U.S.
[6] CANUS CSA Report, 2021. https://www.csagroup.org/article/research/towards-the-harmonization-of-canadian-and-american-masonry-structures-design-standards/