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

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ABSTRACT

As part of a jointly funded 2019 research program titled "*CANUS: Harmonization of Canadian and American Masonry Structures Design Standards Project,*" this article focuses on the comparison of Canadian and American design provisions pertaining to reinforced masonry walls subjected to out-of-plane (OOP) and axial loads. 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 omitted from the scope. Several parametric studies are conducted to quantify and compare the corresponding provisions, identify limitations, and document the opportunities for future research and improvement within each Code. These studies explore factors that directly impact the calculation of combined flexural and axial capacity, wall stiffness, and second-order moments in OOP walls. In general, it was found that CSA S304-14 provisions are more conservative than TMS 402-16, mainly stemming from significant differences in f'_m values, material/strength reduction factors, and the approaches for determining the effective compressive width for partially grouted walls.

KEYWORDS: *masonry walls, out-of-plane resistance, axial capacity, TMS 402, CSA S304*

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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. The primary objective of the CANUS project is to conduct a comprehensive comparison of the design requirements of CSA S304-14 [1] and TMS 402-16 [2] 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.

This is one of the five companion papers authored for this conference under the *CANUS* program. Specifically, for this paper, the authors examined key differences and similarities between the design provisions for reinforced masonry walls subject to out-of-plane (OOP) loading, as set forth in Clauses 10 and 16 of CSA S304-14 and Chapters 7 and 9 of TMS 402-16. Highlights and key take-aways from the series of parametric studies are presented herein, focusing on the impact of material geometric differences on masonry out-of-plane wall design, design provisions for axial and moment capacity, stiffness considerations related to the design strength, and second-order effects. In the near future, the *CANUS* group will be publishing additional papers that will provide additional results too extensive to include in this paper, including: side-by-side comparison of the provisions of each Code related to OOP wall design, discussion of differences between OOP shear provisions in both Codes, and an in-depth summary of the specific impact of the differences in key variables on OOP design aspects.

The review and analyses presented in this report are limited to the limit state design and strength design methodologies of CSA S304 and TMS 402, respectively. Differences in environmental loading and serviceability issues, such as deflections, are outside the scope of this investigation. Structural elements constructed of reinforced concrete masonry are addressed; whereas unreinforced masonry, clay masonry, autoclaved aerated concrete (AAC), and glass block masonry are omitted from 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. The outcomes of this paper will support future research that can provide increased return on investment by strategically targeting research needs that will have the greatest impact.

KEY MATERIAL AND ANALYSIS DIFFERENCES

A companion paper [3] provides a more in-depth comparison of material and geometric differences in masonry design and construction between the two countries, but it is important to note the following key differences between the two Codes that profoundly affect OOP capacity.

Material Properties and Analysis Assumptions

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 (1090 to 1450 psi) with 15 MPa (2180 psi) concrete masonry unit (CMU) strength while the corresponding single typical f'_m of 13.8 MPa (2000 psi) is used in the United States (with 13.8 MPa CMU strength). Because both Codes present axial capacity as a direct linear function of f'_m, differences in f'_m between the two Codes linearly affect calculated axial load capacity as well as affecting flexural capacity, shear capacity, maximum reinforcement limits, and calculated second-order deflection. CSA S304 considers different values of f'_m for ungrouted versus solid or grouted units, but this distinction is not present in TMS 402. Even though Canada uses a 9% higher value for minimum unit strength, the specified masonry compressive strengths in the US are from 38% to 100% greater. This variable contributes to significant differences in combined axial and flexural capacity, as demonstrated by the parametric studies to follow. Additionally, the nominal yield strength of reinforcement is 400 MPa (58 ksi) in CSA S304 and 413.7 MPa (60 ksi) in TMS 402, moderately affecting moment capacity for low-axial, tension-controlled cross sections, in a linear manner (e.g., a 3.5% increase in f_y produces a roughly 3.5% increase in moment capacity).

The masonry stress of the equivalent rectangular stress block is taken as 0.85 and 0.80 times f'_m in CSA S304 and TMS 402, 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 and 0.0025 in TMS 402. The relative increase in flexural capacity afforded by these differences for OOP members designed under CSA S304 is currently more than offset in capacity calculations by the compounding impacts of a significantly lower f'_m for comparable materials described above and penalizing phi factors (0.60 for masonry and 0.85 for reinforcement in CSA S304 compared to a single factor of 0.90 in TMS 402). Moment capacity under CSA S304 is 94% of what it would be using TMS 402 phi factors for tension-controlled sections (most common in design), decreasing to 67% in compression-controlled sections.

The combined effect of the differences in phi factors, maximum compressive strain, reinforcement grade, etc., as more fully explained in the companion paper [3], results in about a 41% difference in the cumulative coefficients on the compression force calculations. This is before any considerations regarding the vast differences (up to 84% for similar assemblies of CMU and mortar) between f'_m values that reduce the capacity of CSA S304 designs, as well as the maximum reinforcement provisions that reduce the capacity of TMS 402 designs.

Effective Mortared Area and Effective Compression Zone Width

Although both CSA S304 and TMS 402 use a minimum face shell thickness in capacity calculations, CSA S304 also adopts the concept of *effective mortared area*, allowing the designer to take advantage of additional effective contact area where the face shell transitions into mortared webs with the units above and below. This additional cross-sectional area is effectively 'smeared' and treated as a uniform increase in face shell thickness. The resulting flexural capacity increase is moderate (approximately 10%). For a partially grouted wall, if TMS 402 were to use this approach, the thicker face shell would result in a tangible increase in moment capacity.

CSA S304 limits the effective compression zone width for walls laid in running bond to 4 times the *actual* wall thickness or the spacing between bars, while TMS 402 sets this limit at the minimum of 6 times the *nominal* wall thickness, the spacing between bars, or 1.83 m (72 inches). For OOP wall behaviour where section depth is minimal, limiting the compression zone width has a significant impact on flexural capacity and a moderate impact on secondary moment calculations by way of the cracked moment of inertia, I_{cr}, which is used to determine flexural stiffness. The effect of this variable is illustrated further in the parametric studies to follow.

Slenderness and Second-Order Effects

Slenderness effects are considered differently between the two Codes. In TMS 402, a slenderness cap is applied as part of the axial load capacity calculation. When the slenderness ratio of h/r is less than or equal to 99, it is considered at risk of material failure (crushing) and the capacity is reduced by $\left[1-\left(\frac{h}{140r}\right)^2\right]$. When the h/r ratio is greater than 99, it is considered at risk for stability failure and the capacity is reduced by $\left[\left(\frac{70r}{h}\right)^2\right]$. CSA S304 does not have an explicit slenderness coefficient applied to axial capacity, but a similar result is obtained by the inclusion of an accidental eccentricity provision that ensures the wall is adequately designed for a minimum primary moment. This moment is obtained by multiplying the axial load acting on the wall by an accidental eccentricity (set as $0.1t$ where t is the actual thickness of the wall). As this minimum moment is also included in the calculation of second-order effects (discussed in Sections 2.3 and 3.2), it effectively establishes a slenderness-based limit on the axial load capacity of the wall.

Both codes consider an effective height-to-thickness ratio of 30 to be a defining threshold value for second-order effects. Per TMS 402, an h/t ratio above and below 30 prompts different axial stress limitations if the P-delta method is to be used for second-order effects, while the alternative moment magnifier method can be used without axial stress limitations. CSA S304 limits the permissible factored axial stress for slender walls ($kh/t > 30$) to a maximum of 10% of f'_m, while TMS 402 is more stringent, as it limits stresses to 5% of f'_m. The stress limits in TMS are imposed only under the P-Delta option, and are more restrictive for slender walls (5% of full section stress). 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 the code) and is not yet widely adopted.

CSA S304 contains a reduction factor for stiffness, ϕ_{er}, with a value of 0.75 that significantly increases secondary moments calculated with both the P-delta and moment magnification methods, particularly at higher axial loads. TMS 402 commentary Section 9.3.5.4.3 attributes the lack of a stiffness factor for cracked, reinforced masonry walls (in contrast to reinforced concrete slender wall design in the U.S., which does use the 0.75 factor) to the fact that the use of the cracked moment of inertia *(I_{cr})* for the entire wall height already provides sufficient conservatism, and because the moment magnifier calculations without the stiffness factor matched results from the P-delta analysis.

Maximum Reinforcement

TMS 402-16 provides limitations on the maximum area of flexural reinforcement wherein flexural tensile reinforcement is limited to that required to maintain equilibrium under a strain gradient of ε_{mu} and $1.5\varepsilon_y$ with an axial force from the loading combination $D + 0.75L + 0.525Q_E$. Compression reinforcement is allowed to be included in determining the maximum reinforcement, whether laterally restrained or not. Except for very slender walls, maximum reinforcement will effectively control the maximum permissible axial force instead of the upper bound axial threshold prescribed to limit slenderness.

Conversely, CSA S304 has no maximum reinforcement requirement for non-slender walls ($kh/t \leq 30$) and the authors find this to be a sensible approach. Slender reinforced walls under low axial load are defined as "reinforced walls having a slenderness ratio kh/t greater than 30". In this case, Clause 10.7.4.6.5 states that the maximum area of reinforcement provided shall be less than or equal to that provided by the condition shown in Equation (1):

$$\frac{c}{d} \leq \frac{600}{600+f_y} \tag{1}$$

Note that TMS 402 includes axial load in determining the maximum reinforcement while CSA S304 does not for non-slender walls. In a direct comparison between the maximum reinforcement ratios for slender walls using Grade 400 (Grade 60) steel, the coefficient to determine ρ_{max} is $0.408\frac{f'_m}{f_y}$ and $0.291\frac{f'_m}{f_y}$ for CSA S304 and TMS 402, with c/d equal to 0.60 and 0.45, respectively. CSA S304 appears to allow 1.4 times as much reinforcement as TMS 402 for slender walls, but this does not account for material property differences. It should also be noted that, if the TMS 402 maximum compression strain value was to be increased from 0.0025 to 0.003 to match CSA S304, roughly a 10% increase could be achieved in the maximum reinforcement ratio.

SELECTED PARAMETRIC STUDIES

To quantify the differences between TMS 402 and CSA S304, the authors conducted several parametric studies to evaluate the impact of isolated parameters on the capacity of walls loaded out-of-plane. Depending on the context of the parametric study, soft conversions (e.g., CMU strength available in Canada versus CMU strength available in the US) or direct imperial-to-metric unit conversions (hard conversions) are used. For presentation purposes, when units are given in text or tables, both imperial and metric units are provided. Design charts are presented in metric units only as they involve direct comparison of the two provisions and unit equivalence and consistency is important.

Flexural Capacity Study

The first of these studies examined interaction diagrams for specific wall configurations as calculated with the TMS 402 and CSA S304 out-of-plane wall provisions. Canadian CMU size and strength, rebar size, and rebar strength are used, with all values hard-converted into SI units (Table 1) for insertion into both CSA S304 and TMS 402 equations. Variable parameters include: rebar spacing, rebar size, wall height and CMU strength. The authors also evaluated the effect of different CMU thicknesses but found that characteristic wall behaviour did not change as wall thickness varied, so those results are not included.

Table 1: Values Used in Flexural Capacity Studies

	Parameter	**Canada**	**US (hard conversion)**	**US code equivalent**
Constants used for all studies	Yield Strength of Steel (f_y)	400 MPa	58 ksi	
	Modulus of Elasticity of Steel (E_s)	200,000 MPa	29,000 ksi	
	Maximum compressive strain in masonry (ε_{mu})	0.0030	N/A	0.0025
	Face shell thickness	36.2 mm	1.43 in.	
	CMU thickness – Nominal	200 mm	8 in.	
	CMU thickness – Actual	19 mm	7.48 in	
Variables	Rebar spacing (for vertical bars)	200 mm, 600 mm, *1000 mm*, 1200 mm	7.48 in., 23.6 in., *39.4 in.*, 47.2 in.	
	Rebar size	*15M*, 25M		*No. 5*, No. 8
	Rebar area per bar	*200 mm^2*, 500 mm^2	*0.31 $in.^2$*, 0.76 $in.^2$	
	Wall height (h)	*3 m*, 4.6 m, 5.8 m	*9.84 ft*, 15.1 ft, 19.0 ft	
	Block strength	*15 MPa*, 20 MPa		*2,000 psi (13.8 MPa)*, 2,600 psi (17.9 MPa)
Note: *Underlined, italicized* values are considered to be the "baseline".				

Effect of Rebar Spacing and Effective Compression Width

Notable differences appear when the interaction diagrams of partially grouted walls loaded out-of-plane, as calculated by each Code, are overlaid on the same plot (Figure 1), when all underlined wall parameters in Table 1 are fixed and the rebar spacing is varied. Increasing rebar spacing to 1200 mm (47.2 in.) for the 20 cm (7.87 in.) CMU examined invokes the 4t effective compression flange width limitation of CSA S304 (previously discussed above), limiting the maximum effective flange width to 760 mm (29.9 in.). This causes a sharp discontinuity in the tension region of the interaction diagram, indicated with an arrow in Figure 1, that is not present in the TMS counterpart. For low axial force combined with high moment where the wall is tension-controlled, the stress block is so small that there is little difference between the flexural capacity calculated by CSA (ϕ_s=0.85) and TMS (ϕ=0.90), which highlights the significant impact that the 4t effective flange limit has on flexural capacity. Because S304 requires f'_m to reflect the different values from grout and CMU, and allows an effective (averaged) value to be used, there are discontinuity points where the compression depth goes past the face shell thickness, and then again where it becomes beneficial to take the entire compression area (face shell + grout) with effective f'_m rather than just the face shell with the higher f'_m, as indicated with an arrow in Figure 1.

The effect of the TMS 402 maximum reinforcement provisions is also seen, as reflected in Figure 1 as the diagram upper boundary. As the spacing decreases, or the amount of steel increases, the maximum axial load decreases. For a 600 mm spacing, the maximum axial load in TMS 402 is less than that in CSA S304 due to the maximum reinforcement provisions.

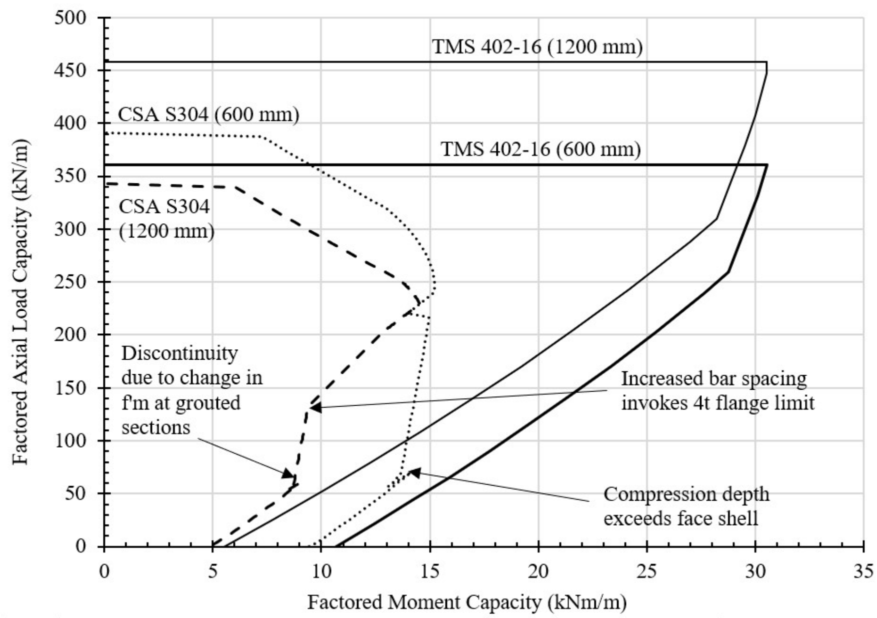

Figure 1: Effect of Variable Bar Spacing on Factored Capacity of Bearing Walls Loaded Out-of-Plane

Effect of Rebar Size

Using the baseline wall parameters underlined in Table 1, the interaction diagrams for two rebar sizes are plotted in Figure 2. Increasing the rebar area from 200 mm^2 (15M bar) to 500 mm^2 (25M bar) (0.31 in.^{2} to 0.77 in.^{2}, No. 5 to No. 8 bar) has a more pronounced impact on the maximum flexural capacity of the wall section calculated with TMS 402. Increasing the rebar size from 15M to 25M using TMS 402 provides a 135% increase in the maximum factored moment capacity (at 0 kN axial load), while the same rebar size increase using CSA S304 provides only a 76% increase. This is primarily due to the comparatively lower f'_m used in Canada for the same CMU strength, which results in a smaller internal lever arm and a smaller sensitivity to the area of steel.

The factored moment capacity increase resulting from the larger (25M) bar size is also truncated prematurely when bar spacing invokes the CSA 4*t* flange limitation, striking an almost asymptotic limit in this example wherein additional axial force does not provide a meaningful increase in moment capacity.

The maximum reinforcement provisions of TMS 402 again result in a reduced axial load capacity, as the area of reinforcement increases. For higher axial loads, a smaller size reinforcement provides more capacity in TMS 402. Although this is initially counter-intuitive, the smaller size reinforcement provides more ductility.

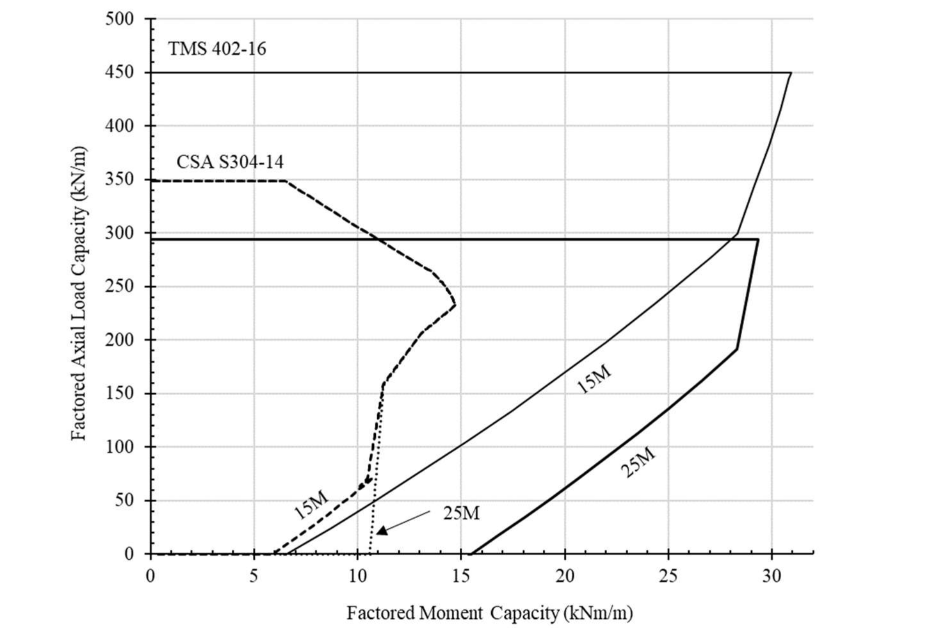

Figure 2: Effect of Variable Bar Size on Factored Capacity of Bearing Walls Loaded Out-of-Plane

Effect of Wall Height

Figure 3 illustrates the reduction in maximum factored axial load capacity correlated to wall height-to-thickness ratio increase, as previously discussed. The slenderness axial cap of the interaction diagram, as determined using TMS 402 Section 9.3.4.1.1, gradually decreases with wall height. However, the maximum reinforcement provisions of TMS 402 generally control. In this example, the maximum reinforcement provisions would control for $h/t < 32.8$. Note that the maximum axial limit in TMS 402 is a small function of the live to dead load ratio, and a value of L/D = 0.50 is used in this paper. Some variation would occur with differing load source composition.

Also, shown in Figure 3 are the axial limits for using the slender wall method in TMS 402 Section 9.3.5.4.2. There is a dramatic drop for $h/t > 30$ wherein the maximum axial stress due to strength level axial loads is limited to $0.05 f'_m$. There is a similar sudden dramatic drop in axial capacity for $h/t > 30$ with CSA S304 where the axial load is limited to $0.06 f'_m$. However, TMS 402 has alternate design methods for $h/t > 30$, where the moment magnification method or a second-order analysis could be used. For this relatively heavily reinforced wall, TMS 402 maximum reinforcement provisions are the limiting criterion for axial load.

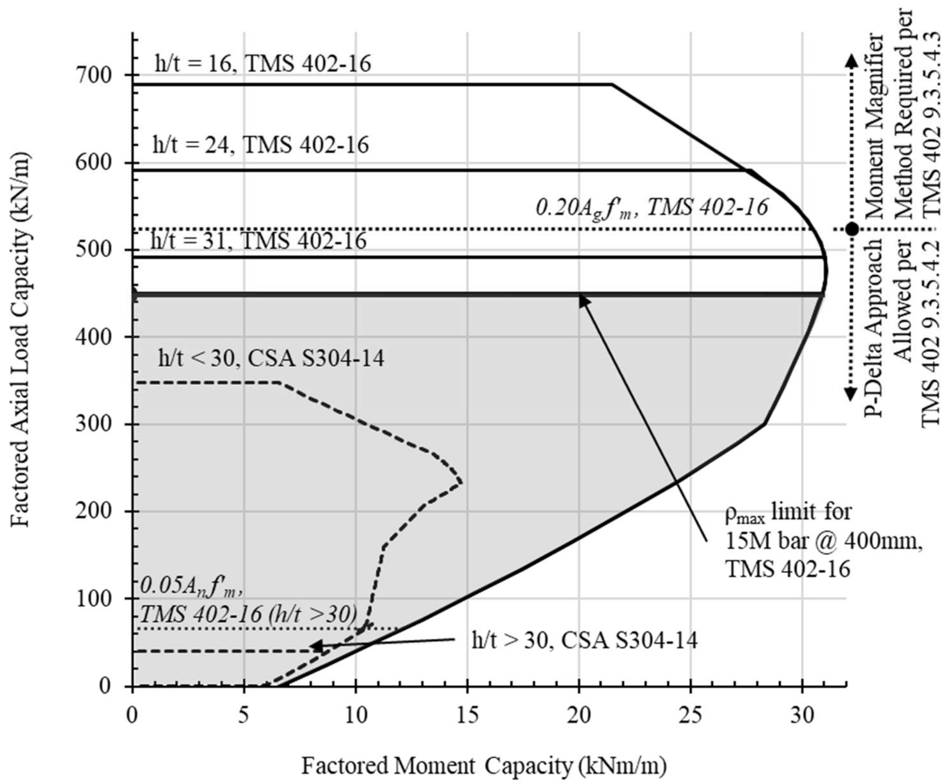

Figure 3: Effect of Variable Wall Height on Factored Capacity of Bearing Walls Loaded Out-of-Plane

Effect of f'_m

With the rebar spacing reduced to 200 mm on center, the trial wall becomes fully grouted. Figure 4 highlights the differences in CMU strength available for design, plotted using f'_m for TMS 402, and $f'_{m,eff}$ for CSA S304. This graph highlights the restrictive effect of the TMS 402 maximum reinforcement provisions for heavily reinforced walls on the permitted axial load. It also highlights that modest increases in the compressive strength, f'_m, can have a significant impact on the maximum reinforcement provisions.

Stiffness Study Highlights

Several differences in the calculation I_{cr} exist between the provisions of CSA S304 and TMS 402, and the most impactful of which are highlighted below.

Effect of using "c" versus "kd" in I_{cr} equations

CSA S304 uses a neutral axis location based on a linear stress distribution. This results in smaller cracked section moments of inertia (I_{cr}) values than what would be if ultimate strain/stress distributions were considered with a neutral axis depth of c. A 15% increase in I_{cr} is possible by using c instead of kd. TMS 402 uses a nonlinear stress distribution for these calculations and also includes the effect of axial load. The effect of axial load on I_{cr} is less than 5% for typical single-story masonry buildings but can be much higher for multi-story loadbearing masonry buildings.

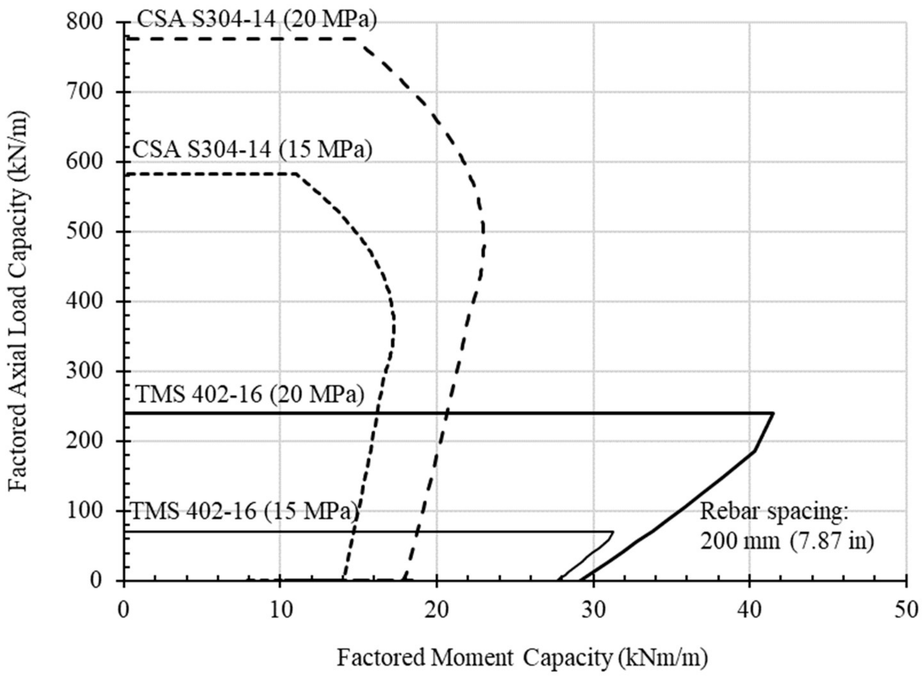

Figure 4: Effect of Block Strength on Factored Capacity of Bearing Walls Loaded Out-of-Plane

Figure 5 shows the change in the moment magnifier, $\left(\frac{1}{1-{P_f}/{P_{cr}}}\right)$, for different percentage increases in I_{cr}. Because $P_{critical}$ is proportional to I_{cr}, any increase in I_{cr} is the same increase in $P_{critical}$. Although these are not transformational changes, using I_{cr} based on c instead of kd, and using the TMS deflection equation for slender walls in CSA S304 (instead of the current equations), would result in an approximate 30% increase in I_{cr}. This, in turn, will reduce the secondary moment effects when using the magnifier and will decrease the total factored moment that the wall must resist. As the slenderness of the wall increases and the secondary moment effects increase, increasing I_{cr} would create potential reductions in the amount of vertical reinforcement needed; therefore, the authors have identified this as an area of future research work.

Effect of b on I_{cr}

The 'b' value used in a Canadian equation for I_{cr} will be lower than the 'b' value used in the TMS 402 equation because of the $4t$ (actual) versus $6t$ (nominal) requirement that defines the effective compression zone. For a wall with large enough bar spacing to trigger this difference (>$4t$), a design under TMS 402 would have a higher I_{cr}, hence less deflection, and, therefore, lower moment. Note that the effect of this will vary based on the axial load at the section under consideration; at lower axial loads I_{cr} is dominated by the contribution from steel rather than masonry, so this factor is less of a concern for that condition.

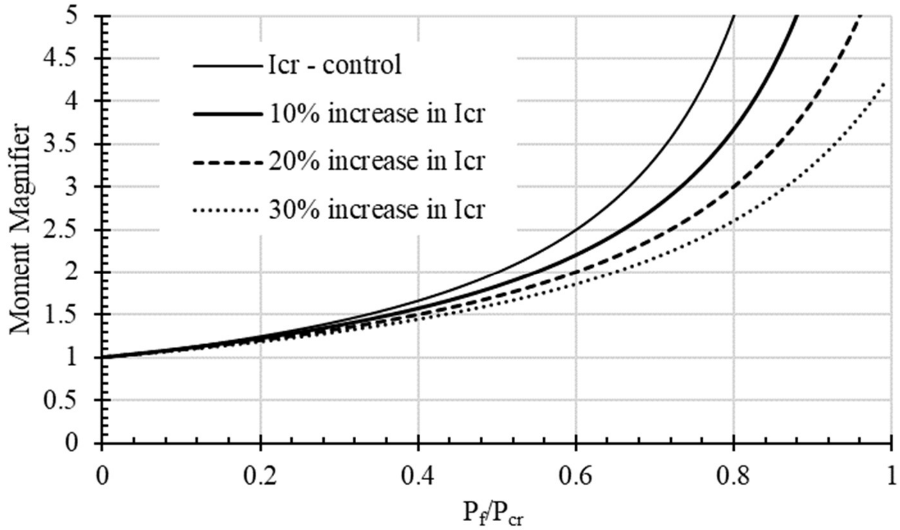

Figure 5: Change in Moment Magnifier with Respect to Increase in I_{cr}

RECOMMENDATIONS

This study revealed a number of research needs and elucidated opportunities for future Code changes that would not only harmonize the provisions of CSA S304 and TMS 402 but also improve the efficiency of masonry wall designs for out-of-plane loading. The authors identified the following research needs and Code changes, for CSA S304 and TMS 402 individually, as well as common needs that apply to both:

CSA S304-Specific Research Needs and Code Changes

- f'_m and ϕ_m: The procedures outlined in the CSA S304 for testing masonry prisms are fundamentally different than the long-accepted means used in American design through the ASTM. This makes it prohibitive to test for masonry strength, and results in strengths that are substantially less than those used in American design with no apparent difference for design of members that would otherwise account for this. Furthermore, the use of a phi-factor on the prism strength to account for system defects adds a compounding effect to the already-reduced masonry strength. The fundamental philosophy behind the current prism strength procedures and the derivation and application of the masonry phi factor must be re-examined.
- Moment Magnifier and ϕ_{er}: The presence of a stiffness reduction factor in CSA S304 increases the secondary moment significantly. CSA S304 could benefit from reducing the conservatism in determining moment magnifiers.
- The effective compressive width: TMS 402 suggests least of: a) center-to-center bar spacing, and b) 6t (nominal), or 72 inches (1829 mm). CSA S304 limits to 4*t* (actual). CSA S304 is

conservative, but some research [4] shows even the TMS 402 limitation may also be conservative. Limits need to be based on rational analysis and experimental evidence, likely leading to possible design conditions where different effective compression zone widths could be applied, in lieu of a blanket statement for all walls.

TMS-Specific Research Needs and Code Changes

- ρ_{max} : The maximum reinforcement requirements in TMS 402-16 are very limiting. As a result, some or all practicing engineers may switch to the alternative provisions, namely the Allowable Stress Design (ASD) requirements, especially when designing tall, special reinforced masonry walls. This switch can require more reinforcement, which is not very rational.
- Maximum compressive strain: Two values, 0.0025 and 0.0035, are used for concrete masonry and clay masonry, respectively. The Code can benefit from using 0.003 for all masonry, similar to CSA S304, backed by a research program.
- Slenderness vs. Minimum Eccentricity: TMS 402 might examine the benefits of adopting an accidental eccentricity approach rather than the current slenderness term. This would retain the current intent because the accidental eccentricity will get moment-magnified and still serve as a slenderness guard at the top of the interaction diagram while also accounting for accidental eccentricity (e.g., due to construction tolerance mistakes) at the bottom of the interaction diagram.
- Moment Magnifier: TMS 402 uses the cracked moment of inertia (I_{cr}) conservatively for the entire wall height when determining the reduced stiffness for second order effects for the moment exceeding the cracking moment. It may be better to use a reduced I_{eff} (such as $0.75I_{eff}$) or other approach rather than using I_{cr} for the entire wall height.
- Effective mortared area: CSA S304 allows the use of a larger face shell thickness for flexure calculations, called the effective mortared area, which increases the available compressive area considerably for partially grouted walls. In contrast, TMS 402 requires the use of a *minimum* face thickness for all flexural calculations. TMS 402 should consider adopting an effective face shell thickness to be used in flexural calculations.
- Effective f'_m: TMS 402 could consider adopting an effective f'_m because grout strength need only match the assembly strength and is less than the unit strength for values over 13.8 MPa (2000 psi). When the neutral axis falls within the face shell, as is commonly the case for OOP walls, using a higher f'_m for the face shell in compression would yield a limited increase in flexural capacity.

Common Research Needs and Code Changes (CSA S304 and TMS 402)

- Cracked/Effective Cross-Section Determination: In CSA S304, slenderness effects, I_{cr}, and EI_{eff} significantly impact the deflected shape and moment force magnification in the moment magnifier method but could benefit from simpler, more user-friendly equations, backed by research/experimental results. This research should likely be done as a collaboration between U.S. and Canadian researchers to leverage resources, especially with its roots in universal fundamentals of engineering mechanics.

- Slender Walls: Both standards impose limits on axial load when the h/t ratio is equal to or greater than 30. Most consider these limits conservative (probably more so for CSA S304) but have a long-standing historical foundation that makes them difficult to adjust.
- Minimum eccentricity:

a. CSA S304 has a minimum eccentricity requirement and a P_{max} limit that technically does not allow walls in pure axial compression. While this makes sense and it is conservative, the language is a little confusing and should be cleaned up.

b. TMS 402 (technically/in reality) does not have a minimum eccentricity requirement (other than that included in second order effects), but there is a confusing, and potentially inaccurate, commentary statement (9.3.4.1.1) that suggests one of the "0.8" coefficients in TMS 402 equations 9-15 and 9-16 account for this. This needs to be revisited.

CONCLUSIONS

The differences between the CSA S304 and TMS 402 Codes are broad, varied, and pervasive. Separating out each variable's effect on out-of-plane masonry wall capacity is complex, as each parameter affects multiple aspects of design capacity with variable degrees of significance. However, the most significant variables causing differences in out-of-plane capacity between the two Codes are: conservative f'_m values in CSA S304, different ϕ factor methodologies, conservative compression flange effective widths, differences in the calculation of I_{cr}, and the restrictive maximum reinforcement ratio in TMS 402. The research needs described above provide suggested 'next steps' for research that will facilitate changes to CSA S304 and TMS 402 with an eye towards improved harmonization between the two Codes while also improving the convergence of rational design methods that accurately predict strength and behavior of masonry assemblages.

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Team Canada	Team USA
Bennett Banting, Canada Masonry Design Centre	Richard Bennett, University of Tennessee
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David Stubbs, Canada Masonry Design Centre	Jason Thompson, National Concrete Masonry Association

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