CANUS Project: Key Takeaways

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What is CANUS?

Canada/US (CANUS) collaborative project: Harmonization of Canadian and American Masonry Structures Design Standards

Project Goals:

1. Identify the similarities and differences in design considerations for reinforced concrete masonry structures
2. Improve the masonry design provisions in both countries
3. Identify future research needs towards that goal

Sponsors:

- National Concrete Masonry Association (NCMA) foundation
- Canadian Concrete Masonry Producers Association (CCMPA)
- Canada Masonry Design Centre (CMDC)
- Canadian Standards Association (CSA)

Team Members

Extensive collaborative work of a team of practicing engineers and academics from U.S. and Canada

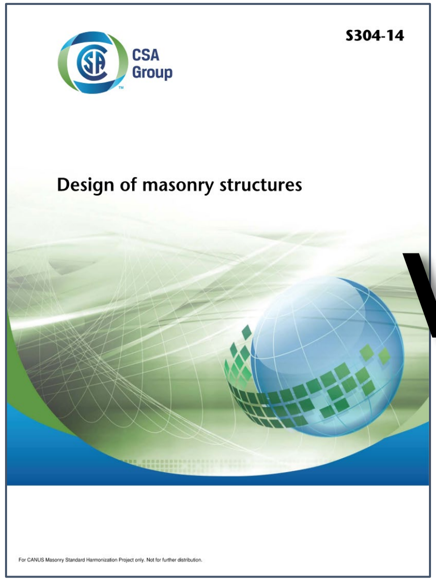
Team Canada	Team USA
Bennett Banting, CMDC	Jason Thompson, NCMA
Hélène Dutrisac, CMDC	Ece Erdogmus, Georgia Tech
Bart Flisak, Crosier, Kilgour & Partners Ltd.	Richard Bennett, University of Tennessee
Kevin Hughes, Tacoma Engineers	Lane Jobe, Miller Consulting Engineers
Carlos Noguez University of Alberta	Phillippe LeDent, Masonry Institute of Michigan
Clayton Petit, University of Alberta	Russ Peterson, Ensoltech
David Stubbs, CMDC	Heather Sustersic, Colby Company Engineering

What's in the scope?

- Limit state design of CSA S304-14 and strength design methodologies TMS 402-16
- Reinforced **<u>concrete</u>** masonry <u>only</u>
- Seismic design categories and related prescriptive methods
- 3 levels: 1) side-by-side code comparison, 2) parametric studies, 3) archetype design comparison
- Three structural member categories: Beams, OOP Walls, IP Walls

What is <u>out</u> of scope?

- Unreinforced masonry
- Clay masonry
- Autoclaved aerated concrete (AAC)
- Glass
- High wind loads



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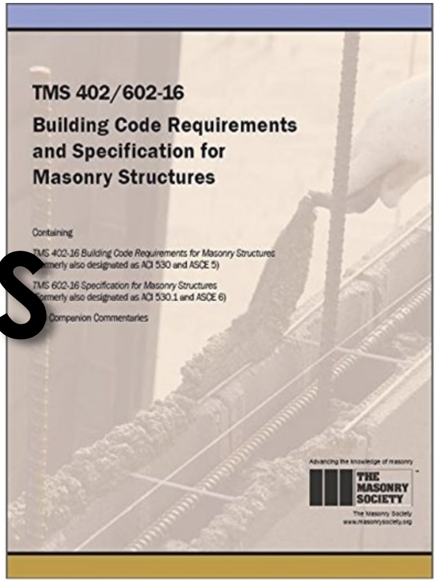


Clauses 10 & 16

Chapters 7 & 9

Geometrical and Section Properties

- Area:
  - Hollow: CAN > U.S. by 12 %
  - Solid: U.S. > CAN by 2%
- Moment of Inertia
  - Hollow CAN> U.S. by 3.3%
  - Solid U.S. > CAN by 6%

Section Properties of Walls Constructed of 20 cm Units (Canada)

Nominal Unit Size	Cross Section Type	Effective Mortared Area, A_e	Moment of Inertia, I_o	Section Modulus, S_e
		in.^{2}/ft	in.^{4}/ft	in.^{3}/ft
20 cm	Hollow	34.2	319.3	85.4
	Solid	89.8	418.9	112.0

Section Properties of Walls Constructed of 8-inch Units (U.S.)

Nominal Unit Size	Cross Section Type	Net Area, An	Net Moment of Inertia, In	Net Section Modulus, Sn
		in.2/ft	in.4/ft	in.3/ft
8 inch (203 mm)	Hollow (face shell)	30.0	308.7	81.0
	Solid	91.5	443.3	116.3

Typical Block Strengths & f'_m

Canada (per CMDC)

- **15 MPa block**: approximately 80% of projects ($\rightarrow f'_m$ = **1,088 psi**)
- 20 MPa block: approximately 10% of projects
- 25 MPa block: approximately 5% of projects
- 30 MPa block: approximately 5% of projects

U.S. (per NCMA)

- $\mathbf{f'_m \leq 2000}$ **psi**: ~ 75% of projects
- $f'_m \leq 3000$ psi: ~ 90% of projects
- $f'_m \leq 4000$ psi: ~ 100% of projects

Block strengths:
→ 8% advantage Canada (2,175 psi in Canada versus 2,000 psi in the U.S.)

***f'*$_m$:**
→ **84%** advantage U.S (**1,088 psi** in Canada versus **2,000 psi** in the U.S.)

Modulus of Rupture/Tensile Strength

	f_t per CSA S304-14 (psi) **Mortar type**		f_r per TMS 402-16 (psi) **Mortar Type**	
	S	**N**	**M or S**	**N**
Fully grouted hollow units Parallel to bed joints	124	80	267	200
Fully grouted hollow units Normal to bed joints	94.3	72.5	163	158

Comparison of Material Properties

Material Property	Units	TMS 402-16	CSA S304-14	Ratio (CAN/US)
f_m	psi	2,000	1,088	**0.54**
E_m	ksi	1,800	928	**0.51**
ε_{mu}	psi	0.0025	0.003	**1.20**
f_r – Parallel to Joint-Type S Mortar	psi	267	124	**0.46**
f_r – Parallel to Joint-Type N Mortar	psi	200	80	**0.40**
f_r – Perpendicular to Joint-Type S Mortar	psi	163	94.3	**0.58**
f_r – Perpendicular to Joint-Type N Mortar	psi	158	72.5	**0.46**
f_y	ksi	60	58	**0.97**
E_s	ksi	29,000	29,000	**1.00**
ε_y	-	0.002	0.002	**1.00**
Modular Ratio ($n = E_s / E_m$)	-	16.10	31.37	**1.95**

Material & Strength Reduction Factors

CSA S304-14→ Material strength reduction	TMS 402-16 → Strength reduction
4.3.2.1 Masonry Compression, tension, shear, and bearing in masonry shall be taken as **ϕ_m = 0.60**	**9.1.4.4 Combinations of flexure and axial load in reinforced masonry** **ϕ =0.90**
4.3.2.2 Reinforcement **ϕ_s = 0.85** for reinforcing bars	**9.1.4.5 Shear and Shear-Friction** **ϕ = 0.80**

TMS 402/602- **2022** has now a variable ϕ for flexure!

Sample Parametric Studies

Out-of-plane load resisting walls (OOP)

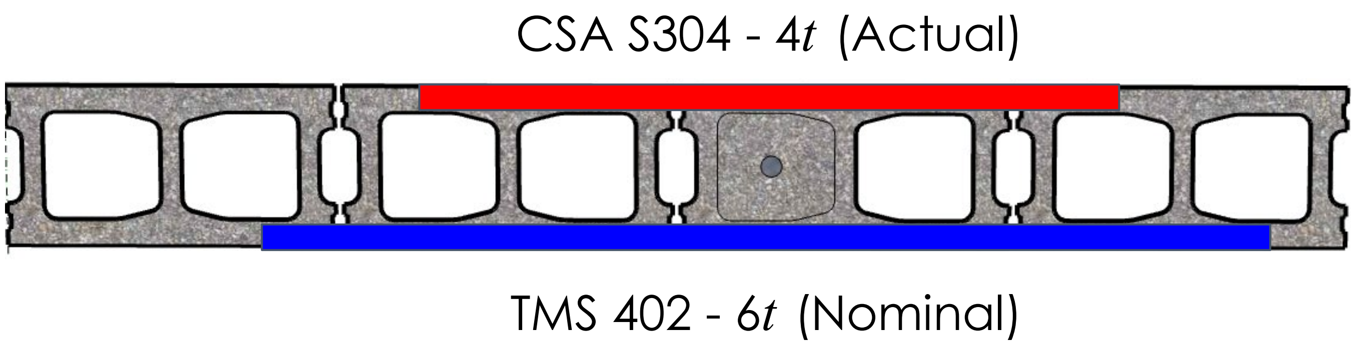
OOP: Compressive Area Comparison

Canada

- Effective Compression Zone Width is 4*t* (Actual)

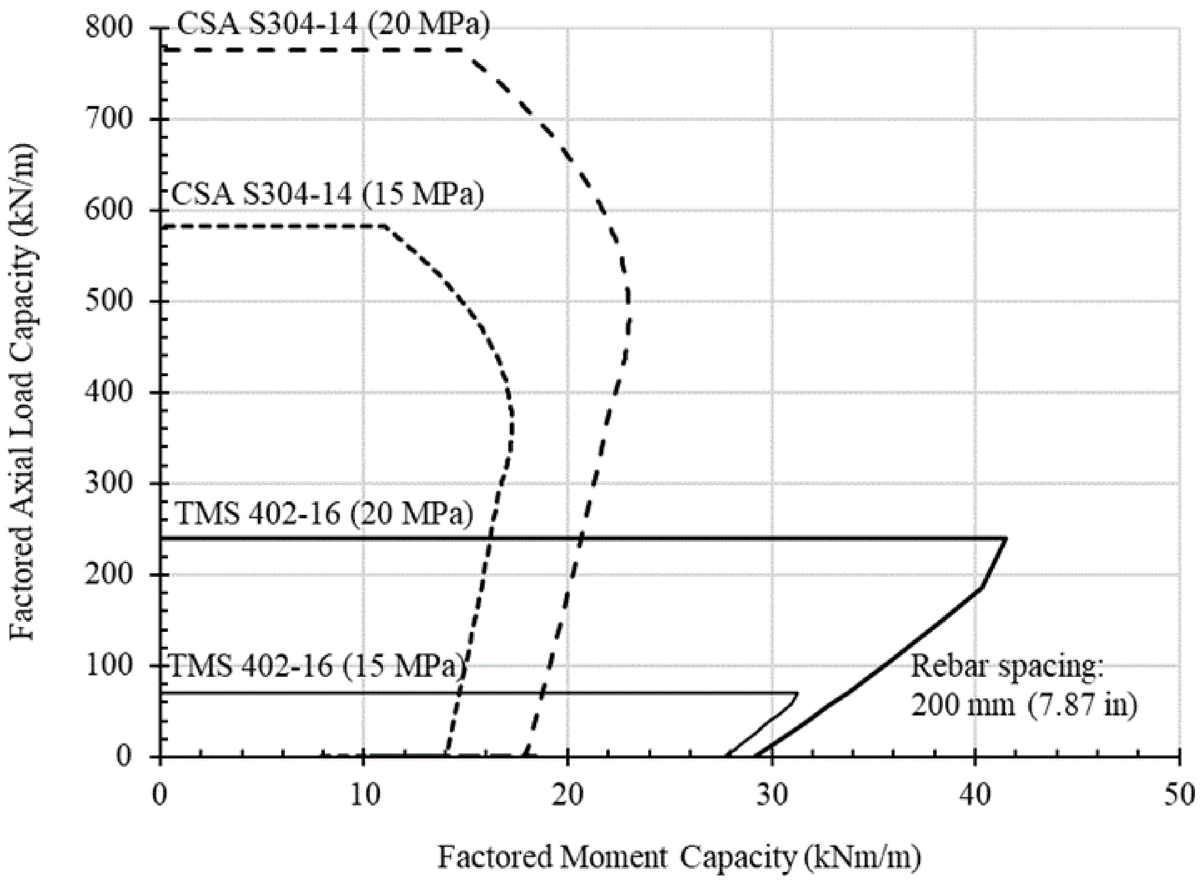
USA

- Effective Compression Zone Width is 6*t* (Nominal)



Using a Compression Zone Width of 4*t* (actual thickness) instead of 6*t* (nominal thickness) has a ***significant impact on flexural capacity*** and a moderate impact on secondary moment calculations.

OOP: Combined Effects of f'_m and Max Reinforcement



Effect of Block Strength (& f'_m) on Factored Capacity of Bearing Walls Loaded Out-of-Plane

In-plane load resisting shear walls

Shear Walls

CSA 304-4 Cl. 10.2.8 Moment-arm reduction

Squat walls ($h_w/l_w < 1.0$):

→shall be designed with a reduced moment arm between the compression zone and the tensile reinforcement

→effective depth, *d* set as $0.67l_w$ of the section depth, but not greater than $0.7h_w$.

No such provision in TMS 402-16

Shear Walls

<table>
<tr><th>Height of wall (h_w)</th><th>Length of Wall (ℓ_w)</th><th>Aspect Ratio (h_w/ℓ_w)</th><th>Squat per CSA S304-14?</th></tr>
<tr><td rowspan="3">118 in.</td><td>31.5 in.</td><td>3.75</td><td>No</td></tr>
<tr><td>126 in.</td><td>0.94</td><td rowspan="2">Yes: Consider Clause 10.10.2.2 and use reduced moment arm</td></tr>
<tr><td>480 in.</td><td>0.25</td></tr>
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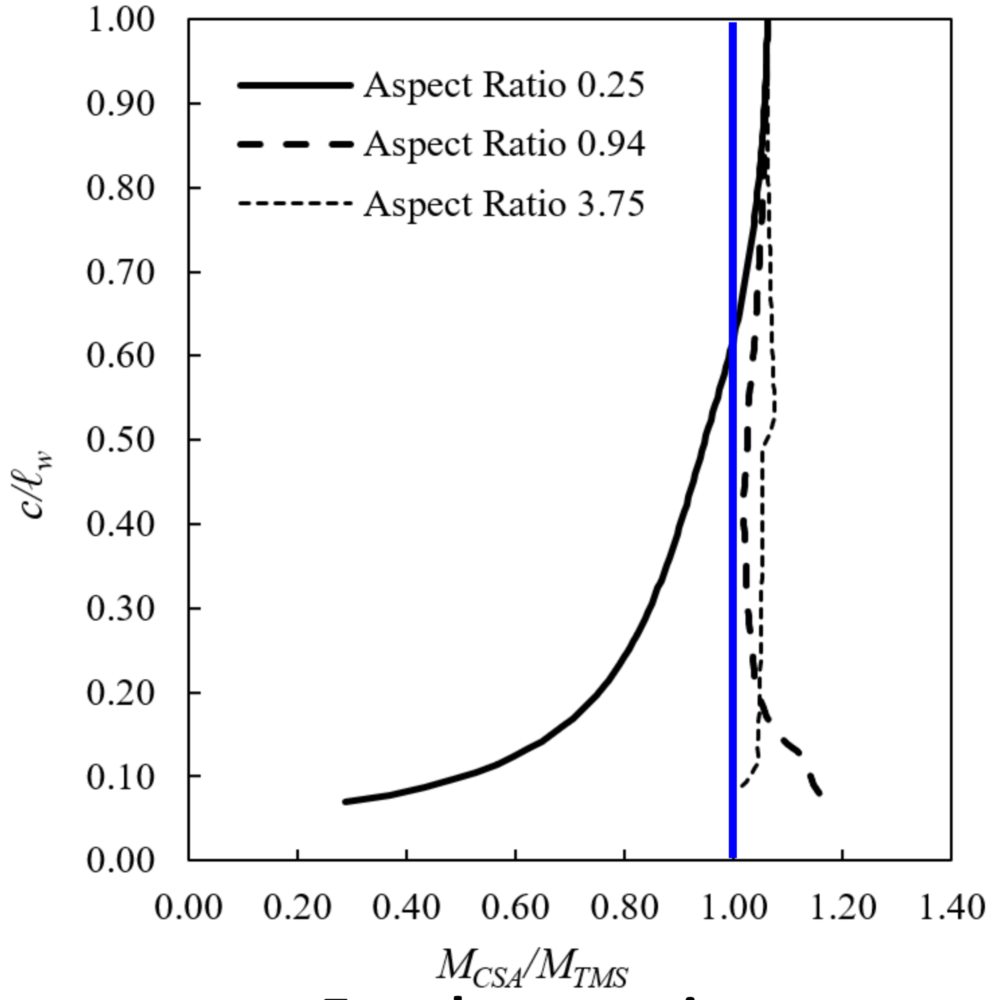
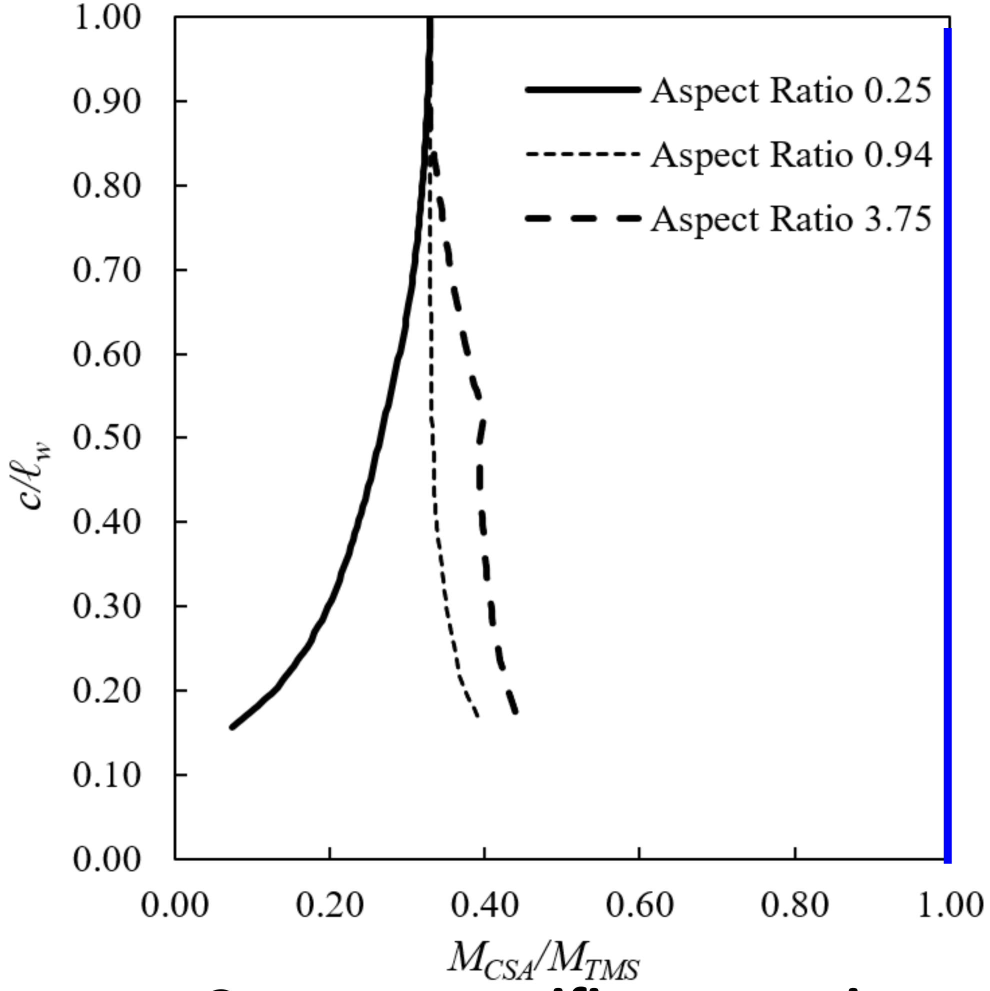
Shear Walls

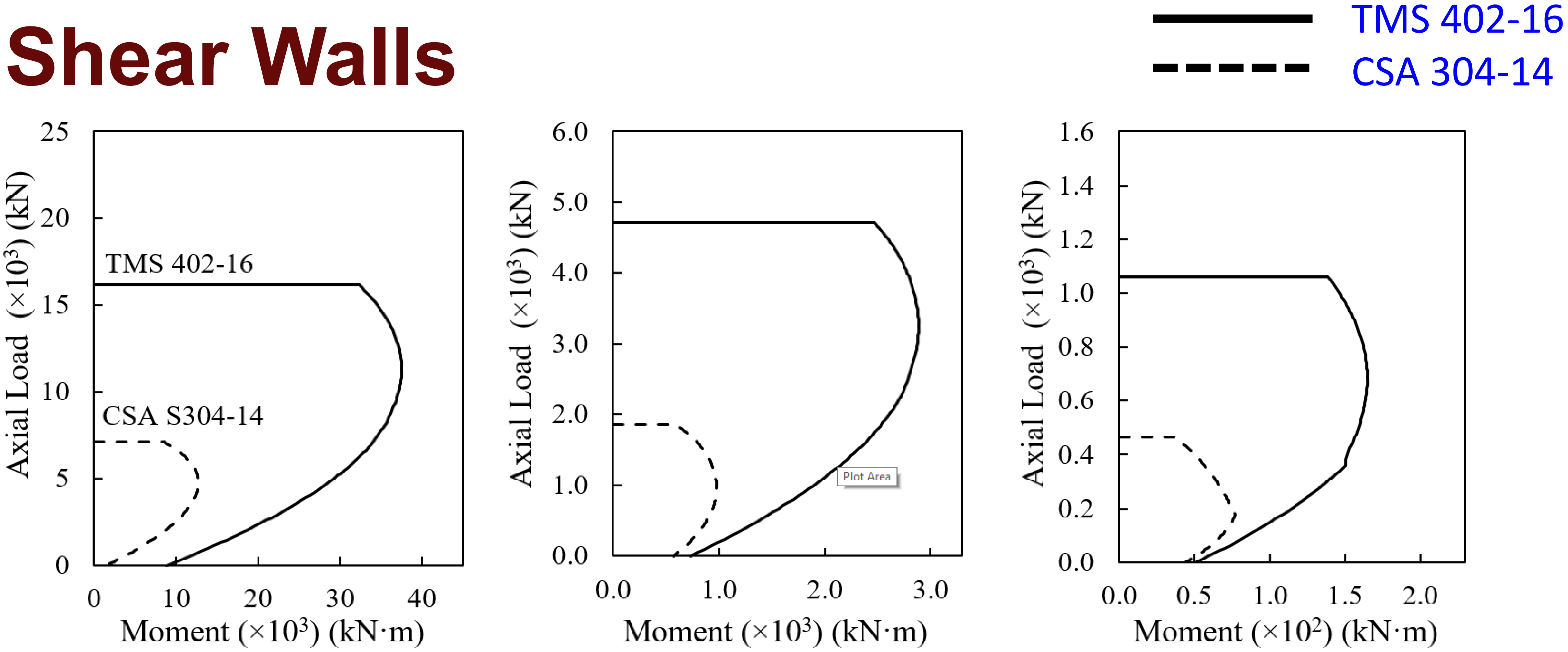


Equal properties



Country-specific properties

Shear Walls



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

Country-specific properties

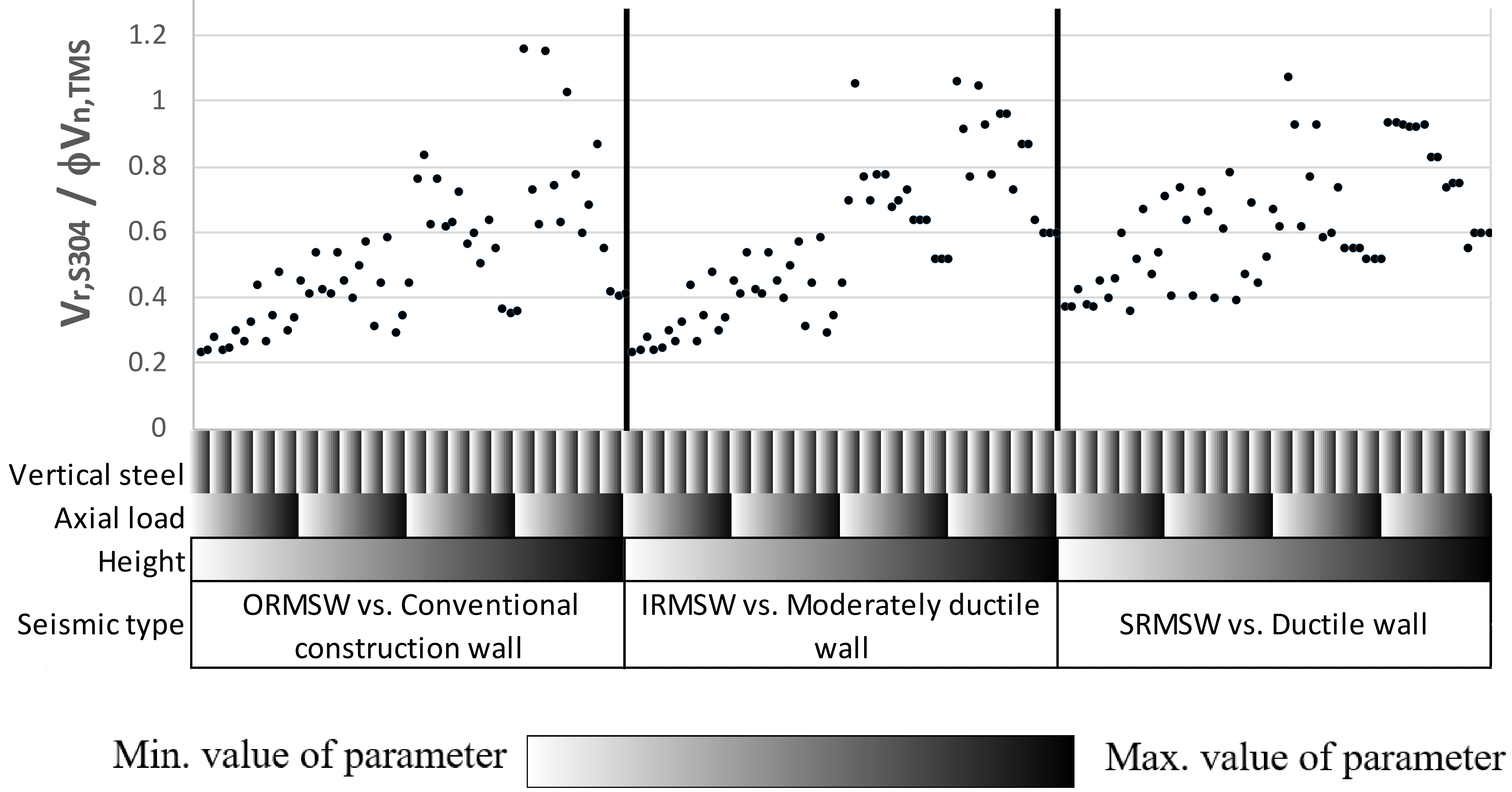
Seismic Provisions

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

Seismic response

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., 15 ft., 25 ft., 33.33 ft.
Vertical rebar size and spacing	15M@203 mm, 15M@406 mm, 15M@610 mm	#5@8 in., #5@16 in., #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	Conventional Construction Moderately Ductile Walls Ductile Walls	ORMSW IRMSW SRMSW

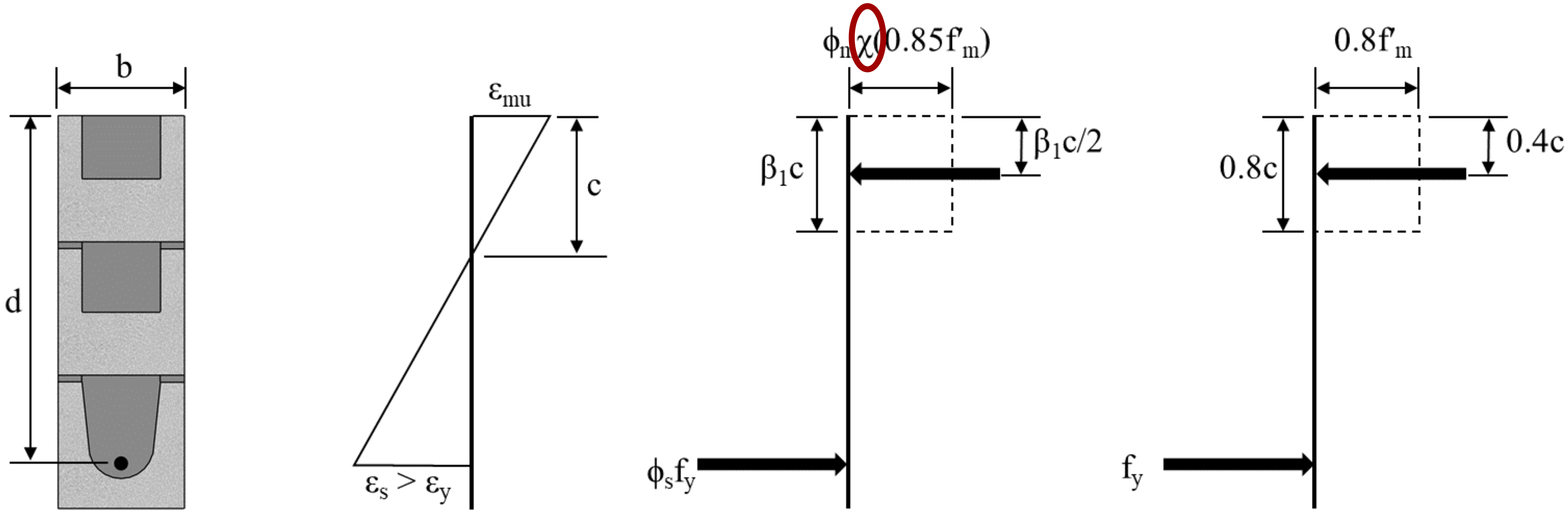
Shear Capacity Comparison – Country-specific properties



Masonry Beams

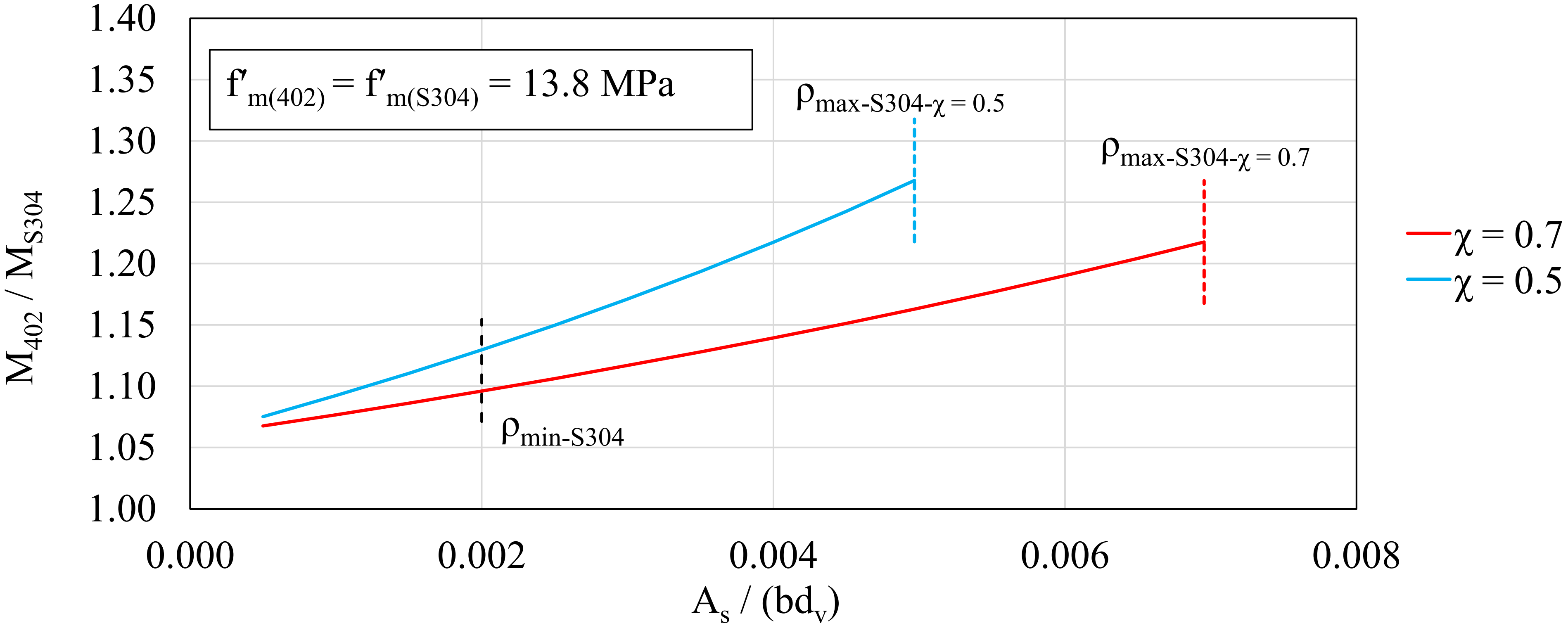
Beams

Flexure – stress block

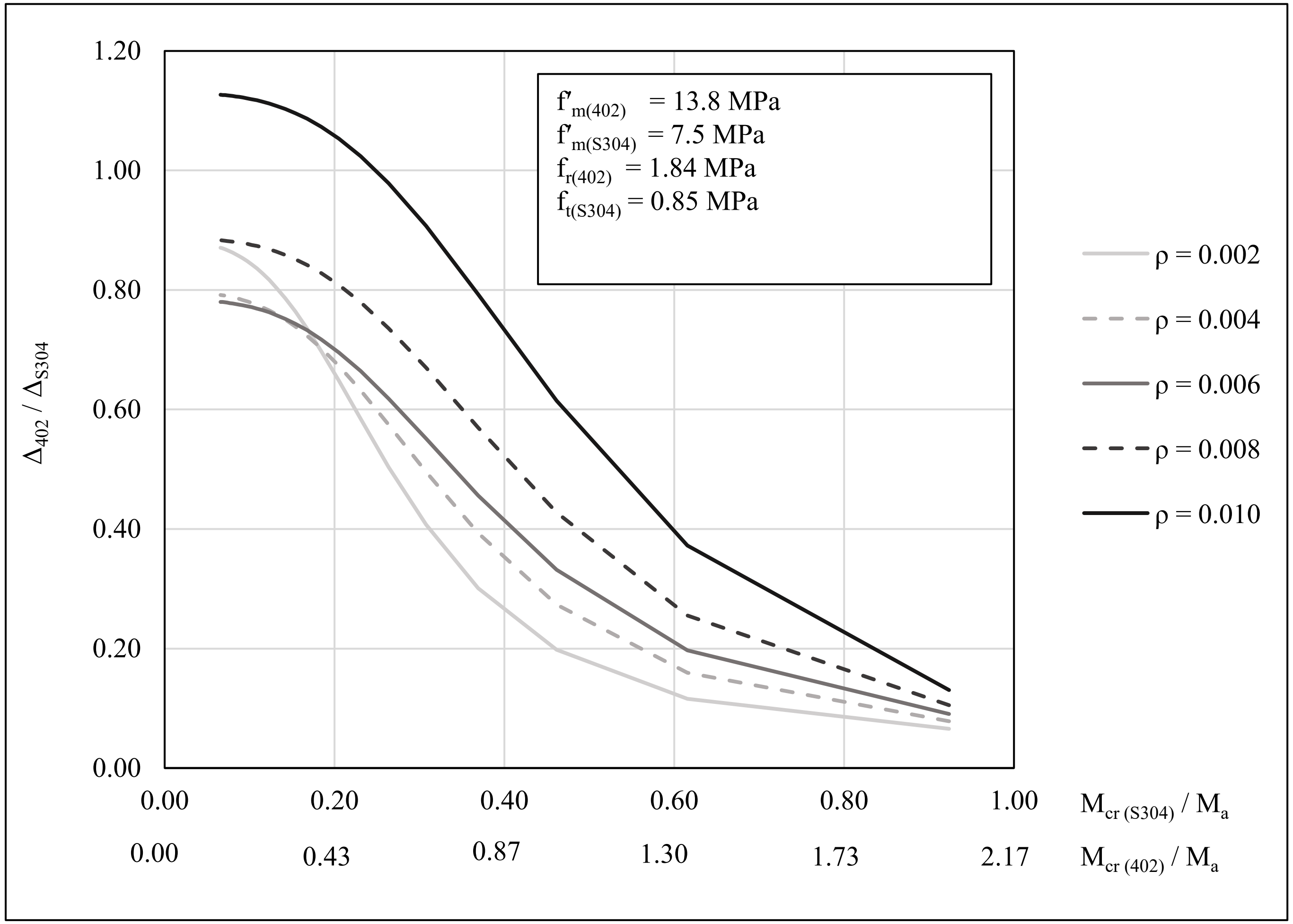


Beams

With equal *f'ₘ*, flexural capacity of US beams are 5-30% higher



Beams



Deflection comparison when all parameters are set to country specific values:

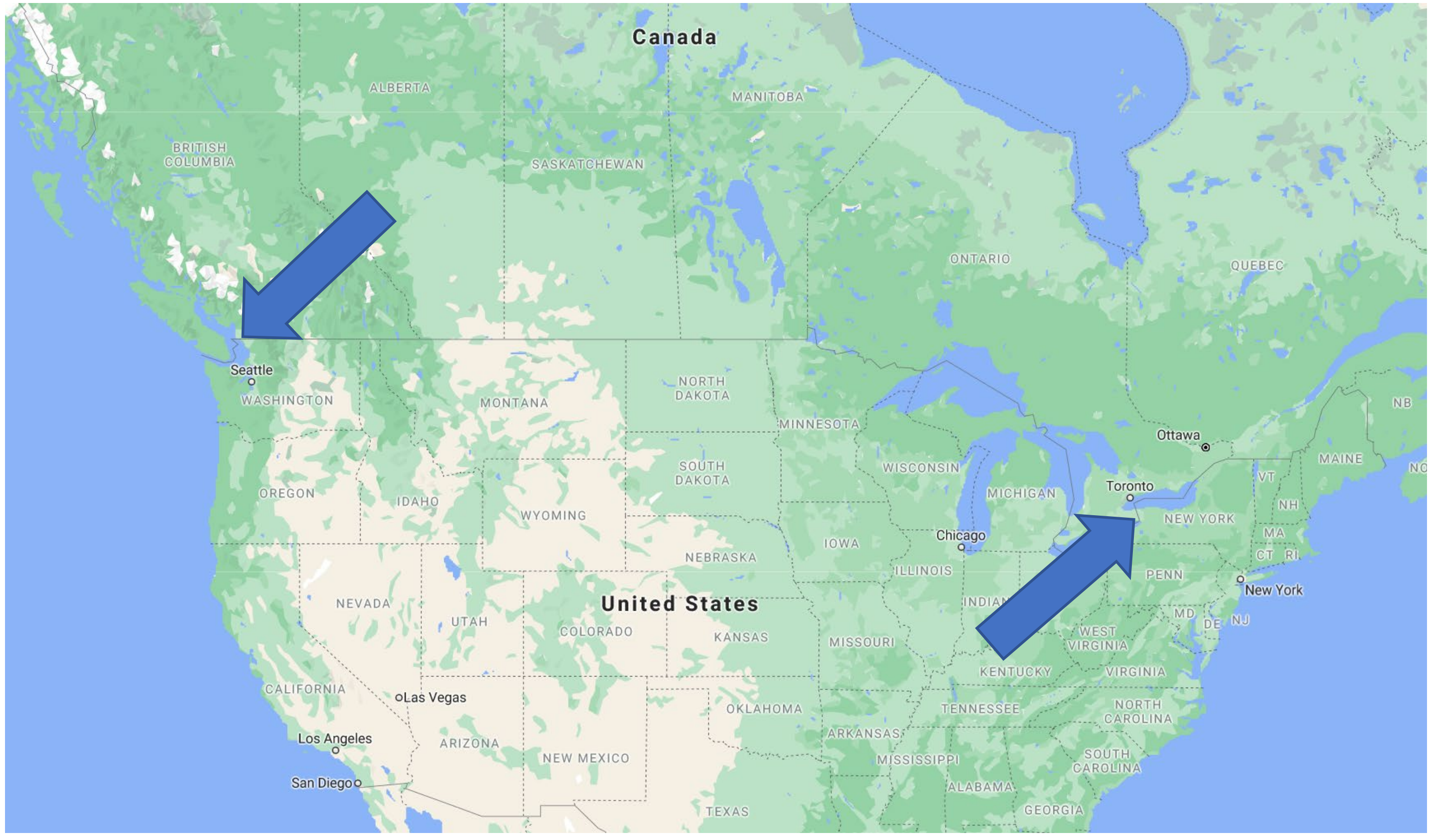
Deflections predicted by TMS402 are up to 90% smaller!

Design Examples/Archetypes

Baseline Parameters

Selected two locations near the U.S./Canadian border – one east and one west.

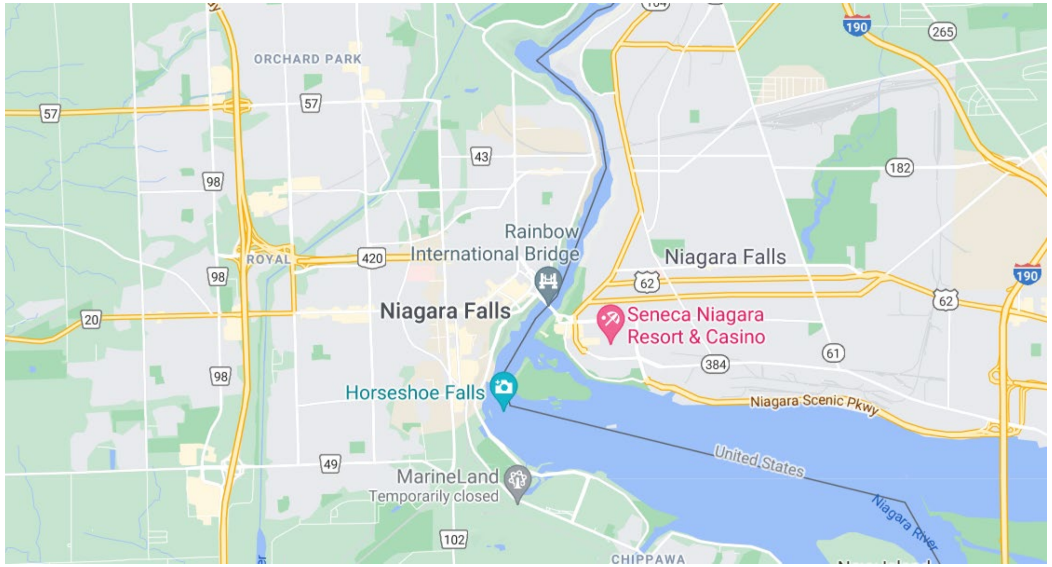
Environmental design loads should be very similar at each location.

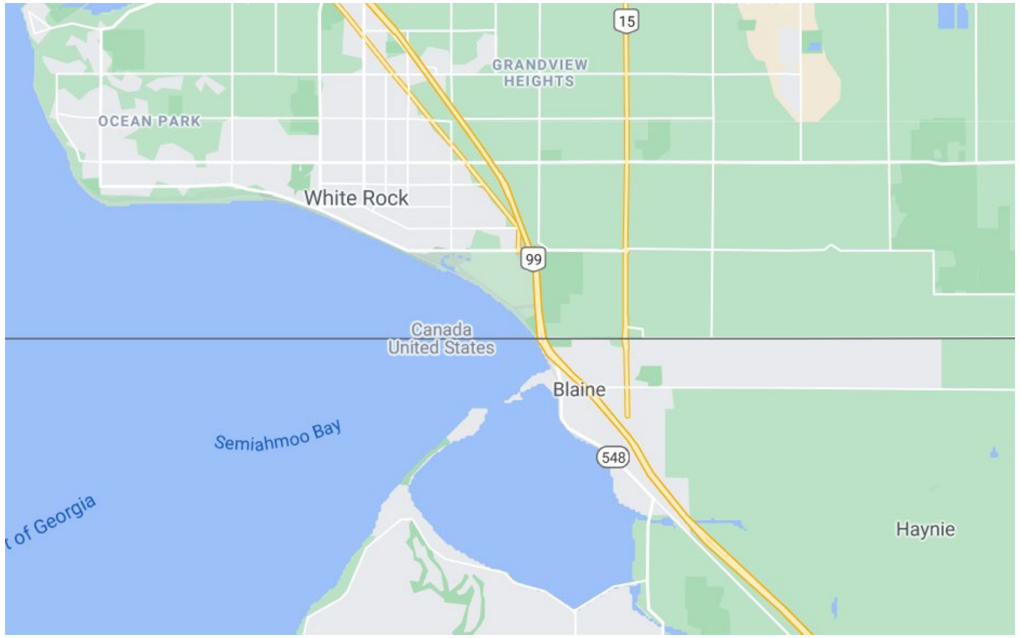


Baseline Parameters

Typical masonry buildings were designed at each location using the respective governing building code.

- Wind Governed
  - Niagara Falls, OT
  - Niagara Fall, NY
- Seismic Governed
  - White Rock, BC
  - Blaine, WA

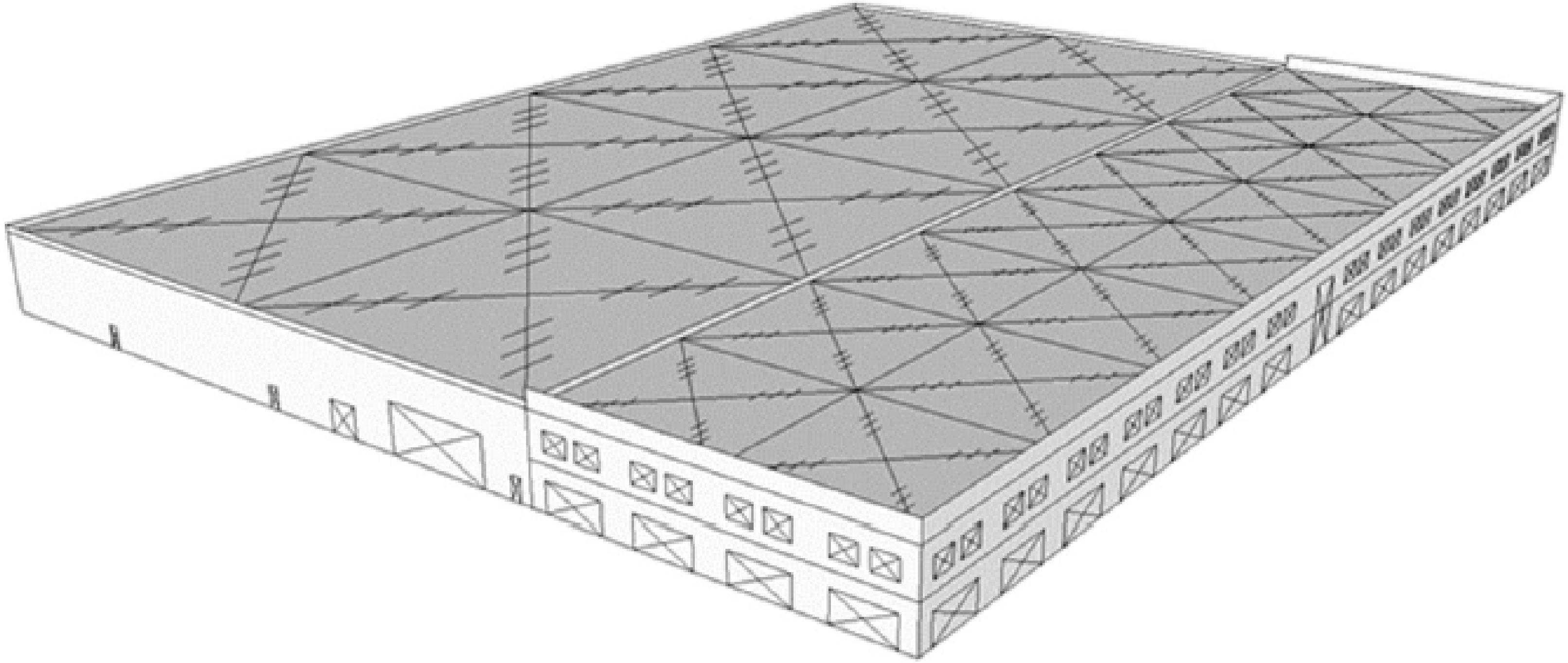




Baseline Parameters

Two buildings analyzed at each location:

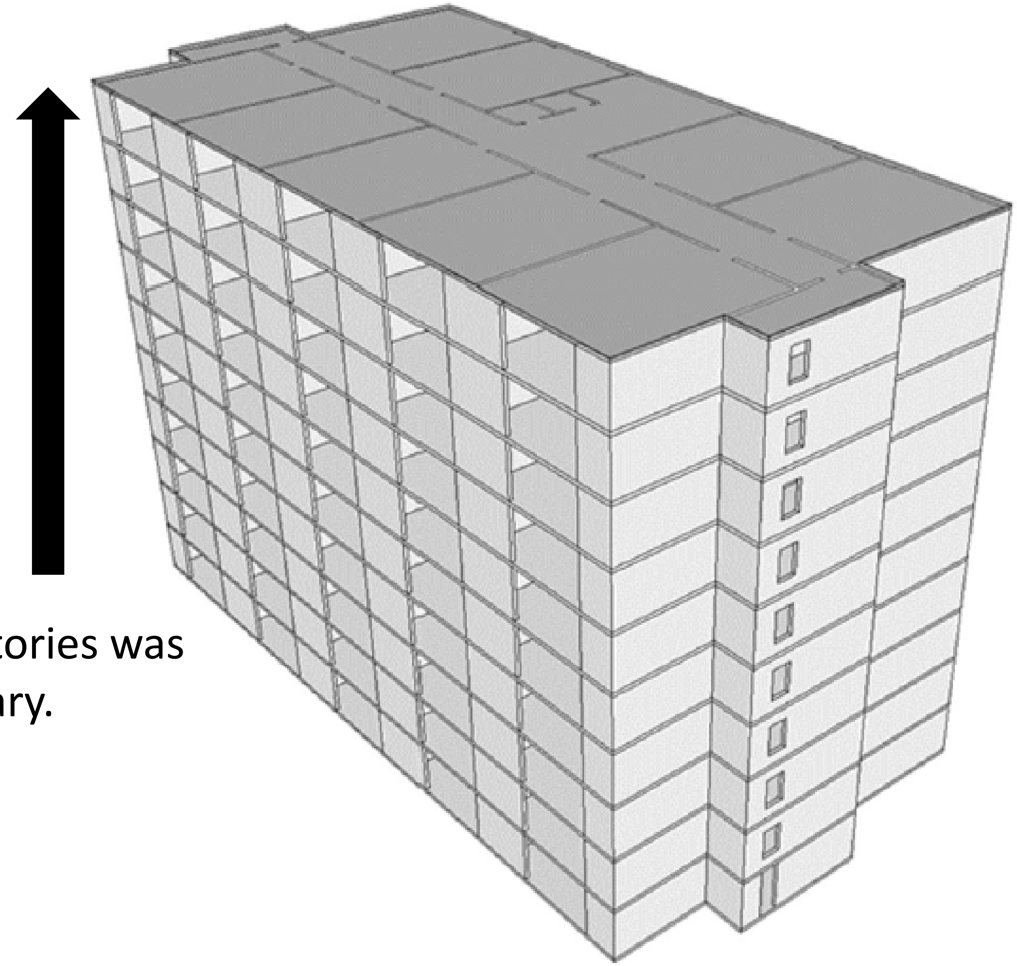
- Warehouse/Office



Baseline Parameters

Two buildings analyzed at each location:

- Warehouse/Office
- Multi-Family Residential

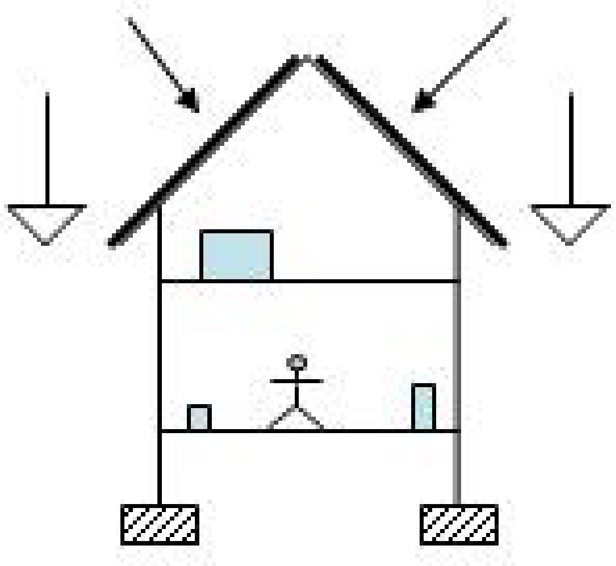


Number of stories was allowed to vary.

Design Criteria

Design loads were determined using the 2015 NBCC for the buildings on the Canadian side of the border and ASCE 7-16 on the U.S. side.

Nothing particularly interesting or different in how dead and live loads were taken into account or their magnitudes.

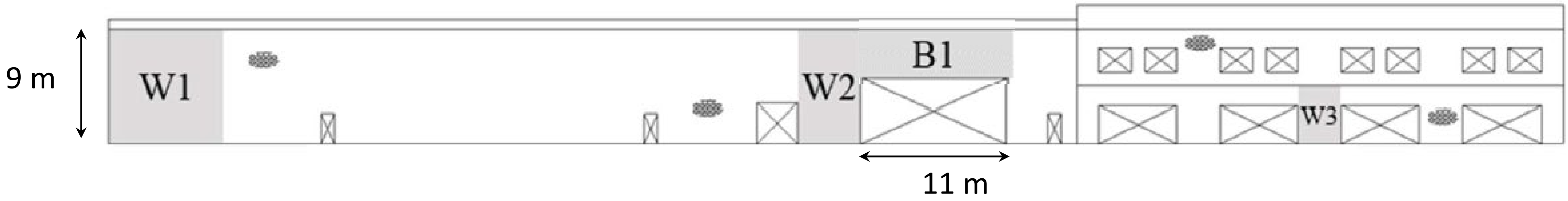


Findings – Warehouse/Office Building

Warehouse/Office Building

Design focused on several key elements within this building:

- W1 – Wall governed by out-of-plane loading.
- W2 – Wall governed by axial loading.
- W3 – Wall governed by in-plane loading.
- B1 – Masonry beam spanning 11 m opening.



Findings – Warehouse/Office Building

Overall, the U.S.-based design resulted in a more economical solution.

While compliant designs were obtained under CSA S304, they may not be practical/feasible.

Table 5: Governing Design of Two-Storey Mixed-Use Archetype in Niagara Falls, ON / Niagara Falls, NY

Wall/Beam Element		Niagara Falls, ON CSA S304-14 & NBCC 2015	Niagara Falls, NY TMS 402-16 & ASCE 7-16
W1	Block Size	25 cm (10 in.)	20 cm (8 in.)
	Block Strength	20 MPa (2,900 psi)	13.8 MPa (2,000 psi)
	Flexure Rebar Size	20M (300 mm^2)	No. 7 (387 mm^2)
	Spacing	600 mm (23.6 in.)	1,220 mm (48 in.)
	Shear Rebar Size	20M (300 mm^2)	BJR* (21.9 mm^2)
	Spacing	2,400 mm (94.5 in.)	406 mm (16 in.)
W2	Block Size	30 cm (12 in.)	30 cm (12 in.)
	Block Strength	30 MPa (4,351 psi)	13.8 MPa (2,000 psi)
	Flexure Rebar Size	2 × 25M (1,000 mm^2)	No. 8 (509 mm^2)
	Spacing	1,200 mm (15.7 in.)	3,048 mm (120 in.)
	Shear Rebar Size	-	BJR* (21.9 mm^2)
	Spacing	-	406 mm (16 in.)
W3	Block Size	20 cm (8 in.)	20 cm (8 in.)
	Block Strength	20 MPa (2,900 psi)	13.8 MPa (2,000 psi)
	Flexure Rebar Size	20M (300 mm^2)	No. 7 (387 mm^2)
	Spacing	800 mm (31.5 in.)	1,220 mm (48 in.)
	Shear Rebar Size	-	BJR* (21.9 mm^2)
	Spacing	-	406 mm (16 in.)
B1	Courses	10	10
	Block Size	20 cm** (8 in.)	20 cm (8 in.)
	Block Strength	30 MPa	13.8 MPa (2,000 psi)
	Tensile Rebar Size	6 × 15M (1,200 mm^2)	2 × No. 9 (645 mm^2)
	Compression Rebar Size	2 × 20M (600 mm^2)	-
	Shear Rebar Size	10M (100 mm^2)	-

* Bed Joint Wire Reinforcement
** A 30 cm unit that would be needed to match W2 in an actual building

Findings – Multi-Family Residential

Design focused on the number of stories that could be constructed under each code.

- TMS 402 capped out at 3 stories for both locations (rho max governed).
- CSA S304 capped out at 10 stories (30m) for 20 cm block in Niagara Falls; but limited to 15 m (5 stories) in B.C. unless a more ductile shear wall was used.

Table 6: Governing Design of Multi-Storey Loadbearing Archetype in Niagara Falls, ON / Niagara Falls, NY

Number of Stories (Height)		Niagara Falls, ON CSA S304-14 & NBCC 2015	Niagara Falls, NY TMS 402-16 & ASCE 7-16
3 (9 m)	Block Size Block Strength Flexure Rebar Size Spacing Shear Rebar Size Spacing	Not Considered	20 cm (8 in.) 13.8 MPa (2,000 psi) No. 5 (200 mm^2) 2,240 mm (88 in.) BJR (21.9 mm^2) 406 mm (16 in.)
6 (18 m)	Block Size Block Strength Flexure Rebar Size Spacing Shear Rebar Size Spacing	20 cm (8 in.) 20 MPa (2,900 psi) 15M (200 mm^2) 1,200 mm (47.2 in.) HD BJR (35.6 mm^2) 200 mm (7.9 in.)	Not Permitted
10 (30 m)	Block Size Block Strength Flexure Rebar Size Spacing Shear Rebar Size Spacing	20 cm (8 in.) 30 MPa (2,900 psi) 15M (200 mm^2) 1,200 mm (47.2 in.) HD BJR (35.6 mm^2) 200 mm (7.9 in.)	Not Permitted

Summary: Design Examples

- Higher design loads in NBCC compared to ASCE 7. This difference was most dramatic for wind and seismic forces.
- Ductility requirements under each code differ, with each limiting the practicality of a design in different ways.
- Masonry beams designed under CSA S304 are **impractical.**

Conclusions

- Fundamentals same. Vast difference in design applications.
- In some cases: Close alignment
- In other: **minor to significant** differences
- There are also instances where one of the standards is silent on a topic while the other addresses it comprehensively.
- In general, it is observed that TMS 402-16 allows a larger applicability of masonry design compared to CSA S304-14 due to:
  - **Canada's lower trust in masonry's material strength**
  - **Stricter considerations in design equations**
  - **Higher/more conservative loading assumptions**
- TMS 402-16 appears more practical for the designer's use, but the collaboration between academics and professionals identified that the strength design is not "user friendly" at times and switch between methods happen in these cases.

Thank you CANUS Sponsors!

- National Concrete Masonry Association (NCMA) foundation,
- Canadian Concrete Masonry Producers Association (CCMPA),
- Canada Masonry Design Centre (CMDC)
- Canadian Standards Association (CSA).

Thank you!
Questions/Discussion?

Additional Slides for Q&A/Handouts

Why f'_m is so different? Prism Testing Differences

- In ASTM C1314 (therefore TMS 402-16): prism construction and configuration are standardized.
- CSA S304-16 attempts to replicate the proposed construction with the fabrication of the prisms.
- Block manufacturing and masonry construction practices are similar
- Research from the 1990s state that many factors have disproportionate influence on the prism strength compared to full scale wall specimens.
- Ultimately, there is empirical evidence that the material strengths used in the U.S. do not cause catastrophic failures

Compressive Strength Comparison

Two methods for determination of f'_m are allowed in both:

1. Unit strength method
2. Prism testing (rare in U.S., virtually never in Canada)

CSA S304-14					TMS 602-16 (Specifications)		
Adopted from Table 4 in CSA S304-14					Adopted from Table 2 in TMS 602-16		
Block Strength	f'_m				f'_m	Block Strength	
	Type S Mortar		Type N Mortar			Net Area Compressive Strength of Unit	
	Ungrouted hollow units	Solid units or grouted hollow units	Ungrouted hollow units	Solid units or grouted hollow units		Type M or S Mortar	Type N Mortar
4,351 (30 or more)	2,538 (17.5)	1,958 (13.5)	1,740 (12)	1,305 (9)	*2,000 (13.8)	2,000 (13.8)	2,650 (18.3)
2,900 (20)	1,885 (13)	1,450 (10)	1,450 (10)	1,088 (7.5)	2,250 (15.51)	2,600 (17.3)	3,400 (23.44)
*2,175 (15)	1,450 (10)	1,088 (7.5)	1,160 (8)	870 (6)	2,500 (17.24)	3,250 (22.41)	4,350 (28.96)
1,450 (10)	943 (6.5)	725 (5)	870 (6)	653 (4.5)	2,750 (18.96)	3,900 (26.89)	-

OOP/Maximum Reinforcement

- CSA S304 has no maximum reinforcement requirement for non-slender walls ($kh/t \leq 30$) → **sensible**
- CSA S304 **uses balanced (yield) strain** for steel, while TMS 402 uses **1.5 times yield strain**
- **Maximum compressive strain:** 0.003 in CSA S304 vs 0.0025 in TMS 402
- TMS 402 include **axial load for max reinforcement** calcs., S304 provisions do not
- CSA S304 -- **0.85** f'_m vs. TMS 402 -- **0.80** f'_m to define the compression zone magnitude
- In general, axial loads on walls per CSA S304/NBC are higher than TMS 402/ASCE 7
- **Result:** CAN-to-US maximum reinforcement ratio for slender walls: 1.4

Overall: Lower material stresses for steel (f_y) and masonry (f'_m) for CSA S304. So, overall CSA S304 is still more restrictive for moment capacity for non-slender walls, TMS 402 more restrictive for slender walls.

Summary of Parametric Comparison

- Geometrical and section properties
  - Hollow: Advantage CAN, Solid: Advantage: US
- Block strength: Advantage CAN
- f'_m: Advantage US
- Beams: Advantage US
- Max height: Advantage CAN
- Modulus of rupture/Tensile strength: Advantage US for walls… Info for beams -- not accurate.
- Material/Strength Reduction factors: A bit of an apples to oranges situation.

Summary of Parametric Comparison

- Max reinforcement limits (in 402-2016): Advantage CAN. In the US, this causes practitioners to switch to ASD.
- Reduced moment arm in squat shear walls: the fact that it is considered is-advantage CAN (but not consistent)
- R values: Consistent.
- Many shear walls that can be built in the US are not permitted right across the border due to a combination of lower f'_m, higher loads, and different approach in the requirement of ductility provisions
- χ factor in Beams in CAN should be reevaluated. Beam design is practically impossible in most cases in CAN.
- Overall code/masonry:
  - Level of detail: Advantage CAN
  - Practicality: Advantage US
- Masonry-related research funding/opportunities: Advantage CAN

Research Needs: TMS 402

1. Further harmonization of SD & ASD
2. Maximum reinforcement limitations: Already acted upon!
3. Minor shear walls: No provisions for minor shear walls. S304 can serve as an inspiration but more research is needed.
4. Extra penalty for masonry for story drifts in ASCE 7 compared to other materials.
5. Prescriptive seismic detailing requirements: Hooks at the end of special reinforced masonry shear walls are not easy to construct.
6. Shear friction requirements and determination of A_{nc}: already acted upon!
7. There are many further research needs for beams: Intermediate reinforcement, A_{nv}, definition, modulus of rupture, coupling beams, beam torsion, deflection limits for reinforced beams
8. Max compressive strain value could be increased to 0.003 for CMU with further study.
9. Slenderness v. accidental eccentricity (TMS does not adequately address this)

Research Needs: TMS 402

10. Joint reinforcement: Should it be included in in-plane/oop wall design calcs? Detailing requirements?
11. Effective cross-section properties: Both codes can benefit from simpler equations.
12. Squat shear wall considerations can be further studied.
13. Slender walls with h/t > 30 can be further studied.
14. Effective compressive width: 6t in TMS 402 with no explanation of how to treat the "unreinforced" sections in the middle, 4t in CSA S304.
15. High strength/new materials are not addressed in many section of the code.
16. Partially grouted walls can be further studied.
17. Lightweight grout can be further studied.