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

DESIGN EXAMPLES DEMONSTRATING THE DIFFERENCES BETWEEN CSA S304-14 LIMIT STATES AND TMS 402-16 STRENGTH DESIGN METHODS

Banting, Bennett[1], Thompson, Jason[2], Dutrisac, Hélène[3]; Ledent, Philippe[4]; Hughes, Kevin[5]; Flisak, Bart[6] and Erdogmus, Ece[7]

ABSTRACT

This paper is one of the five companion papers from the project "*CANUS: Harmonization of Canadian and American Masonry Structures Design Standards Project".* The first four papers present a side-by-side comparison of the key provisions and parametric studies on specific elements (walls subjected to in-plane loads, walls subjected to out-of-plane loads, and beams). This last paper presents a comparison of the design of selected elements from two archetypes at two locations along the Canada-U.S. border: a mixed-use warehouse / office building and a multi-storey multi-family residential building, per CSA S304-14 and TMS 402-16, respectively. For loading and general building design considerations, NBCC 2015 and ASCE 7-16 are consulted; however, certain assumptions were made to make the loading as equivalent as possible, because comparison of building codes is outside of the scope of the CANUS program. Further, Masonry Analysis Structural Systems (MASS) and Direct Design Software (DDS) are utilized to perform these comparisons for the Canadian and U.S. designs, respectively, indirectly showcasing the benefits of these software packages in masonry design.

KEYWORDS: *reinforced masonry building design, direct design software, MASS, CSA S304, TMS 402*

[1] Director of Technical Services, Canada Masonry Design Centre, 360 Superior Blvd., Mississauga, ON, Canada, Bbanting@canadamasonrycentre.com
[2] Vice President of Engineering, National Concrete Masonry Association, 13750 Sunrise Valley Drive, Herndon, VA, U.S.A, jthompson@ncma.org
[3] Formerly of Canada Masonry Design Centre, 360 Superior Blvd., Mississauga, ON, Canada, helene.dutrisac@gmail.com
[4] Executive Director, Masonry Institute of Michigan, 24725 W 12 Mile Rd, Suite 388, Southfield, MI, U.S.A., phil@masonryinfo.org
[5] Structural Consulting Engineer, Renoasis Engineering, Aurora, ON, Canada, kevin@renoasis.ca
[6] Structural Engineer, Crosier, Kilgour & Partners Ltd., Bart.Flisak@ckpeng.com
[7] Professor, Durham School of Architectural Engineering and Construction, University of Nebraska-Lincoln, 1110 S. 67th Street, Omaha, NE 68182, eerdogmus2@unl.edu

INTRODUCTION

This paper is part of a series of five companion papers summarizing the findings of the work of an international collaborative research initiative to strive for better harmonization between Canadian and American design standards for structural masonry. As part of this initiative, a team of practicing engineers and academics from Canada and the United States (U.S.) worked together to examine the key differences and similarities between the ultimate limit states design provisions of the CSA S304-14 standard on "Design of Masonry Structures" [1] and the strength design provisions of the TMS 402-16 "Building Code Requirements for Masonry Structures" [2]. Using a three-fold approach, the research program entailed the following:

(1) a side-by-side comparison of the design loading and masonry resistance requirements of each country's respective building code and design standard [5];
(2) parametric studies of primary reinforced masonry structural members [8-10];
(3) the design of masonry building archetypes.

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 expected outcomes of the project are potential revision proposals to one or both standards and a list of short- and long-term research needs. 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 process and the findings for the last step above, (i.e., design examples) where two masonry building archetypes are designed to both Canadian and American design codes and standards at two different locations along the Canada – U.S. border sharing similar geographical coordinates. The geographic locations selected were

- Niagara Falls, ON / Niagara Falls, NY; and
- White Rock, BC / Blain, WA.

The building archetypes selected were representative of a two-storey mixed-use warehouse/office building and a multi-storey loadbearing multi-unit residential building. The rationale for the archetype design comparison was that differences that may otherwise appear within each country's respective masonry design standards are tempered and reduced when viewed within the lens of the design loads being resisted in each country. Because code and standard development are often intrinsically linked, each material design standard would be tailored to their respective model code and applicable loads.

The hypothesis of the design team entering this exercise was that the same masonry building placed on either side of the Canada-U.S. border should produce similar designs (e.g., unit size, unit strength, rebar size, rebar spacing, and grouting pattern) because materials, construction methods and environmental loads would not vary significantly, only the applicable codes and design standards differ.

BUILDING ARCHETYPES

As illustrated in Figure 1, the first archetype chosen is a two-storey mixed-use building with a two-storey office space at the front and an attached single storey warehouse space at the back of the building for a total building area of approximately 16,050m^2 (172,800 sf). The composition of the roof consists of a lightweight roof system supported on open web steel joists and steel beams. The second floor consists of a concrete slab on steel deck supported on open web steel joists and beams. Both the roof and floor levels are supported at the perimeter by masonry walls and, on the interior, by steel columns. The warehouse space is separated from the office area with a full height reinforced masonry loadbearing wall. As shown in Figure 1, a 1.8 m (6 ft) high parapet is included at the building roof perimeter over the office space to simulate construction practices to conceal rooftop mechanical equipment. The remainder of the perimeter parapet is 0.7 m (2.33 ft). The office space storey height was set at 4.2 m (14 ft) with the overall storey height of the warehouse space fixed at 8.4 m (28 ft).

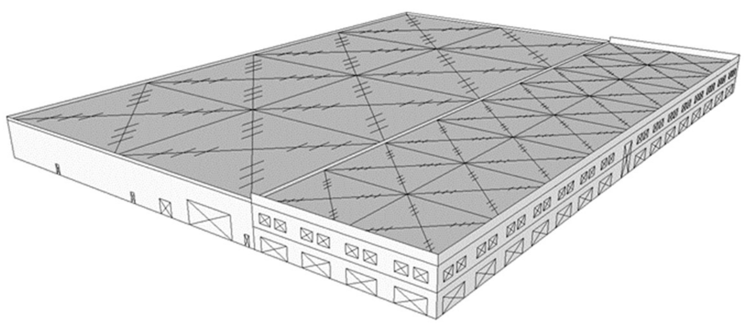


Figure 1: Two-Storey Mixed-Use Warehouse/Office Archetype

The second archetype is a multi-storey residential building consisting of a rectangular floor plan with a central corridor and stairwells at each end of the building. The overall floor plan area covers an approximate area of 990 m^2 (10,656 sf). The roof and floor construction assemblies consist of 250 mm (10 in.) hollow-core slab systems supported on reinforced masonry walls, forming the separation between residential units. The storey height was fixed at 3.0 m (10 ft). A 3D model of the structure is shown in Figure 2. Although the illustration depicts a ten-storey structure, the intent of the study was to determine feasible building height limits that could be designed under each respective standard.

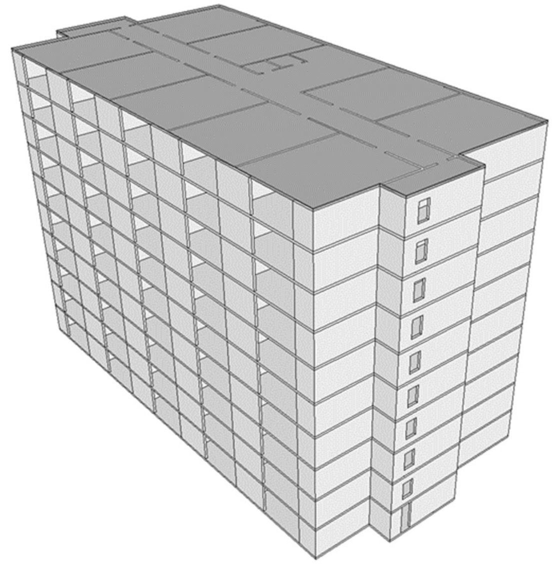


Figure 2: Multi-Storey Residential Building Archetype

DESIGN LOADS AND ASSUMPTIONS

Design loads were derived for the four cities based on the applicable national model code values, either from the 2015 National Building Code of Canada (NBCC 2015) [3] or the 2016 American Society of Civil Engineers Standard 7 (ASCE 7-16) [4]. The geographic proximity between the pairs of Canada and U.S. locations was expected to yield similar environmental loads (e.g., snow, wind, and earthquake). There were, however, some significant differences between the locations that will be discussed. Non-masonry building dead loads were based on the materials and layouts of the building archetypes and were constant between matching locations. Live loads and partition loads were each determined, according to the respective governing building code.

Both archetypes were assumed to be classified under the Normal Importance Category per NBCC 2015 and a Risk Category II under the ASCE 7-16 requirements, respectively. Importance factors for snow, wind and earthquake design loads are all 1.0 in this case within each code.

Dead and Live Loads

Dead loads for the two archetypes account for the self weight of the structural members and include allowances for roofing materials, mechanical and electrical systems, ceilings, and flooring. These were held constant between countries. Live loads were based on the use and type of occupancy, as prescribed by the respective codes. Notably, partition loads are considered as a dead load under the NBCC 2015 and as a live load under ASCE 7-16. In lieu of a detailed description of the loads, only differences between the codes will be described.

The two-storey mixed-use archetype and multi-storey loadbearing archetype each had a slightly different roof live load of 1.00 kPa (20.9 psf) per NBCC 2015 and 0.96 kPa (20.1 psf) per ASCE 7-16. Also, in each code the partition allowance was taken as 1.00 kPa (20.9 psf) dead load in NBCC 2015 while the partition live load in ASCE 7-16 was taken as 0.72 kPa (15.0 psf).

Otherwise, dead and live loads were equal between the countries except when the building designs themselves caused a difference (i.e., requiring a larger block or more grouting in one country versus the other).

Snow Loads

In both countries, the amplitude of the specified snow load is a function of the ground snow load (based on a 1 in 50-year return period), the importance factor of the building, the wind exposure, the slope of the roof and is adjusted to account for snow drifting at roof obstructions. A summary of snow load parameters used for each code and in each archetype are summarized in Tables 1 and 2. NBCC 2015 uses an associated rain in the computation of the specified snow load, while the basic snow load factor is set at 0.8, except for large roofs where increased values are prescribed to account for the fact that wind is less effective at removing the snow from these roofs. ASCE 7-16 adopts a basic ground-to-roof conversion factor of 0.7. This factor does not increase for large roofs, but it is intended to account for the thermal properties of the roof.

Table 1: Two-Storey Mixed-Use Archetype Specified Snow Loads

Snow Load Parameter	**Niagara Falls, ON**	**Niagara Falls, NY**	**White Rock, BC**	**Blaine, WA**
	kPa (psf)			
Ground Snow	1.80 (37.6)	2.39 (50.0)	2.00 (37.6)	0.77 (16.0)
Rain	0.40 (8.4)	-	0.20 (8.4)	-
Total Uniform Load	2.02 (42.2)	1.68 (35.0)	2.00 (42.2)	0.77 (16.0)
Warehouse Snow Drift				
Peak Load	4.05 (84.6)	5.89 (123.0)	3.95 (82.5)	4.06 (84.8)
Extent, m (ft)	6.13 (20.1)	9.90 (32.5)	6.13 (20.1)	5.58 (18.3)
Office Snow Drift				
Peak Load	-	2.29 (47.8)	-	1.79 (37.5)
Extent, m (ft)	-	1.52 (5.0)	-	3.98 (13.1)

Table 2: Multi-Storey Loadbearing Archetype Specified Snow Loads

Snow Load Parameter	**Niagara Falls, ON**	**Niagara Falls, NY**	**White Rock, BC**	**Blaine, WA**
	kPa (psf)			
Ground Snow	1.80 (37.6)	2.39 (50.0)	2.00 (37.6)	0.77 (16.0)
Rain	0.40 (8.4)	-	0.20 (4.2)	-
Total Uniform Load	1.84 (38.4)	1.68 (35.0)	1.80 (41.8)	0.77 (16.0)
Roof Snow Drift				
Peak Load	-	2.29 (47.8)	-	1.79 (37.5)
Extent, m (ft)	-	1.52 (5.0)	-	3.98 (13.1)

Unlike the dead and live loads, snow loads between countries differ considerably. Despite a lower ground snow load parameter, the basic uniform snow load for the two-storey mixed-use archetype in Niagara Falls, ON is 20% greater than its counterpart location across the border. The differences in uniform design snow load are more pronounced at the western location. The Canadian uniform design snow loads are 160% and 133% greater in White Rock, BC than Blaine, WA for the two-storey mixed-use and multi-storey residential archetypes, respectively.

Wind Loads

The U.S. procedure for computing wind design loads is slightly different than the Canadian procedures. ASCE 7-16 prescribes wind velocity for various locations as a function of the risk category (importance category). In the transition from the 2005 to 2010 editions of ASCE 7, the wind velocity maps were readjusted to be strength-design based instead of allowable stress-level speeds (i.e., the basic wind speed values increased), and, consequently, the wind load factor has been reduced from 1.6 to 1.0. This strength-level wind velocity is then used in conjunction with several adjustment factors to compute a wind velocity pressure. NBCC 2015 uses a 1-in-50 hourly wind pressure multiplied by the importance factor for wind, $I_w q$ (kPa). Table 3 compares these values and the ASCE 7-16 wind pressures calculated as $0.000613V^2$ (kPa), where V is the wind velocity given in meters per second, for each of the designated locations. This parameter was comparable to the product of $I_w q$ in NBCC 2015.

Table 3: Comparison of NBCC 2015 and ASCE 7-16 Wind Pressures

Wind Pressures	**Niagara Falls, ON**	**Niagara Falls, NY**	**White Rock, BC**	**Blaine, WA**
	kPa (psf)			
$\mathbf{I_w q}$	0.43 (9.0)	-	0.44 (9.2)	-
$\mathbf{0.000613V^2}$	-	1.45 (30.3)	-	1.18 (24.6)

Although the pressures noted for the U.S. locations are significantly higher than the Canadian values, it is important to remind readers that the load combination in Canada requires the application of a load factor of 1.4 to the wind load whereas this factor is 1.0 in the U.S. In addition, the C_pC_g (GC_p) combined gust and external pressure coefficients prescribed by the NBCC 2015 are significantly higher than those prescribed by ASCE 7-16 as indicated in Table 4. The net results of these differences are higher total factored governing out-of-plane wind pressures in Canada resulting in a larger primary moment used for the archetype design.

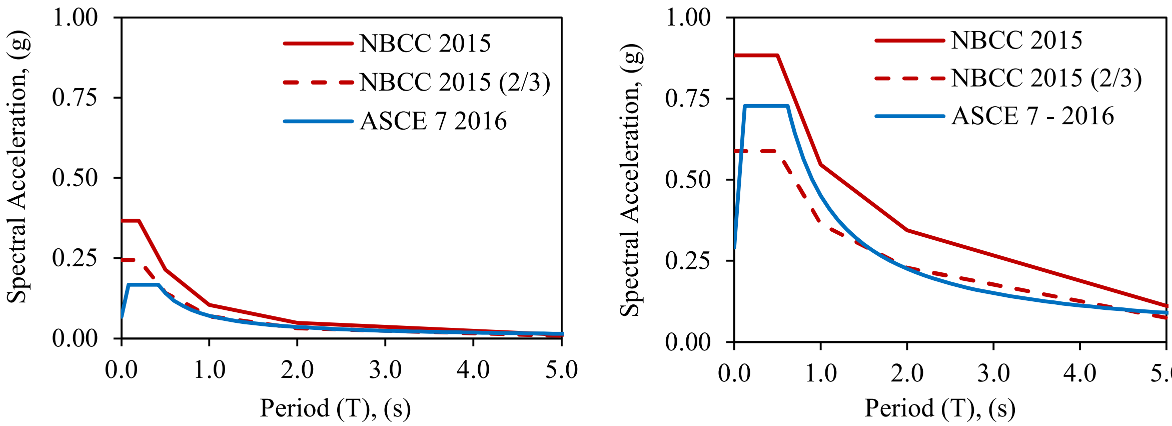
Table 4: Combined Gust Factor - Pressure Coefficients C_pC_g (GC_p) for Low-Rise Buildings

Description	**NBCC 2015**	**ASCE 7-16**
Primary actions (MWFRS)	-2.0 to 1.5	-1.07 to 0.8
Individual walls and secondary structural members (C&C)	-2.1 to 1.75	-1.4 to 1.0
Roofs and secondary structural members (C&C)	-5.4 to 0.5	-3.2 to 0.3

Seismic Loads

A static force approach was used for the determination of seismic loads. This approach is known as the *Equivalent Static Force Procedure* in the NBCC 2015 and the *Equivalent Lateral Force Procedure* in ASCE 7-16. Hazard values in both countries are generally specified on the basis of a 2% in 50 year probability of exceedance. The design earthquake level in the U.S. is based on two-thirds of the MCE hazard values, whereas Canada uses the values as-is. However, short period Canadian designs are capped to the larger of two-thirds of the design spectral acceleration at 0.2s and the design spectral acceleration at 0.5s. The NBCC design seismic base shear for structures with fundamental periods of vibration in excess of 0.5s do not benefit from the short hazard cap and, in essence, *are designed for 1.5 times the prescribed forces in comparison to the U.S.* In addition, the NBCC prescribes a higher mode factor to account for the effects of higher mode participation. Under both regimes, the elastic base shear is adjusted by a force modification factor that accounts for the seismic force resisting system (SFRS) ductility. For both countries, all seismic forces were computed assuming a seismic Site Class 'D'.

Design response spectrums for periods up to 5s are shown in Figure 3. The NBCC spectrum is denoted by the red line. The U.S. design response spectrum, which is reflective of the design earthquake level (two-thirds of MCE), is denoted by the blue line. The dotted red line denotes the NBCC response spectrum adjusted by two-thirds to facilitate comparison with the US design response spectrum. Except for short periods, the adjusted NBCC response spectrum (two-thirds) closely matches the U.S. design response spectrum.



a) Niagara Falls, ON / NY b) White Rock, BC / Blaine, WA

Figure 3: Design Response Spectrums

Both the NBCC 2015 and ASCE 7-16 recognize various masonry seismic force resisting systems (SFRS) that each possess various degrees of ductility. These systems are subject to restrictions and height limitations as prescribed within each code. To the extent possible, SFRSs with the lowest ductility were selected for the study. NBCC 2015 design base shear ratios for low-rise buildings governed by the short-period cap are consistently and significantly higher than the those prescribed by the ASCE 7-16. Notably, seismic design forces for low-rise buildings in Niagara Falls, ON are 8-to-69% greater than in the U.S., depending on the type of SFRS selected; whereas values are 8-to-41% greater in White Rock, BC compared to Blaine, WA. This is significant for low-rise structures, which typically occupy the short period range for design.

TWO-STOREY MIXED USE BUILDING ARCHETYPE DESIGN RESULTS

Design of the masonry structural elements was conducted using specialized masonry design software in each country. For design to CSA S304-14, Masonry Analysis Structural Systems (MASS) software [6] was used and, for TMS 402-16 design, Direct Design Software (DDS) [7] was used.

Summarized here are only the design results of critical governing elements within the structure. As indicated in Figure 4, the critical wall sections for in-plane and out-of-plane design were located in the East/West exterior elevations of the building. Pictured are the 3 selected wall design locations, defined as:

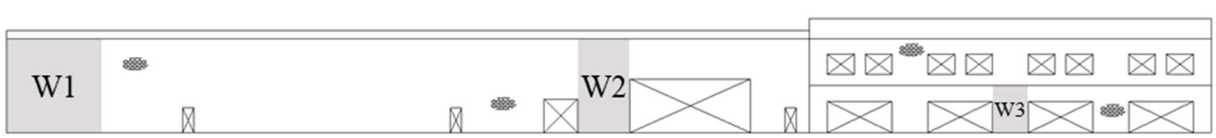
W1- A generic warehouse wall that would represent most of the design, including other exterior elevations, discounting any flanging effects at building corners. The unit and reinforcement configuration selected here would dictate the economic feasibility of the project. Under both standards, the design is dominated by wind loads acting along the out-of-plane direction. The length of each wall panel W1 was dictated by the movement joint spacing, which was optimized for each design based on lateral load distribution.

W2- The most critical wall in the structure due to the high tributary axial loads from the beams spanning the adjacent openings and the concurrent out-of-plane loads imposed on the wall. The design of this wall was considered to be unique and would require details that would differ from the rest of the building, at an added expense, but not as to dictate the economic feasibility of the structure as a whole necessarily.

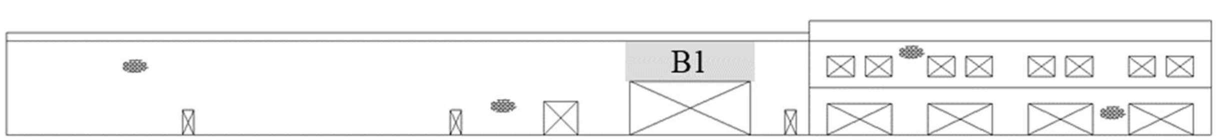
W3- Generic office wall, which represents the bottom storey of the construction in the 2-storey section of the structure. Because these walls are relatively short in height, their design is governed less by out-of-plane loading.

Design of the masonry beam critical in the East/West elevation is pictured in Figure 4, which is defined as the following:

B1- An exceptionally large masonry beam located over a 11.0 m (36 ft) wide opening. This is not a typical masonry beam but represents some of the designs that are unique to U.S. practice compared to Canadian design. A 10-course beam design is presented to be consistent between designs. Although the beam height can be varied and block size would have to be consistent with adjoining walls, this was neglected to compare the most efficient design with the smallest block possible.



a) East/West Elevation with the Designed Walls Indicated



b) East/West Elevation with the Designed Beam Element Indicated

Figure 4: East/West Elevations for the Two-Storey Archetype

Niagara Falls, ON / Niagara Falls, NY

Buildings were designed as conventional construction (ordinary) shear wall systems. Out-of-plane wind loads were the dominant load for these locations where the relatively tall warehouse walls (8.4 m (28 ft) in height) and their out-of-plane bending effects dictated wall details. The design standard comparison and parametric studies related to out-of-plane wall bending behaviour are provided in the companion paper by Sustersic et al. [8]. A summary of the governing design details is given in Table 5 and cross-section details of different masonry elements are depicted in Figure 5.

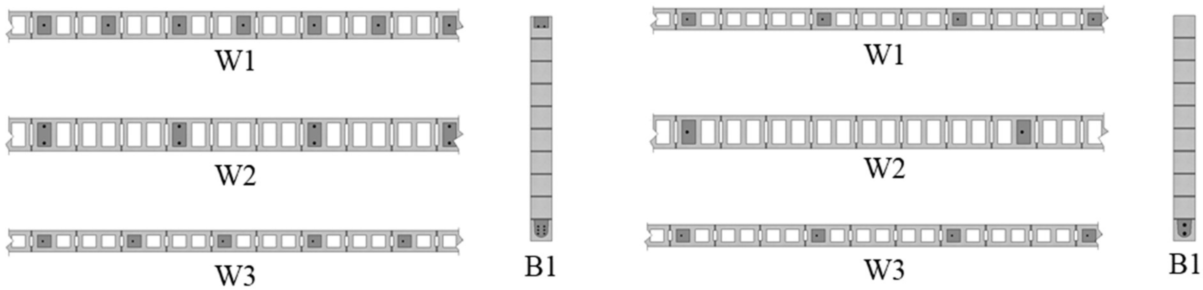
Table 5: Governing Design of Two-Storey Mixed-Use Archetype in Niagara Falls, ON / Niagara Falls, NY

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

Wall W1 being the most common wall detail best illustrates the differences between the two design codes/standards. Using a 25 cm unit, along with the closer reinforcement/grout spacing required in Canada, would increase material and labour costs significantly. The primary reason a 25 cm unit is required for W1 in Niagara Falls, ON stems from moment amplifications due to secondary effects. It was observed when comparing designs that the primary moment derived from ASCE 7-16 loads and the amplification effects derived from TMS 402-16 were both smaller in magnitude compared to the Canadian design.

In Niagara Falls, NY, Wall W1 had a governing factored primary out-of-plane moment of 8.5 kN·m/m (22,994 in·lb/ft) and a corresponding amplification factor of the primary moment equal to 1.24. By comparison in Niagara Falls, ON, the governing primary moment acting on W1 was 13.5 kN·m/m (36,428 in·lb/ft), and, even for the larger and stronger unit selected in the Canadian design, the amplification factor for the primary moment to account for secondary effects was equal to a staggering 1.61. A more thorough review of the impacts of the out-of-plane design provisions of the two standards is presented in Sustersic et al. [8].



a) Niagara Falls, ON b) Niagara Falls, NY

Figure 5: Cross-Sections of Critical Masonry Elements

White Rock, BC / Blaine, WA

In Blaine, WA, ASCE 7-16 requires that a special reinforced masonry shear wall be used ($R = 5.0$); whereas, a conventional construction shear wall system ($R_dR_o = 2.25$) is the minimum permitted in White Rock, BC per NBCC 2015. This, however, did not fundamentally affect the design in the U.S. Wall W1 and Wall W3 could be designed with the same unit strength and size as in Niagara Falls, NY, but this time with a No. 7 (387 mm^2) bar spaced at 813 mm (32 in.) instead of 1,220 mm (48 in.). The walls also required a bond beam consisting of a No. 6 (284 mm^2) spaced at 1,220 mm (48 in.) in lieu of bed joint wire reinforcement. Also, Wall W2 now required a 20.7 MPa (3,000 psi) block strength with No. 7 (387 mm^2) bars placed at 813 mm (32 in.) and a bond beam consisting of a No. 6 (284 mm^2) spaced at 1,220 mm (48 in.). Beam design is not affected by the increased seismic loads.

The relatively small changes to reinforcing and block strength required in the U.S. design stands in stark contrast to the Canadian results. No feasible design could be established for conventional construction masonry. In fact, even if higher ductility SFRSs were selected (moderately ductile or ductile shear walls) per the NBCC 2015, the in-plane shear forces exceeded the maximum permissible shear resistance for the masonry, per CSA S304-14 due to the large tributary roof weight. This structure could not be built on the Canadian side of the border using the CSA S304-14 and NBCC 2015 considering the highest possible level of ductility category, maximum unit size, maximum unit strength, and up to 2 reinforcing bars per cell. No combination of design parameters offered a passing design.

MULTI-STOREY RESIDENTIAL BUILDING ARCHETYPE DESIGN RESULTS

The objective of the multi-storey residential building archetype was to determine how many storeys can be built based on a storey height of 3.0 m (9.8 ft). Modeling of the archetype was carried out in a similar fashion, as noted for the two-storey mixed-use archetype. Although the layout of the floor plan indicated that flanged walls would be a design option, for simplicity and based on typical design practice, this option was not considered here. The building plan is shown in Figure 6, and loads were derived using the whole building layout. For ease of comparison between design standards, lateral forces were divided equally between shear walls. Impact of elevator shafts, cores, and shear wall flanges was not considered in the analysis. Axial load paths are based on one-way slab action of the precast hollow core slabs.

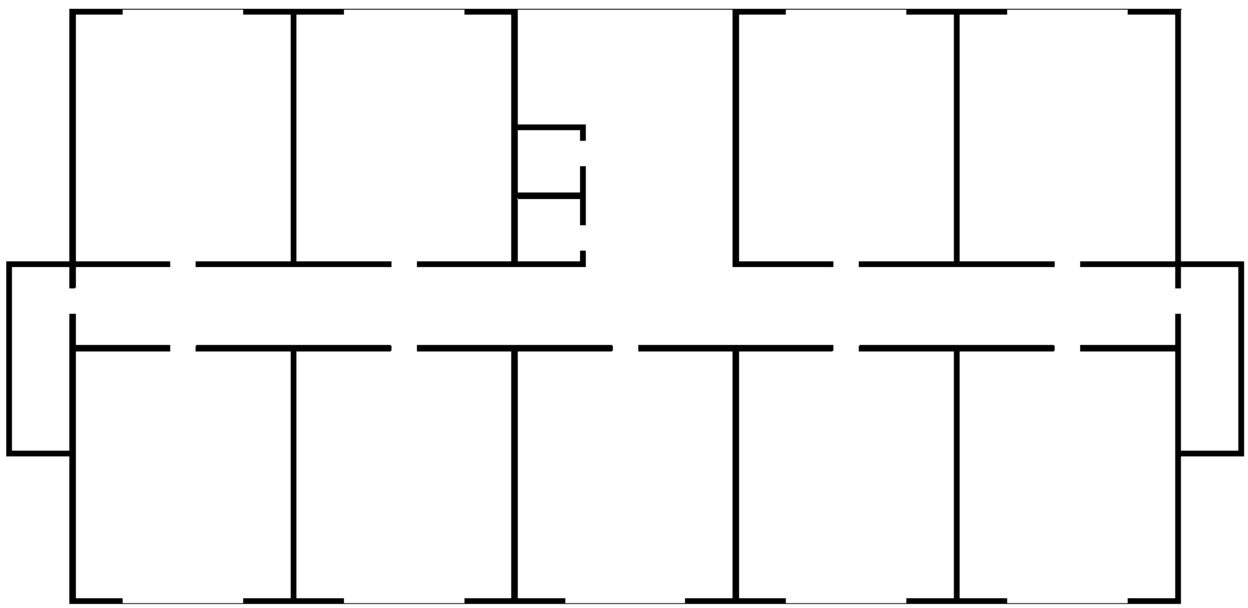


Figure 6: Shear Walls in Building Plan of the Multi-storey Loadbearing Archetype

Niagara Falls, ON / Niagara Falls, NY

Buildings were designed as conventional construction (ordinary) shear wall systems. The Canadian design team first looked at a 6-storey structure and then a 10-storey structure. Only a 20 cm unit was considered for the design to compare with the U.S. design team. In-plane design loads arising from seismic forces governed the design for both countries. The limiting factor for U.S. design is the requirement for yielding reinforcement in all masonry located within the structural plan. This posed a technical challenge for certain locations where U.S. maximum reinforcement limits caused failures in small wall segments around doorways and openings, which was a problem not faced in the Canadian design. The design standard comparison and parametric studies related to in-plane (shear) wall behaviour are provided in the companion paper by Erdogmus et al. (2021) [9]. A summary of the results for the multi-storey design are provided in Table 6.

A passing design was achieved for Niagara Falls, NY up to 3 stories in height. Once a 4-storey building was attempted, the maximum reinforcement provisions of TMS 402-16 govern design of the piers in walls adjacent to openings. By 5 stories in height, the interior walls collectively reach the maximum reinforcement limit. Thus, only a 3-storey structure could be accommodated in Niagara Falls, NY using an 8 in. (20 cm) unit. By contrast, the axially-driven walls in Niagara Falls, ON are able to be accommodated in design up to a height of 10 stories for the given loads. In all cases, the walls in Niagara Falls, ON are fully grouted. It was clear that it was still possible to go even higher with a 20 cm (8 in.) unit; however, the NBCC 2015 would require that for this location the SFRS would have to comply with a moderately ductile shear wall system. It is likely then that, when using the higher ductility category, design issues similar to the U.S. team would be encountered due to the requirement for reinforcement to yield in tension.

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	Not Considered	20 cm (8 in.)
	Block Strength		13.8 MPa (2,000 psi)
	Flexure Rebar Size		No. 5 (200 mm^2)
	Spacing		2,240 mm (88 in.)
	Shear Rebar Size		BJR (21.9 mm^2)
	Spacing		406 mm (16 in.)
6 (18 m)	Block Size	20 cm (8 in.)	Not Permitted
	Block Strength	20 MPa (2,900 psi)	
	Flexure Rebar Size	15M (200 mm^2)	
	Spacing	1,200 mm (47.2 in.)	
	Shear Rebar Size	HD BJR (35.6 mm^2)	
	Spacing	200 mm (7.9 in.)	
10 (30 m)	Block Size	20 cm (8 in.)	Not Permitted
	Block Strength	30 MPa (2,900 psi)	
	Flexure Rebar Size	15M (200 mm^2)	
	Spacing	1,200 mm (47.2 in.)	
	Shear Rebar Size	HD BJR (35.6 mm^2)	
	Spacing	200 mm (7.9 in.)	

White Rock, BC / Blaine, WA

Axial loads, not lateral, governed the designs by the U.S. team in Niagara Falls, NY. These loads would not be affected by the change in location to Blain, WA, and, as such, the results would not differ with the building limited to 3 stories.

By contrast, the conventional construction shear wall system selected for masonry would be limited to a height restriction of 15 m (49 ft) in White Rock, BC. It might have been possible to go taller, but that would require the use of a moderately ductile or ductile shear wall system. Furthermore, the higher seismicity of White Rock, BC would also artificially limit the axial loads permitted on the walls to $0.1f'_m$ without additional comprehensive analysis. However, this limit did not come into play due to the high seismic shear forces encountered that governed design. At the maximum building height of 15 m (49 ft) considered, neither 20 cm (8 in.) nor 25 cm (10 in.) units could meet the shear force demands being limited by maximum shear force limits. A 4-storey building could be accommodated with 30 cm (12 in.) units with 25 MPa (3,630 psi) block strength, fully grouted, with vertical reinforcing consisting of 20M (0.48 in.^{2}) bars placed at 1,000 mm (40 in.) spacing and horizontal reinforcement consisting of HD BJR placed at 200 mm (8 in.), along with 10M (0.12 in.^{2}) bond beams placed at 1,200 mm (47.2 in.) vertically in the walls. This, however, would not be a practical design for such a small structure as the switch to a 30 cm (12 in.) unit size is undesirable, architecturally.

CONCLUSIONS

The following conclusions can be drawn from the exercise of comparing the possible masonry design options for two archetypes at low and high seismicity regions across the border of the U.S. and Canada:

- There are fundamental differences from the application of the respective masonry design standards even within the context of the applicable national model code. It was demonstrated when comparing the two-storey mixed-use archetypes that snow, wind, and seismic forces result in higher factored loads acting on the masonry under the Canadian code provisions. This led to increased primary out-of-plane moments (+59%) and an increase to the primary moment amplification factor to account for secondary effects (+30%) in the Canadian design. This occurred even though a larger unit with higher strength and more reinforcement were used in design (which should increase wall stiffness and reduce secondary moment amplification effects).
- Seismic forces, just as wind and snow, are generally more punitive for low-rise structures in Canada than in the U.S. where the latter's 2/3 base shear cap and requirements for the use of higher ductility systems based on seismic hazard level result in significantly lower shear demands for the low-rise archetype. As with wind loads, increased forces from the building code in Canada were combined with lower masonry resistances, typically due to in-plane shear failure due to reaching a maximum shear resistance limit.
- The maximum reinforcement limit in the TMS 402-16 often controls the design in the U.S., most notably in cases where high axial loads are present. Examples include the Wall W2 in the two-storey mixed use building archetype as well as the multi-storey residential structure. In these cases, the design provisions of CSA S304 offered more design flexibility in achieving feasible results.
- Large beams are technically possible by Canadian design; however, the steel detailing requirements make construction impractical and expensive. Beam B1 in the two-storey mixed use building archetype demonstrated that restrictions to Canadian design may be overcome to resist the loads, but the necessity of tied compression steel, shear stirrups, and multiple layers of tension reinforcement would make this impractical to physically construct in an economical

manner. In comparison, the same beam could be designed without compression reinforcement or stirrups in the U.S.

- Within the context of the ASCE 7-16 design provisions, an increase in the seismic design force is prescriptively tied to an increase in the required ductility of the seismic force-resisting system for all materials. In Canada, the short and long period triggers do not necessarily force an increase in ductility, but rather limits the height of systems with lower ductility. In higher Canadian seismic zones, masonry construction of low-rise buildings with conventional construction SFRS are unable to accommodate the high seismic design forces; thus, the construction requires the use of a SFRS with higher ductility to accommodate the associated seismic demand. In such cases, the use of masonry SFRSs with higher ductility renders this type of construction cost-prohibitive in comparison to conventional construction SFRSs of other materials, such as concrete, which can accommodate higher seismic demands.

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] 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.

[4] 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.

[5] 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.

[6] Masonry Analysis Structural Systems (MASS) Design Software, National Masonry Design Products, Mississauga, ON, Canada https://www.masonryanalysisstructuralsystems.com/.

[7] Direct Design Software for Masonry Structures, National Concrete Masonry Association, Herndon, VA, U.S. https://ncma.org/software/direct-design/

[8] Sustersic, H.; Stubbs, D.; Peterson, R.; Bennett, R.; Pettit, C.; Flisak, B.; Erdogmus, E.; Thompson, J.; Banting, B.; and Cruz-Noguez, C. (2021). "Parametric Studies on Reinforced Masonry Walls Resisting Out-of-Plane Loads: A Comparison of CSA S304-14 and TMS 402-16." *Proc., 14th Canadian Masonry Symposium,* Montreal, QC, Canada.

[9] Erdogmus, E.; Cruz-Noguez, C.; Ledent, P.; Jobe, L.; Hughes, K.; Banting, B.; and Thompson, J. (2021). "Parametric Studies on Reinforced Masonry Shear Walls Resisting In-Plane Loads: A Comparison of CSA S304-14 and TMS 402-16." *Proc., 14th Canadian Masonry Symposium,* Montreal, QC, Canada.

[10] Erdogmus, E.; Bennett, R.; Thompson, J.; and Banting, B. (2021). "Parametric Studies on Reinforced Masonry Beams: A Comparison of CSA S304-14 and TMS 402-16." *Proc., 14th Canadian Masonry Symposium,* Montreal, QC, Canada.