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EVALUATION OF MASONRY ASSEMBLAGE STRENGTH IN ACCORDANCE WITH CSA S304-14 AND ASTM C1314-18 REQUIREMENTS

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ABSTRACT

Requirements for the geometry, construction, loading, and testing of masonry prisms differ based upon whether U.S. or Canadian standards are followed. Prisms constructed in accordance with CSA S304-14 (R2019) include face shell bedding, are commonly constructed in running bond, and are one block wide and 3 courses tall. In contrast, prisms built in accordance with U.S. standard ASTM C1314-18 include full mortar bedding, a baseline height-to-thickness ratio of 2, and may be as little as one-half block wide. The resulting masonry assemblage strength is affected, and serves as input for the design of members subject to bending, axial loads, and shear. Such a difference is therefore intrinsic, and does not allow for a direct comparison between Canadian standard *CSA S304-14 (R2019) – Design of Masonry Structures* and U.S. code *TMS 402/602-16 – Building Code Requirements and Specifications for Masonry*. An evaluation is essential to reconcile design requirements for masonry as is underway by the Canada Masonry Design Centre and the National Concrete Masonry Association, as was initiated to establish synergies and allow for cost savings related to this construction material. An experimental investigation is therefore underway at the University of Saskatchewan to evaluate the resulting differences in masonry assemblage strength. This initial paper describes the motivation for this work and examines the influential parameters in the context of the available literature.

KEYWORDS: *masonry assemblage strength, masonry prisms, mortar bedding, bond pattern, prism geometry, testing methods*

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INTRODUCTION

Masonry's common use in construction has made the industry an integral part of Canada's local economies. That stated, the increasing gap in materials, design, and construction methods for masonry as are being used in Canada and the U.S. is affecting the industry, and potentially holding back synergies and cost savings that may otherwise be available.

The Canada Masonry Design Centre and the National Concrete Masonry Association in the U.S. are striving to harmonize design requirements for masonry as are included in Canadian Standard *CSA S304-14 (R2019): Design of Masonry Structures* [1], and U.S. code *TMS 402/602-16: Building Code Requirements and Specifications for Masonry Structures* [2]. These standards were developed independently, with the makeup of each code committee limited to domestic members. As a result, the requirements included in each of the two codes and their supporting standards vary markedly in certain circumstances, even though both were fundamentally derived from the results of a small pool of supporting literature that has been published worldwide. While some differences between the two codes are isolated and so quite specific, others such as the effect of differences in reported masonry assemblage strength are intrinsic, and make a comparison between the two codes difficult without first conducting a thorough analysis.

Tests of individual concrete blocks, mortar cubes, and grout cubes and cylinders as typically prescribed by standards worldwide allow for the evaluation of the strength of the constituent materials in a masonry assemblage to ensure that they meet project specifications. In contrast, masonry structures are comprised of a combination of concrete blocks that are mortared together and potentially grouted, and the strength of this assemblage differs from that of any of the individual constituent materials. Masonry prisms are the small-scale specimens constructed and tested to prescribed standards as are used to evaluate the masonry assemblage strength, f'_m. Masonry assemblage strength, therefore, serves as input for the resistance of structural masonry members to bending, axial load, and shear. Differences in the geometry, construction, and testing of masonry prisms as specified in different national standards not only affect their resulting compressive but also affect the development of the height-to-thickness *(h/t)* correction factors. As a result, f'_m is pervasive when attempting to compare design provisions used in different countries.

An experimental investigation is therefore currently underway at the University of Saskatchewan to evaluate differences in resulting masonry assemblage strength based upon the testing of prisms constructed in accordance with the requirements as set out in the U.S. and Canadian standards. This initial paper highlights the differences in the geometry, construction, loading, and testing as prescribed by Canadian and U.S. standards. The influence of all parameters is then examined in the context of the available literature.

COMPARISON OF ASTM AND CSA REQUIREMENTS FOR THE TESTING OF MASONRY PRISMS

Table 1 shows a comparison of the geometry, construction, loading, and testing requirements for hollow concrete block masonry prisms as prescribed by Canadian standard *CSA S304-14 (R2019*

[1] and U.S. standards *ASTM C1314-18 – Standard Test Method for Compressive Strength of Masonry Prisms* [3] and *ASTM C1716/C1716M-20 – Standard Specification for Compression Testing Machine Requirements for Concrete Masonry Units, Related Units, and Prisms* [4]. Properties influencing the geometry and the construction of masonry prisms include their minimum width and height, the baseline height-to-thickness (h/t) ratio, bond pattern, and mortar bedding type. *CSA S304-14 (R2019)* states that the prisms can be laid in a stack pattern when experimental evidence shows a definite strength correlation between stack pattern and running bond. That stated, masonry prisms in Canada are typically constructed in running bond to replicate the construction method most commonly used on jobsites. Testing masonry prisms, as shown in Figure 1, is dictated by the minimum diameter of the hemispherical metal head, and the loading rate.

Table 1: Testing Requirements for Prisms made of Hollow Masonry Concrete Block Units as Provided in CSA S304-14 (R2019) [1] & ASTM C1314-18 [3]

	CSA S304-14 (R2019) [1]	**ASTM C1314-18 [3] & C1716-20 [4]**
Prism geometry & construction:		
Minimum height	3 courses	2 courses
Minimum width	1 concrete masonry unit	½ concrete masonry unit
Baseline h/t ratio[1]	5	2
Bond pattern	Running bond	Stack pattern
Mortar bedding	Face shell	Fully bedded
Testing setup & method:		
Min. Diameter of a hemispheric metal head	125 mm	150 mm
Loading rate	Up to one-half of the load (from 0 to $0.5P_{max}$) can be applied at a convenient rate, with the remaining load (from $0.5P_{max}$ to P_{max}) applied within one to two minutes at a uniform rate.	

[1] For a correction factor of unity in accordance with either standard.

Table 1 shows that a number of parameters related to prism geometry and construction differ between CSA S304-14 (R2019) [1] and ASTM C1314-18 [3] requirements and is driven by the intended use of prisms in the two countries. Prisms in the United States are primarily used onsite for quality assurance purposes whereas in Canada they are used to establish the masonry assemblage strength of the as-constructed structure.

In contrast, the test setup and loading requirements as included in CSA S304-14 (R2019) [1] and ASTM C1716-20 [4] are similar. Figure 1 shows that the masonry prism is set up for testing between upper and lower metal platens. Both platens are fabricated from metal having a hardness not less than HRC55 (HB550), with the upper platen including a hemispherical head allowing for free rotation to ensure that the load is applied parallel to the longitudinal axis of the prism. At 125 and 150 mm, respectively, the minimum diameter of the hemispherical head is similar in CSA S304-14 (R2019) [1] and ASTM C1716-20 [4]. The upper platen serves as a bearing block and must cover the area of the prism with 6 mm of overhang all around to eliminate the need for an additional steel plate between the prism and the platen. Table 1 shows that the rate at which loading is applied is identical for CSA S304-14 (R2019) [1] and ASTM C1716-20 [4]. A single test setup can therefore be designed for testing in accordance with either CSA S304-14 (R2019) [1] or ASTM C1716-20 [4] requirements.

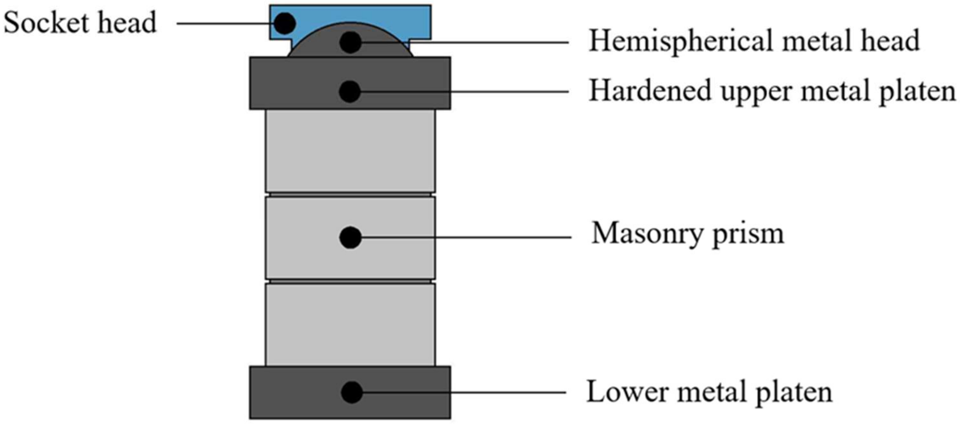

Figure 1: Masonry prism test setup

A clear understanding of the impact of factors associated with prism geometry and construction on the resulting masonry assemblage strength is lacking. These will be discussed in turn in the following sub-sections in the context of the available literature.

Minimum Prism Dimensions

Minimum prism geometry differs between the two standards, with CSA S304-14 (R2019) [1] requiring prisms that are one concrete masonry block wide and three courses tall, and ASTM C1314-18 [3] specifying prisms that are at least one-half block wide and two courses tall. The smaller prisms as prescribed by ASTM C1314-18 [3] are advantageous as they are simpler to construct, store, and transport, and are more economical. Three courses tall prisms, as constructed in accordance with CSA S304-14 (R2019) [1], exceed the testing clearance limitations of most common testing machines, and so requirements included in CSA S304-14 (R2019) [1] therefore discourage the construction of prisms on job sites in Canada. This becomes problematic when a constituent material (i.e. the blocks, mortar, or grout) is found to be understrength as there is no means to potentially confirm that the masonry assemblage strength still meets project specifications if prisms are not available for testing. A critical review of prism geometry may allow for a reduction in the minimum prism geometry as prescribed in CSA S304-14 (R2019) [1] and so result in the increased use of prisms on-site.

Table 2 summarizes results reported in several experimental [5, 6] and analytical [7, 8] studies that evaluated the impact of prism width on the resulting masonry assemblage strength. The differences in the results of experimental and analytical studies related to variations in material properties. These variations occur inherently in experimental studies but were considered to be deterministic in all analytical investigations. The results reported in the analytical works were therefore based on idealized masonry prisms and so suggest that FEM analyses may overestimate the strength of prisms. Nonetheless, the use of FEM was still beneficial for structural evaluation purposes because of its reduced the associated cost in comparison with experimental investigations.

Prisms, as constructed, were either one-half or one block wide and so reflect the minimums permitted by ASTM C1314-18 [3] and CSA S304-14 (R2019) [1], respectively. Both grouted and ungrouted prisms with *h*/*t* ratios between 2 and 5 are included in the overall database and these results were not modified by any *h*/*t* ratio correction factors. While Drysdale and Hamid [5] reported no difference in the resulting masonry assemblage strengths between one-half and one block wide prisms that were either grouted or ungrouted, Khalaf [6] found that masonry assemblage strengths reported from tests of prisms that were one-half block wide exceeded those that were a full block wide, and went on to state that results from one-half block wide prisms would overestimate masonry assemblage strength. Masonry assemblage strengths reported in the analytical studies as conducted by Hassanli [7] and Abasi et al. [8] are believed to be unconservative given that they assumed that the material properties of the constituent materials were deterministic. Both Hassanli et al. [7] and Abasi et al. [8] reported that the resulting masonry assemblage strengths for one-block wide prisms exceeded those obtained for one-half block wide prisms. Hassanli et al. [7] also reported that the assemblage strength of one-half block wide prisms was insensitive to prism height. Abasi et al. [8] concluded that the assemblage strength of one block wide prisms exceeds that of half-block wide prisms due to the increased confinement stress resulting from the larger frictional contact area of the wider prisms.

Table 2: Reported strengths of half and full-block length prisms

		Drysdale 1979		Khalaf 1996		Hassanli 2015		Abasi et. al. 2020	
		Prism Strength, MPa		Prism Strength, MPa		Prism Strength, MPa		Prism Strength, MPa	
h/t ratio	Grouted (Y/N)	Full Block[1]	Half Block[2]	Full Block[3]	Half Block[4]	Full Block[5]	Half Block[6]	Full Block[7]	Half Block[8]
2	Y	10.8	11.3	16.8	23.2	30.6	27.3	22.7	21.3
3	Y	-	-	14.5	20.5	27.6	26.5	21.7	20.4
4	Y	-	-	-	-	26.5	26.4	20.4	19.9
5	Y	-	-	-	-	26.5	26.5	19.5	19.5
6	Y	-	-	15.2	15.6	-	-	-	-
2	N	15.8	15.9	14.0	14.3	-	-	-	-
3	N	-	-	12.0	14.1	-	-	-	-
6	N	-	-	9.8	12.9	-	-	-	-

[1] Regular flat-ended 150 mm block

[2] Half-blocks cut from a 150 mm splitter block

[3] 190 mm x 390 mm x 190 mm frog-ended block

[4] 190 mm x 195 mm x 196 mm frog-ended block

[5] 203 mm x 406 mm x 203 mm frog-ended block

[6] 203 mm x 203 mm x 203 mm frog-ended block

Researchers have yet to reach a consensus regarding the effect of prism width on the resulting masonry assemblage strength. While narrower prisms are beneficial as a result of reductions in their weight, construction time, and cost, additional research is warranted to better understand the influence of prism width.

Height-to-Thickness (h/t) Ratio and Resulting Correction Factors

The height-to-thickness (h/t) ratio, as defined in Figure 2, is a means of quantifying the aspect ratio of prisms. Baseline h/t ratios differ between CSA S304-14 (R2019) [1] and ASTM C1314-18 [3], with a value of 2 as included in ASTM C1314-18 [3] and 5 prescribed by CSA S304-14 (R2019) [1]. The h/t ratio of 2 prescribed by ASTM C1314-18 [3] is based upon the geometry of concrete cylinders as used in reinforced concrete construction, which, in accordance with ASTM C31/C31M-19a [9] require cylinder length to be twice the diameter. CSA S304-14 (R2019) [1] includes a baseline $h/t = 5$ to ensure that prisms are sufficiently tall such that their resulting masonry assemblage strength is not influenced by the confining effects of the upper and lower platens as included in the test setup (Figure 1).

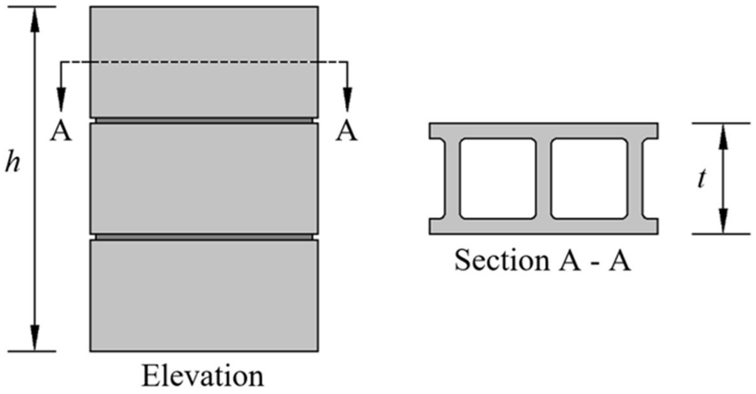

Figure 2: Height to thickness, *h*/*t*, ratio

Table 3 shows that both CSA S304-14 (R2019) [1] and ASTM C1314-18 [3] permit the construction of prisms with h/t ratios not meeting the baseline value. When this occurs, correction factors as are included in Table 3 must be applied to the as-tested value of masonry assemblage strength to convert it to the equivalent strength at the baseline h/t ratio. Correction factors equal to unity are applied when the h/t ratio of a prism is equal to the baseline value as prescribed in either standard, and so for $h/t = 2$ and 5 for ASTM C1314-18 [3] and CSA S304-14 (R2019) [1], respectively. Table 3 shows that correction factors of less than one are applied for h/t ratios less than the baseline value of 5 in accordance with CSA S304-14 (R2019) [1] to account for the increase in as-tested masonry strength resulting from confinement due to the upper and lower platens as are included in the test setup (Figure 1) as reported by Boult [10] and Drysdale and Hamid [5]. Similarly, correction factors in excess of unity are prescribed in ASTM C1314-18 [3] when the h/t ratio of a particular prism exceeds the baseline value of 2 given the expected reduction in as-tested masonry assemblage strength of taller prisms.

Table 3: Correction factors to account for *h*/*t* ratio

h/*t*	1.3	1.5	2	2.5	3	4	5
CSA S304-14 (R2019) [1]	-	-	0.85	0.88	0.90	0.95	1.00
ASTM C1314-18 [3]	0.75	0.86	1.00	1.04	1.07	1.15	1.22

Consensus has been achieved by researchers examining the influence of *h*/*t* ratio on masonry assemblage strength: all [5, 10, 11, 12] have found that masonry assemblage strength is inversely proportional to *h*/*t* ratio as are reflected in the correction factors reported in Table 3. Wong and Drysdale [11] reported that the masonry assemblage strength of grouted and ungrouted prisms with an *h*/*t* ratio equal to two were 13 and 26% greater, respectively, than those reported for prisms with greater *h*/*t* ratios. Drysdale and Hamid [5] concluded that masonry assemblage strength was insensitive to *h*/*t* ratio for $5 \leq h/t \leq 12$. In other words, once a masonry prism is five times as tall as it is thick, the influence of confinement due to the upper and lower platens as included in the test setup are eliminated.

Bond Pattern

Figure 3 shows the two most common patterns used for the construction of concrete block masonry, and relates to the arrangement of the concrete masonry units in subsequent block courses. ASTM C1314-18 [3] requires prisms to be constructed in a stack pattern (Figure 3(b)). In contrast, CSA S304-14 (R2019) [1] states that the bond pattern used for prisms should generally match that of the structures they are attempting to replicate for the purposes of estimating their masonry assemblage strength. Prisms constructed in running bond (Figure 3(a)) are often built as a result.

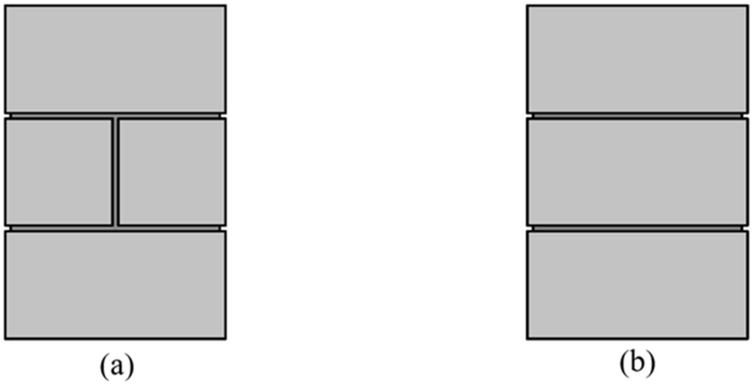

Figure 3: Bond pattern: (a) running bond, and (b) stack pattern

Few researchers [12, 13] have investigated the influence of bond pattern on the masonry assemblage strength of prisms and the results of the studies that do exist are in conflict with one another. Hamid et al. [12] reported that masonry assemblage strength as derived from tests of prisms is insensitive to bond pattern. In contrast, Ganesan and Ramamurthy [13] found that the masonry assemblage strength of prisms constructed in running bond was 20 to 40% lower than prisms built using a stack pattern.

Mortar Bedding

Mortar bedding requirements as prescribed in CSA S304-14 (R2019) [1] and ASTM C1314-18 [3] differ. Prisms built in accordance with CSA S304-14 (R2019) [1] require face shell bedding (Figure 4(a)) whereas full mortar bedding (Figure 4(b)) is used for prisms built in accordance with ASTM C1314-18 [3]. Prism constructions in accordance with ASTM C1314-18 [3] are fully bedded given that they intend to verify that the strength of materials as-supplied meets project specifications. In contrast, the face shell bedding called for by CSA S304-14 (R2019) [1] is intended to replicate the construction methods used in full-scale structures.

The type of mortar bedding influences both the effective loaded areas and stress distribution within masonry members. Researchers [13, 14] concur that masonry assemblage strength as obtained from tests of prisms were greater for those that were fully bedded as compared to those constructed using face shell bedding. Chukewunenye and Hamid [14] showed that the absence of mortar on the webs induced large, non-uniform lateral tensile stresses in prisms and cause crack propagation in the webs to initiate at relatively low levels of applied stress. These large, non-uniform stresses were also reported by others [13] who also found that the masonry assemblage strength of prisms constructed using face shell bedding were 32 to 58% less than those that were fully bedded.

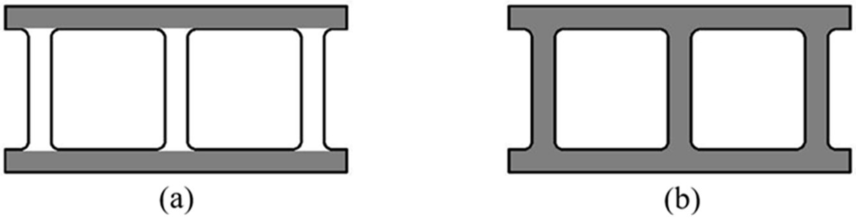

Figure 4: Mortar bedding types: (a) face shell bedding, and (b) full mortar bedding

SUMMARY AND CONCLUSIONS

A comparison of the geometry, construction, loading, and testing of masonry prisms in accordance with U.S. and Canadian standards was presented herein. Differences in the geometry and construction of prisms built in accordance with CSA S304-14 (R2019) and ASTM C1314-18 were also presented in the context of the available literature.

The following conclusions were noted:

1. Prism height and width, height-to-thickness ratio, bond pattern, and mortar bedding differ between CSA S304-14 (R2019) and ASTM C1314-18 requirements. Such differences have been shown to affect the resulting masonry assemblage strength and prevalence of prisms as constructed on-site.
2. The loading and test setup of prisms as prescribed by CSA S304-14 (R2019) and ASTM C1716-20 are similar, and can be accommodated for using a single test setup and loading arrangement.
3. The intended use of prisms differs between the two countries and so is reflected by the standards that prescribe their geometry and construction. Prisms constructed in accordance

with ASTM C1314-18 are intended to be used for quality assurance purposes and so confirm that supplied materials meet project specifications. In Canada, prisms are generally used to establish the masonry assemblage strength of the as-constructed structure.

4. Masonry prism strength serves as input to many design provisions as included in both Canadian and U.S. standards and so differences in the resulting designs are pervasive as long as the standards for the construction and testing of prisms, as included in ASTM and CSA standard differ. An experimental program, examining the parameters that influence masonry assemblage strength when derived from the testing of prisms is therefore underway at the University of Saskatchewan in an effort to reconcile differences in design requirements as included in design codes as adopted by the two countries.

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