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TOWARDS DETERMINING THE IN-PLANE SHEAR STRENGTH OF MASONRY

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ABSTRACT

The Canadian Masonry Design Standard, CSA S304-14, specifies that the in-plane diagonal shear strength of masonry, v_m, is a function of the factored moment and factored shear at the location of interest in a wall. Thus, components of the external load effect side of the ultimate limit states design are included in the estimation of the shear resistance, contrary to the basic principle of that method. We have therefore begun to examine experimental methods of determining the diagonal shear strength of masonry as well as the ways that other codes and standards predict the strength of a wall subjected to in-plane shear. Through finite element analysis, we have determined that of the triplet and diagonal shear tests, the triplet test appears to cause stresses in the mortar joint more similar to those in a wall than does the diagonal shear test. The triplet test also appears easier to conduct and more amenable to the application of normal stress. Other codes and standards utilize the results of such tests or estimate the diagonal shear strength from some other strength of the masonry. It is well known that the diagonal shear strength of masonry varies with the applied normal stress in a Mohr-Coulomb relationship, so the effective shear strength will vary in a wall subject to varying moment up its height. Thus, a method needs to be developed to allow for the effect of varying moment on the load effect side of the ultimate limit state design. We review the experimental test methods and the resulting stresses along with the methods used in other codes and standards to lay a foundation for how the clauses in CSA S304 might be revised.

KEYWORDS: *in-plane shear, diagonal shear, shear strength, triplet test, diagonal shear test*

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INTRODUCTION

A masonry shear wall is a structural component designed to resist in-plane shear loads. The in-plane shear capacity normally consists of contributions from the masonry, the reinforcement, and the axial load. To predict the in-plane shear capacity, the shear strength of the masonry should be determined. The Canadian Standards Association (CSA Group) defines the masonry shear strength in CSA S304-14 [1] as the following Eq. (1):

$$v_m = 0.16\left(2 - \frac{M_f}{V_f d_v}\right)\sqrt{f'_m} \tag{1}$$

Where M_f and V_f are the externally applied factored moment and factored shear loads; d_v is the effective shear depth of the wall; and f'_m is the compressive strength of the masonry. There are two major issues in this equation. First, when the wall is being constructed, the mason cannot adjust the strength according to the external factored loads at a given location. Second, the presence of factored loads in the equation is contrary to the principle of ultimate limit state design. Material strength should be obtained from testing and be part of the shear resistance, while the external loads cause the load effect, which the resistance should exceed to ensure structural safety.

In order to correctly define the masonry shear strength, standards from around the world were examined. The relevant equations are provided in Table 1. The Australian Standard 3700:2018 [2] defines the shear strength of continuous horizontal mortar joints as 1.25 times the flexural tensile strength. However, the standard refers to the European EN 1052.3 [3] Triplet Test for mortar joint shear properties, the American Diagonal Tension Test (ASTM E519 [4]) for the shear strength of a wall panel and ASTM C1006 [5] to define the splitting tensile strength of individual units. The American standard, TMS 402/602-16 [6], uses a similar relationship as Eq. (1) but different coefficients for their masonry shear resistance. The Eurocode EN 1996-1-1 (2005) [7] specifies that the shear strength of masonry should be determined from experimental results. The Chinese standard, GB50003-2011 [8], specifies ungrouted masonry shear strength of masonry units in a table, as in Table 2, and the grouted masonry shear strength from compressive strength, but the standard also adopts a similar relationship for shear capacity prediction as Eq. (1). The Brazilian standard [9] defines the sliding shear strength of unreinforced masonry as a function of the precompression load and the strength of the type of mortar used, while the shear strength of reinforced masonry includes a function of the longitudinal reinforcement rate.

Among all the standards mentioned, the Triplet Test and the Diagonal Tension Test are experimental methods of determining shear strength. The stresses resulting from these methods will be compared and discussed in the following sections using Finite Element Analysis (FEA) models. With the shear stress obtained from the small-specimen tests, it is possible to obtain the shear strength of masonry from the following Eq. (2):

$$\tau = \tau_0 + \mu\sigma \tag{2}$$

Where τ_0 is the initial shear stress without any precompression; μ is the coefficient of friction; and σ is the normal compression stress.

Table 1: Masonry Shear Strength and Equations from Some Standards

Standard	Material Shear Strength	Wall In-plane Shear Resistance
Canada CSA S304-14 [1]	$v_m = 0.16\left(2 - \frac{M_f}{V_f d_v}\right)\sqrt{f'_m}$	Unreinforced diagonal failure: $V_r = \phi_m\left(v_m b_w d_v + 0.25P_d\right)\gamma_g$ Reinforced diagonal failure: $V_r = \phi_m\left(v_m b_w d_v + 0.25P_d\right)\gamma_g + \left(0.60\phi_s A_v f_y \frac{d_v}{s}\right)$
USA TMS 402/ 602-16 [6]	Not specified, but similar parameters as the CSA found in the shear equation	Reinforced: $V_n = \left(V_{nm} + V_{ns}\right)\gamma_g$ $V_{nm} = \left[4.0 - 1.75\left(\frac{M_u}{V_u d_v}\right)\right]A_{nv}\sqrt{f'_m} + 0.25P_u$ $V_{ns} = 0.5\left(\frac{A_v}{s}\right)f_y d_v$
Australia AS 3700: 2018 [2]	Unreinforced: $f'_{ms} = 1.25 f'_{mt}$ Reinforced: For $H / L \le 2.3$: $f_{vr} = 1.50 - 0.5H / L$ For $H / L > 2.3$: $f'_{vm} = 0.35MPa$	Unreinforced: $V_d \le V_o + V_l = \phi f'_{ms} A_d + k_v f_d A_d$ Reinforced: For $H / L \le 2.3$: $V_d \le \phi\left(f_{vr} A_d + 0.8 f_{sy} A_s\right)$ For $H / L > 2.3$: $V_d \le \phi\left(f'_{vm} b_w d + f_{vs} A_{st} + f_{sy}\frac{A_{sv} d}{s}\right)$
Eurocode EN 1996-1-1 (2005) [7]	f_{vd} obtained from test results	Unreinforced: $V_{Rd} = f_{vd} t l_c$ Reinforced: $V_{Rd1} + V_{Rd2} = f_{vd} t l + 0.9 A_{sw} f_{yd}$
China GB50003-2011 [8]	Ungrouted: f_v obtained from Table 2 Grouted: $f_{vg} = 0.2 f_g^{0.55}$ Where f_g is the compressive strength of masonry	Unreinforced: $V \le \left(f_v + \alpha\mu\sigma_0\right)A$ Reinforced subjected to shear + compression: $V \le \frac{1}{\lambda - 0.5}\left(0.6 f_{vg} b h_0 + 0.12N\frac{A_w}{A}\right) + 0.9 f_{yh}\frac{A_{sh}}{s}h_0$, where $\lambda = \frac{M}{V h_0}$ Reinforced subjected to shear + tension: $V \le \frac{1}{\lambda - 0.5}\left(0.6 f_{vg} b h_0 - 0.22N\frac{A_w}{A}\right) + 0.9 f_{yh}\frac{A_{sh}}{s}h_0$, where $\lambda = \frac{M}{V h_0}$

Table 1 (Continued)

Brazil PN 002: 123.010-001/1 [9]	Unreinforced sliding: $f_{vk} = 0.10 + 0.5\sigma \leq 1.0$ for mortar strength from 1.5 to 3.4 MPa $f_{vk} = 0.15 + 0.5\sigma \leq 1.4$ for mortar strength from 3.5 to 7.0 MPa $f_{vk} = 0.35 + 0.5\sigma \leq 1.7$ for mortar strength above 7.0 MPa Reinforced: $f_{vk} = 0.35 + 17.5\rho \leq 0.7$	Reinforced: $V_{design} \leq V_a + V_s$ $V_a = f_{vd}bd$ $V_s = 0.75 f_{yd} bd \frac{A_{sw}}{s} \leq 0.4bd \frac{\sqrt{f_{pk}}}{\gamma_m}$

Table 2: Shear Strength when Cracking Occurs along the Stressed Sections of Mortar Joints of Masonry in Chinese Code GB50003-2011 (MPa) [8]

Type of Masonry Unit	Strength Grades of Mortar			
	≥M10	M7.5	M5	M2.5
Clay bricks, hollow clay bricks	0.17	0.14	0.11	0.08
Concrete bricks, hollow concrete bricks	0.17	0.14	0.11	-
Sand-lime brick, fly ash silicate brick	0.12	0.10	0.08	-
Concrete blocks	0.09	0.08	0.06	-
Rubble stone	-	0.19	0.16	0.11

FINITE ELEMENT ANALYSIS MODELS

To compare the testing methods, both the Triplet Test and the Diagonal Tension Test were modelled with the FEA software Abaqus 2019. In addition, a model of a wall with uniformly applied stress was created to compare with the shear strength tests. Standard hollow blocks with dimensions of 190 x 190 x 390 mm were used, with the taper in the cores modelled. Mortar joints were 10 mm thick on the face-shells and in the head joints. Steel plates with various thickness were used at the boundaries. Material properties summarized in Table 3 were assumed to be linear elastic in this preliminary study, with failure and cohesive behaviour not being taken into account. 8-node linear brick elements (C3D8) were used to model the blocks and mortar, and the same elements with reduced integration (C3D8R) used to model the steel plates. The element size was adjusted for results to be independent of the mesh.

Table 3: Material Properties Used for the Finite Element Models

Material Type	Elastic Properties	
	Young's Modulus (MPa)	Poisson's Ratio
Block	11,950	0.2
Mortar	4,509	0.2
Steel	200,000	0.3

Triplet Test

The Triplet Test [3] is used to determine the shear strength of mortar joint interfaces. A three-high prism is placed horizontally and supported as shown in Figure 1. Downward vertical load is applied to the head of the middle block and transferred to the block through rollers near its edges. The supports for the triplet are on the other side of the mortar joints, on the two outer units as shown in Figure 1a. The applied load is thus transferred through the mortar joints as shear. Horizontal precompression can also be applied to the specimen as shown. In the FE analysis, a precompression stress of 0.25 MPa was applied to the left side of the specimen, with the right side restrained from lateral displacement, as Step 1. Step 2 involved the application of a vertical displacement of 10 mm to the middle block. The right and the bottom edges of the specimen were fixed as shown in Figure 1b. (Note that the blocks are tapered, so the problem is not symmetric.)

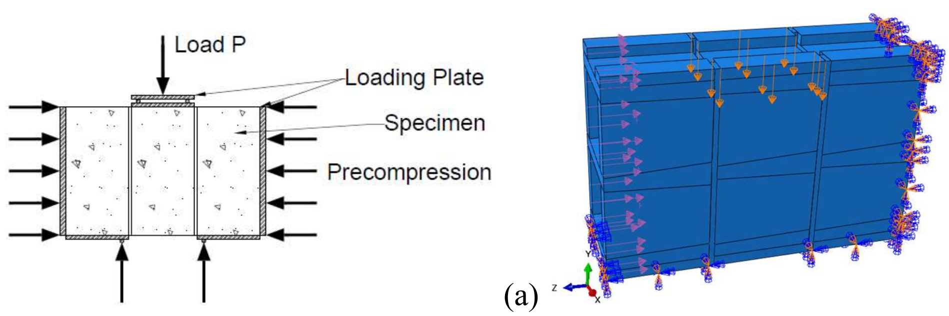


Figure 1: (a) Triplet Test with Precompression Load; (b) Abaqus Model of Triplet Test

Diagonal Tension Test

The Diagonal Tension Test [5] identifies the diagonal tensile and shear strength of masonry panels by applying compression loads on steel shoes at opposite corners of a 1.2 m x 1.2 m wall (Figure 2). The bearing length of both steel shoes is 150 mm, and they are positioned to be centered on the bearing surfaces. The applied compression load is equivalent to applying a shear and a normal load to the wall. For the FEA model, the bottom steel shoe was fixed in both translation and rotation along its edge. Similar to the Triplet Test, the upper shoe was then displaced downwards as would occur in an actual test. A vertical displacement of 10 mm was applied along the edge of the top shoe, which was equivalent to 7.07 mm in both the shear and normal directions.

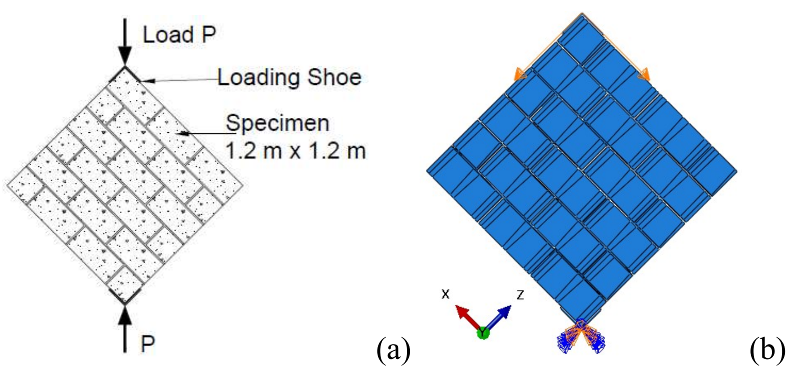


Figure 2: (a) Diagonal Tension Test; (b) Abaqus Model of Diagonal Tension Test

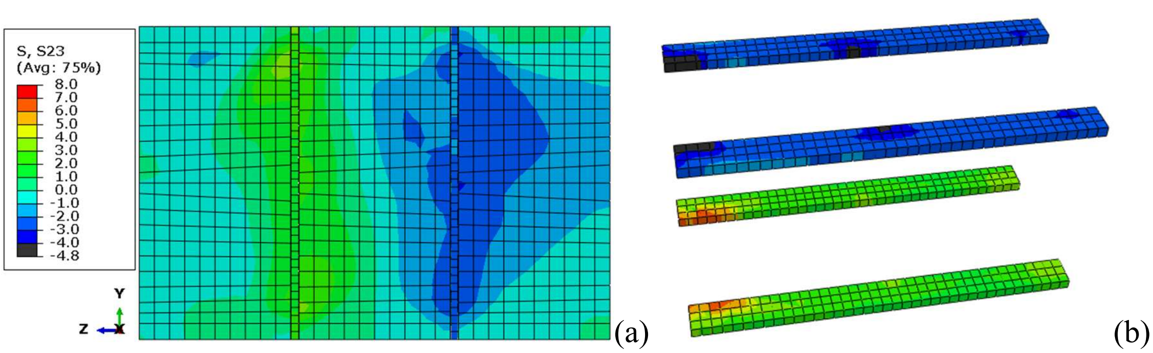
Wall with Uniform Stress

A 1.2 m x 1.2 m control wall model with axial compression and in-plane shear loads was created to compare with the results obtained from the Triplet and Diagonal Test models. Steel plates were placed on the top and bottom of the wall, with loads applied to the top plate while the bottom plate was fixed. The thickness of the plates was first set to 12 mm, as in the Triplet Test, but the plates deformed under compression and caused stress concentrations in the wall. Thus, the top plate thickness was increased to 25 mm. A uniform compressive stress of 0.25 MPa was applied to the top surface of the steel plate as Step 1 in the analysis, followed by an in-plane shear stress of 0.25 MPa as Step 2. The normal stress ensured that contact between the plate and the masonry was maintained as the shear stress was applied. These boundary conditions were aimed at creating the stress conditions that would occur from slabs above and below the wall acting as diaphragms.

RESULTS

Triplet Test

As mentioned previously, a horizontal precompression of 0.25 MPa and a vertical displacement of 10 mm were applied to the model of the triplet test. The resulting shear and minimum principal stresses were examined. The distribution of shear stress over the specimen is shown in Figure 3a. The left and right blocks are subject to relatively similar shear stress distributions of opposite directions from 1 to 3 MPa (recall the lack of symmetry due to taper of blocks). When the mortar joints were considered (Figure 3b), it may be seen that higher shear stresses are located at the ends where the displacement was applied – the right mortar segment was subject to 4 to 4.8 MPa, and the left segment to 5 to 7 MPa. The right mortar segment had the higher stress at the inner side of the centre, and the left centre also had a smaller area of higher stress. The minimum principal stress distributions shown in Figure 4, were not perfectly symmetrical because of the effects of the taper in the cores. The compressive stress gradually increased from the outer edges to the middle, with the highest magnitude on the top half of the middle block and the right half of the left block. Within the mortars, the compressive stress varied across the mortar segments. However, the highest compressive stress was on the edge where the displacement was applied, from 6 to 15 MPa, gradually decreasing along the mortar segments. A small area of lower compressive stress was found on the inner side of the mortar.



(a) (b)

Figure 3: Shear Stress Distribution of Triplet Test: (a) Entire Specimen; (b) Mortars Only

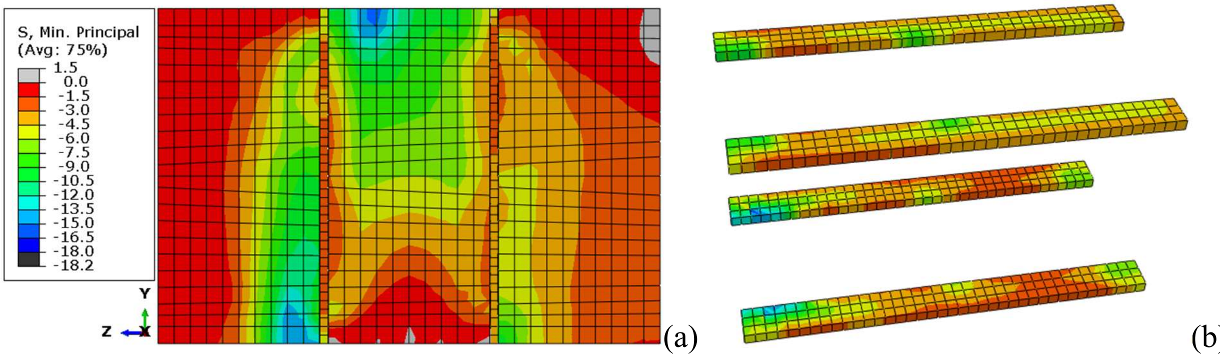


Figure 4: Minimum Principal Stress Distribution of Triplet Test: (a) Entire Specimen; (b) Mortars Only

Diagonal Tension Test

In order to compare results from this model to others, the Diagonal Tension Test model was rotated so the top loading shoe was at the top left corner and bottom shoe at the bottom right corner. As may be seen in Figures 5a and 6a, a compression strut formed along the diagonal between these two corners. Three mortar segments were analyzed, located between first and second, third and fourth, and fifth and sixth courses, respectively (boxed in red).

For the shear stress distribution in the diagonal test, higher stresses of 2 to 5 MPa were found in the compression strut, with the highest value being over 10 MPa at the uppermost and lowest mortar joints. Outside of the compression strut, shear stresses of 0 to 2 MPa were found with the opposite signs. When looking closely at the mortar joints, all segments at the selected locations show differing stress magnitudes across the mortar. The tapered cores create different bearing areas at the top and the base of the mortar joint, with the smaller area being at the top of the joint (the taper being such that the area of the core is larger at the bottom of a unit than at the top). Thus, a line of lower shear stress was found where there was no bearing on the mortar (see the red and yellow areas in Figures 5b, c and d). For the top and bottom corner mortar segments, the magnitude of the shear stress built up from the end to the head mortar joint, from +1 MPa to -8 MPa, whereas for the middle mortar segment, higher shear stresses of -4 to -6 MPa were found near the head joints with lower stress between the joints, from around -4 to -1 MPa.

The compression strut is clearly visible in the minimum principal stress distribution of the diagonal test shown in Figure 6a. The highest compressive stresses were located near the loading shoes. Again, for all mortar segments, the tapered cores created zones with low compressive stress where the unit did not bear on the full mortar bed. For the mortar segments in the top and bottom regions of interest, the highest compressive stresses surrounded the low stress zone. For the middle mortar segment, the stress distribution was more irregular, with stress varying from 0 to -6 MPa.

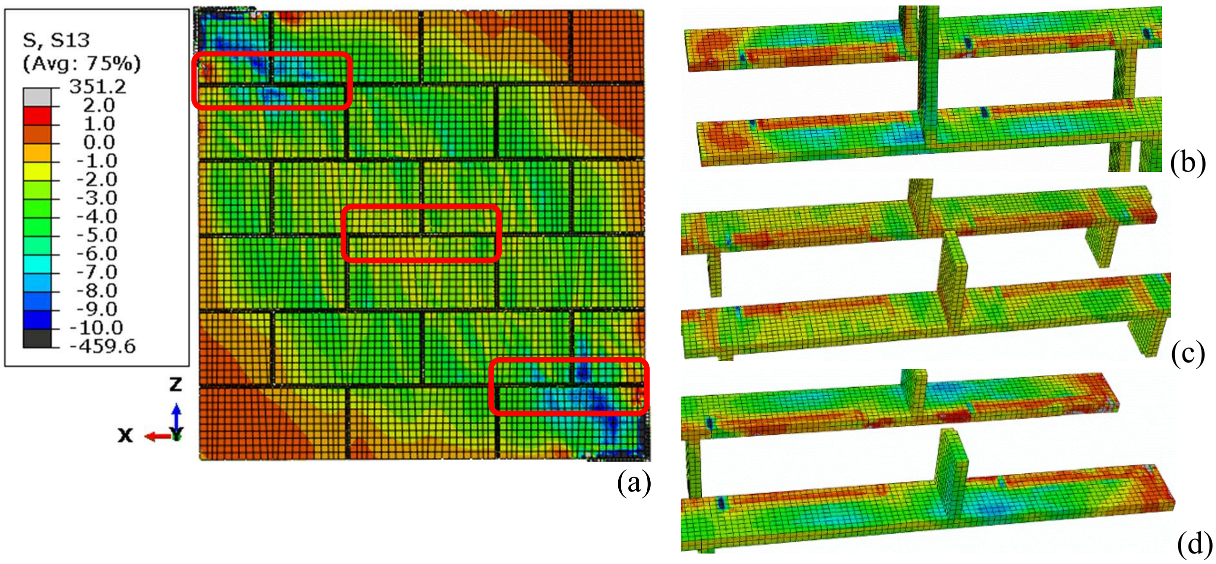


Figure 5: Shear Stress Distribution of Rotated Diagonal Tension Test Model: (a) Entire Specimen; (b) the Top Mortar; (c) the Middle Mortar; (d) the Bottom Mortar

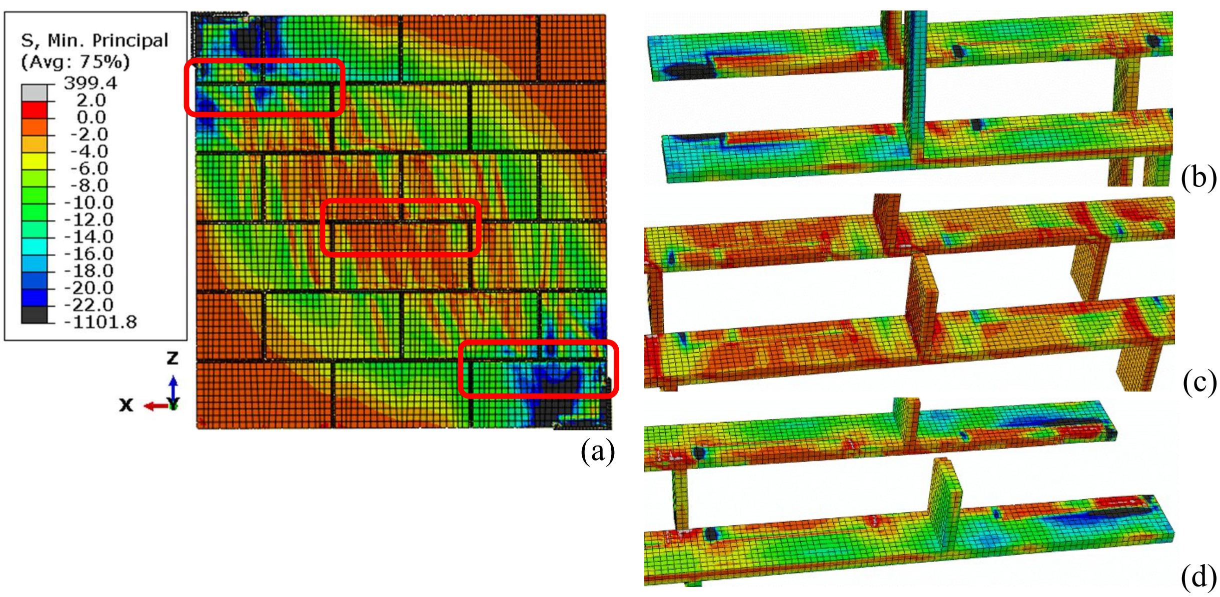


Figure 6: Minimum Principal Stress Distribution of Rotated Diagonal Tension Test Model: (a) Entire Specimen; (b) the Top Mortar; (c) the Middle Mortar; (d) the Bottom Mortar

Wall with Uniform Stress

Results obtained from wall model with uniform stress were compared with the results from the Triplet and Diagonal Tension Tests. The shear and minimum principal stresses for the wall model subject to 0.25 MPa compressive and shear stress on the top surface are shown in Figures 7 and 8. A compression strut formed and three mortar segments along the strut were checked.

The shear stress distribution showed that highest shear stresses occur at the bottom right of the specimen, as shown in Figure 7a. While the shear stress in most of the wall had magnitude between 0 and 1 MPa, the compression strut had stress values from 1 to over 4.5 MPa. When the mortar segments were considered in isolation, it was noticeable that the shear stress was higher in locations in the compression strut (generally to the right of the segments shown). As before, a zone of lower stress was present at the inner side of the mortar, where the units were not bearing on the bed joint due to the core of the unit. For the top and middle mortar segments examined, the highest shear stress was found near the head joints. The highest shear stress (18.8 MPa) was found in the bottom mortar segment.

The minimum principal stress distribution of the wall had similar trends to the shear stress – a clear compression strut and the highest stress at the bottom right corner, as shown in Figure 8a. The majority of the wall had a compressive stress of 0 to 2 MPa, whereas in the compression strut the stress varied between 2 and a little over 20 MPa. For the top segment, higher stress was found on the left half of the mortar and near the right head joints, from 2 to 4 MPa. The middle mortar segment had higher compressive stress in the compression strut near the top of the mortar joints. As before there was a zone of low stress at the inner side where the cores of the units left a section of mortar unloaded (most obvious in the compression strut). The left half of the bottom mortar segment had tensile stress of 4 MPa which dropped to 0 MPa in the middle, and then steadily developed to compressive stress of 4 MPa to the head joints. The right half of the bottom mortar had the maximum compressive stress at the end of over 20 MPa.

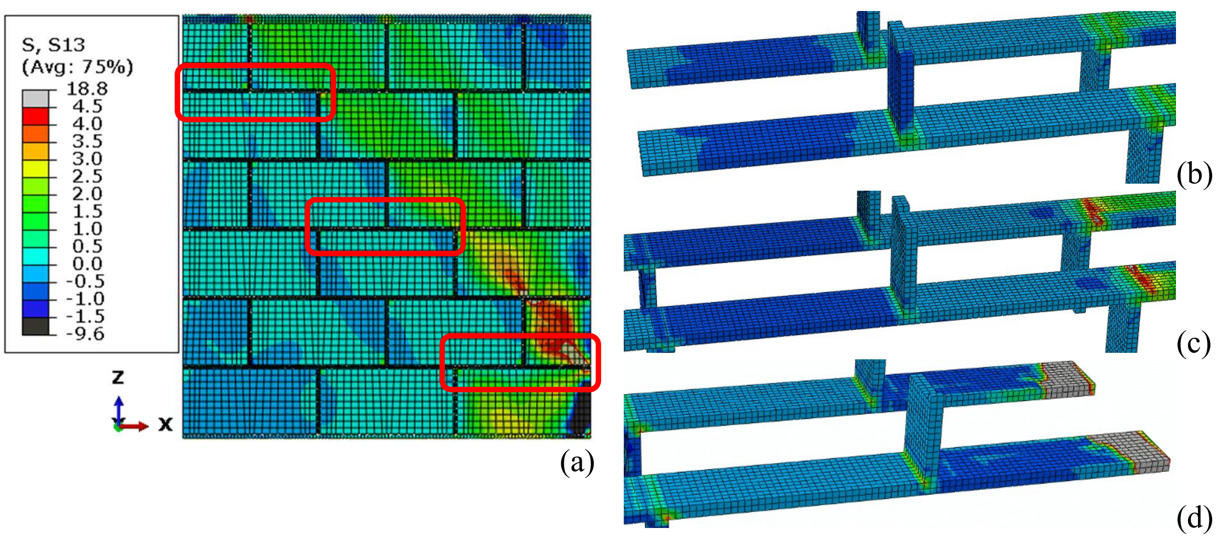


Figure 7: Shear Stress Distribution of Wall with Uniform Stress: (a) Entire Specimen; (b) the Top Mortar; (c) the Middle Mortar; (d) the Bottom Mortar

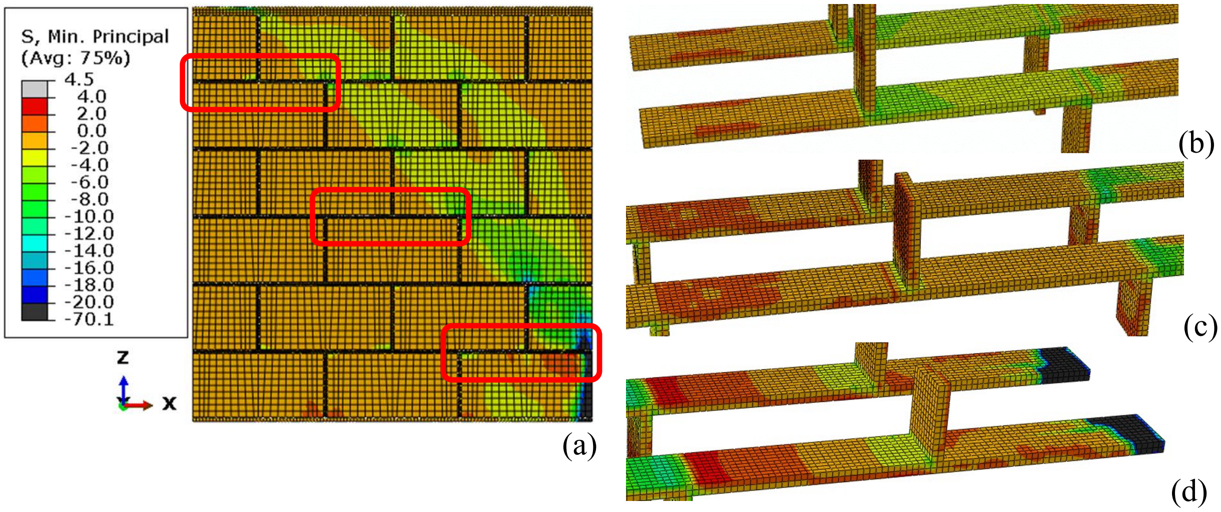


Figure 8: Minimum Principal Stress Distribution of Wall with Uniform Stress: (a) Entire Specimen; (b) the Top Mortar; (c) the Middle Mortar; (d) the Bottom Mortar

DISCUSSION

The Triplet Test, Diagonal Tension Test and the wall with uniform stress had some similarities in the shear stress and minimum principal stress distributions. For example, higher stress values were generally found at the end of mortar segments or near the head joints of the mortar. Additionally, zones of low stress occurred at the inner side of the mortar where the unit did not bear on the bed joint and higher stress surrounded that zone because the load was being applied over the smaller area of the face-shell. The tapered cores thus caused a stress concentration where the thinner face-shells bore on the mortar. However, the stress distribution was more irregularly scattered across the mortar joint in the Diagonal Tension Test compared to the Triplet Test and the wall with uniform stress. The latter two had more distinct development of stress distribution along the mortar segments. Further analytical studies should be conducted to study the reasons for the differences.

As the analyses presented are the preliminary stage of the project, only linear-elastic properties were included in the modelling: cohesive damage properties will be included in the future studies, in conjunction with failure criteria. This will enable strength measurements from the tests to be examined against strengths from more load and displacement boundary condition combinations for the control wall. Various situations for the latter would simulate various possible in-situ loading situations. The results of such modelling will be checked against test results presented in the literature and new tests performed in the laboratory. To date, there has been no explicit demonstration of the equivalent to a strain gradient effect as seen in eccentric compression tests: results will be examined to determine if such an effect exists for shear, depending on the rigidity of the diaphragms above and below the wall.

CONCLUSIONS

There is a divergence in the way that the in-plane shear strength of masonry is determined in standards around the world. The American, Canadian, and Chinese standards mix load effects into the resistance side of design. Other standards define the shear strength of masonry through or from some sort of testing. That is, these standards define masonry shear strength as a material property and then determine the strength of a wall from that property, wall dimensions and any reinforcement. Only the American and Canadian standards increase strength due to the effect of dead load, although in other standards, the shear strength for a particular level of normal stress can be determined by test. The diversity in approaches to determining the in-plane shear strength of masonry indicates that there is not consensus world-wide on how to define or determine such strength. Further research is warranted to provide better understanding of the issues and develop procedures for safe design and efficient use of the material.

From the numerical modelling presented here, both the Triplet Test and Diagonal Tension Test showed considerable compliance with the shear stress distribution in the mortar joints of a wall subject to applied uniform stresses. Between the two strength testing techniques, the Triplet Test only requires a three-block specimen, whereas the Diagonal Tension Test requires a 1.2 m x 1.2 m panel. In addition, it is possible to add precompression loads more easily in the Triplet Test, and the applied loads are directly transferred to shear in the mortar. The size of the specimen in the triplet test means that it can be assessed in a greater range of test machines than the diagonal shear test specimen. Therefore, the Triplet Test would appear more amenable for application in industry and is more likely to be adaptable to replicate in-situ situations. Future research should take more material properties into consideration, as well as exploring the failure of the materials to provide estimates of "strength" as obtained from the test in relation to the "strength" that would be obtained in a wall. The analytical modelling results also need to be verified by existing literature and future experimental results.

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