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A DETAILED MICRO FINITE ELEMENT MODEL FOR PREDICTING MASONRY PRISM BEHAVIOR UNDER COMPRESSIVE LOAD AND ITS APPLICATION

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ABSTRACT

The compressive strength of masonry is a critical material parameter in the design and analysis of masonry structures, and it is commonly determined based on physical testing (e.g., prism testing) in the laboratory or semi-empirical analytical models (e.g., unit strength method). Being a less expensive and still accurate approach, finite element (FE) modeling is attractive for predicting the masonry compressive strength. This paper presents the development and application of a three-dimensional (3D) detailed FE model for masonry prisms using commercial software ABAQUS. In this model, concrete damage plasticity (CDP), together with the uniaxial compressive behavior described by the modified Kent-Park model, was adopted for both concrete units and mortar layers. In addition, the tensile behavior was characterized using the concept of fracture energy. The developed FE models were validated using the experimental tests of concrete masonry prisms. Following the validation, a series of parametric studies was conducted to learn how material properties or testing configurations can affect the FE-based masonry strength prediction. Numerical prism testing was then carried out to study the prediction ability of the proposed FE model compared to the current masonry design codes. Results indicate that the compressive behavior of masonry prisms is more significantly affected by concrete unit compressive strength and the mortar thickness, which shed lights on the importance of construction quality.

KEYWORDS: *finite element model, hollow masonry prism, detailed micro-modeling approach, masonry compressive strength*

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INTRODUCTION

Two primary ways of determining the compressive strength of masonry are the prism testing method and the unit strength method, as mentioned in the current Canadian masonry design code CSA S304-14 [1]. However, the values provided by the unit strength method given in CSA S304-14 were based on the research work conducted by Maurenbrecher [2] several decades ago, which were proved to be unduly conservative [3]. Masonry industry has grown a lot since the 1980s, and thus a lot of advanced research about the masonry construction and design technology was developed. Nowadays, a much more developed understanding of the behavior of masonry under compression has been formed compared to when those prescribed values were first introduced [3].

Compared to the costly experimental tests (i.e., [4] [5] [6]), finite element (FE) modeling is a more affordable alternative when it comes to masonry structures. Particularly, a FE model to simulate the masonry prism test can be developed to predict the behavior of masonry prisms under uniaxial compression. Former research was carried out regarding 3D finite element modeling applied to the prediction of hollow concrete unit masonry: Hamid and Chukwunenye [7] conducted research using 3D FE model to study the compressive behavior of both face shell and fully bedded hollow concrete masonry prisms. The influence of the interaction properties between masonry prisms and loading plates was emphasized. Pina-henriques and Lourenço [8] proposed a simplified 3D modeling method while conducted that the simplified method can lead to different prediction results comparing with the detailed methods. Later, another study was carried out by the authors Pina-henriques and Lourenço [9], and the conclusion was that 3D FE modeling method works better on masonry prisms comparing to the other simplified method (i.e., plane-strain modeling and plane-stress modeling). Köksal et al. [10] carried out a nonlinear 3D FE analysis and different model parameters were evaluated. An equation consisted of unit compressive strength and mortar compressive strength was proposed but the effect of other parameters were not discussed. Thus, the influence of parameters on the mechanical behavior of masonry prism needs to be further studied.

As such, a detailed micro-FE model is developed to simulate the masonry prism test in this paper. The proposed FE model is first validated based on the experimental tests carried out by Barbosa et al. [11]. A python script is developed to facilitate the implementation of the presented 3D FE model and can be subsequently applied to the parametric study and to automate numerical prism testing. A parametric study is carried out to study the sensitivity of the masonry compressive strength with respect to different micro model parameters. Numerical masonry prism testing is then conducted based on 293 groups of hollow concrete masonry prisms collected from 48 literatures, including 1375 specimens in total, to show the accuracy of the numerical prism testing based on the micro-FE modelling.

MASONRY PRISM TESTING

Masonry prism specimens are usually constructed using multiple masonry units and mortar layers, which are typically layered up in the stack-bond configuration, with face shell bedding as commonly adopted in North America. During the test, masonry prism specimens are typically placed between two planks to help reduce the confinement effect of the loading machine (i.e., [3] [4] [5] [6]). According to Berto et al. [12], the failure mechanisms of masonry prism under compressive load mainly depend on the interaction between masonry units and mortar layers due to their different characteristics. The commonly observed failure modes include the tension cracks parallel to the loading direction (i.e., the tensile splitting failure), which occurs among the prisms constructed with mortar weaker than units; and shear failure along some lines of weakness which occurs among the prisms constructed with mortar stronger than units. Thus, 3D detailed mechanics-based FE model is developed here, which can further be used to study the failure mechanisms, reproduce the stress-strain curves, to study the effect of micro model parameters, and to serve as a strength prediction model. Additionally, the FE model can be used to assist developing data-based masonry strength prediction models and uncertainty quantification of the existing strength prediction models.

FINTIE ELEMENT MODEL

General Information

In this study, 3D micro-FE models are developed to simulate the masonry prism test using commercial software ABAQUS. Concrete units, mortar layers, the interfaces between masonry components, and the interfaces between the masonry prism and loading plates are modeled explicitly. Eight-node linear brick elements with reduced integration (C3D8R) are adopted to model concrete units and mortar layers. A mesh sensitivity study is carried out and the results are shown in Figure 1. It can be conducted that when the mesh size has a significant impact over the overall stress-strain behavior when it is over 20 mm. Thus, the average mesh size for concrete units and mortar layers is 20 × 20 × 20 mm and 20 × 20 × 10 mm respectively, to ensure computational efficiency and accuracy. The dimensions of the prism are shown in Figure 1. Concrete damage plasticity (CDP) model [13] is used to describe the behavior of both concrete unit and mortar with two failure mechanisms considered: compressive crushing failure and tensile cracking failure. The plasticity and damage parameters are detailed in the following sections.

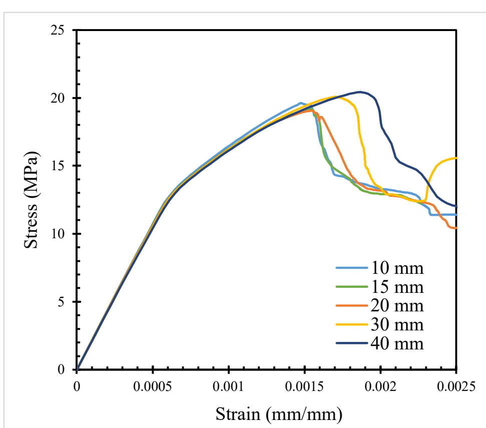


Figure 1: Mesh sensitivity analysis of a three-course hollow concrete masonry prism.

Uniaxial Compressive Behavior

A modified Kent-Park model (σ-ε) proposed by Chaudhari and Chakrabarti [14] is adopted to describe the compressive behaviors of concrete and mortar with different material parameters. The adopted model consists of two branches, including a parabolic ascending branch and a linear descending branch, which are presented below in Equation 1 and Equation 2, respectively.

$$\frac{\sigma}{\sigma_{cu}} = 2\frac{\varepsilon}{\varepsilon_0'}(1-\frac{\varepsilon}{2\varepsilon_0'}), \varepsilon \le \varepsilon_0 \tag{1}$$

$$\frac{\sigma}{\sigma_{cu}} = 1-0.15(\frac{\varepsilon-\varepsilon_0'}{\varepsilon_{cu}-\varepsilon_0'}), \varepsilon > \varepsilon_0 \tag{2}$$

where σ_{cu} is the peak compressive strength, provided in the material coupon tests of units and mortar; ε_0' is the strain corresponding to the peak compressive strength, which is assumed as 0.002 [15]; and ε_{cu} is the ultimate strain, which is assumed as 0.003 [15].

Uniaxial Tensile Behavior

Tensile splitting failure is one of the most common failure modes during masonry prism testing. Thus, a well-defined tensile model is crucial to predict the behavior of masonry prisms including the compressive strength since the tested masonry prism is under triaxial stress state. Tension-stiffening effect is considered after the pre-cracking linear elastic stage. Tension stiffening can be defined by two approaches: stress-strain relationship or fracture energy cracking criterion. The fracture energy criterion proposed by CEB-FIP [16] is adopted in this study to define the post-cracking behavior (e.g., tension stiffening) due to its mesh independence [17], see Equation 3. Tensile strength is provided in the material coupon tests in the experiment used for validation, while Equation 4 [18] can be used to calculate the tensile strength when no experimental result is available:

$$G_f = 0.073\sigma_{cu}^{\ 0.18} \tag{3}$$

$$\frac{\sigma_t}{\sigma_{cu}} = 0.387\sigma_{cu}^{\ -0.37} \tag{4}$$

where σ_{cu} is the peak compressive strength, σ_t is the tensile strength and G_f is the fracture energy estimated.

Elastic-Plasticity Parameters

Elastic parameters (i.e., elastic modulus, Poisson's ratio) are obtained from material coupons tests of units and mortar, as typically provided in the literature. The plasticity parameters as commonly used are presented in Table 1. The flow potential eccentricity ε is taken as 0.1. The ratio between the initial equi-biaxial compressive yield stress f_{b0} and the initial uniaxial compressive yield stress f_{c0} is taken as 1.16. The second stress invariant ratio K is taken as 0.667 (ABAQUS User's Manual

[19]) and different values for the other uncertain parameters (e.g., dilation angle Ψ, the viscosity parameter) will be used to study their effects on the prediction results.

Damage Parameters

Damage parameters are used in the CDP model as numerical indicator of material degradation in the post-peak range. In order to accurately predict the prism behavior under compression, damage parameters are included to better predict the failure patterns. Equation 5 [20] and Equation 6 [21] are adopted to compute the compressive and tensile damage parameter d_c and d_t, respectively:

$$d_c = (\sigma_{cu} - \sigma_c) / \sigma_{cu} \tag{5}$$

$$d_t = 1 - \frac{\sigma_t E_c^{-1}}{0.9\varepsilon_t^{in} + \sigma_t E_c^{-1}} \tag{6}$$

where σ_{cu} is the peak compressive strength, σ_c is the compression stress along the descending stress-stain curve, σ_t is the tensile strength, E_c is the modulus of elasticity and ε_t^{in} is the tensile inelastic strain.

Unit-mortar Interfaces

The interactions between different masonry components (i.e., units and mortar layers) are crucial to the behavior of the masonry prism tested. To better represent the mechanism of the interaction, a "surface-to-surface" contact is defined between the concrete unit and the mortar layer. The normal behavior is defined by as a "hard" contact to avoid penetration. The tangential behavior is defined assuming Coulomb friction with finite sliding, and the frictional coefficient range from 0.6 to 0.8 [22] [23].

Boundary and Loading Conditions

In order to mimic the real loading condition, the two loading plates are simulated by two rigid surfaces, and a "surface-to-surface" contact is used to simulate the interaction between the loading plates and the prisms in the same manner as for the unit-mortar interfaces, but with different frictional coefficients. The two loading plates are restrained in all degrees of freedom except the vertical displacement along the prism.

FE MODEL VALIDATION

To validate the proposed FE model, the prisms tested in the experimental program [11] are simulated, in which a total of four groups of prisms tested, with three specimens in each group. The main difference between the four groups is the ratio between the unit compressive strength and mortar compressive strength. Group 1 and Group 2 have a higher ratio of 2.4 while Group 3 and Group 4 have a lower ratio of 1.6. Concrete block samples and mortar mixer samples are manufactured and tested according to Brazilian standard. All the necessary material properties (i.e., compressive strength of both concrete blocks and mortar, tensile strength and fracture energy of both concrete blocks and mortar, etc.) were documented. All specimens are subjected to axial compressive loads under displacement control with a constant displacement velocity. A loading steel plate is placed between the loading machine and the tested prism specimen. The dimensions (mm) of the hollow concrete blocks and the lay-out of the prisms used in the validation FE model are the replica of the tested specimens. The 3D illustrations are presented in Figure 2. Full bedding is adopted as in the experiment [11]. The compressive and tensile strength of concrete units and mortar are presented in Table 1.

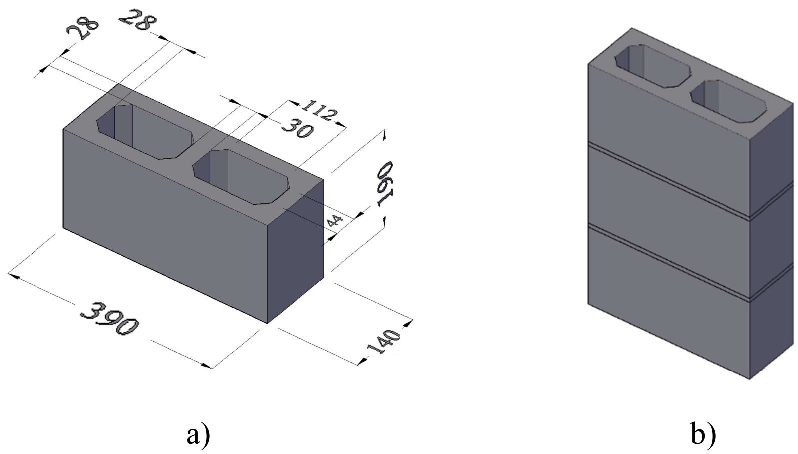
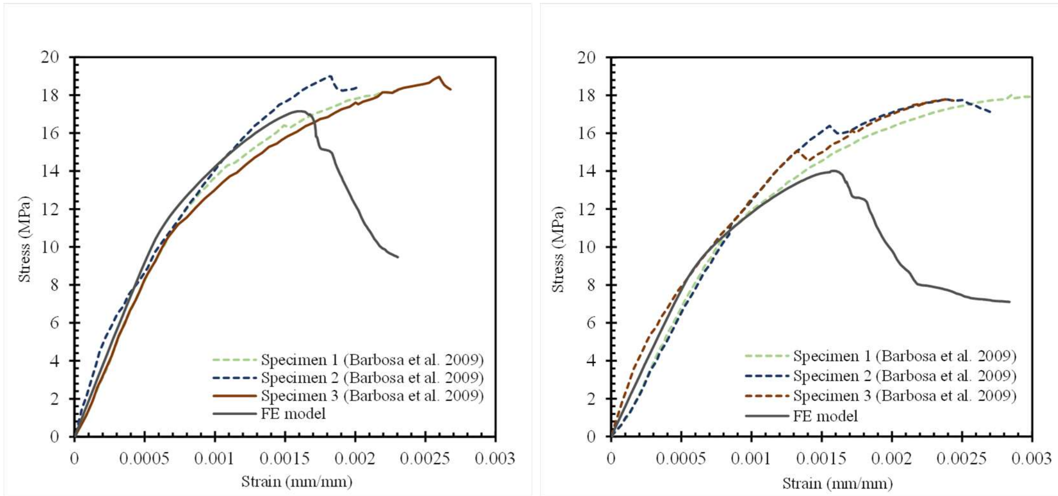


Figure 2: The Dimensions (mm) and Lay-out of Masonry Specimens: a) Hollow Concrete Unit, b) Three Block Stack-Bond Prism

Table 1: The Compressive and Tensile Strength of Concrete Units and Mortar (Barbosa et al. 2009)

Group	**Material**	$f_c(MPa)$	$f_t(MPa)$
Group1	Concrete	9.4	1.1
	Mortar	22.8	2.2
Group2	Concrete	7.7	0.9
	Mortar	18.6	1.7
Group3	Concrete	15.5	1.8
	Mortar	24.9	2.4
Group4	Concrete	22.2	2.6
	Mortar	36.2	3.1

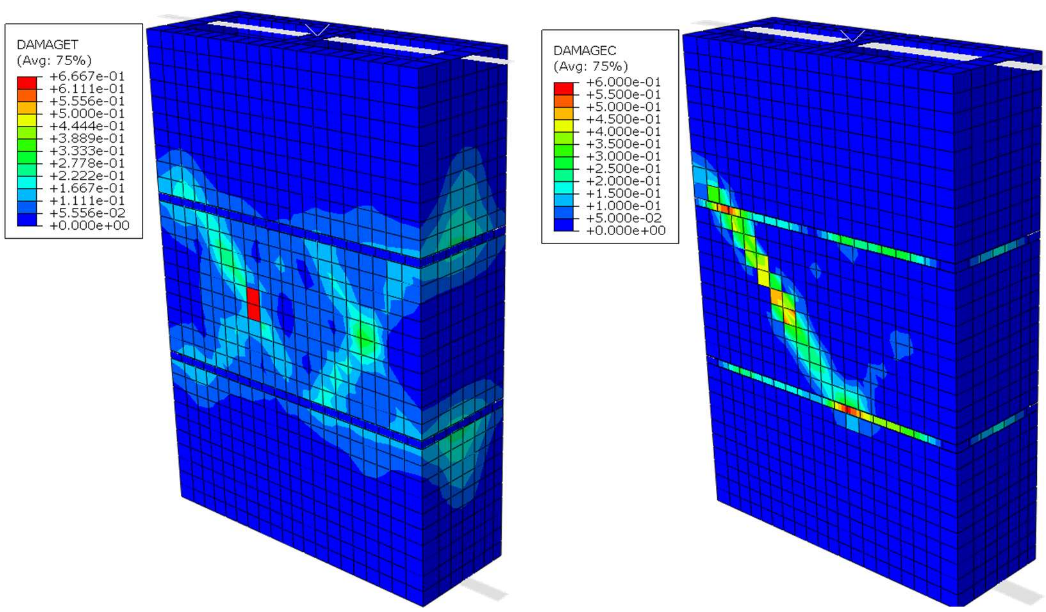
The comparisons of the stress-strain curves between the FE-predictions and the experimental results are presented in Figure 3 for Group 1 and Group 2, respectively. The comparison showed a good agreement between the FE-predicted and the experimental results. Specifically, it can be observed that the nonlinear behavior of prisms is well captured by the FE model, except a slightly underestimated compressive strength, which is calculated by the net area here. Note that the most common failure mechanism for weak mortar-strong unit combination in prism testing, i.e., tensile splitting failure, is observed in the FE prediction results, as shown by the contour plots of the tensile damage parameter (DAMAGET) and compressive damage parameter (DAMAGEC) in Figure 4 for the tested specimens.



a) b)

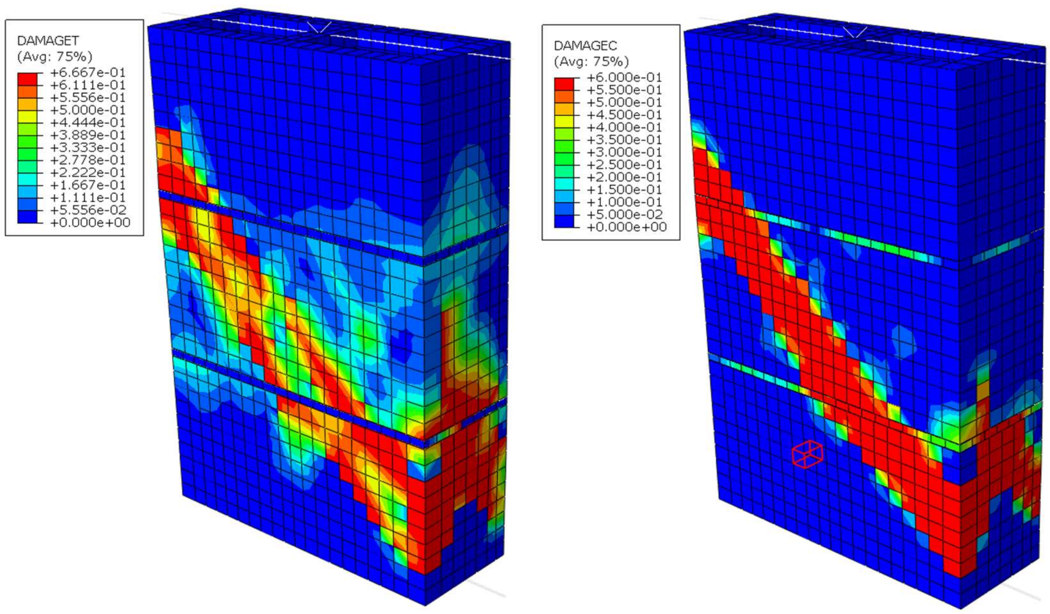
Figure 3: Comparison of Stress-Strain Curves between FE Predictions and Experiment: a) Group 1, b) Group 2

The total displacement applied to the tested prism specimen is 2 mm [11]. According to the test results, the crack first occurred in the face shell of the concrete unit near the center line, then mortar crushing occurred. At the peak load, vertical cracks occurred in the center of the transverse web. The vertical cracks across the face shell and the transverse web progressed at the ultimate test load.



a) b)

Figure 4: The Failure Mechanism Occurred in the FE model: a) Tensile Damage (Peak Load), b) Compressive Damage (Peak Load)



c) d)

Figure 4: c) Tensile Damage (Ultimate Load), d) Compressive Damage (Ultimate Load)

The comparisons of the masonry prism strength predicted by the FE models and experiment are summarized in Table 2 for all the four groups of prism testing. The prediction errors for Group 1, Group 3, and Group 4 are relatively small (less than 7.7%), while the prediction error for Group 2 is larger (21.35%). The same trend can be observed in the FE model prediction in [11]. This phenomenon can be explained due to the relative higher fracture energy tested of both the concrete blocks and mortar adopted in Group 2. The proposed FE model showed an overall consistent prediction based on the prediction error.

Table 2: Summary of FE and Experimental Compressive Strength

	Group 1		Group 2		Group 3		Group 4	
	Value (MPa)	Error	Value (MPa)	Error	Value (MPa)	Error	Value (MPa)	Error
Experimental (Barbosa et al. 2009)	18.2	-	17.8	-	21.4	-	30.1	-
FE Model (Barbosa et al. 2009)	16.4	-9.80%	14.2	-20.00%	19.7	-7.94%	30.4	+1.18%
FE model (this study)	17.2	-5.49%	14.0	-21.35%	19.8	-7.48%	27.8	-7.64%

FURTHER DEVELOPMENT AND APPLICATION

Automated Prism Model Generation

In order to achieve the numerical prism testing goal, a new tool is developed to automate the prism generation process, which is developed based on python in this study. All prism related parameters can be modified through the generator, including both material property parameters and geometrical property parameters. All the simulation results can be extracted directly after the FE analyses.

Parametric Study

This section studies the sensitivity level of the prism behaviour with respect to the dilation angle Ψ of both units and mortar layers, the compressive strength of both unit and mortar, the thickness of mortar layer h_m, and the course number of concrete masonry unit n. The sensitivity study results of dilation angle, thickness of mortar layers, course number, and the compressive strength of both concrete units and mortar layers are presented in Figure 5 a), b), c) and d), respectively.

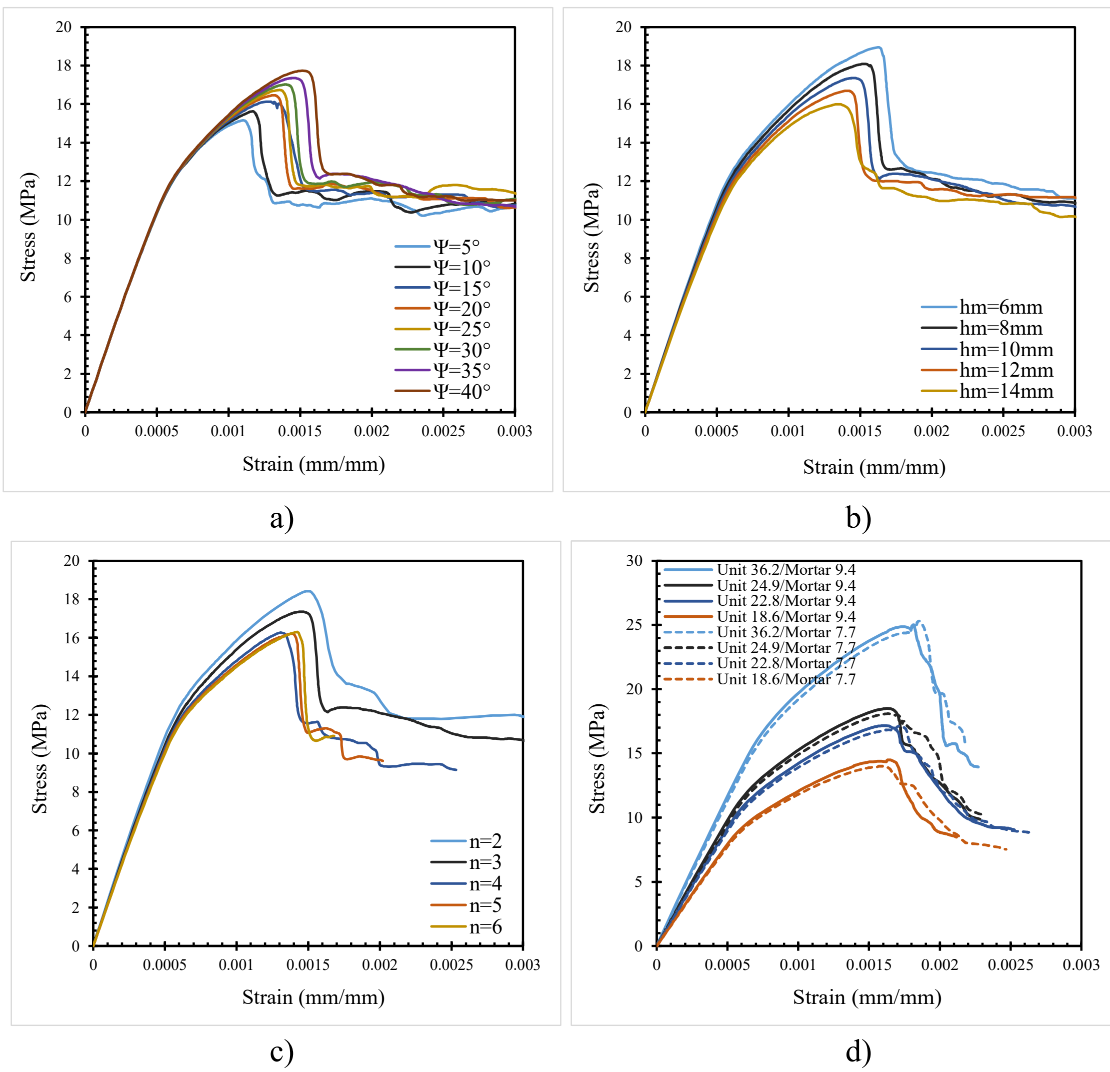
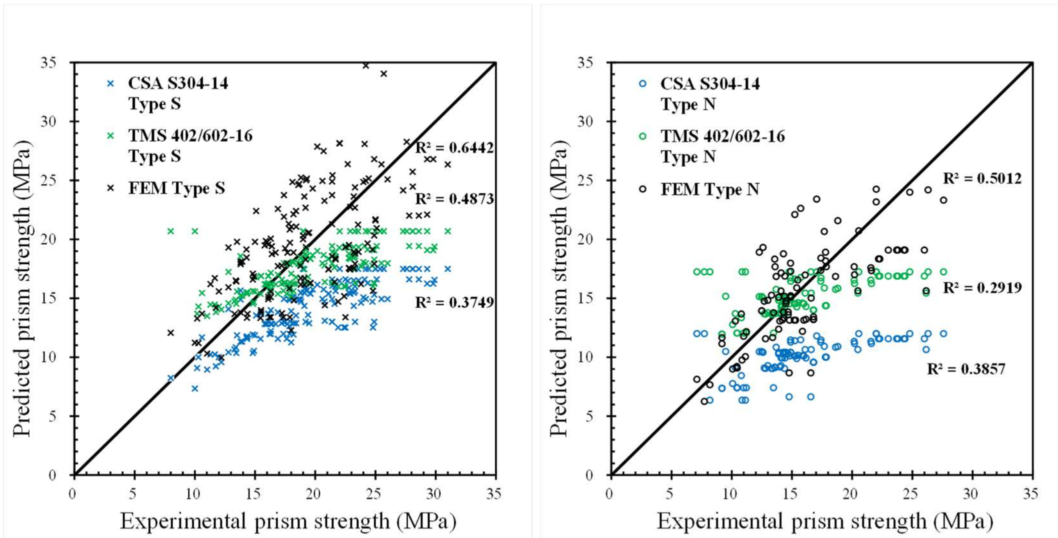


Figure 5: Parametric study of the proposed FE model: a) Dilation Angle, b) Mortar Thickness (mm), c) Course Number, d) Compressive Strength of Unit and Mortar

Numerical Prism Testing

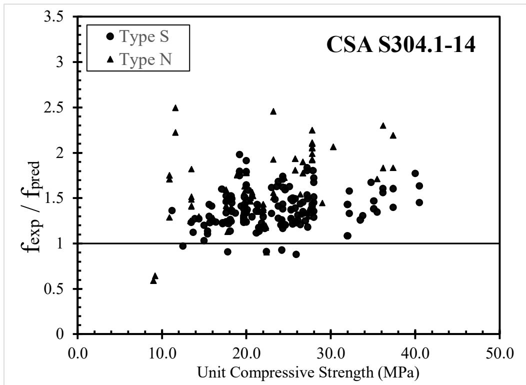
Based on the prism generation tool developed in this study, a series of FE models used to simulate the masonry prism testing are carried out. The proposed FE model is applied to a larger database consisting of 293 groups of hollow concrete masonry prisms, which are collected from 48 literatures, including 1375 prism specimens. The whole database is divided into two groups based on the mortar type: type S or type N mortar. Prediction results by the FE model are compared to the results from the Canadian masonry design code CSA S304-14 [1] and the American masonry design code TMS 402/602-16 [24]. The comparison and the corresponding prediction error are presented in Figure 6 and Figure 7, respectively.



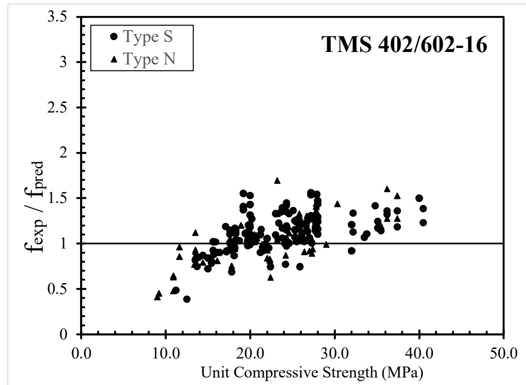
a) b)

Figure 6: Prediction of Masonry Compressive Strength of the FE model, CSA S304-14 and TMS 402/602-16 Based on the Collected Database: a) type S mortar, b) type N mortar

It is shown in Figure 6 that there is a relatively larger underestimation when the prisms are constructed using Type N mortar for both TMS and CSA codes. The prediction error in Figure 7 is the ratio between the experimental compressive strength and the predicted compressive strength. The compressive strength predicted by using CSA S304-14 is the most conservative. TMS 402/602-16 showed a relatively better prediction. However, the compressive strength is over-predicted when the unit strength is smaller than 20 MPa, while it is under-predicted when the unit strength is greater than 20 MPa. In contrast, the proposed numerical prism testing provided an overall good prediction without a systematic bias.



a)



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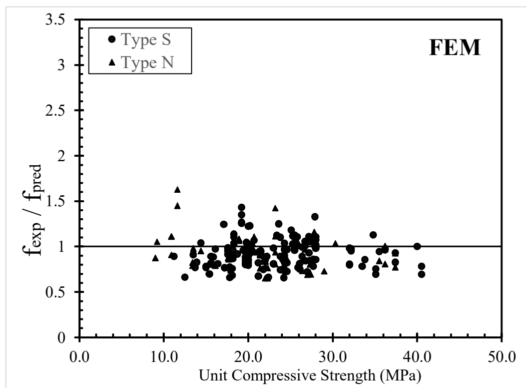

c)

Figure 7: Prediction Error of the FE model, CSA S304-14 and TMS 402/602-16 Based on the Collected Database: a) CSA S304-14, b) TMS 402/602-16, c) FE model

CONCLUSIONS

A 3D detailed micro finite element model is developed in this study to analyze the behavior of hollow concrete masonry prisms under compression load using commercial software ABAQUS. In this model, concrete damage plasticity (CDP), together with the uniaxial compressive behavior described by the modified Kent-Park model, is adopted for both concrete units and mortar layers. In addition, the tensile behavior is characterized using the concept of fracture energy.

The developed FE models are validated using the available experimental tests of concrete masonry prisms. Validation results proved that the proposed FE model is capable of accurately predicting the behavior of masonry under compression load. A series of parametric study is subsequently carried out. Results indicated that the compressive behavior of masonry prisms is more significantly affected by the physical material parameters and the mortar thickness, which shed lights on the importance of construction quality.

Furthermore, the developed FE model is used to conduct a series of numerical prism tests. The results can be applied into the future probabilistic study. Also, workmanship study can be carried out by modifying the geometric parameters of mortar layers using the developed numerical prism generation method in the future study.

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