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Behavior of Clay Masonry Prism under Vertical Load Using Detailed Micro Modeling Approach

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Abstract— The aim of this research is to assess the validity of Detailed Micro-Modeling (DMM) as a numerical model for masonry analysis. To achieve this aim, a set of load-displacement curves obtained based on both numerical simulation and experimental results of clay masonry prisms loaded by a vertical load. The finite element method was implemented in DMM for analysis of the experimental clay masonry prism. The finite element software ABAQUS with implicit solver was used to model and analyze the clay masonry prism subjected to a vertical load. The load-displacement relationship of numerical model was found in good agreement with those drawn from experimental results. Evidence shows that load-displacement curvefound from the finite element model has almost the same shape and pattern of the experimental one. The curves in both situations become more and more resembling as the load increasing till they reach failure.

Keywords—Clay units, Detailed micro modeling (DMM), Finite element method (FEM), Masonry prism, Uniaxial vertical compression load.

1. Introduction

Masonry is a composite heterogeneous material that consists of units and joints with or without mortar with different bond arrangements [1]. Due to the heterogeneous nature and the nonlinear behavior, modeling and analyzing masonry structures is challenging [2].

Modeling of ancient and modern masonry structures is very different. Ancient masonry is a very complex material with three-dimensional internal arrangements, generally unreinforced nonetheless, may contain reinforcemnt. While modern masonry usually constructed in a regular arrangement from masonry units, steel reinforced or not reinforced. The fact that the variability of the materials which form masonry structures as well as the different technologies makes masonry’s computational modeling complex [1].

Masonry is considered as an ancient building material that nevertheless been commonly utilized in today's buildings. New development in the materials and applications of masonry occurred in the last years but the assemblage techniques of masonry units are basically similar to the ones developed a hundred decades ago. As expected, countless variations of masonry materials, techniques, and applications occurred during the progression of times, influenced by the local culture and capital, materials and tools knowledge and availability and architectural reasons. The greatest advantages of masonry construction are its simplicity. Pieces of stone or brick are laid on top of each other, either with or without cohesion via mortar, is a simple, nevertheless suitable technique that has been effective ever since ages. Additional significant characteristics are the aesthetics, strength, durability, quiet low maintenance, versatility, absorption of sound and protection against fire. Load bearing walls, infill panels which are used to resist wind load sand seismic, low-rise buildings and pre-stressed masonry cores are constructions examples where the use of structural masonry is currently viable [3].

Nevertheless, innovative structural masonry applications are way behind by the fact that the development of the design rules has not kept pace with the concrete and steel developments. The fundamental reason behind that hindered the design rules development is the insight deficiency and models that describebehavior complexity

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of units, mortar joints, and masonry as a composite material. Methods of calculation that currently existare essentialtoempirical and traditional and the numerical tools used for the analysis and/or design of masonry structures is fairly primary [3].

Nowadays, complicated numerical tools have been introduced, which are able to predict the structure behavior starting from the linear stage, during the course of cracking and degradation up to complete strength loss. This goal can be accomplished only through the implementation of an accurate and robust constitutive model using innovative solution procedures of equations system, which consequences from the finite element method. Detailed Micro-Modeling (DMM) method is a modern technique of finite element analysis that comprises separately the masonry units and bonding mortar. The DMM method was firstly adopted by Lourenco in 1995 where the representation of masonry units and mortar joints is by continuum solid elements while there presentation of unit-mortar interface is by discontinuous contact elements [3]. A comprehensive micro model has to include all the failure mechanisms of masonry, viz., joints cracking, sliding over one head or bed joint, units cracking and masonry crushing [4]. In addition, the computer hardware evolutions recently allowed sophisticated analysis methods to be implemented, which allow the structures detailed modeling and the following behavior simulation while subjected to distinctive actions. However, advanced methods usage requires, generally, also a complicated characterization of the model, including viz. a detailed representation of the geometry and a huge number of material parameters [5].

2. Experimental Work

2.1 *Prism construction and curing*

A set of three clay masonry prisms were constructed by a skilled mason using English bond. The primes were subjected to daily moist curing for 28-days. Fig. 1 shows the set of three prisms that constructed and prepared for the loading test. The top surface of the prisms was leveled using electrical grinder so as to ensure the uniformity of the loadapplication. The prisms were built with a height-to-thickness ratio, h_p/t_p, of about 2. The dimensions of the clay units were 240 mm 115 mm 75 mm. The dimensions of each prism were 500 mm high 240 mm wide 240 mm thick. The age of the tested prisms was 28-days. Prisms' tests were conducted in accordance with ASTM C1314-16 standard [6].

Figure 1: Set of three prisms constructed for test

2.2 *Load Test Setup*

The main objective of this test is to obtain the specified compressive strength of the masonry prisms. A set of three prisms which constructed from the same material were tested at the same age. The test was conducted using a self-supporting I-section steel frame. In such frame, the top and bottom I-sections are connected with each other by I-section columns to behave as one unit and supply sufficient reaction for the applied load. Due to the small width of the bottom I-section, a base plate with dimensions 400 mm long 250 mm wide 100 mm thick was laid beneath the prism specimens. Above the prism, a steel plate with 25 mm thick was placed to ensure the uniformity of theapplied load. A load cell with a capacity of 100 ton was used to acquire the load data that applied by the hydraulic jack of a capacity of 100 ton. The loading assembly is handing on the top I-section of theloading frame. Finally, a dial gauge of 0.01 mm precision was used to record the vertical displacement. The tested prisms specimens were centered and aligned properly with respect to the hydraulic jack, the load cell inside the loading frame. A Quasi-static monotonically increasing load was applied until the prism failed in crushing. Figure 2 illustrates the prism test setup. The evenness of the prisms' surfaces established by taking care of it during the construction process and by using a grinder with exfoliation paper to ensure the load will distribute evenly on the prism. The prisms were constructed on the frame to avoid lifting the prisms and maybe damaging them. Fig. 3 shows the load-displacement diagrams for the three prisms that were tested under the same conditions. Table 1 Summarizes the results of the maximum force, stress, and displacement for each of the three prisms.

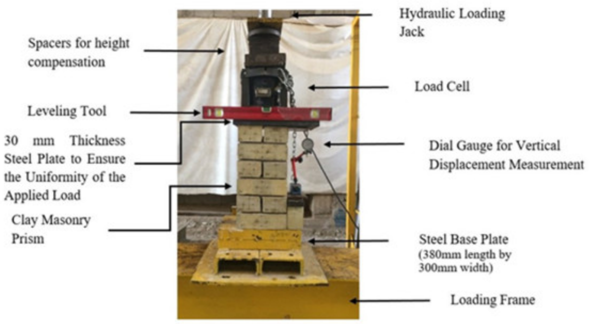

Figure 2: Prism test setup [7]

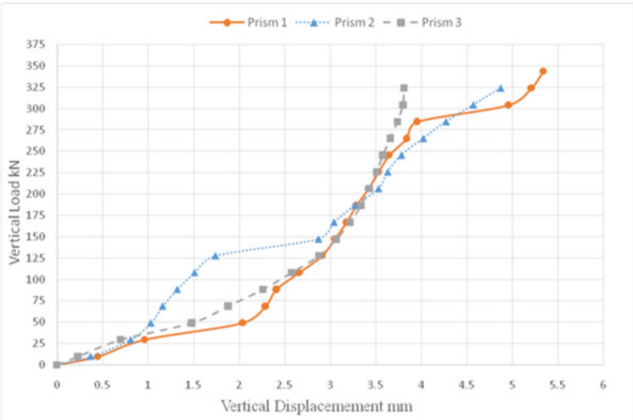

Figure 3: Load-displacementdiagram for 3 prisms

Table 1: Maximum displacement, force, and stress

Prism no.	Maximum Displacement mm	Maximum Force kN	Maximum Stress kN/m^2
1	5.388	343	5961
2	4.87	324	5620
3	3.81	324	5620

3. Modeling Technique

Masonry is a material displaying individual directional properties because of the mortar joints [8], which act as planes of weakness [4]. In general, the numerical representation approach followed depends on the accuracy level and the simplicity preferred. Micro-modelingapproach was considered to represent the components as individuals, viz. unit (brick, block, etc.) and mortar. The micro modeling approach is divided into simplified and detailed micro modeling [9].

The detailed micro-modeling (DMM) technique was used where the representation of masonry units and mortar in the joints is by continuum solid elements where the representation of unit-mortar interface is by discontinues contact elements. In this approach [9]:

1. Consideration of both units and mortar elastic properties (i.e. Young's modulus (E) and Poisson's ratio (ν)) and inelastic properties.
2. Representation of the interface as a potential crack/slip plane with initial dummy stiffness (slave elements) in order to avoid interpenetration of the continuum (master elements).
3. This approach illustrates the unit, mortar and unit-mortar interface combined action to be examined.

Figure 4 illustrates the adopted modeling strategy used in this study.

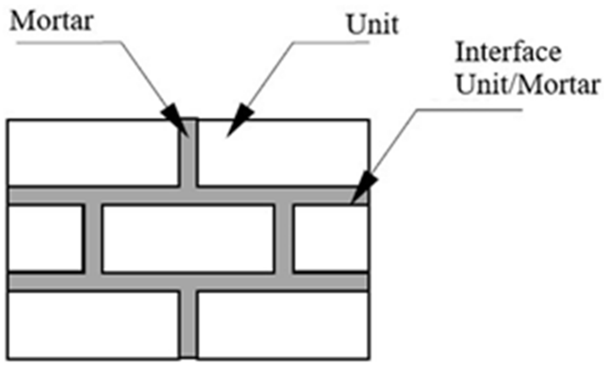

Figure 4: Adopted modeling strategy [9]

Interface elements allow discontinuities occurrence in the displacement field, their behavior is defined according to the relation between the tractions t and relative displacements u through the interface. The generalized stresses and strains can be written in a linear elastic relation in the standard form as in equation 1 [3].

$$\sigma = D\,\varepsilon \qquad (1)$$

where, for a 2D configuration

$\sigma = \{\sigma, \tau\}^T$

$D = diag\,\{k_n\,, k_s\}$

$\varepsilon = \{\Delta u_n\,, \Delta u_s\}^T$

n and s = Normal and shear components, respectively.

The elastic stiffness matrix D is capable to be found from the units and mortar properties which they are masonry components and the joint thickness as in equations 2 and 3 below [3].

$$k_n = \frac{E_u E_m}{h_m(E_u - E_m)} \quad (2)$$

$$k_s = \frac{G_u G_m}{h_m(G_u - G_m)} \quad (3)$$

where,

E_u and E_m = The Young's moduli, respectively for unit and mortar.

G_u and G_m = The shear modules, respectively for unit and mortar.

h_m = Joint thickness.

A multi-surface model, with yield functions, can be used to define constitutive interface model, as in Figure 5. This model composed of three separate yield functions associated with softening behavior for the three modes [1].

Tensile criterion:

$$f_t(\sigma, k_t) = \sigma - \sigma_t'(k_t) \quad (4)$$

Shear criterion:

$$f_s(\sigma, k_s) = |\tau| + \sigma tan\phi - \sigma_s'(k_s) \quad (5)$$

Compressive criterion:

$$f_c(\sigma, k_c) = (\sigma^T P \sigma)^{\frac{1}{2}} - \sigma_c'(k_c) \quad (6)$$

Here,

$\phi =$ The friction angle

P = a projection diagonal matrix, based on material parameters.

σ_t', σ_s' *and* σ_c' = The isotropic effective stresses of each of the adopted yield functions.

k_t, k_s *and* k_c = scalar internal variables that affect the isotropic effective stresses.

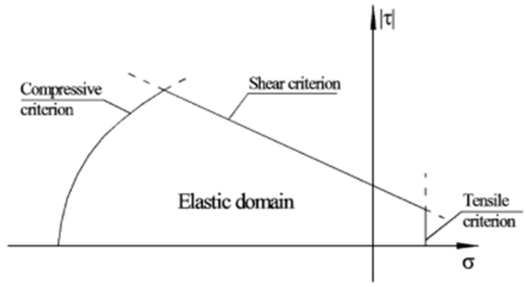

Figure 5: Multi-surface constitutive interface model [4].

4. Numerical Simulation

The FE software, ABAQUS, was utilized in this study to develop FE model of clay masonry prism. Suggested modeling strategy, units, and mortar joints are modeled with continuum elements where the unit-mortar interface represented by Interaction Properties. Potential tensional vertical cracks in the center of the units are modeled with cracks with zero thickness. The followed approach here is that all damages to be concentrated in the relatively weak joints and, if necessary, in pure tension potential cracks in the units located vertically in the middle of each unit [10] as cracks are major source of nonlinear behavior in masonry [8]. The implicit solver was selected in ABAQUS to model the masonry prism. This method is efficient computationally and has the capability to simulate linear static loading which was included in this study. Masonry units, mortar, and loading steel plates were modeled using Continuum Plane Stress with 8 nodes Reduced IntegrationCPS8Relements, while the interface element (i.e. Interaction between Units and Mortar) was modeled using tangential and normal behavior available in ABAQUS as can be seen in Figure 6. This model was selected due to its ability to model frictional and cohesive materials, such as granular-like soils and rock [3]. Normal, tangential, and cohesive behavior interactions existed in interaction module in ABAQUS were utilized during the interaction modeling between the units and mortar [11]. The assumption is that when two surfaces in contact, shear as well as normal forces transmitted across the interface. Friction between the contacting bodies is known as the general relationship between these two force components. Data that were conducted form experimental tests by the researcher were used as an input data in the simulation process.

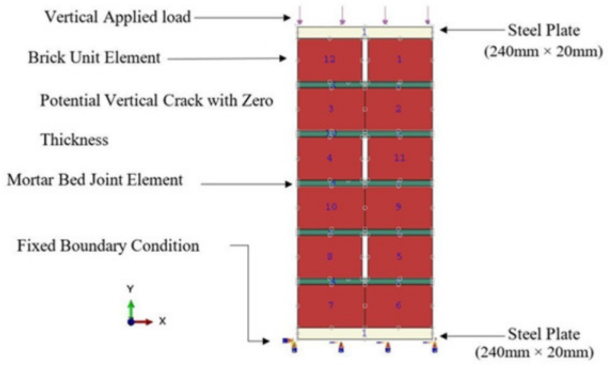

Figure 6: Suggested numerical modelling 2D simulation where units and mortar are represented by continuum elements. Potential vertical cracks are modeled with zero thickness in the centerline of the masonry units [7].

5. Verification Results and Discussion

Figure 7 shows the behavior of the load-displacement diagram of the simulation model which has almost the same pattern of the experimental load-displacement diagram of the tested masonry prisms [7]. It can be seen that at the beginning of the applied load there is a difference in the displacements between the experimental and the numerical model. As the load increases the difference decreases significantly. At the load of about 130 , hair cracks were noticed at different locations on the bricks of the tested prisms. Cracks formation and failure of the masonry prisms can be seen in Figure 8. While the numerical model does not exhibit any decrease in strength as can be seen in Figure 9. With increasing the load to about 200k the cracks become more visible and increased in width. The displacements at the maximum load where the failure occurred are 5.071 mm and 4.629 mm for the numerical model and experimental prisms respectively which shows a good agreement. Table 2 and 3 show the material properties that were used as an input data for the simulation process.

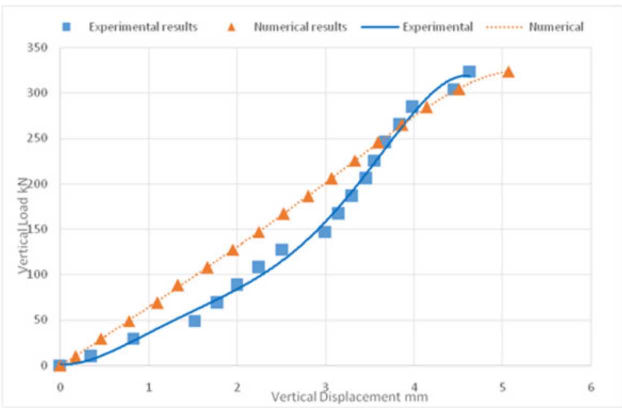

Figure 7: Load-displacement curves for the numerical and experimental results [7].

Figure 8: Cracks formation and failure of the clay masonry prisms

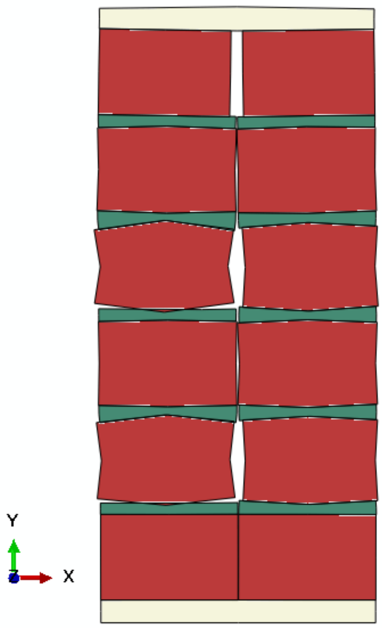

Figure 9: Cracks formation in the numerical modeling

Table 1: Elastic properties

Properties	Masonry Units	Cement Mortar
Modulus of Elasticity MPa	4000	1500
Poisson's ratio	0.15	0.2

Table 2: Stress-strain data

Stress	Strain
0.1703	0
0.5109	0.0007000
0.8516	0.0016473
1.1922	0.0030320
1.5328	0.0035520
1.8734	0.0039920
2.2141	0.0044987
2.5547	0.0050187
2.8953	0.0059920
3.2359	0.0062920
3.5766	0.0065980
3.9172	0.0069187
4.2578	0.0071120
4.5984	0.0073387
4.9391	0.0076787
5.2797	0.0079753
5.6203	0.0088853
5.9610	0.0092587

6. Conclusion

A comparison between numerical FE simulation and experimental results were conducted through a case study on clay masonry prisms to examine and evaluate the load-displacement curves using the DMM approach for the numerical simulation process.

- The evaluation of the load-displacement diagram on the masonry prisms shows that DMM simulation technique can offer an accurate estimation for masonry prisms under uniaxial vertical compression.
- DMM simulation technique offers to be an appropriate alternative to predict strength and displacement of masonry prisms. Visualization of the load-displacement curve can be well detected.
- The investigation of this study shows that this simulation can be used to specify the strength and displacement of the masonry prismswith reasonable accurateness and less expensive of the traditional prism test method.

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تصرف موشور البناء الطيني تحت الحمل العمودي باستعمال تقنية الموديل المايكروي المفصل

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الخلاصة – ان الهدف من هذا البحث هو تقييم دقة النموذج المايكروي المفصل (DMM) كنموذج عددي لتحليل المنشآت البنائية. لتحقيق هذه الغاية، تم الحصول علىمجموعة من منحنيات الحمل-الازاحة المبنية على أساس كل من المحاكاة العددية والنتائج المختبرية لمواشير البناء الطينية المحملة عموديا. تم تطبيق طريقة العناصر المحددة في DMM لتحليل موشور البناء الطيني المفحوص مختبريا. تم استخدام برنامج العناصر المحددة ABAQUSمع implicit solver لنمذجة وتحليل موشور البناء الطيني المعرض لحمل عمودي. تم الحصول على توافق جيد لعلاقة الحمل-الازاحة بين النموذج العددي والنتائج المختبرية. تشير الأدلة إلى أن منحنى الحمل-الازاحة التي وجدت من نموذج العناصر المحددة لديها تقريبا نفس الشكل ونمط المفحوصة مختبريا. المنحنيات في كلتا الحالتين تصبح أكثر تشابه بزيادة الحمل حتى تصل إلى الفشل.

الكلمات المفتاحية: موشور البناء، وحدات البناء الطينية، طريقة العناصر المحددة، تقنية الموديل المايكروي المفصل، حمل انضغاط عمودي احادي.