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MODELING OF NONLINEAR BEHAVIOR OF CONFINED MASONRY USING DISCRETE ELEMENTS

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ABSTRACT

Confined masonry is a popular building technique used throughout the world. It is especially prevalent in Latin America and Asia. Despite its wide use, relatively little research has been conducted on these systems, especially on large deformation behavior. When available, experimental studies are usually terminated at 80% post-peak strength. Numerical and analytical efforts either are unable to predict ultimate damage states or they predefine failure modes. Quantification of the ultimate capacity of confined masonry could significantly improve the relevance and applicability of predictive damage models, such as the GEM and PAGER. Additionally, it is not well documented or understood how the structural features of confined masonry contribute to its seismic performance. Advancements in this area could improve and clarify current design recommendations.

In an effort to close the knowledge gap, a detailed numerical model is developed of a traditionally built confined masonry shearwall. A micro-modeling approach is taken using the discrete element method, which computes the motion and effect of a large number of individual bodies. This approach allows for detailed joint behavior and large deformation. The model successfully captured initial stiffness, peak strength, stiffness degradation and energy dissipation. Validation of this numerical approach was performed against micro-material tests, as well as the in-plane pushover testing of an unreinforced masonry shearwall.

This model is being used in an ongoing investigation to study the effect of several geometric aspects on the seismic performance of confined masonry. Preliminary results suggest that the relative stiffness of the masonry panel to the reinforced concrete columns is of primary importance to lateral capacity. Ultimately, this effort endeavors to contribute to general design guidelines and improve understanding of confined masonry systems.

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Modeling of Nonlinear Behavior of Confined Masonry Using Discrete Elements

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ABSTRACT

Confined masonry is a popular building technique used throughout the world. It is especially prevalent in Latin America and Asia. Despite its wide use, relatively little research has been conducted on these systems, especially on large deformation behavior. When available, experimental studies are usually terminated at 80% post-peak strength. Numerical and analytical efforts either are unable to predict ultimate damage states or they predefine failure modes. Quantification of the ultimate capacity of confined masonry could significantly improve the relevance and applicability of predictive damage models, such as the GEM and PAGER. Additionally, it is not well documented or understood how the structural features of confined masonry contribute to its seismic performance. Advancements in this area could improve and clarify current design recommendations.

In an effort to close the knowledge gap, a detailed numerical model is developed of a traditionally built confined masonry shearwall. A micro-modeling approach is taken using the discrete element method, which computes the motion and effect of a large number of individual bodies. This approach allows for detailed joint behavior and large deformation. The model successfully captured initial stiffness, peak strength, stiffness degradation and energy dissipation. Validation of this numerical approach was performed against micro-material tests, as well as the in-plane pushover testing of an unreinforced masonry shearwall.

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Introduction

Confined masonry (CM) is a popular structure type used throughout the world and is especially prevalent in developing countries. It is a relatively straightforward building method, consisting of a masonry wall surrounded by a reinforced concrete frame. The ease of construction makes it popular as a non-engineered, self-constructed building option. Confined masonry is a seismically

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safe alternative to unreinforced masonry and reinforced concrete frames with masonry infill. Employing the same materials as infilled frames, the construction sequence of confined masonry is reversed such that the masonry wall panel is assembled prior to the surrounding concrete frame. This alteration results in improved load path resolution and increased seismic capacity. The successful performance of confined masonry is well recognized and its use and promotion continues to increase worldwide. Efforts such as the Confined Masonry Network (www.confinedmasonry.org) encourage the dissemination and adoption of this building method.

An estimated 80% of the global population resides in non-engineered, self-made masonry dwellings such as confined masonry. Much of this building stock is located in developing countries and is seismically vulnerable. Compounding this problem, urbanization is a growing issue worldwide. It frequently results in unchecked and unsafe building practices in the world's most populace cities. As such, it is imperative to improve our understanding of how these structures perform in earthquakes. By anticipating the impact of disasters on the built environment, pre-event mitigation and post-event response efforts can be improved. Predictive catastrophe models, such as the Global Earthquake Model (GEM) and Prompt Assessment of Global Earthquakes for Response (PAGER), estimate human and financial losses from earthquakes and relay that information to decision-makers. Losses are derived from the generalized structural performance of archetypical buildings specific to a region of interest. When considering structure types in developing countries, however, there is a broad information gap. Compared with our vast knowledge of housing types in the United States, relatively little research has been conducted on the seismic performance of typical buildings in developing countries. Even fewer investigations focus on large deformation or collapse behavior, an important aspect of catastrophe modeling.

In an effort to close the information gap and take a step toward improving the relevance of predictive models for non-engineered buildings, this investigation explores application of the discrete element method (DEM) to the non-linear, large deformation behavior of unreinforced masonry, specifically confined masonry. Rooted in Newton's equations of motion, the discrete element method computes the motion and interaction of a large number of individual bodies (see [1, 2]. While DEM is relatively computationally expensive, advancements in today's computing power make it increasingly accepted as an effective method for addressing engineering problems of discontinuous materials, such as masonry. Using a micro-modeling approach, the discrete element method readily allows for cracking, separating and impacting of bodies. Individual masonry units are discretized as either rigid or deformable units. The interaction law between units, which generalizes the brick-mortar joint behavior, is captured through interface elements that employ the cohesive zone model. This interface model allows for a full description of realistic joint behavior in shear and tension, including bond adhesion and Coulomb's law of sliding units. A great advantage of this modeling approach is the ease with which overall structural performance, including large deformation and collapse behavior, can be captured based on knowledge of the brick-mortar joint behavior alone.

To demonstrate and validate the ability of DEM to capture the behavior of masonry, an in-plane pushover test of an unreinforced masonry shearwall is modeled [3, 4]. The wall stiffness, strength plateau and decline, along with the cracking pattern were captured. Micro-material property tests of joint behavior in shear and tension were also conducted as part of this investigation and are likewise successfully modeled. These results demonstrate the capability and promise of using the DEM approach to model other masonry building types.

The experimental testing of a traditionally built confined masonry shearwall is then modeled. This wall was tested at the National Center of Disaster Prevention (CENAPRED) in Mexico as part of an experimental program to gauge the effectiveness of different strengthening techniques [5, 6]. The wall was subjected to multiple in-plane loading cycles up to 1% drift, resulting in significant stiffness degradation. Using discretized deformable units to represent the bricks, the numerical model closely resembles the physical construct of the CM wall. The reinforced concrete columns were modeled using discretized deformable units joined together with elastic wire, representative of steel reinforcement. Column behavior was validated independently of the wall. Overall, the numerical model performed well, matching initial stiffness, peak strength and stiffness degradation. Total hysteretic energy dissipation was also well captured by the model (95% of actual).

Model Development and Validation

In the early 1990's an extensive research program was undertaken in The Netherlands to increase the knowledge of how masonry materials and structures behave. This program was a joint project between Eindhoven University of Technology and Delft University of Technology (TNO-Delft). The purpose of this endeavor was to coalesce experimental techniques with numerical mechanics and analytical methods. The research included a series of small scale experiments performed on bricks, mortar and several brick-mortar combinations to obtain detailed material properties. Using the same materials, pushover tests of masonry shearwalls were also performed. Experimental results were then used to help develop numerical models based on a micro-modeling approach. See [3, 4].

Micro Behavior: Brick-Mortar Joint

As part of the TNO-Delft project, four different brick types in combination with five different mortars were thoroughly tested to obtain a variety of material properties, including generalized behavior of the brick-mortar joint in the tensile and shear directions. This investigation focuses on a single brick-mortar combination termed "JG.B". The brick was an extruded wirecut clay unit, while the pertinent mortar had a mix proportion of cement:lime:sand of 1:2:9, by volume.

In the normal direction, a total of three tension tests were conducted consisting of two bricks bonded together with a 10 mm thick mortar joint (see Figure 1(a)). Each brick was fixed against rotation by gluing to the loading apparatus. The bricks were pulled apart in displacement control until separation (i.e., fracture) of the brick-mortar bond occurred. The resulting tensile bond strength, f_{tu} of specimen JG.B was 0.30 N/mm^2 ± 24%. The secant tensile elastic modulus, E_t, taken at 50% of the failure load, was 2970 N/mm^2 ± 9%.

To characterize behavior of the brick-mortar joint for the purpose of the numerical model, the micro-material tests performed by TNO-Delft were simulated using the DE software program, LMGC90. This is an open source platform for modeling interaction problems between discretized bodies using various numerical strategies such as non-smooth contact dynamics [7, 8]. Rigid elements were used to represent the bricks and a zero-thickness cohesive zone model (CZM) was employed to capture the joint behavior (see Figure 2(a)). CZM is an effective means of capturing realistic material fracture. In a general sense, this interface model captures adhesive behavior between two bodies. When two bodies bonded together are pulled apart, the force required to do so increases until a maximum is reached, indicative of failure. In the case of masonry, this failure point represents the brick-mortar joint separating or cracking. In the tensile direction (Mode I failure), once the bond is broken the force drops to zero (see Figure 1(b)). In shear (Mode II failure), the transverse force decreases to a Coulomb friction model (see Figure 3(b)). The area under these curves represents fracture energy, or the amount of energy required to break the bond. Additionally, a damage factor is assessed for all contact points. Once a bond is broken it cannot be re-established numerically, and any re-contact between bodies only transfers impact load and Coulomb friction, if sliding. More information about the CZM can be found in [3], [9], and [10].

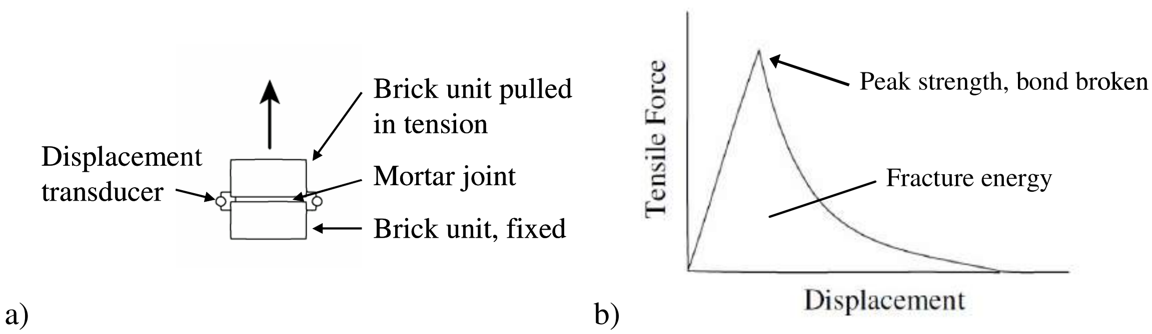


Figure 1 (a) Experimental set-up of tension test [3], and (b) generalization of the joint force-displacement behavior in tension.

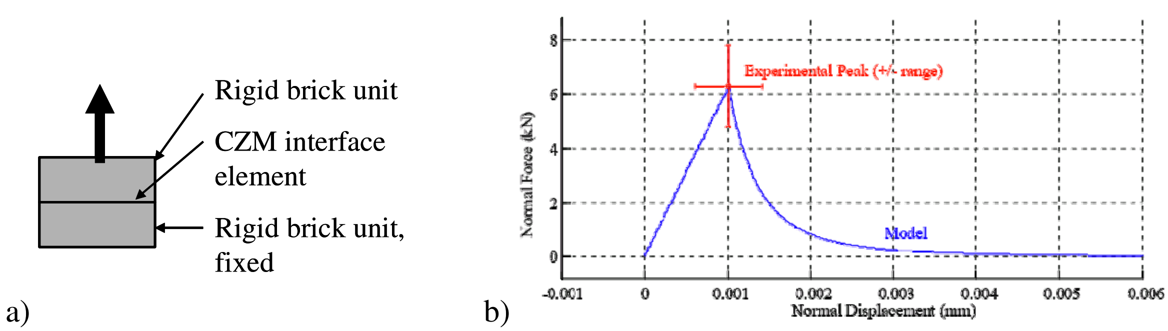


Figure 2 (a) Model representation of the experimental tension test including zero thickness CZM interface element and rigid brick units, and (b) numerical model results of the CZM interface element in tension (shown in blue). The range of experimental values at peak strength [3] is indicated by the red bars.

To calibrate the CZM interface element in the tensile direction, the point of fracture or peak strength was targeted by using the elastic modulus and strain at failure. The secant tensile elastic modulus at failure, E_{tu} reportedly ranged between 50% and 70% of E_t. Therefore, E_{tu} is assumed to be 60% of E_t, or 1782 N/mm^2. In combination with the tensile bond strength, f_{tu}, the target ultimate strain was determined to be $\varepsilon_{tu} = f_{tu} / E_{tu} = 0.00017$ mm/mm. The resulting model behavior in the tensile direction is shown in Figure 2(b) in blue along with a range of targeted experimental values shown in red.

In the transverse direction, researchers of the original TNO-Delft study were uniquely able to isolate shearing action between two bonded bricks. They were able to omit rotation of the bricks, which contributes a wedging effect and subsequent moment across the brick face (see Figure 3(a)). To model this action numerically, a brick unit was sandwiched between to two other units then pulled in displacement-control (see Figure 4(a)). This arrangement was needed to maintain as pure of a shearing action as possible; the resulting force was halved to obtain the force-displacement of a single bond, as seen in Figure 4(b). The two lines shown are the force-displacement results of the top and bottom contacts. Because shearing action for this arrangement was not perfect some rotation of the middle unit still resulted, causing unequal normal forces at the top and bottom contacts. The subsequent friction forces differ in proportion to these normal forces, while a constant sliding friction coefficient is maintained.

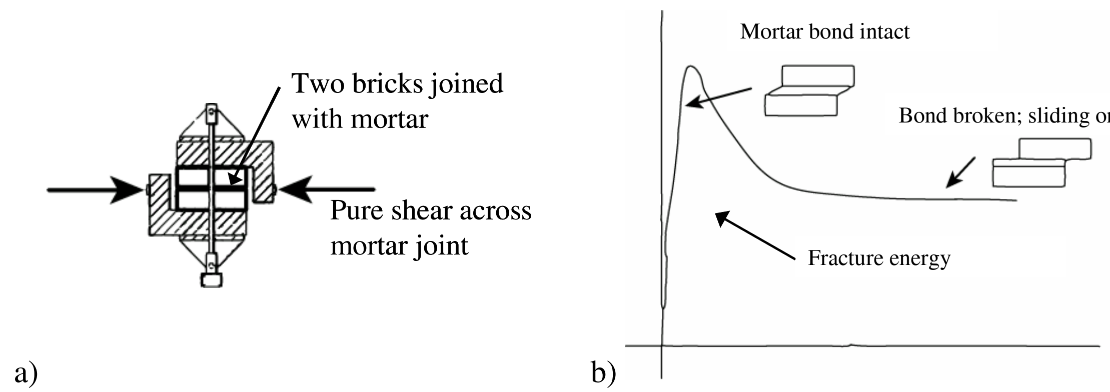


Figure 3 (a) Experimental set-up of shear test [3], and (b) generalization of the joint force-displacement behavior in shear.

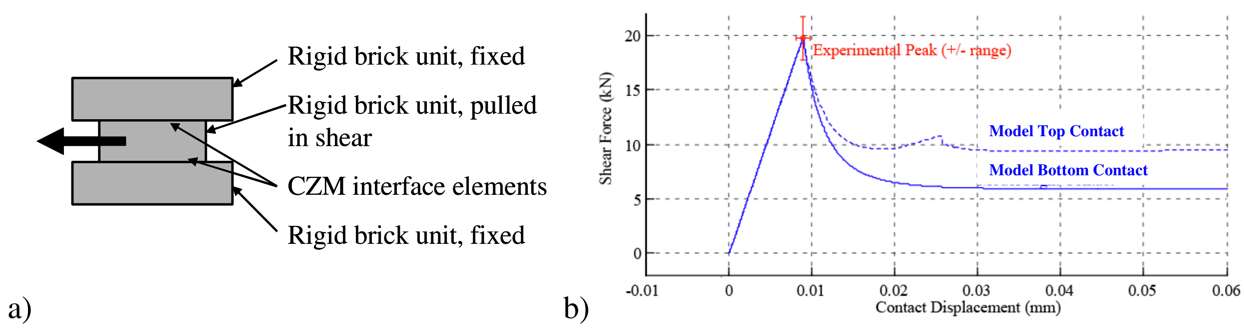


Figure 4 (a) Model representation of the experimental shear test, and (b) model results of the CZM interface element in shear (shown in blue). The range of experimental values at peak strength [3] is indicated by the red bars.

Macro Behavior: URM Shearwall

As part of the same TNO-Delft investigation, a series of masonry shearwalls were subjected to in-plane pushover loading to assess whether the numerical models they developed from the micro-material tests could reproduce macro behavior of a structural component such as a wall. One of these shearwalls, “J2G”, was assembled with the same JG.B brick-mortar combination used in the small scale experiments described previously [3]; [4]. The wall was 1 meter tall by 1 meter wide (see Figure 5(a)). It consisted of 18 rows of unreinforced masonry joined together with mortar joints of 10 mm thick. The top and bottom rows were bonded to the testing apparatus. An opening of 1 brick wide by 6 rows high was positioned roughly in the middle. A stiff reinforced concrete beam was positioned at the top of the wall and held in place with two vertical actuators. The wall was pre-loaded in compression to 30 kN then held fixed against vertical displacement and rotation. In-plane horizontal displacement was applied at a pseudo-static loading rate.

Using LMGC90, wall J2G was modeled with discrete elements as seen in Figure 5(b). Because the joint thickness was zero, the discretized units are slightly larger than the individual brick dimensions. Joint properties determined in the previous section were employed for the CZM interface elements between brick units. To properly model boundary conditions of the wall, the top and bottom rows of bricks were coupled to rigid beam elements. The top rigid element applied the vertical load, as well as the imposed horizontal displacement.

Figure 5(c) and (e) show reported cracking patterns of the wall at 2.5 mm and 25 mm, respectively. The corresponding damage generated from the numerical model is seen in Figure 5(d) and (f). To best showcase damage patterns, the color gradation references rotation of the brick units. Clearly, the model is able to replicate the major lines of crack propagation, and thus load path resolution. Further, a benefit of DEM is the generation of attractive visual displays which closely resemble actual conditions. This is a useful aspect that can be utilized in the communication of anticipated earthquake damage to decision-makers.

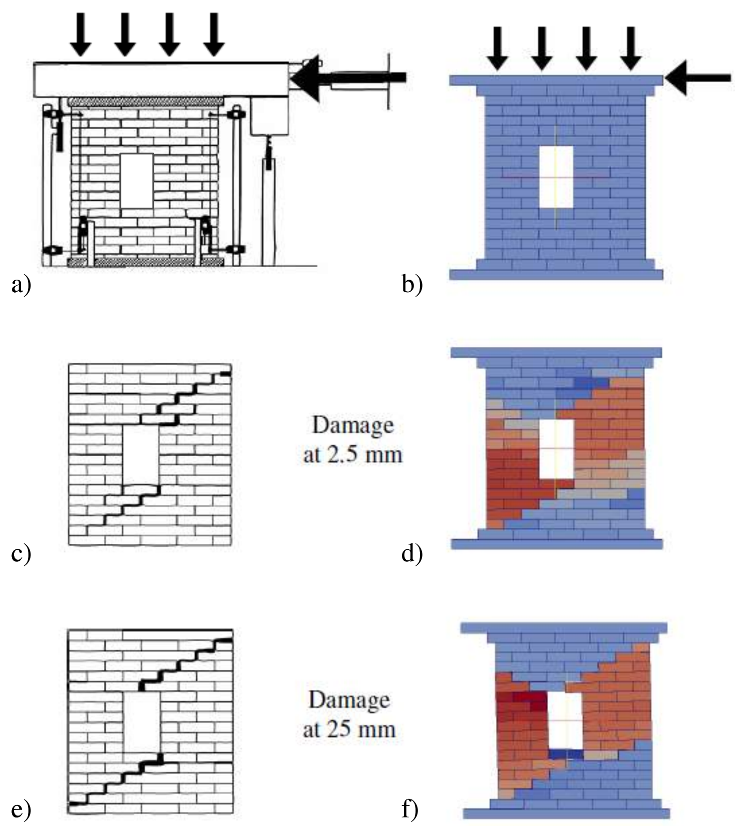


Figure 5 (a) Experimental test set-up of wall J2G, and (b) model representation. Cracking pattern of the wall and model at 2.5 mm ((c) and (d)), and at 25 mm ((e) and (f)) [4].

Figure 6 presents the force-displacement results of the experiment and numerical model. As can be seen, the DE model successfully captured the overall structural behavior of the URM shearwall, including initial stiffness, peak load and plateau, as well as strength degradation. The sudden losses of strength at various points throughout loading are the result of cracking, or loss of tensile and/or shear bond adhesion between brick units, and the subsequent redistribution of loads. As these results suggest, the DEM, as well as LMGC90, can provide a successful alternative to traditional finite element or analytical methods for the modeling of unreinforced masonry construction. This approach can be easily applied to non-traditional, irregular masonry structures which are difficult or unrealistic to model as continuous bodies (in the case of finite element analysis), or for the purpose of obtaining large deformation or collapse behavior without assuming damage modes or capacity a priori.

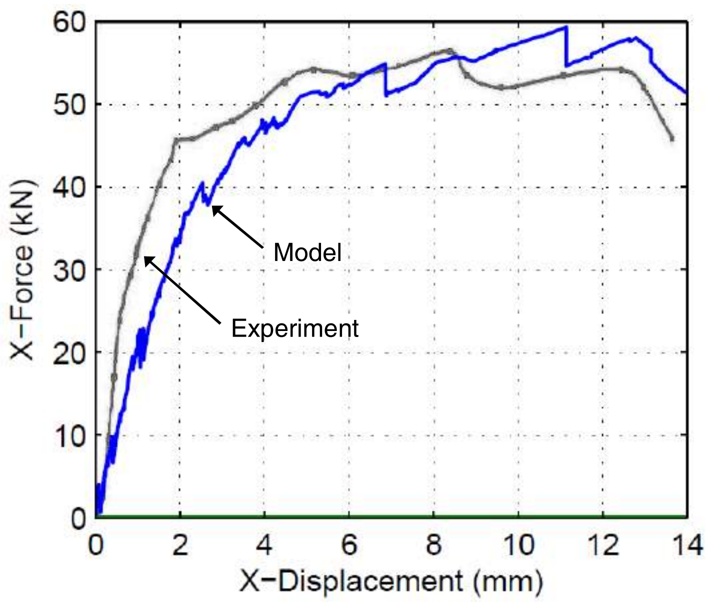
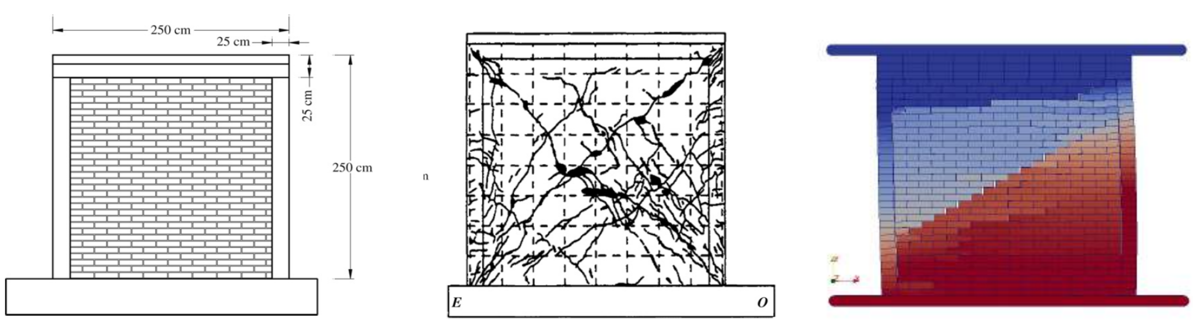


Figure 6 Experimental versus numerical results of the unreinforced masonry wall J2G

Modeling of a Confined Masonry Shearwall

Researchers at CENAPRED undertook a large study on the performance of CM structures including strengthening techniques. As part of this effort, a traditionally built CM wall with no improvements was tested as a control specimen [5, 6]. This wall, "M-2", was assembled with unreinforced clay brick masonry surrounded by a reinforced concrete frame with slender columns (see Figure 7(a)). The wall was 2.5 m wide by 2.5 m tall. It was loaded with a constant vertical force of 142 kN, representative of a 4 or 5 story building. The pseudo-static loading protocol consisted of three force-controlled loading cycles followed by duplicate displacement-controlled cycles at roughly 0.25%, 0.5%, 0.75% and 1% drift (see Figure 9(a)).



a) b) c)

Figure 7 Confined masonry wall (a) experimental test set-up [5], (b) resulting damage at 1% drift [5], and (c) DE numerical model damage pattern at 1% drift.

Using LMGC90, individual bricks were modeled as deformable units using the modulus of elasticity reported in literature, E_m = 728 MPa [5]. Configuration of the brick units matched the actual wall geometry, as seen in Figure 7(c). Mortar joint behavior was modeled using zero-thickness CZM interface elements. To determine the CZM parameters, shear and tensile testing of the brick-mortar joint should ideally be carried out. However, these tests were not performed as part of the CENAPRED investigation. Traditional masonry material property tests, such as prism and wallet tests, do not provide a complete description of the brick-mortar joint behavior. In the absence of this information, the joint properties determined and verified for the URM wall described previously were employed for the CM model. This was done for the brick to brick interface, as well as the brick to concrete interface at the wall panel-column junction.

The reinforced concrete frame was modeled with deformable discrete elements, seen in Figure 7(c) at the specimen's edges. The element height was intentionally made to be the same as the brick rows, such that cracks could propagate from the masonry panel into the column. The concrete modulus of elasticity obtained from cylindrical compressive tests was employed in the model. To account for the contribution of longitudinal reinforcement in the columns, elastic wire elements were added between the concrete units (not visible in Figure 7(c)). These elements only engage in tension. To validate the behavior of the column component of the model, a pushover test was created in LMGC90 and compared against results from the sectional analysis program, Response 2000 [11]. For both cases, the column was fixed against rotation at the top and a vertical load proportional to that seen in the CM wall was applied. Results from this comparison were used to calibrate parameters for the concrete to concrete interface and the elastic wires in LMGC90.

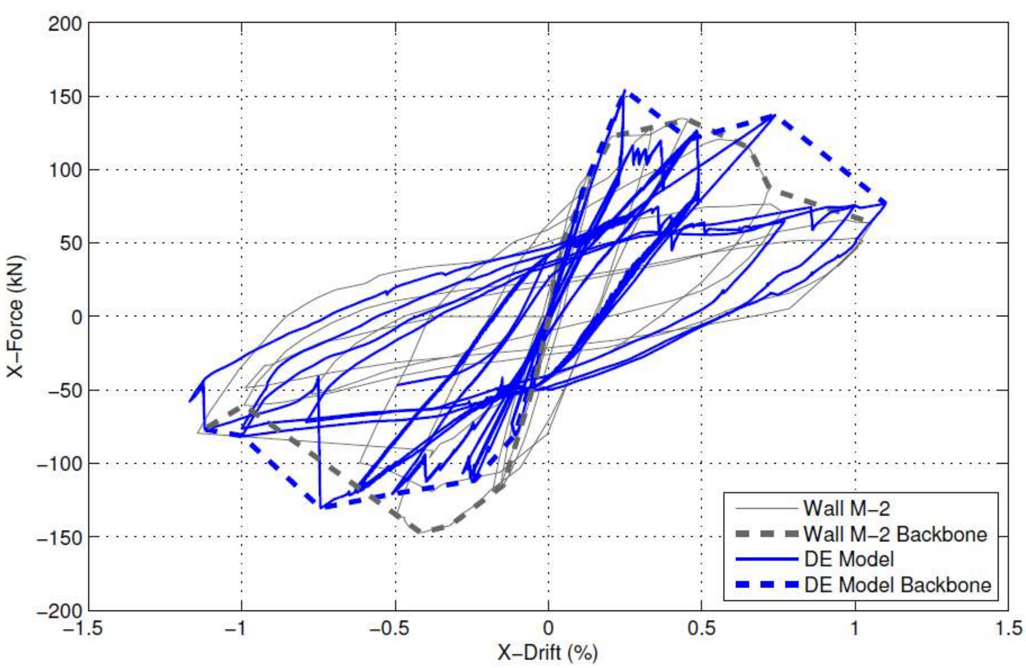
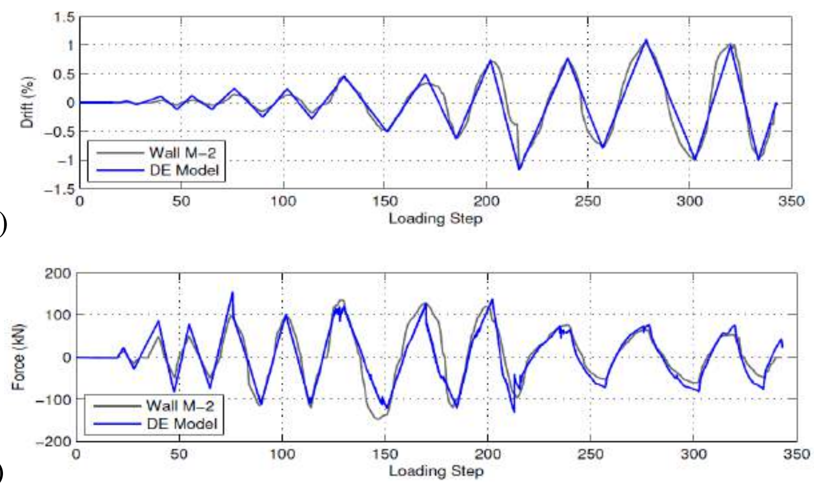


Figure 8 Force-displacement results of experimental and numerical model of a confined masonry wall subjected to cyclic loading [5].

Force-displacement results from the model and experiment are shown in Figure 8. Backbone curves tracing the first peak of each loading cycle are shown in thick dashed lines. In general, the numerical model was able to capture the initial stiffness, peak strength, stiffness degradation and hysteretic energy of the experiment. The instances of sudden strength decrease of the model are attributed to the loss of bond adhesion between units (i.e., cracking) and the subsequent load redistribution. Performance in the positive and negative loading directions varied, primarily because of the discontinuous nature of this numerical model. If a crack forms during the push direction the tensile load transfer across that crack is reduced or eliminated. When loading reverses to the pull direction, that same crack can still transfer significant compressive loads, hence causing unequal performance between the positive and negative directions. Figure 9(a) shows the drift-controlled time-histories of the experiment and model. The model's imposed history attempts to match the experiment's, despite fluctuations. Figure 9(b) shows the resultant force time-histories of the experiment and model. The model was able to generate approximate peak strength values throughout the loading history, including a strength decrease as the protocol progressed. The instances of strength loss can be readily seen here.



a)

b)

Figure 9 (a) Drift and (b) force time-histories of the experiment and model.

As seen in Figure 8, the hysteretic behavior generated by the model closely approximates that of the experiment, including peaks, loop width and degradation. Figure 10 tracks the cumulative hysteretic energy dissipated throughout loading for the experiment and model. While energy dissipated by the model lags behind the experiment in initial cycles, it ultimately is able to capture 95% of the cumulative energy loss. This finding points to the ability of the model to reproduce a realistic degree of damage through cracking and separating of units.

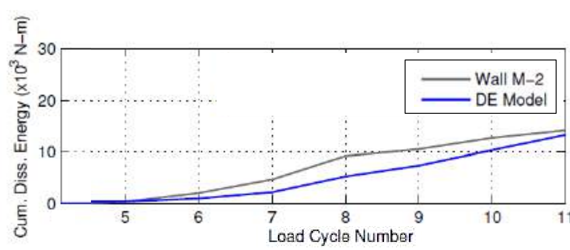


Figure 10 Cumulative energy loss by cycle number.

Conclusions

A detailed 2D numerical model of a confined masonry wall is developed using the discrete element method and a micro-modeling approach. Individual brick units are modeled as discretized deformable bodies. The brick-mortar joint is represented with cohesive zone interface elements, which provide a realistic representation of bond adhesion in shear and tension. This method successfully captures the linear and nonlinear behavior of a confined masonry shearwall subjected to in-plane multi-cyclic loading up to 1% drift, including the matching of force-displacement results, energy loss and damage distribution. Based on these results, a sensitivity investigation is ongoing to assess how various features of CM contribute to seismic performance.

Use of the discrete element method for the analysis of structures is gaining popularity as computing power improves. Applying DEM to masonry buildings is a natural fit given the discontinuous and heterogeneous nature of the material. With minor modifications, this approach can accommodate reinforced concrete elements and thus serve as a powerful modeling method of CM systems. It can also be readily adapted to 3D, allowing for out-of-plane failures. Without knowing target performance or failure modes a priori, this method can be used to study realistic nonlinear and collapse behavior of typical masonry structures in developing countries. In turn, this knowledge can improve the accuracy and applicability of today's catastrophe models, such as GEM and PAGER, as well as facilitate education, mitigation and recovery efforts.

Acknowledgments

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