OVERVIEW AND ASSESSMENT OF ANALYSIS TECHNIQUES FOR CONFINED MASONRY BUILDINGS

A. F. Lang[1], F. J. Crisafulli[2] and G. S. Torrisi[3]

ABSTRACT

Confined masonry is a construction technique widely used in seismic regions of Latin America and Asia for low-rise and medium-rise buildings up to six stories. Experience obtained from past earthquakes and experimental results indicate that confined masonry, if properly built, exhibits an adequate seismic response. For this reason, the Confined Masonry Network (www.confinedmasonry.org), under the auspices of several international organizations, promotes the use of confined masonry as an alternative for both unreinforced masonry and RC frame construction.

This paper is divided into three parts. The first part briefly describes the structural response of confined masonry, considering that the proper modeling of this system requires complete understanding of the structural behavior. The second part presents an overview of different numerical and analytical modeling techniques currently used to examine confined masonry systems. Advantages and disadvantages of each approach are presented with designers and researchers in mind. Modeling approaches presented include simplified techniques, macro modeling, such as strut-and-tie, and micro modeling using detailed refined numerical methods. A case study is used to compare and contrast the different techniques discussed. A single confined masonry wall tested in-plane is used as a benchmark. Emphasis is placed on the ability of a technique to match pre- and post-peak behavior, including energy dissipation capacity. Results indicate that both macro and micro modeling approaches successfully capture the overall performance of confined masonry. The macro model underestimated the total dissipated energy by roughly half, however, while the micro model was within 10% of the specimen performance. The speed and ease of use make the macro model approach an ideal choice for designers and researchers alike, while those requiring a more detailed analysis or special design can find success with micro modeling.

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Overview and Assessment of Analysis Techniques for Confined Masonry Buildings

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Confined masonry is a construction technique widely used in seismic regions of Latin America and Asia for low-rise and medium-rise buildings up to six stories. Experience obtained from past earthquakes and experimental results indicate that confined masonry, if properly built, exhibits an adequate seismic response. For this reason, the Confined Masonry Network (www.confinedmasonry.org), under the auspices of several international organizations, promotes the use of confined masonry as an alternative for both unreinforced masonry and RC frame construction.

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Introduction

Confined masonry walls represent a particular type of masonry construction in which the masonry walls, built in a first stage, are surrounded by a reinforced concrete frame. The frame is cast after the construction of the walls to assure adequate bond between the masonry and the concrete, providing partial confinement to the wall (see Figure 1). Confined masonry originated as a new structural system in Italy after the 1908 Messina Earthquake and later spread to other parts of the world. Now it is widely used in seismic regions of Latin America and Asia for lower

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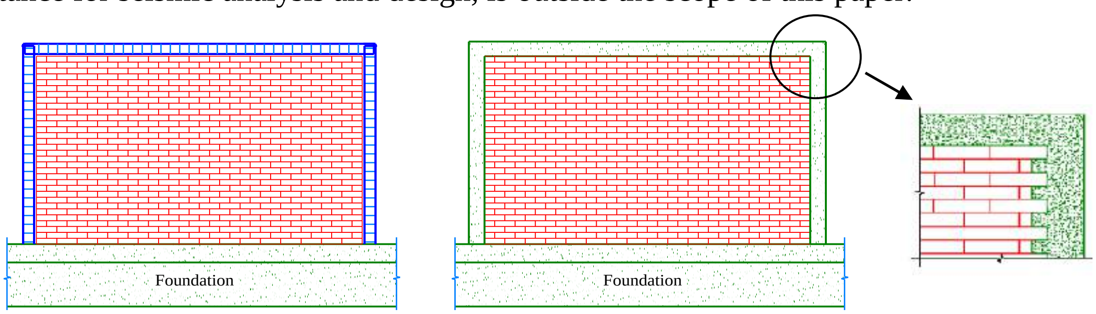
rise buildings, commonly three or four stories but as high as six. It is also used extensively for single family dwellings, which are typically non-engineered and self-constructed.

Observations from past earthquakes, experimental data, and analytical results indicate that confined masonry, if properly built, exhibits an adequate seismic response for collapse prevention [1]. Consequently, this system represents a good alterative in those seismic regions where masonry is widely used due to economic or traditional reasons. For these reasons, the Confined Masonry Network (CMN) was created in 2008 with the main objective of promoting this building technique in developing countries (www.confinedmasonry.org/). The CMN currently has financial sponsorship from Risk Management Solutions and is supported administratively by the World Housing Encyclopedia of the Earthquake Engineering Research Institute. Recently, the CMN published the *Seismic Design Guide for Low-Rise Confined Masonry Buildings* [2].

The increasing use of confined masonry requires reliable methods to analyze structural response, not only for the design of new construction but also for the assessment of existing buildings. This is very important in order to reduce the loss of life and property associated with severe damage or structural failures from earthquakes. Consequently, the main objective of this paper is to present and compare the different numerical and analytical modeling techniques currently available for evaluating the in-plane response of confined masonry. This is done with designers and researchers in mind. Discussion about out-of-plane behavior, despite its importance for seismic analysis and design, is outside the scope of this paper.



(a) (b) (c)

Figure 1. Overview of confined masonry wall construction, including a) positioning of the RC frame reinforcement around the existing masonry wall, b) casting of the concrete frame around the wall, and c) close-up of toothed interface between the masonry wall and RC column.

In-Plane Response of Confined Masonry.

Confined masonry walls exhibit complex nonlinear behavior. The structural response is influenced by different parameters such as material properties, workmanship, slenderness ratio, relative stiffness between the RC frame and the masonry wall, and conditions of the masonry wall panel and RC frame interface (hereafter referred to as the “panel-frame interface”). In this section, the structural response from in-plane lateral loading is described, considering that the proper modeling of the system requires complete understanding of the structural behavior.

The in-plane structural response of confined masonry is nearly elastic and behaves as a monolithic wall at the initial stage. The masonry wall panel and RC frame elements perform in unison, attributed to the bond that exists at panel-frame interfaces. This bond is the result of adhesion of the concrete to brick, as well as the mechanical interlocking in a toothed manner of the bricks with the concrete column, when such a staggered connection is present (see Figure 1(c)). The system can be considered similar to a cantilever wall, as shown in Figure 2(a) by the distribution of principal stresses. This conclusion was experimentally verified by Crisafulli [3] by comparing the measured stiffness of a single confined masonry wall to that obtained from structural analysis assuming a monolithic wall.

As the lateral force increases beyond the elastic range, stresses redistribute in the wall and the overall response changes from a cantilever type, in which the masonry wall and RC frame are displaced together, to a dual system consisting of a masonry shear wall and moment resisting frame. This stress redistribution results in a diagonal compression strut forming across the masonry panel, typically resulting in shear friction failure. The brick units may also fracture, as well as separation at or adjacent to the panel-frame interface. The extent of interface separation is dependent on several factors, such as the strength of adhesion, the relative stiffness between the frame and wall, and the stagger distance of the bricks when a toothed connection is used. In a general sense, cracking of the masonry wall or separation at the panel-frame interface results in the same outcome from a structural point of view. Stresses at the tensile corners are relieved while those near the compressive corners are significantly increased. The masonry is mainly subjected to compressive stresses along the loaded diagonal (see Figure 2(b)). This change in the structural response does not affect the resistance of the confined wall, but significantly decreases its stiffness.

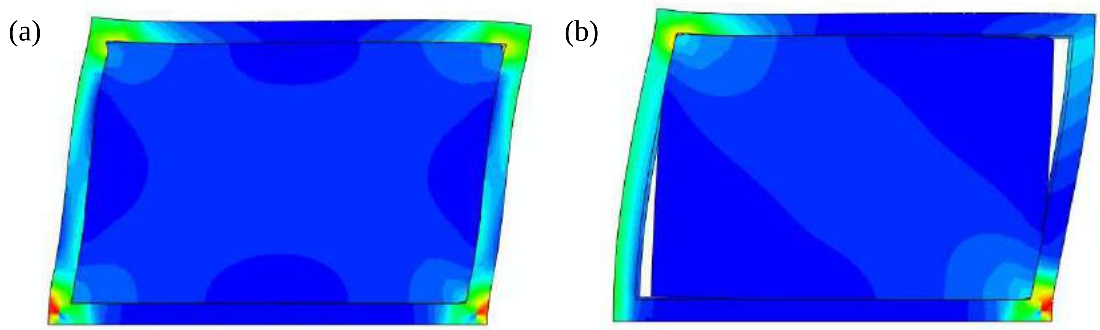
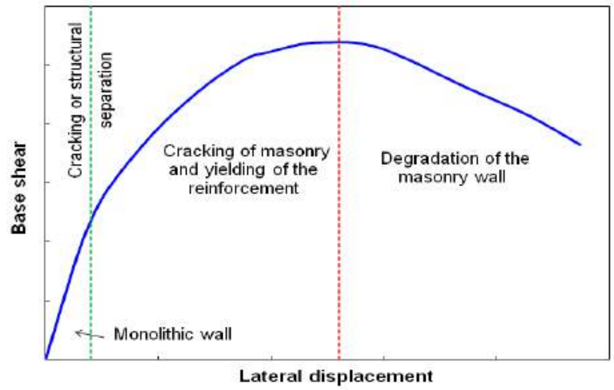


Figure 2. Deformed shape and von Mises stresses in a finite element model of a confined masonry wall (a) at the initial stage, and (b) after stress redistribution due to cracking and/or interface separation [4].

Beyond cracking, increased displacement and lateral force demands result in increased cracking throughout the masonry wall, greater separation of the panel-frame interface, and localized instances of crushing of brick units in the corners. Most load transfer between the wall and frame is restricted to regions adjacent to the compressed corners. Cracking of the masonry panel causes a significant decrease in the stiffness until the maximum lateral resistance is attained. In the RC frame the members are subjected to bending moments, shear and axial forces, and, consequently, cracking, plastic hinges or axial yielding [5]. At final stages, the ultimate failure mode is dominated by the frame capacity, which restrains or confines the cracked masonry wall. Typically, large cracks in the wall will propagate into the confining concrete columns at the corners, resulting in shear failure and a racking collapse mechanism. Figure 3 summarizes the complete performance cycle of confined masonry subjected to in-plane lateral loading.

Figure 3. Performance summary of a confined masonry wall under in-plane lateral loading.



Modeling Approaches

Reinforced concrete frames with infilled masonry have been used since the beginning of the 20th century for low and medium-height buildings. This structural system differs from confined masonry, since the construction sequence is reversed. The masonry infill is assembled after the frame and, consequently, shrinkage of the masonry or defects due to inaccurate workmanship usually result in no or little bond at the panel-frame interfaces. Furthermore, the structural contribution of the masonry wall is typically ignored in the design process and, consequently, the cross sectional area of the RC frame members is larger than those used in confined masonry systems.

It has been established that the design criteria and construction techniques for confined masonry walls and RC frames with infilled masonry are different. However, in the authors' opinion, the gross response of these structural systems subjected to in-plane seismic loading is somewhat similar, at least in early loading stages. In both cases, the behavior is mainly controlled by the complex nonlinear response of the masonry wall panels and the surrounding RC elements. Hence, the description presented in the previous paragraphs and represented in Figure 2 and Figure 3 is also valid for infilled frames. A parametric study conducted by Torrisi and Crisafulli [6] validates this conclusion. Consequently, with adequate modification both structural systems can be analyzed with similar models and approaches.

For those confined masonry systems that differ significantly from infilled frame construction, such as those with significant bonding at the interface, or those which require detailed analysis, more refined modeling tools may be needed. Confined masonry walls exhibit complex and highly inelastic behavior, not only due to the material nonlinearity of masonry and reinforced concrete but also due to joint degradation at the panel-frame interfaces. The proper consideration of these nonlinear effects requires refined computational techniques, usually not a practical option for the designer. A wide variety of modeling techniques have been developed for the analysis of confined masonry walls, with different degrees of refinement and precision. They can be divided in three main groups, namely, (i) simple models, (ii) macro models and (iii) micro models. The main characteristics of these techniques are described in the next sections.

Simple Models

Simple models are mainly used for practicing engineers to evaluate the design of a confined masonry wall by determining the lateral stiffness and strength. They are also useful for checking the results obtained from more robust modeling techniques.

The monolithic wall model considers that cracking or interface separation has not occurred and, therefore, assumes that the wall can be represented by a homogenous rectangular section of masonry (with thickness, t, and length, L) as shown in Figure 4(a). It can be demonstrated from basic structural analysis principles that the lateral stiffness, K, of the wall is:

$$K = \frac{3\,E_m\,I}{h^3\,(1+\lambda)} \tag{1}$$

where E_m is the elastic modulus of masonry, $I = t\,L^3/12$ is the moment of inertia of the wall, h is the wall height, and $\lambda = 0.75\left(\frac{L}{h}\right)^2$ (this equation assumes the shear modulus, $G_m = 0.4\,E_m$).

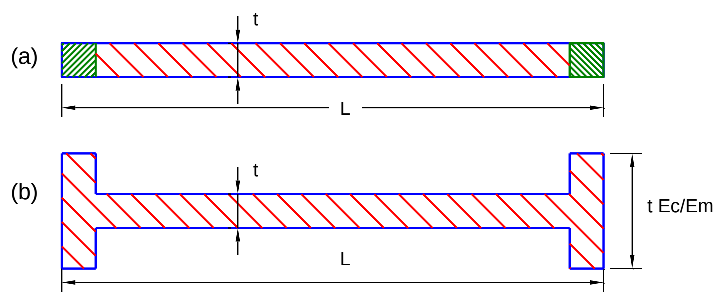


Figure 4. Cross section of the monolithic wall model, (a) rectangular section, and (b) transformed section.

The use of a rectangular section to calculate K using Eq. 1 does not consider that the elastic moduli of the concrete and masonry are different. This effect can be taken into account with a transformed section in which the thickness of the reinforced concrete column is increased by the ratio E_c/E_m, where E_c is the elastic modulus of concrete, to obtain an I-shaped section as shown in Figure 4(b). In this case, $\lambda = \frac{7.5\,I}{h^2\,A_s}$, where A_s is the shear area of the transformed section. It is worth noting that the monolithic wall model represents the behavior of the wall only at the initial stage, before cracking occurs. Therefore, the applicability of this model is very limited and should be used with caution for seismic design since behavior is usually dependent on post-peak performance. Furthermore, the monolithic wall model cannot properly consider the effect of openings in the wall.

The wide-column method is an alternative simple modeling method which considers the wall as a monolithic section, represented with two-node elements [7]. Rigid beams are also used as auxiliary members to model structures with walls and openings for doors and windows. This technique is suitable for designers for the structural analysis of confined masonry structures (2D or 3D) with commercial computer programs. Figure 4(a) presents an example of a two-story confined masonry wall with openings, and Figure 4(b) depicts the wall using the wide-column method. It must be noted that, depending on the computer program, the use of rigid beams with very large stiffness may result in numerical errors. As mentioned previously, the hypothesis of monolithic behavior, assumed by the wide-column method, is mainly valid to represent the elastic response at the initial stage. However, the section properties of the wall members can be reduced with empirical factors to represent the effect of cracking of the masonry or nonlinear elements can be used to extend the validity of the model.

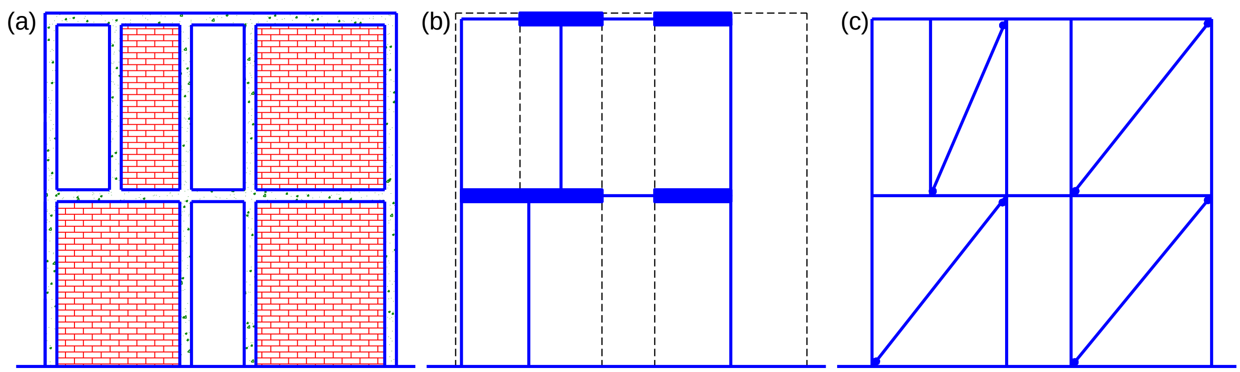


Figure 4. (a) Example of confined masonry wall with openings, (b) wide-column model, and (c) equivalent strut model.

Simple equations have been developed to evaluate the lateral strength of confined masonry walls, particularly for design purposes. A wide variety of equations have been developed for design codes based on empirical and experimental results in Latin America and Asia (see [2] for more details). Despite subtle differences, these equations can be represented as:

$$V = \mathrm{C}_1 \, \mathrm{v} \, A_w + \mathrm{C}_2 P_u \tag{2}$$

where C_1 and C_2 are empirical coefficients specific to each code, v is the shear strength of masonry, A_w is the wall gross area, and P_u is the axial compressive force due to gravity loads.

Macro Models

Macro models represent a compromise solution between simplicity and precision, with a main objective of analyzing large structures such as a complete building with many confined masonry walls. These models use a combination of two-node elements and axial, shear, and flexure springs, depending on the complexity of the formulation. The simplest macro model is the equivalent strut, proposed by Polyakov and Holmes in the 1960s, as reported in reference [3]. For this method, the masonry wall is represented by a compressive strut and the surrounding frame is modeled with beam elements, as seen in Figure 4(c). This model can approximately calculate stiffness of the confined masonry wall and axial forces in the frame, which is useful for design purposes. However, it cannot predict local effects, shear and bending forces in the frame, and stress in the masonry.

Many researchers have modified the single strut model in order to improve the precision of the model, for example, (i) using two, three or more diagonal struts to capture internal forces in the frame and to model walls with openings, (ii) incorporating shear springs to represent the nonlinear behavior of masonry, or (iii) using several elements and springs to improve the representation of the RC frame. As a result of these modifications and improvements, there are macro models than can predict the overall nonlinear response of a confined masonry wall and different types of failure. However, these models are not usually available in commercial structural analysis programs. The programs RUAMOKO (www.ruaumoko.co.nz) and SeismoStruct (www.seismosoft.com) incorporate a panel model that can be used for the nonlinear analysis of confined masonry and infilled frames.

In this paper, due to space limitations, only the equivalent strut model proposed by Torrisi et al. [5] is briefly described. The model represents a masonry panel using six strut members which are located in the diagonal direction of the panel. The RC members are represented with a column macro element. Axial strength of the masonry struts is determined according to a general failure theory by considering the strut inclination and the following failure modes: sliding shear, diagonal tension, and compression failure. Formulation of the column macro element considers interaction between the bending moments and axial forces and between shear forces and axial forces (the interaction between bending moments and shear forces is not considered, although they are coupled by equilibrium in the stiffness matrix).

Micro Models

The simple and macro models described previously provide an adequate approximation of the general performance of confined masonry systems. However, by design these techniques predetermine load paths and failure modes. While material variability can be accounted for, structural aspects that deviate from the original prototype cannot be tested, such as openings or brick stagger distance at the panel-frame interface. Effects from such geometric features are especially pronounced in the inelastic range, after cracking occurs and load paths redistribute. The capability to model these features can be important for assessing capacity and ultimate failure modes. Using micro modeling techniques, the actual layout of bricks and other geometric features, along with resultant load paths, can be captured. Micro models can also incorporate realistic contact properties at the brick-mortar and brick-concrete interfaces.

With a micro modeling approach individual brick units are modeled as either rigid or deformable bodies connected together with nonlinear joints. Numerically, both the finite and discrete element methods can be employed (FEM, DEM). When using FEM, the brick units can be modeled as linear-elastic continuum elements or smeared crack elements. Alternatively, today's improved computers have made DEM an increasingly popular alternative. Rooted in non-smooth contact dynamics, this approach closely resembles the natural configuration of masonry whereby individual bodies can separate, interact, and impact [12]. Brick units can be deformable or rigid, the latter less computationally expensive. Interface elements that employ the cohesive zone model can be used to model behavior of the brick-mortar joint, including adhesion, cracking, and Coulomb friction. Initially, the element has an elastic stiffness equivalent to joint adhesion. Once peak strength is reached, equivalent to the mortar bond breaking, a crack occurs and the strength reduces to zero in the normal direction and to Coulomb friction in shear.

Micro modeling has been used successfully to examine the interactions of mortar and brick, and the performance of small wall assemblages and larger masonry structures [8, 9, 13]. This modeling approach was recently adapted for confined masonry systems using DEM (see below and [11]). Commercial DEM software includes 3DEC and UDEC; freeware programs are also available such as LMGC90 [10]. Most commercial FE programs can be used to for the micro modeling of masonry described herein.

Micro modeling can be a powerful tool for the assessment of confined masonry structures. However, this method can be impractical for designers. Despite today's technological advancements, micro modeling remains computationally expensive, especially in comparison with macro models. Detailed knowledge of joint properties can also be elusive to obtain. Small scale experiments involving bricks, mortar, and brick-mortar joints are ideal for describing the most accurate joint relationships. Traditional material property tests, such as masonry prism tests, do not sufficiently describe the brick-mortar bond. Nonetheless, micro modeling offers the most comprehensive and accurate means of capturing the behavior of confined masonry systems.

Case Study

A case study is presented to compare the micro and macro modeling approaches presented. A single confined masonry wall tested in-plane is used as a benchmark. This traditionally built wall was tested at CENAPRED as part of an experimental program to gauge the effectiveness of strengthening techniques. Wall M2 was used as a control specimen and was unreinforced (see **¡Error! No se encuentra el origen de la referencia.**(a)). The specimen consisted of hand-made solid clay bricks surrounded by a RC frame. A constant vertical load of 142 kN was applied, representative of a 4 to 5 story building. The loading protocol consisted of 11 monotonically

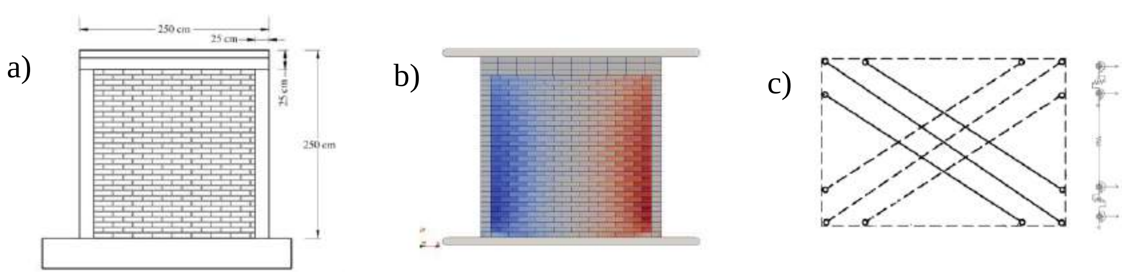


Figure 5. Overview a) of Wall M2 [14], b) discrete element model, and c) multi strut model.

increasing drift cycles, up to 1% [14].

For the micro modeling approach, LMGC90 was used to develop a discrete element numerical model of Wall M2. As seen in Figure 6(b), individual bricks were modeled as deformable units in a layout similar to Wall M2. Joint properties were represented by the cohesive zone model. The top beam of the RC frame was represented by a large deformable unit. The RC columns were represented by discretized concrete units (to allow for crack propagation). In addition to the cohesive zone model, elastic wire elements also connected the units together, representing steel reinforcement.

Using the equivalent strut macro model developed by Torrisi et al [5], the masonry panel was represented by six diagonal struts, while the RC columns were represented by column macro elements. Vertical load bearing on the wall is not considered with this approach. The modulus of elasticity of the masonry as reported in literature was used as an input parameter.

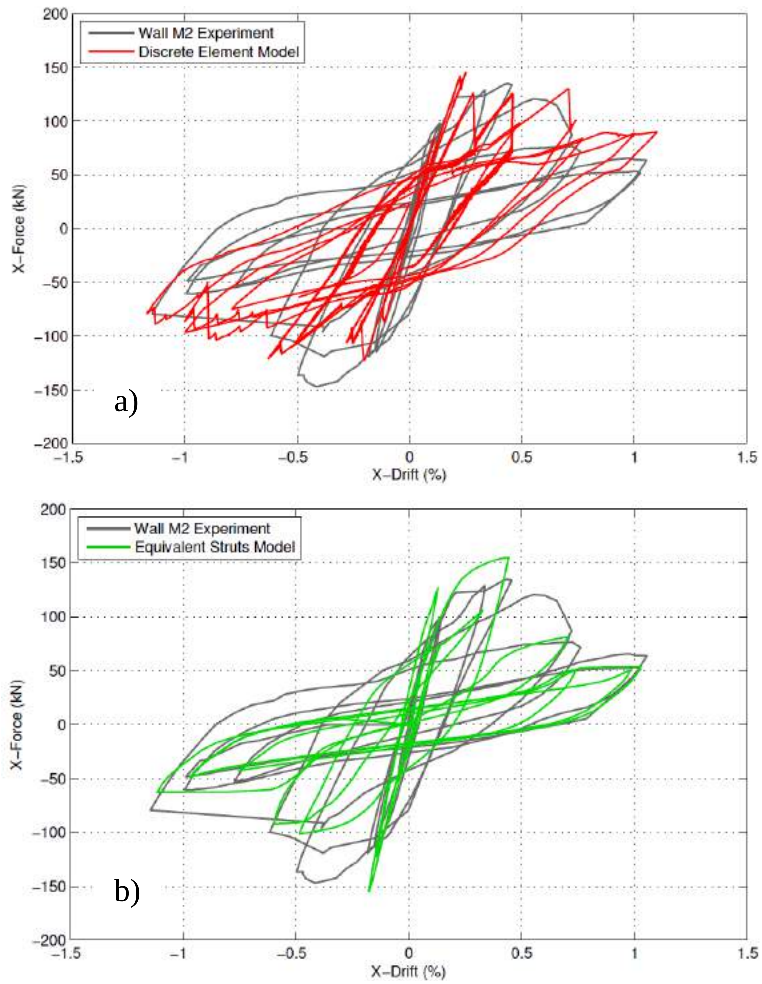


Figure 6. Force displacement results of Wall M2 vs a) the discrete element micro model, and b) equivalent struts macro model.

Force displacement results of the two modeling approaches are seen in Figure 7**¡Error! No se encuentra el origen de la referencia.**. It is evident that both approaches are able to capture the initial stiffness, approximate peak strength and displacement, and post-peak behavior, including stiffness degradation. However, significant discrepancies exist when considering the amount of energy dissipation. The cumulative dissipated energy for the two models was calculated and normalized to that of Wall M2. The discrete element model was able to capture 90% of the total energy dissipated while the equivalent strut model captured just 55%.

The ability to accurately predict dissipated energy can be important when determining ultimate capacity. Further, the DE model presents an attractive means of visually displaying damage, which the equivalent struts method cannot do. Nonetheless, the simplicity with which the equivalent struts model can be executed and its ability to match peak force values makes it an efficient and desirable option for designers and researchers.

Conclusions

Confined masonry systems provide an economical and seismically safe way to build, especially in developing countries. The growing interest in and use of this building type demands more information on its structural behavior and characteristics. This paper strives to clarify and summarize the various analysis methods available to designers and researchers. These methods include simplified techniques, the more sophisticated equivalent strut method, and the refined numerical micro modeling approach. All of these approaches offer advantages and disadvantages to the user. A case study of a confined masonry wall tested in-plane was used to highlight the differences between the equivalent strut and micro model using discrete elements. Both methods successfully capture the wall's initial stiffness, peak strength and displacement and strength degradation. The discrete element micro model was able to accurately capture the total dissipated energy, as well as offer an appealing visual representation of the damage. The equivalent struts method is less computationally intensive and offers a straightforward analytical solution.

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