Journal of Civil Engineering and Architecture 11 (2017) 870-878
doi: 10.17265/1934-7359/2017.09.006

Numerical Modeling and Analysis of Unreinforced Masonry Walls

Isak Idrizi[1] and Zekirija Idrizi[2]

1. Faculty of Civil Engineering and Architecture, Mother Teresa University, Shkup 1000, Macedonia;

2. Faculty of Civil Engineering and Architecture, Hasan Prishtina University, Prishinë 10000, Kosova

Abstract: Estimation of shear strength and other mechanical characteristics of masonry wall panels through experimental research is the most reliable analysis approach. However, considering all the difficulties in performing experimental research, material costs, laboratory preparations and time expenses, it is not difficult to conclude that this approach is also not the most rational. Aside from experimental investigations, advanced analytical methods are considered cheaper and practical, which can approximately describe the mechanical behavior of masonry walls. The aim of this chapter is to demonstrate how advanced analytical methods, based on discrete and applied element methods, are capable of estimating, in close approximation, the realistic behavior of masonry walls. The use of advanced analysis methods for determination of the behavior of full-scaled masonry walls (with and without openings), avails the inclusion of infill masonry walls on the processes of modeling, analysis and design of building structures, without the need of extensive experimental investigations. This would result in achieving more approximate analytical building models in respect to their realistic behavior and ultimately achieve better optimization of structural design.

Key words: URM (unreinforced masonry wall) wall, discrete methods, advanced analysis, numerical modeling.

1. Introduction

Estimation of shear strength and other mechanical characteristics of masonry wall panels through experimental research is the most accurate approach. However, considering all the difficulties in performing experimental research, material costs, laboratory preparations and time expenses, it is not difficult to conclude that this approach is also not the most viable.

Besides experimental investigations, as a more practical approach, that can provide reliable estimate on the mechanical behavior of masonry walls, is considered the advanced analytical methods.

2. General Review on Masonry Wall Modelling Strategies

Due to the enormous progress made on reinforced concrete structures and development of advanced structural analysis techniques, knowledge on masonry behavior improved considerably. Nevertheless, the modeling and analysis methodologies used for RC (reinforced concrete) elements are still impossible to be applied directly to URM walls. Due to the highly heterogeneous nature and orthotropic mechanical characteristics of URM walls, a direct application of RC modeling approach for the URM wall panels would be wrong [1].

Hence, there was a need to develop different constitutive models which would appropriately consider the heterogenic nature of URM walls in the modeling and analysis process. In the current existing literature, there are proposed several modeling strategies and methods of analysis.

The numerical modeling of masonry walls may be approached either by a detailed description of mechanical properties for each individual component of masonry walls (micro-modeling) or by treating the masonry wall as a composite continuous material (macro-modeling). Ultimately, depending on the

Corresponding author: Isak Idrizi, doctor of science, assistant professor; research fields: earthquake engineering and structural engineering. E-mail: isak.idrizi@unt.edu.mk, isak_idrizi@hotmail.com.

required level of accuracy and simplicity in masonry modeling, three principal modeling strategies for masonry walls are classified [2, 3]:

(1) Detailed micro-modeling (two-phase model), where masonry constituents (brick unit and mortar) are modeled as continuum elements and the unit-mortar interface is represented by discontinuous elements (Fig. 1b);

(2) Simplified micro-modeling (two-phase model), where expanded units are represented by continuum elements whereas the behavior of mortar joints and unit-mortar interface is lumped in discontinuous elements (Fig. 1c);

(3) Macro-modeling (one-phase model), where units, mortar and unit-mortar interface are smeared out as one continuum element (Fig. 1d).

An accurate utilization of micro-modeling approach must include all of the basic types of failure mechanisms possible to occur on the micro-level aspect of masonry buildings, respectively, pure tension failure alongside masonry interface (joint tensile cracking), pure shear failure alongside masonry interface (joint slipping), direct tensile cracking of brick units, diagonal tensile cracking of units and masonry crushing. All of these failure modes are figuratively presented by Lourenço [3] (Fig. 2).

The micro-modeling approach of masonry walls by taking proper account to all probable failure modes has been a subject of study to many scientists in the past.

Eventually, Lourenço proposed a composite interface model (also known as "interface cap model"), Fig. 3, which aims at taking into account all of the aforementioned failure modes for the micro-modeling process of masonry walls.

This so called "interface cap model" takes into account the three distinct modes of failure of masonry, i.e., the pure tension failure mode, Coulomb friction failure mode and the failure mode due to high compression stresses (cap mode).

Based on this model for the masonry interface (joints), the refined numerical analyses are capable of tracking the concentrated damages along the relatively weak joints between brick units and the mortar, in addition to the other failure mechanisms mentioned beforehand.

In general, the micro-modeling strategy gives more

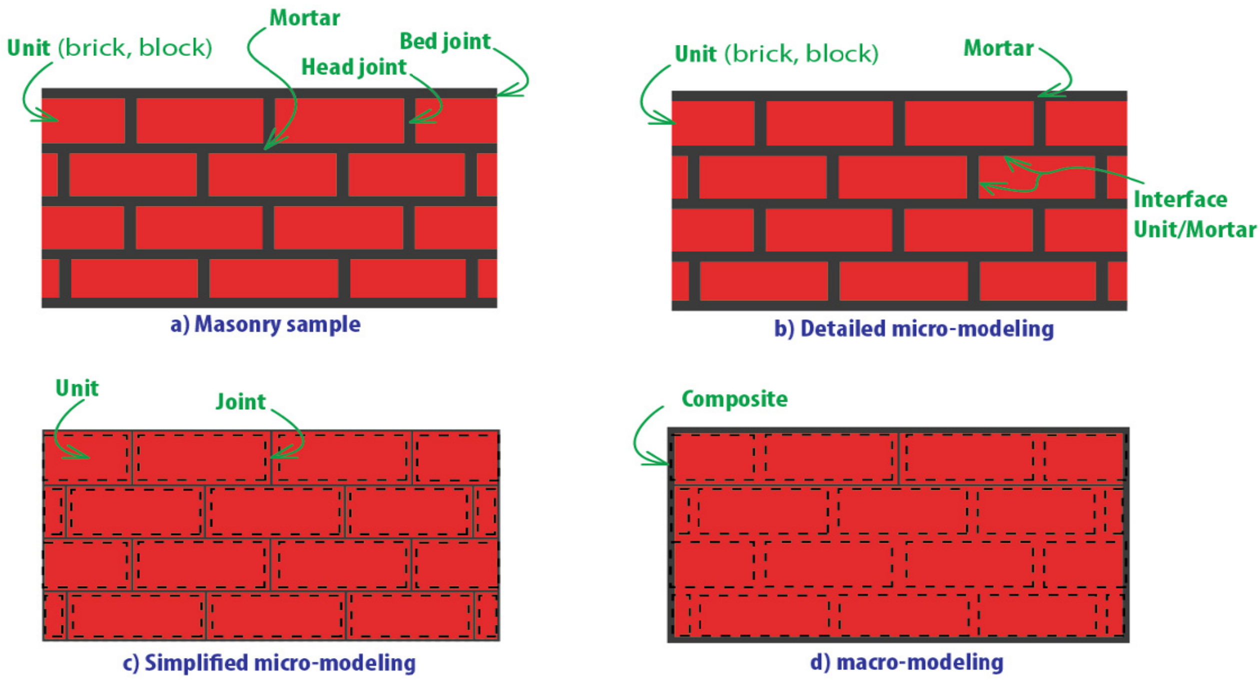


Fig. 1 Modeling strategies for masonry walls: (a) mansonry sample; (b) detailed micro-modeling; (c) simplified micro-modeling; (d) macro-modeling.

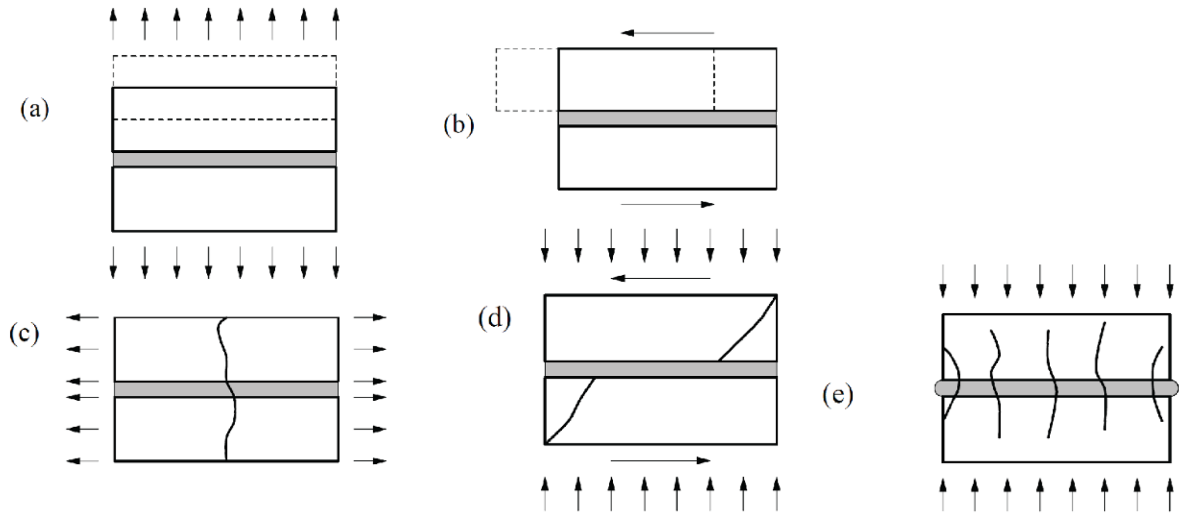


Fig. 2 Masonry failure mechanisms: (a) joint tensile cracking; (b) joint slipping; (c) unit direct tensile cracking; (d) unit diagonal tensile cracking; (e) masonry crushing [3].

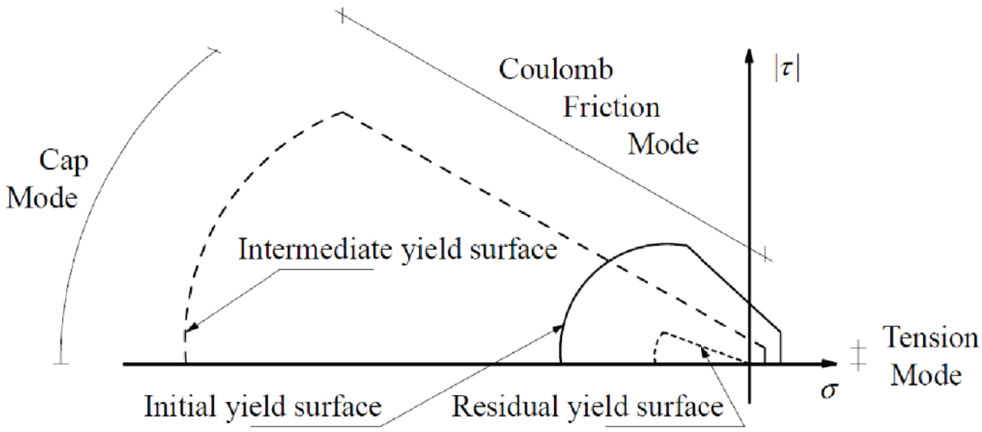


Fig. 3 Composite interface model. An "interface cap model" proposed by Lourenço [3].

realistic results for the local behavior of masonry structures and the failure propagation along masonry walls has a much elaborated form. However, due to the great number of degrees of freedom, computationally intensive calculations are required which makes it "impractical" for professional use in structural design. For the present time, micro-modeling strategies are used generally for research purposes. The input parameters for micro-modeling are more numerous in order to properly consider wall units, mortar and unit/mortar interaction characteristics.

Macro-modeling, on the other hand, is more oriented toward estimation of global performance of masonry structures. The constitutive models of macro-models are easier to use and require less input data. Macro-models are more practice-oriented because the calculation time is significantly lower and the modeling process is significantly faster and simpler (Bakeer).

3. General Review on Numerical Analysis of Masonry Walls

Nowadays, a variety of numerical analysis frameworks are established in order to analyze and simulate the complex mechanical behavior of masonry structures.

While many numerical methods have the ability to accurately analyze the elastic behavior of masonry, the ability to describe the response of masonry near and after the collapse is quite a recent development.

In reference to extensive literature studies, all of existing numerical methods for modeling, analysis and simulation of physical systems are grouped into two major categories (Fig. 4), namely:

- continuum methods; and
- discrete methods.

3.1 Continuum Methods

The most widely used analysis methods representative for the continuum methods of analysis, are the FEM (finite element method) and BEM (boundary element method). Although it was paid much less attention to BEM, Rashed et al. employed BEM to model the non-linear behavior of masonry where cracking, de-bonding and crushing failure modes were considered in masonry wall models.

With FEM based applications, the analysis of masonry structures using continuum models is quite easy and computationally efficient. Many authors have utilized the FEM method for analyzing the behavior of masonry walls. Some of such typical studies are shown in the references section in the end of this book. In reference to the experience gathered from a large number of experimental investigations, it has been verified that FEM based applications give good approximation on the linear response of masonry structures.

Masonry walls subjected to deep nonlinear response manifest a great number of discontinuities thus changing their status from continuum state to an entirely discrete state. Regarding these micro-mechanical characteristics on masonry wall panels, the use of continuum methods on nonlinear analysis of masonry walls offers a crude approximation of what the realistic nonlinear response would be. In order to consider the micro-mechanical characteristics of masonry walls, it was introduced the so-called “smeared crack approach” and the concept of interface elements.

The smeared crack approach considers the softening and local cracking of materials while the interface elements consider the discontinuity at planes of failure. Nevertheless, the use of FEM model with smeared crack approach, or interface elements, is only capable of appropriately analyzing the small displacements before failure of masonry walls. The simulations of large displacements up to total collapse of masonry walls remain impossible to be solved under the utilization of continuum method of analysis.

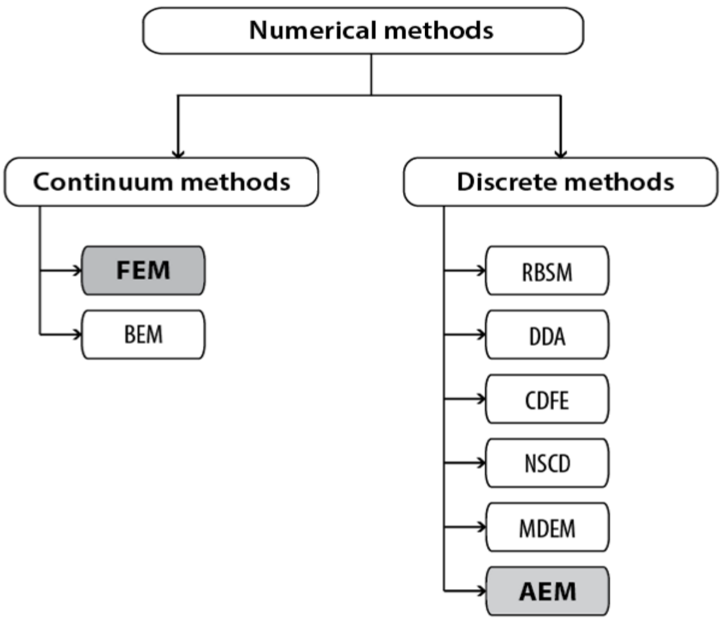


Fig. 4 Numerical analysis methods for masonry structures (Bakeer).

3.2 Discrete Methods

The ingenuity of discrete element method lies in the fact that it is capable to consider an entire physical system and separate it into its constituent discrete components which interact with each-other through "surface interaction laws". The discrete elements can be considered either as rigid bodies or as elements with elasto-plastic mechanical characteristics described through continuum equations. Based on this approach, discrete methods are capable of performing refined nonlinear analysis under large displacements between discrete elements. Although discrete element method is a quite recent development, it has gained enormous interest in engineering research and, so far, there were established several distinct numerical methods based on the discrete element computational formwork, such as:

- RBSM (rigid bodies spring method);
- DDA (discontinuous deformation analysis);
- CDFE (combined discrete-finite elements);
- NSCD (non-smooth contact dynamics);
- MDEM (modified distinct element method); and
- AEM (applied element method).

The AEM is the most recent development in discrete analysis methods which are the only method to accurately track and visualize the complex response of engineering structures starting from initial stress conditions and gradually progressing through states of nonlinear deformations, material degradations, element separations and collisions and up to total structural collapse [4, 5].

As part of this paper, AEM method was extensively used to model, analyze and simulate the nonlinear response of a masonry wall panel being subject of experimental research.

4. Micro-modeling and Analysis of a Classical Wall Panel

This section treats the micro-modeling, analysis and simulation of a classical wall analytical model, and ultimately compares its response with experimentally obtained results from its representative physical model.

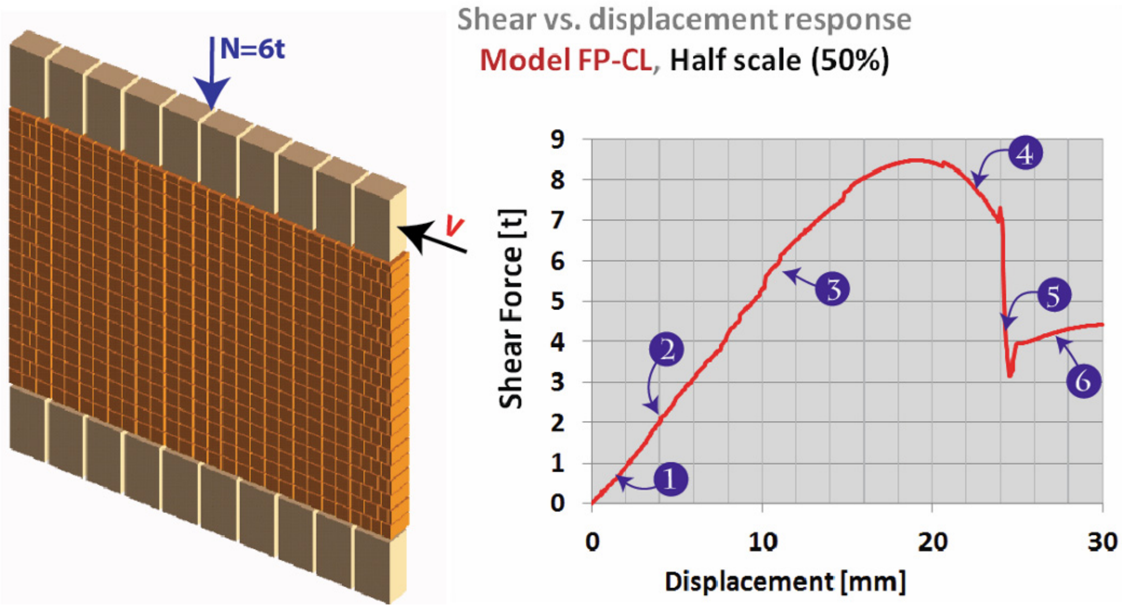
In order to generate a numerical micro-model of wall panels, it was applied a scientifically oriented computer program based on one of the most recent developments in discrete analysis methods, namely AEM method. This method of analysis is, by far, the only method to manage to approximately track and visualize the deep nonlinear response of structures up to their complete failure.

Under AEM method, the wall panels are assumed to be divided into small prismatic elements, which are inter-connected with each other at their contact faces through pairs of normal and shear springs. This modeling approach is especially suitable for the two-phase composite material structure of the masonry walls with distinct anisotropic features.

The masonry wall structure is discretized into small prismatic elements in a way that each brick unit, with dimensions 250 mm × 120 mm × 60 mm, is divided into four equal parts, in the longitudinal direction, thus forming four equal micro-elements with dimensions 60 mm × 120 mm × 60 mm. The mortar joints are automatically considered by the software with thickness of 15 mm. The generated micro-model of the wall panel is presented in Fig. 5a.

The generation of this mathematical model was done to replicate the initially prepared physical wall model. To this respect, all physical and mechanical characteristics of the physical wall panel and its components were measured and used as input parameters on the analysis of the mathematical model, like the mechanical features of constitutive units of the wall panel, respectively brick units, mortar and brick/mortar interface joints. In addition, contact springs, between the faces of prismatic elements, are internally calculated by the software, based on the mechanical properties of wall panel constituents.

The sequence of external actions acting on the wall panel models is set-up in such a way that it simulates



(a) (b)

Fig. 5 Micro-modeling of: (a) "Wall FP_CL" wall; and (b) its shear-displacement response.

the loading scenario carried out by experimental investigations.

The only difference between the experimental and analytical loading conditions is the loading pattern of horizontal deformations. For experimental analysis, a horizontal cyclic "deformation controlled" action was applied. For numerical analysis, a monotonically increasing and "deformation controlled" action was used.

Nevertheless, both experimental and analytical studies show very similar behavior of wall panels in terms of their mechanical strength, deformation, development of cracks and their propagation up until complete failure of wall panels. This similarity is clearly demonstrated by observing Figs. 6 and 7.

Fig. 6 demonstrates six characteristic stages of crack development over a numerical micro-model "Wall FP_CL" subjected to a monotonically increasing shear deformation, preceded by a vertical confinement stress of 0.35 MPa (equivalent to 6 t of vertical force). Actually, this analysis represents a "replica" of the experimental Test 1 of the so called physical model "Wall FP_CL".

If the last deformation stage of the numerical micro-model "Wall FP_CL", Fig. 6, is closely compared with the failure pattern of "Test 1" of physical model "Wall FP_CL", the similarities in failure pattern are very obvious (Fig. 7). Moreover, this similarity is also valid in terms of the shear-displacement response curves, as demonstrated in Fig. 7 (bottom).

According to Fig. 7 (bottom), the shear strength for the numerical model is close to 90 kN (≈ 9 t) which is slightly lower than the shear strength obtained through experimental investigations with a value of 100 kN (≈ 10 t).

Additionally, the ultimate shear deformation of the analytical model (20 mm) is slightly lower than that obtained under experimental "Test 1" of physical model "Wall FP_CL" with a value of 22 mm.

There are many factors that impose differences in mechanical behavior between the two models, respectively, the variation in mechanical properties of wall constituents from one location to another, the unavoidable errors in estimation of mechanical properties of wall constituents; approximations and idealized assumptions during the micro-modeling process and the level of discretization of wall constituents; etc.

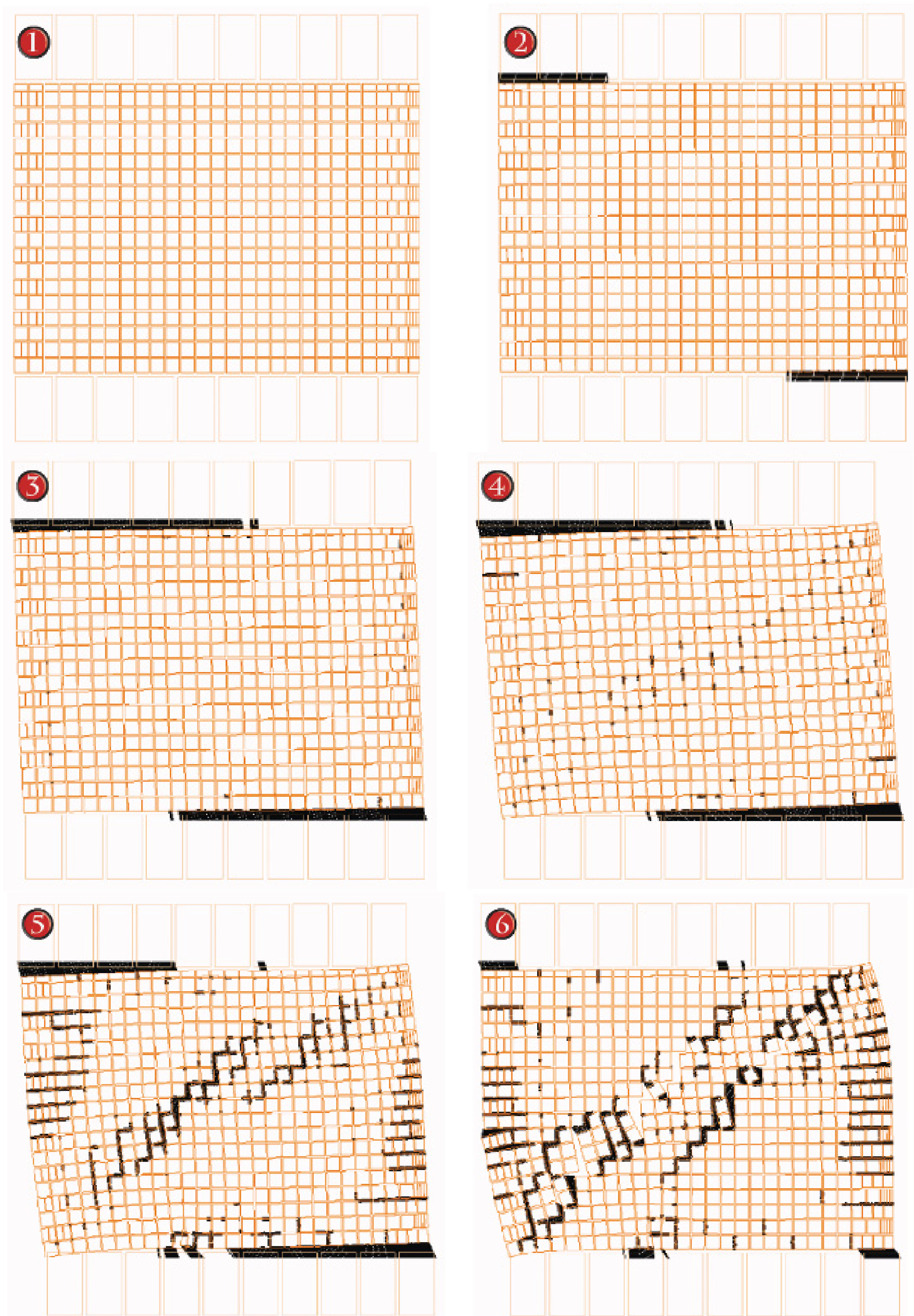


Fig. 6 Progressive collapse analysis over micro-model "Wall FP_CL".

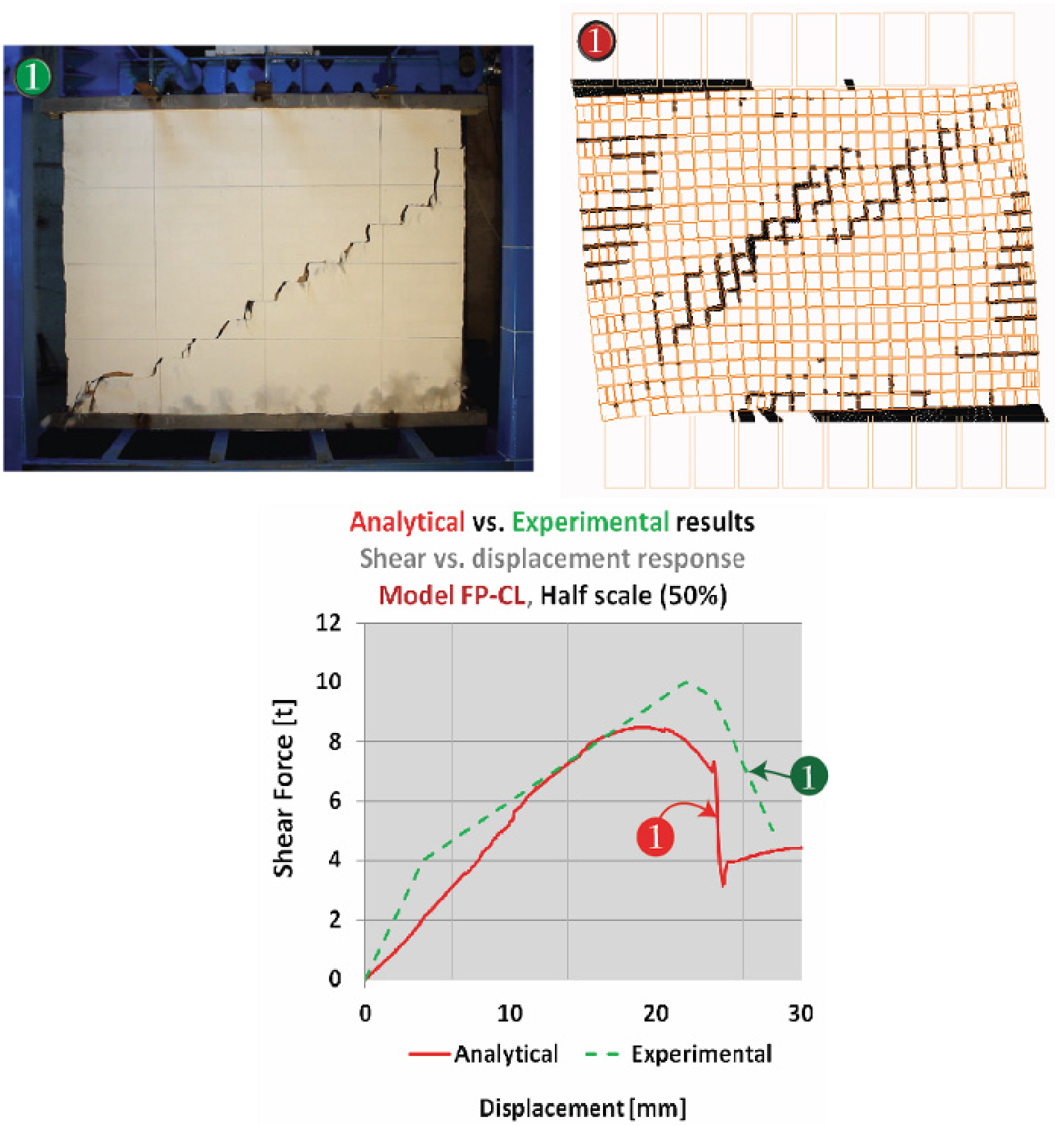


Fig. 7 Shear behavior of model "Wall FP_CL": experimental vs. analytical studies.

However, despite the fact that minor differences between the analytical and experimental investigations do exist, their close similarity in mechanical behavior, as demonstrated by Fig. 7, is remarkable.

5. Conclusions

Based on the obtained results from both study objectives treated in this chapter, the following conclusions are outlined.

Along with the recent advancements in computer technology, there have been developed high-end computer programs which are capable of modeling, analyzing and simulating the behavior of masonry walls in very close approximations to their realistic behavior.

This technological advancement avails to realistically predict the behavior of masonry walls through use of advanced analytical approach and avoids expensive experimental investigations over physical models of masonry wall panels.

Specifically, experimental investigations would only be required for determination of the mechanical characteristics of wall constituents, i.e., testing of brick units, mortar and masonry prisms, which would be used as input parameters in the micro-modelling process of analytical wall panels.

The use of advance analysis approach for realistic determination of the shear behavior of full-scaled masonry walls (with and without openings), serves as a basis for inclusion of infill masonry walls on the processes of modeling, analysis and design of building structures. This would result in achieving more approximate analytical building models in respect to their realistic behavior and ultimately achieve better optimization of structural design.

References

[1] Bakeer, T. 2009. *Collapse Analysis of Masonry Structures under Earthquake Actions: From Research to Practice.* Vol. 8. Publication Series of the Chair of Structural Design, Dresden: Dresden Technical University.

[2] Lourenço, P. B. 1996. *A User/Programmer Guide for the Micro-modeling of Masonry Structures.* Delft University of Technology, Faculty of Civil Engineering, TNO Building and Construction Research.

[3] Lourenço, P. B. 1994. *Analysis of Masonry Structures with Interface Elements—Theory and Application.* Technical report, Delft University of Technology, Faculty of Civil Engineering.

[4] Tagel-Din, H., and Meguro, K. 1999. *Applied Element Simulation for Collapse Analysis of Structures.* Bulletin of Earthquake Resistant Structure Research Center, Institute of Industrial Science, The University of Tokyo, No. 32, March, 1999.

[5] Tagel-Din, H., and Meguro, K. 2002. "Applied Element Method Used for Large Displacement Structural Analysis." *Journal of Natural Disaster Science* 24 (1): 25-34.