Modeling Strategies for Masonry Structures

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Abstract. Three strategies in the finite element analysis are used for modeling masonry structures which, depending on complexity, pertain to micro-, meso- or macro-models. Discrete particle models, as well as combined finite element/discrete models, are employed for analysis of heterogeneous masonry elements. Specially dedicated to the analysis of masonry panels and piers is an equivalent frame or macro-element approach. Different application fields exist for each model type. TNO Diana 10.1 is employed for modeling of wallets exposed to compression and unconfined unreinforced walls loaded in shear. Numerical results are verified against the data obtained from experimental research program performed at the Faculty of Civil Engineering in Sarajevo. TREMURI, PFC2D and FEM/DEM are used to describe other modeling techniques.

Keywords: Masonry · Finite element modeling · Discrete
particle · Macro-element

1 Introduction

Masonry is a composite material that consists of units and mortar. Experimental investigation of masonry is essential in understanding structural behavior, however, numerical modeling can complement experimental research and provide new insights. Masonry structures are usually analyzed by finite elements (FEM) and, based on the level of detail, computational strategies are traditionally divided into following categories: micro-, meso- or macro-modeling techniques. The second group of modeling strategies pertains to discrete element method (DEM) or a finite and discrete element combination (FEM/DEM). Specially dedicated to the analysis of masonry panels and piers is an equivalent frame (macro-element) approach. One modeling strategy cannot be preferred over the other since different application fields exist for each model type.

In this paper, special attention is paid to numerical models developed in finite element package TNO DIANA 10.1 [1]. Attention will be given to meso-model with combined cracking-shearing-crushing interface [2] and macro-model denoted as Engineering Masonry model [3].

The developed models were verified against the experimental data obtained from the tests performed in the laboratory of Institute for materials and structures, Faculty of Civil Engineering, University of Sarajevo. Mechanical properties of masonry components (brick, mortar, interface) were determined using appropriate specimens [4]. Wall

compressive strength and modulus of elasticity were determined on so-called wallets (51.4 × 12 × 63 cm). Unreinforced unconfined masonry walls were built in full scale (233 × 237 × 25 cm) and reduced scale cca. 1:2 (100 × 100 × 25 cm). Walls were loaded in cyclic shear under constant vertical pressure or pushed monotonically.

Discrete element modeling will be briefly described using PFC2D [5], combined finite element and discrete element modeling using FEM/DEM [6] and macro-element modeling TREMURI [7]. Different modeling strategies are shown in Fig. 1.
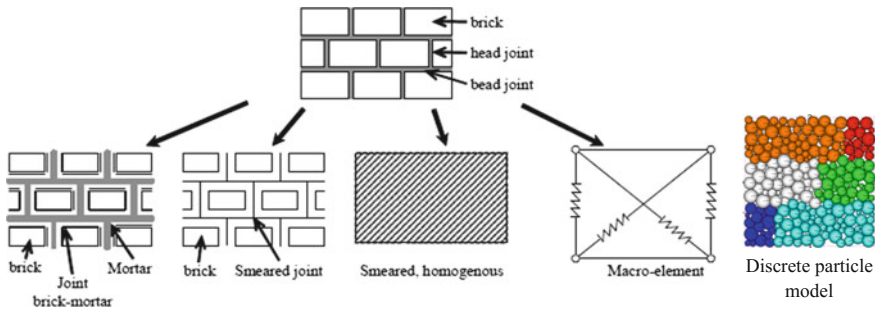

Fig. 1. Different modeling approaches [8, 9]

2   Micro-Modeling

A detailed analysis of masonry, denoted as micro-modeling, should represent all constitutive elements of masonry structure which includes units, mortar and unit/mortar interface. Mortar and brick units are discretized by continuum elements with corresponding failure criteria. Discontinuity in displacement field is introduced by interface elements between mortar and unit which should account for potential cracks. However, due to the complexity, micro models are rarely used.

This approach is suited for small structural elements with a particular interest in strongly heterogeneous states of stress and strain in order to provide a better understanding of the local behavior. The primary aim of micro-modeling is to closely represent masonry from the knowledge of the properties of each constituent and the interface. The necessary experimental data must be obtained from laboratory tests in the constituents and small masonry samples [2]. In Fig. 2 shows a 3D model of the tested wallet and typical displacement pattern of the mortar joint when the wallet is exposed to compression. Even though the loading is uniaxial, the stress state in masonry wallet (prism) is three dimensional due to different mechanical properties of brick and mortar.

Realistic values of elastic moduli for the more compliant mortar versus the stiffer brick units lead to lateral tension in the brick under far-field compression. Simply, the mortar layer is attempting to squeeze out laterally introducing lateral tension in the brick unit in exchange for lateral confinement of the mortar layer. On the other hand, the mortar layer is subjected not only to axial but also to lateral compression whereby the triaxial confinement significantly increases the mortar strength due to internal

friction. Consequently, it is not the weak mortar that fails in compression, but the brittle brick which fails in bilateral tension [10].
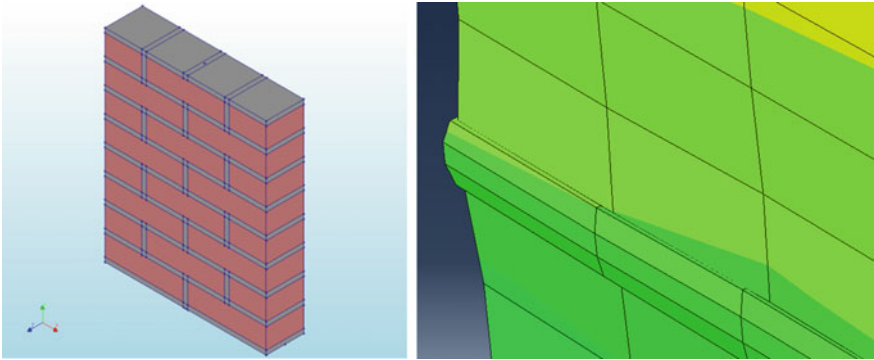

Fig. 2. Micro-model of masonry wallet (left) and typical displacement pattern of mortar joint due to compression (right)

3   Meso-Modeling

Wall geometry is slightly simplified in meso-models since mortar joint and mortar-brick contact are homogenized (lumped) into single interface (discontinuous) element while the units are expanded in order to keep the geometry unchanged. Masonry is thus considered as an assembly of bricks bonded by potential fracture/slip lines at the joints. Additionally, an interface can be introduced at the middle of each brick in order to allow cracking. Poisson effect of mortar which induces biaxial tension in brick units is omitted. Hence, meso-models cannot consider all possible failure modes [2].

3.1   Meso-Modeling in Diana 10.1

The interface material model, also known as the 'Composite Interface model', is appropriate for simulation of fracture, frictional slip as well as crushing along material interfaces, for instance at joints in masonry. Usually, the brick units are modeled as linear elastic, or viscoelastic continua, while the mortar joints are modeled with interface elements, which obey the nonlinear behavior described by this combined cracking-shearing-crushing model [1, 2]. Figure 3 shows the elements of a meso-model, with an additional interface element in the unit middle [1].

A plane stress interface model was formulated by Lourenco [2]. It is based on multi-surface plasticity, comprising a Coulomb friction model combined with a tension cut-off and an elliptical compression cap (Fig. 4). Softening acts in all three modes and is preceded by hardening in the case of the cap mode. The interface model is derived in terms of the generalized stress and strain vectors.
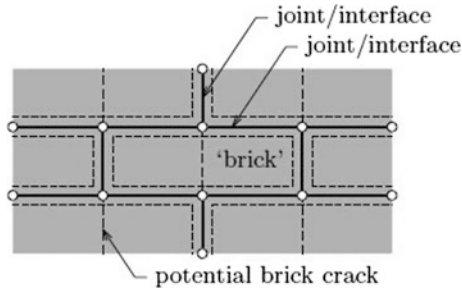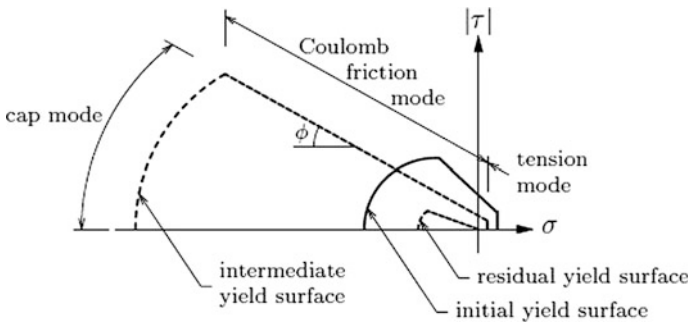
Fig. 3. Meso-model of masonry [1]

Fig. 4. Multi-surface plasticity for combined cracking-shearing-crushing interface model [1]
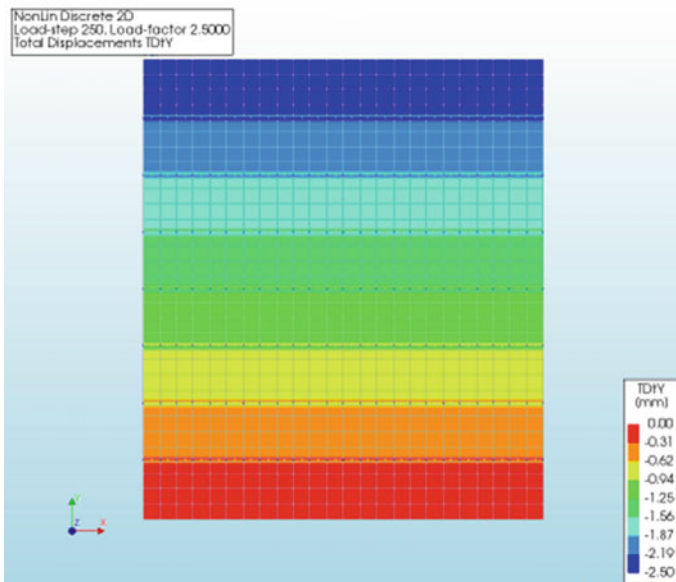

Fig. 5. Displacements in Y direction of the compressed wallet

Figure 5 shows a displacement field of a wallet modeled with the described interface and numerical and experimental results are compared in Fig. 6.
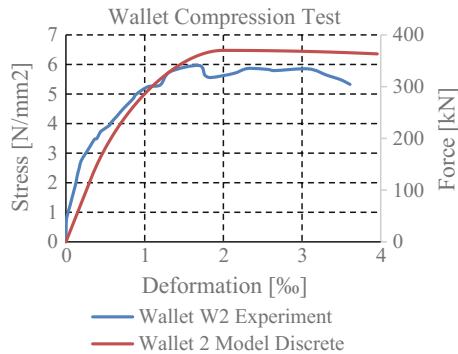

Fig. 6. Experimental versus numerical results

4 Macro-Modeling

Macro-models are applicable when the structure is composed of solid walls with sufficiently large dimensions so that the stresses and strains can be averaged over a macro-length. In the large and practice-oriented analysis the knowledge of the inter-action between units and mortar is, generally, negligible for the global structural behavior. These models approximate heterogeneous masonry wall by single material and discretization is independent of brick layout, i.e. units, mortar and unit-mortar interface are smeared out in the continuum. This is clearly a phenomenological approach, which means that the material properties must be determined from masonry tests of sufficiently large size under homogeneous stress state. A complete macro-model must reproduce an orthotropic material with different compressive and tensile strengths along the material axes as well as different inelastic behavior for each material axis. It is not surprising that only a few macro-models have been implemented due to the intrinsic complexity of introducing orthotropic behavior. The macro-modeling technique is practice-oriented due to the reduced time and memory requirements as well as user-friendly mesh generation. This type of modeling is most valuable when a compromise between accuracy and efficiency is needed [2].

However, it should be stressed that the failure mechanism of a masonry wall is very complex and different failure modes can occur separately or combined which is not easy to capture. Numerical problems may occur in the case of strong localization with a distinguished macro-crack. In macro-models, the cracking is smeared along a certain characteristic length which is not a case in reality. Figure 7 shows possible failure modes for a typical shear wall exposed to vertical compression and horizontal (racking) force [11].
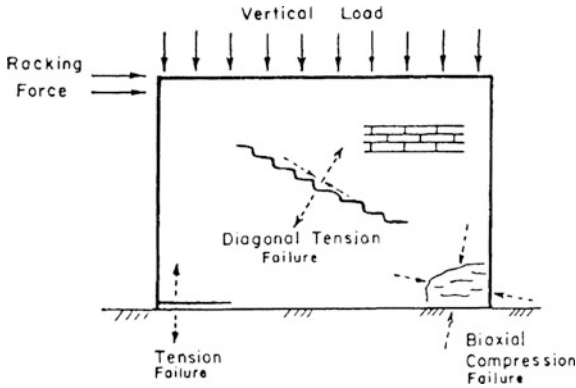
Fig. 7. Typical failure modes of a shear wall [11]

4.1   Macro-Modeling in Diana 10.1

Engineering Masonry model is an orthotropic total-strain continuum model with smeared cracking and it can be used with membrane or shell elements [3]. The model is capable of simulating compression, tensile and shear failure modes and it can crack in the X-horizontal bed joint, the Y-vertical head-joint as well as diagonally in the form of staircase. In comparison with the Total Strain Crack model [1, 3], the Engineering Masonry model defines unloading behavior in compression more realistically (Fig. 8 left). Additionally, Coulomb friction failure criterion is included in the model (Fig. 8
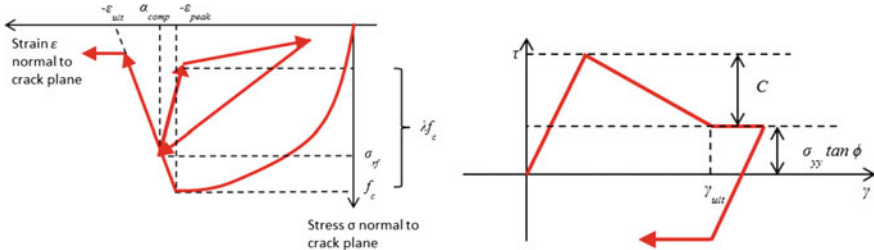

Fig. 8. Engineering masonry model: crushing behavior (left) and shear behavior (right) [3]
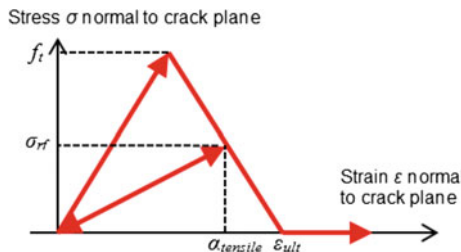

Fig. 9. Cracking behavior of Engineering masonry model [3]

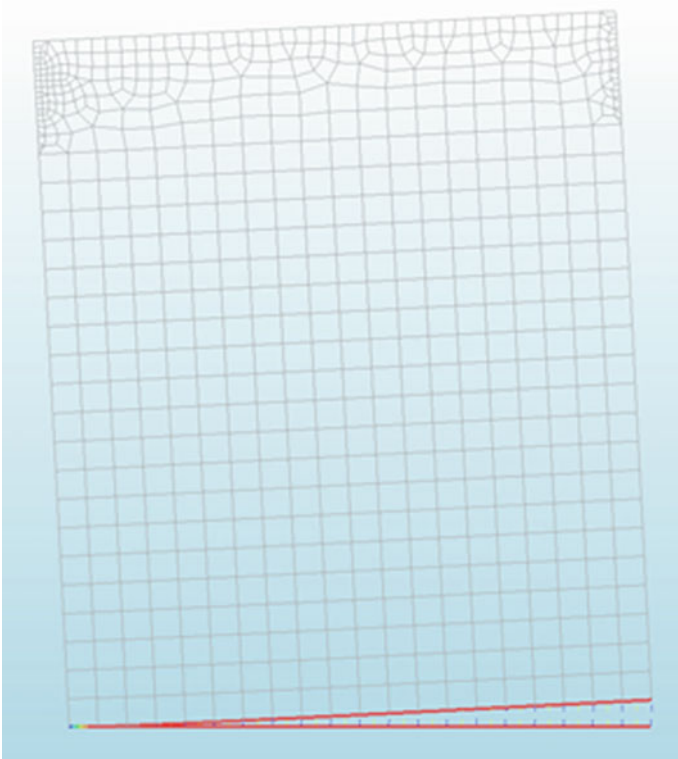right). The tensile behavior is defined linear loading and softening curves shown in Fig. 9.

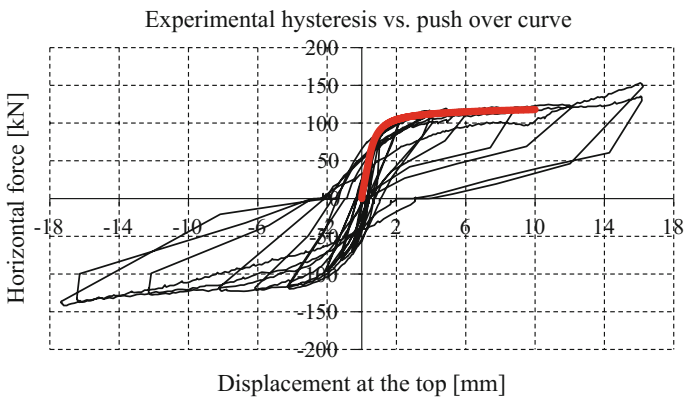Fig. 10. Rocking of the reduced scale wall

Fig. 11. Experimentally determined hysteresis versus numerically obtained pushover curve

Some characteristic results are shown in Figs. 10 and 11. The tested wall exhibited rocking due to low vertical precompression and the experimental and numerical results match well.

5 Discrete Models

When severe geometrical and material nonlinearity occurs in masonry structures, such as fracture or crushing, it can be difficult to consider the damage and discontinuity of the material with finite element methods. Therefore, discrete element method (DEM) is an alternative to solve the problem of fragmentation with a description of the medium as an assembly of discrete elements [12]. In 1971, Cundall proposed DEM using contact and shear slip constitutive relationships, which was a pioneering work mainly suitable for mechanical analysis of discontinuous bodies [13]. Thereafter, various algorithms were developed for DEM analysis, for example [5].

The DEM model needs a few material properties because the response complexity arises from the fact that collections of simple things behave—collectively—in complicated and completely different ways. Particles are basically linear elastic, but the response can be nonlinear or it shows dilation related to mean stress, the transition from brittle to ductile behavior, hysteresis, etc. Furthermore, the DEM model naturally exhibits localization (fractures in a brittle solid, shear bands in a granular material) which in contrast might be problematic for a model with mesh. The weak point of the discrete approach lies in the determination of aforementioned material properties (normal and shear stiffnesses, damping coefficients, interparticle bond). They can only be obtained from macroscopic experiments calibrating the input parameters after experimental results [9].

6 Combined Modeling Techniques

A method which combines finite element and discrete element method is called FEM/DEM [6]. The method uses advantages of both approaches. Namely, the fragmentation process (strong discontinuity between elements) is modeled employing DEM, and the deformation in the element inside is modeled using FEM.

The combined finite-discrete element method simulation comprises a large number of particles which are represented by a single discrete element that interacts with discrete elements close to it. Each discrete element has its own finite element mesh which is used to analyze the particle deformability. The material non-linearity including elastic hysteresis, fracture and fragmentation of discrete elements is considered through contact elements which are implemented within the finite element mesh. The main processes included in the FEM/DEM method are contact detection, contact interaction, finite strain elasticity as well as fracture and fragmentation [14, 15].

Figure 12 shows a gradual fragmentation of the tested wallet. It can be noticed that the cracking pattern is mesh dependent since the triangular elements are employed. In reality, the cracking of the wallet occurs along vertical lines perpendicular to the

loading direction due to biaxial tension in bricks. Figure 13 shows the crack pattern of the shear wall which matches quite well with the experimental results.
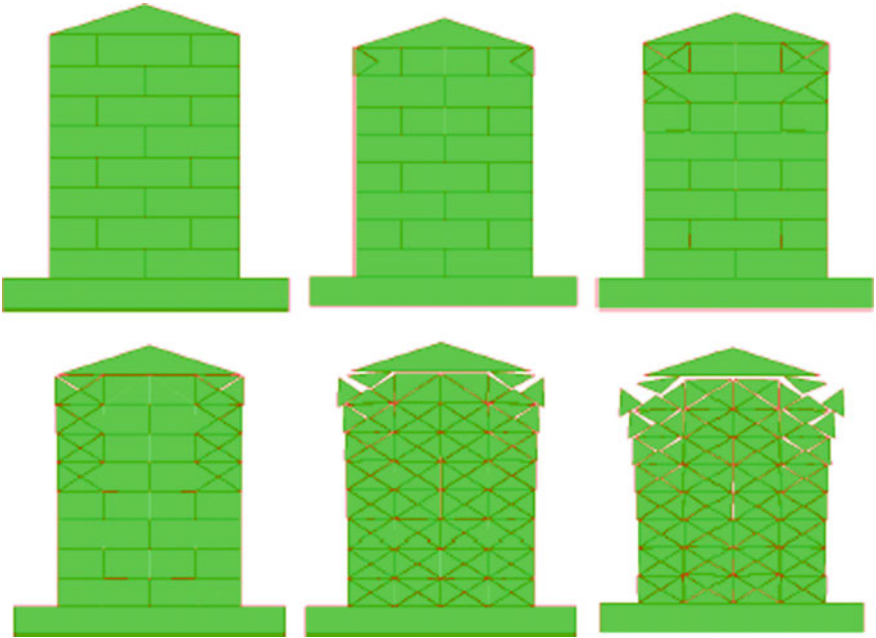

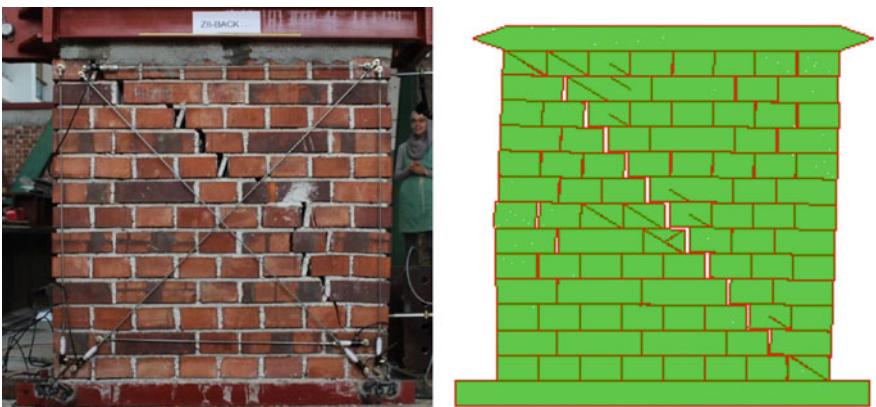**Fig. 12.** Gradual fragmentation of the tested wallet [16]

Fig. 13. Experimental and numerical crack pattern for the tested shear wall [16]

7 Macro-Element Modeling

Complete 3D models of unreinforced masonry structures can be obtained assembling 2-node macro-elements, representing the non-linear behavior of masonry panels and piers. This modeling strategy has been implemented in the TREMURI program with non-linear static and dynamic analysis procedures [7]. By means of internal variables, the macro-element considers both the shear-sliding damage failure mode and its evolution, controlling the strength deterioration and the stiffness degradation, and rocking mechanisms, with toe crushing effect (bending mode).

This approach is suitable for analysis of structures as a whole [17]. Figure 14 shows a typical shearing deformation at the ground floor and the obtained pushover curve [17].
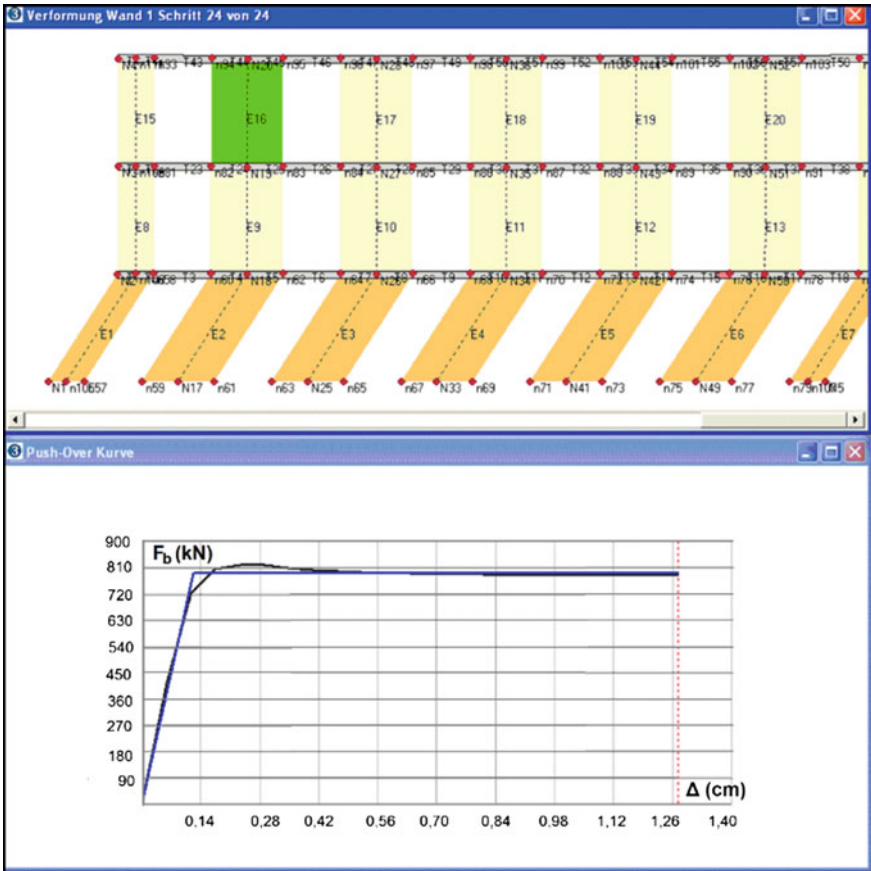

Fig. 14. Failure mechanism and pushover curve for masonry structure [17]

8 Conclusion and Ongoing Work

Numerical models were created using different classes of software. Wallets and walls were simulated with macro-models using engineering masonry material model (smeared cracking type of model) and meso-models using combined cracking-shearing-crushing material model. Some numerical results are compared against the experimental data regarding the wallets and shear walls.

Finite element modeling strategies using engineering masonry model for macro-models and combined cracking-shearing-crushing material model for meso-models can quite well simulate the behavior of masonry structures presented in this paper. Further model upgrades that will include RC jacket strengthening installed on wall sides are currently in development stage.

Macro-element or equivalent frame models can be used quite efficiently for the analysis of the complete structures, however, only basic failure modes can be considered in the model.

Discrete and combined models are expected to become more popular in future since all materials are discontinuous at a certain scale, but these are still confined to the research community.

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