A new modeling approach in the pushover analysis of masonry structures

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ABSTRACT

In this study, the pertinency of different numerical techniques for the analysis of masonry structures is investigated on a full-scale masonry specimen. Two approaches are taken into account. Namely, the nonlinear FEM modeling strategy, based on the concepts of idealized bilinear material behavior and line elements connected by special joints, is used in the version implemented in the commercial software 3Muri[2]. The second method is developed with programme SAP2000 which offers wide possibilities in finite element method models. Using specific modeling tools of SAP2000 is intended to simulate nonlinear behavior of masonry and global response of the structure.

An overview of such numerical methods, as well as a brief description of their specific theoretical aspects, is provided in order to allow easy comparison. A simple 2 story structure is modelled in both SAP2000 and 3Muri software. The key is the modeling with plane elements that have different characteristics in horizontal, vertical, and shear behaviour. Using this method is performed a pushover analysis and the results are compared to 3Muri software results. It is shown that the results prove a reliable modeling strategy by giving very similar output results. Having into consideration the fact that 3Muri software has been calibrated with experimental tests, the modeling approach with SAP2000 offers a satisfactory solution for masonry.

1. INTRODUCTION

Most of the building stock throughout the world, especially in developing countries, like Albania is constituted by masonry structures. The recent seismic activities in neighbouring countries like Italy, Greece and Turkey have showed the vulnerability of masonry buildings and the need to reliably evaluate their seismic capacity.

Numerical modeling of masonry sturctures with FEM is a very computationaly time demanding task because of several reasons. Complex typological characteristis of masonry structures, non-linearity in material behaviour and the lack of reliable experimental data to characterize the material can be counted as three of the several reasons.

Masonry consists of brick units (clay or concrete or stone) and mortar as bonding material. Because of its complex geometric nature, it is necessary to assume a convenient material behaviour (stress-strain) and conduct the analysis with finite element (FEM) methods, to obtain the global response of the structure. On the other hand, when a single element behaviour is studied, two types of approximations seem most effective namely, finite element method with discontinuous line elements and the plane element method.

With the development of construction sciences both design and site methods have become very sophisticated. New methods were developed that could predict the collapse mechanism of a structure. One of these is the nonlinear pushover (static) analysis. Considering that masonry is highly a nonlinear material, this method offers definitely a more realistic approach compared to elastic analysis. Many researchers have offered different solutions to nonlinear modeling of masonry. Between them are distinguished Gambarotta e Lagomarsino, who at 1996 presented a new methodology that was capable of performing nonlinear analysis and the results matched to experimental tests. Their method was used to develop 3Muri software.

In this study, two modeling techniques are briefly presented, showing the results of comparative analysis performed on a full scale masonry two story building. The calculations are performed with the commercial program SAP2000 [3,4,6] that offers several modeling possibilities for both linear and nonlinear analysis. A small sample building is calculated with this proposed method and the results are validated with 3Muri software [2,5]. It is shown that the pushover curves obtained from both software are very close to each other regarding initial stiffness, ultimate capacity and ultimate displacement.

2. MODELING APPROACHES FOR MASONRY

2.1 Modeling with SAP2000 software.

In SAP2000 the Shell element is a three- or four- node formulation that combines membrane and plate- bending behaviour. The shell element can be of two types:

a) Homogeneous is the most commonly used type of shell. It combines membrane and plate behaviour. The membrane behaviour uses an iso-parametric formulation that includes translational in plane stiffness components and a "drilling" rotational stiffness component in the direction normal to the plane of the element [3,4]. Plate-bending behaviour includes two-way, out-of-plane, plate rotational stiffness components and a translational stiffness component in the direction normal to the plane of the element.

b) The layered shell allows any number of layers to be defined in the thickness direction, each with an independent location, thickness, behaviour, and material. Material behaviour may be nonlinear. Out-of-plane displacements are quadratic and are consistent with the in-plane displacements. The layered shell usually represents full-shell behaviour, although this can be controlled on a layer-by-layer basis.

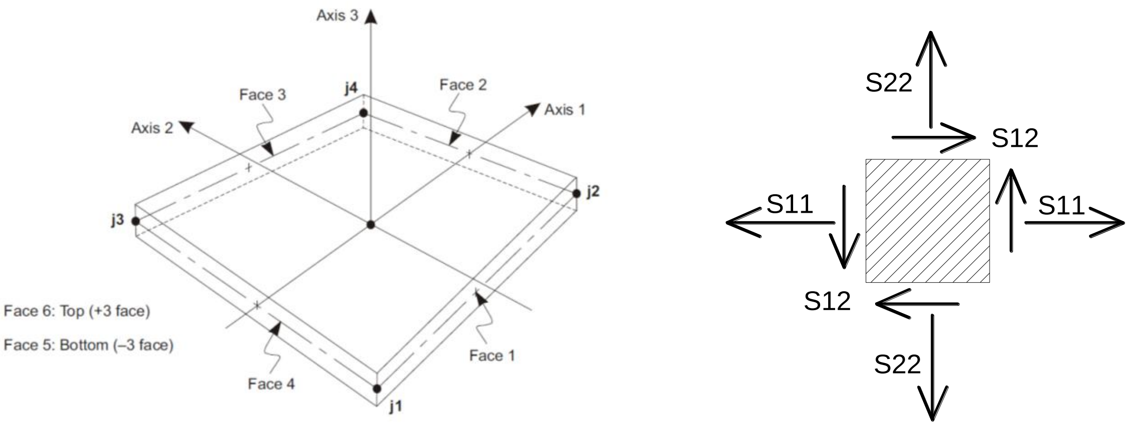

Figure1 – A four node shell element and in plane stresses. [6]

In this paper will be used the nonlinear layered shell element. The anisotropy of masonry will be modelled by 2 different stress strain curves. Each of them will represent respectively vertical and horizontal stress S22 and S11, and shear stress S12 (figure 1). The key to this approach is the prediction as good as possible of the stress strain curves for each direction. Here the S11 and S22 curves will have the same behavior. So far no tests are done in perpendicular direction due to the fact that bricks are mounted horizontally in a wall. Also it is very rare or not possible to apply a horizontal force to masonry and expect it to fail in compression, but in shear. Although no compression tests exist for this direction it is expected that the compression resistance to be higher because the bricks have a greater percentage and they are stronger than mortar.

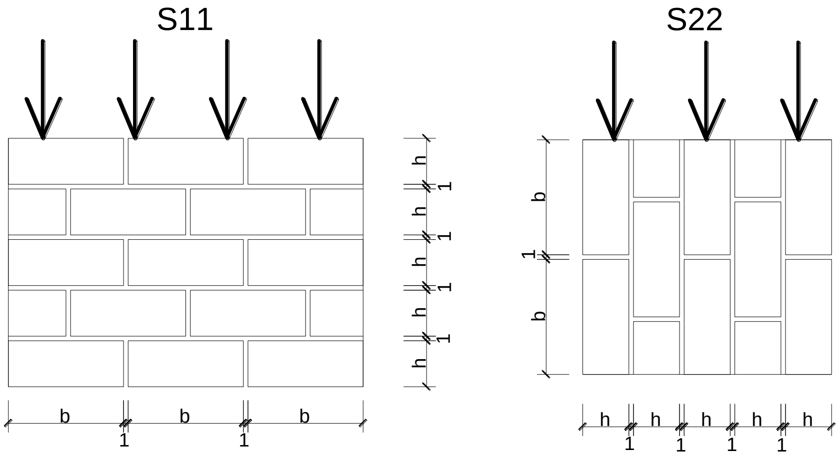

Figure 2 – Compressive stress test used for S11and S22.

S12 curve needs to represent the horizontal failure of a masonry member. In reality when a masonry member is subjected to lateral ground motion the horizontal resisting strength is represented by the cohesion and friction between brick and mortar. This is called Coulomb friction represented by:

$$\tau = c + \sigma \cdot tg\varphi \tag{1}$$

In this equation "σ" is the vertical stress (S22) and tgφ represents friction between elements. So this means a coupled behavior between friction "τ" and vertical stress. It is impossible to present coupled behavior between them for a nonlinear plane element in SAP2000. But it is observed that vertical stress helps to make "efficient" the shear stress. In other words a vertically stressed element does not fail due to flexure tension, but resists more. See figure 3.4, 3.5.

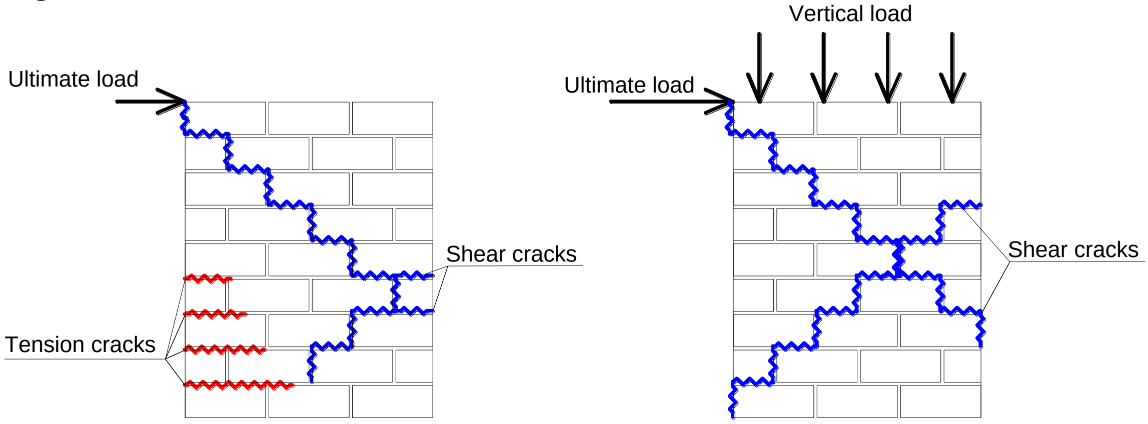

Figure 3. Failure mode of wall with and without vertical compressive stress.

This is a typical situation that leads to an indirect correlation between S22 and S12 stresses that are uncoupled analytically. The vertical load "helps" the shear resistance until there is no tension in the section. Beyond that value the shear resistance remains constant and equal to cohesion. So in SAP2000 shear resistance will be represented by a material nonlinear curve (cohesion). On existing buildings this value must be chosen carefully to account also for degradation.

2.2 Modeling with 3-Muri Software.

This software proposes the line finite element, which is represented by it's axis. It takes a wall of width b and thickness s, consisting of three parts: axial deformability is concentrated in the two extremity elements 1 and 3, of infinitesimal thickness D, infinitely rigid to shearing actions. The tangential deformability is situated in the central body, of height h, which, is non-deformable axially and flexionally. Hence, the complete cinematic model for the macro-element must examine the three degrees of liberty for the nodes i and j, and those of the interface 1 and 2 .

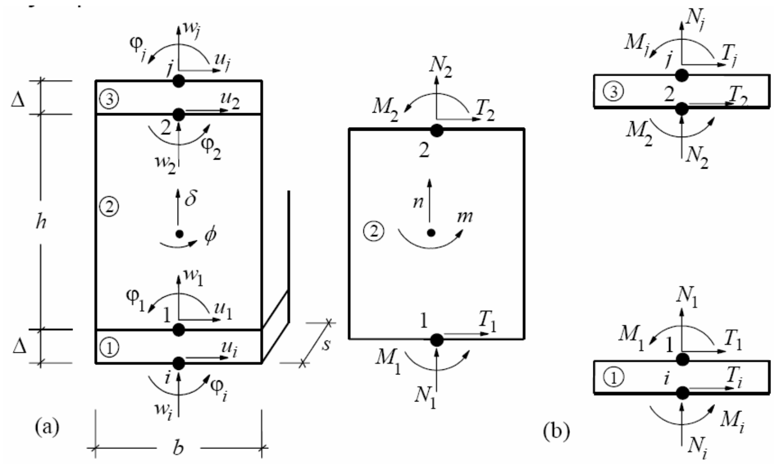

Figure 4. 3Muri finite element view (3Muri manual).

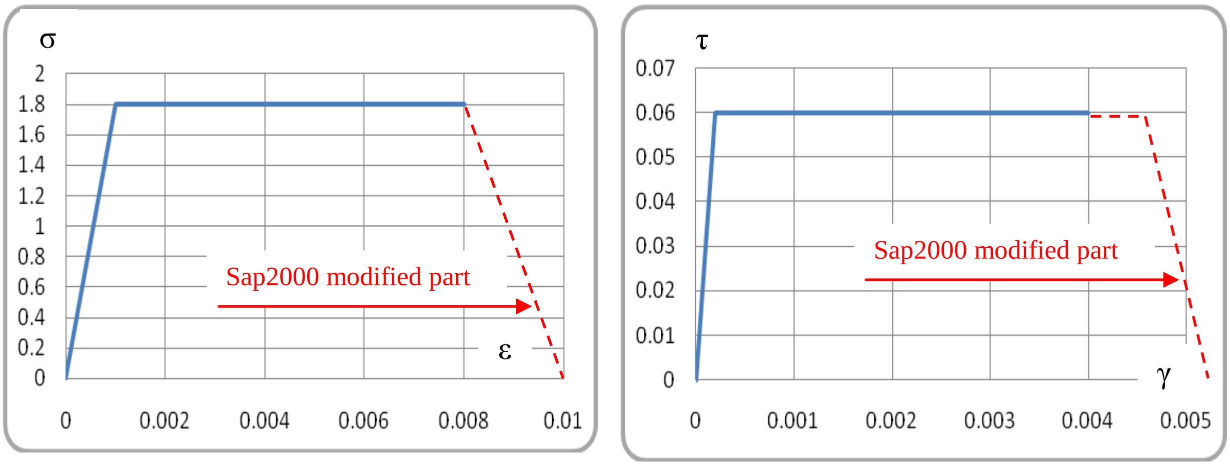

Figure 5. Compression and shear stress strain curve.

$$\varepsilon_{el} = \frac{\sigma_{el}}{E} = \frac{1.8MPa}{1800MPa} = 0.001 \quad , \quad \gamma_{el} = \frac{\tau_{el}}{G} = \frac{0.06MPa}{300MPa} = 0.0002 \qquad (2)$$

3Muri software material behavior for compression and shear for existing buildings. These curves will be used also in SAP2000 with slight modifications at ultimate strains. The lengthening of the shear curve is done to approach 3Muri ultimate displacements. The drop down linear part is necessary for converging calculations.

3. CASE STUDY STRUCTURE

So far two different modeling approaches are introduced. The object of this paper is to use the SAP2000 method with plane elements. For this reason a small masonry model is analyzed with both software, and the results are compared.

- Description of test structure

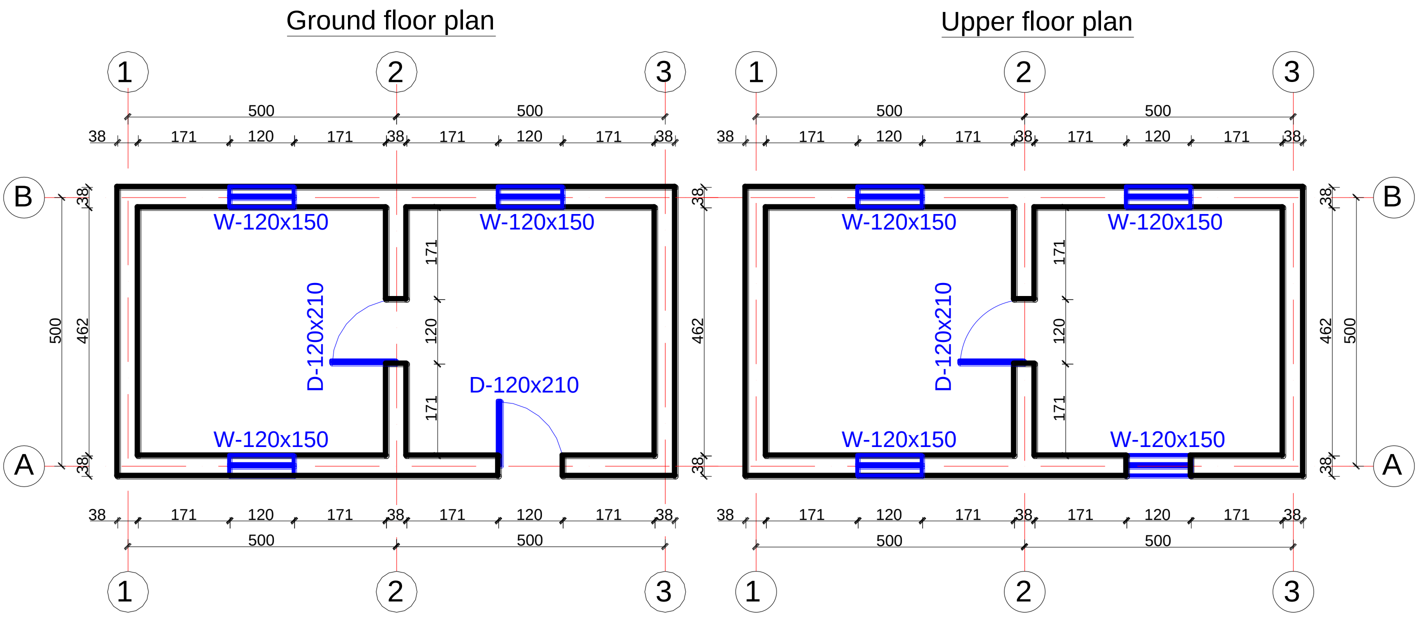

Figure 6. Plan views of test structure.

- This simple structure consists of two floors. The windows are placed 90 cm above the floor. All the walls have 38 cm thickness.
- The slabs are considered flat concrete with 12cm thickness. They one directional regarding load transfer, direction from axis A to B. A dead load of $5kN/m^2$ and a live load of $2\ kN/m^2$ are applied on them.

- 3Muri modeling

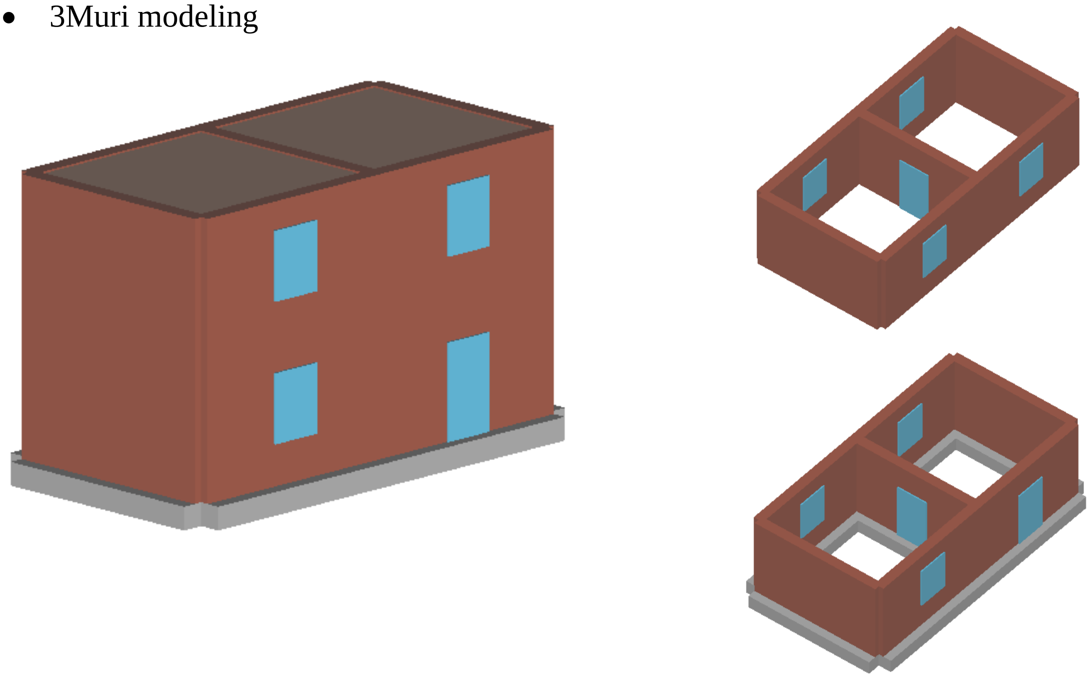

Figure 7. 3D view and story views of test structure in 3Muri.

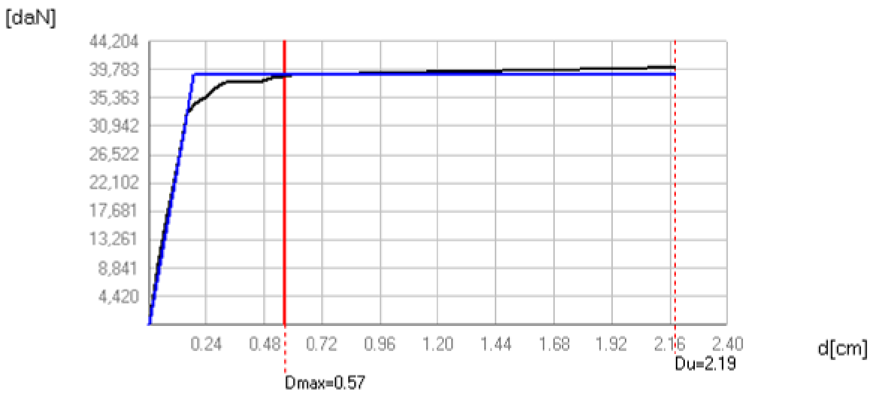

Figure 8. Analysis in 3Muri, pushover curve in X direction. (Mode load pattern)

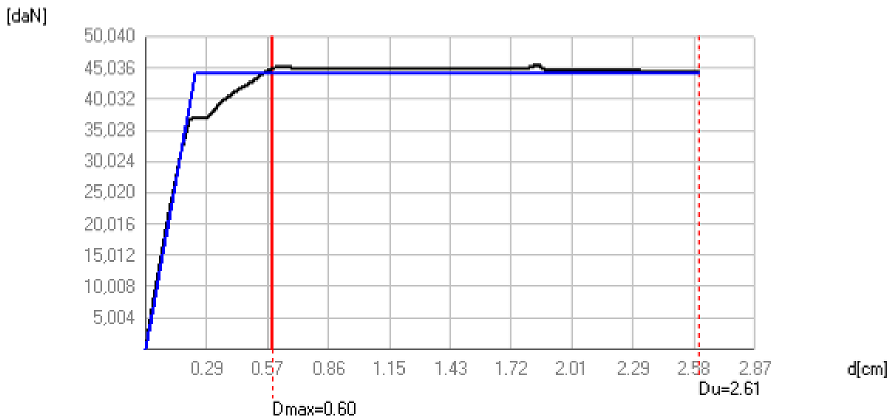

Figure9. Analysis in 3Muri, pushover curve in Y direction. (Mode load pattern)

- Sap 2000 modeling

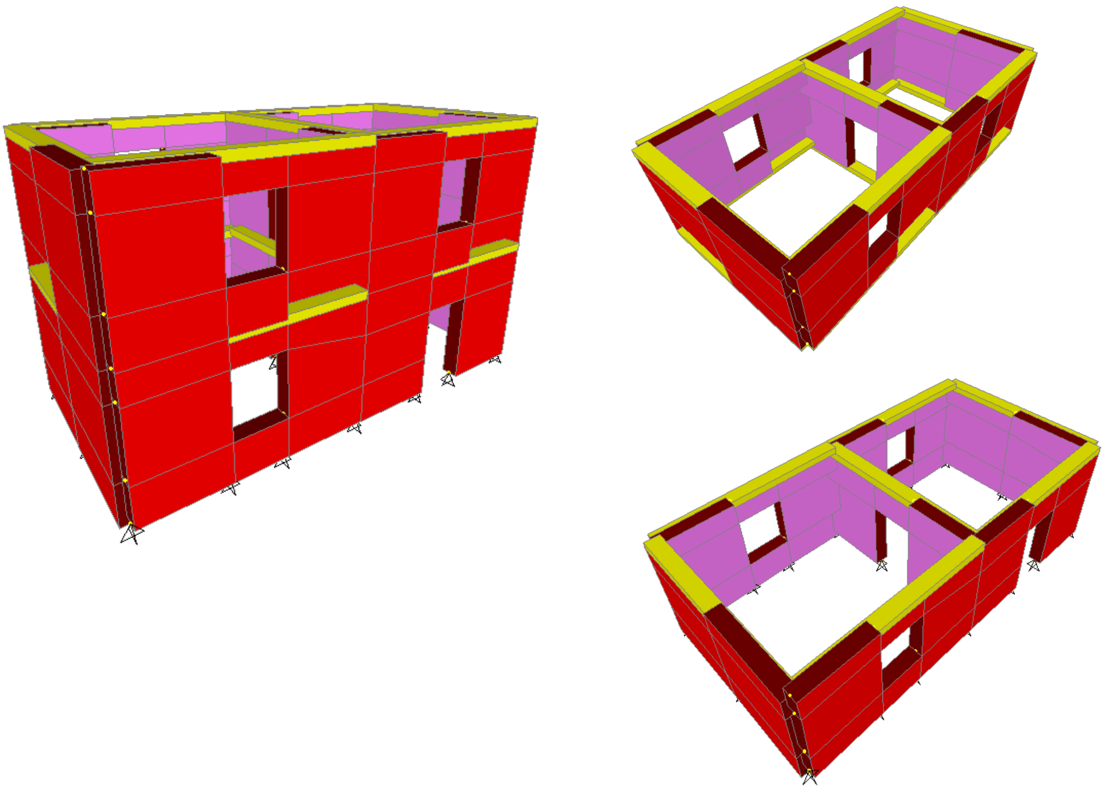

Figure 10. 3D view and story views of test structure in SAP2000.

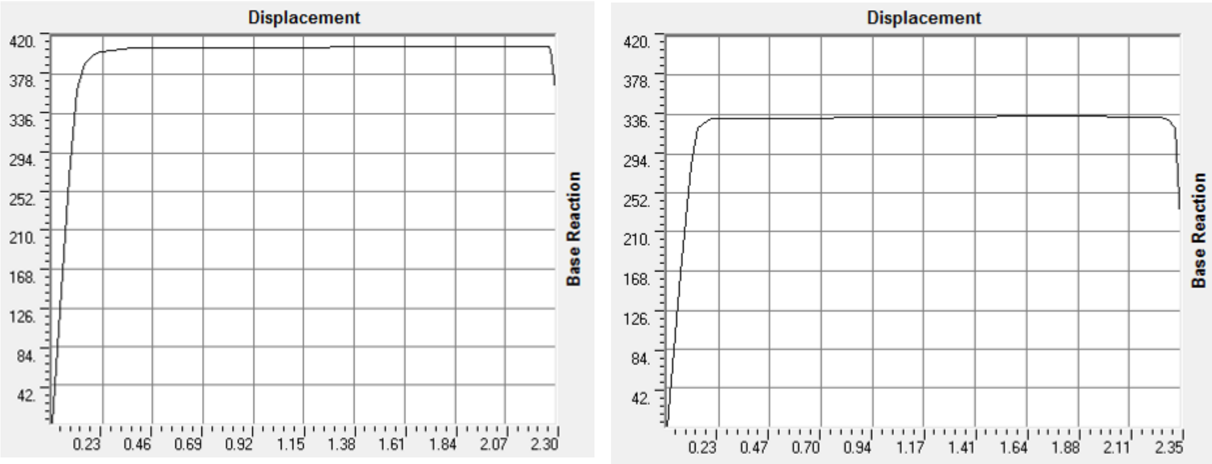

Figure 11. Pushover curves (Xdir-left, Ydir-right) in SAP2000.

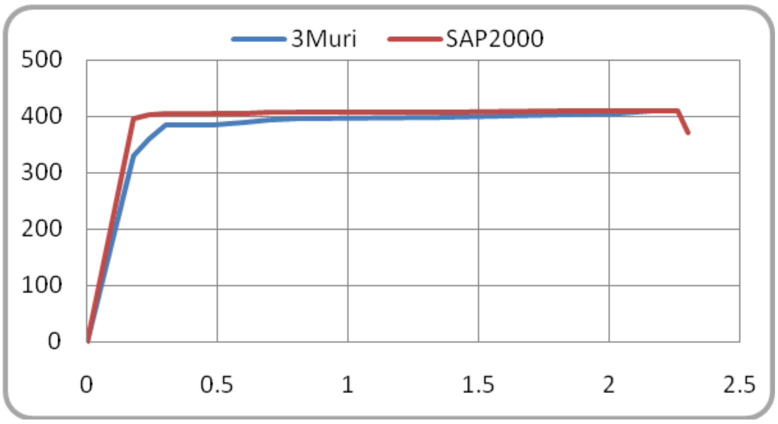

Figure 12. Pushover curves in X direction from 3Muri and SAP2000.

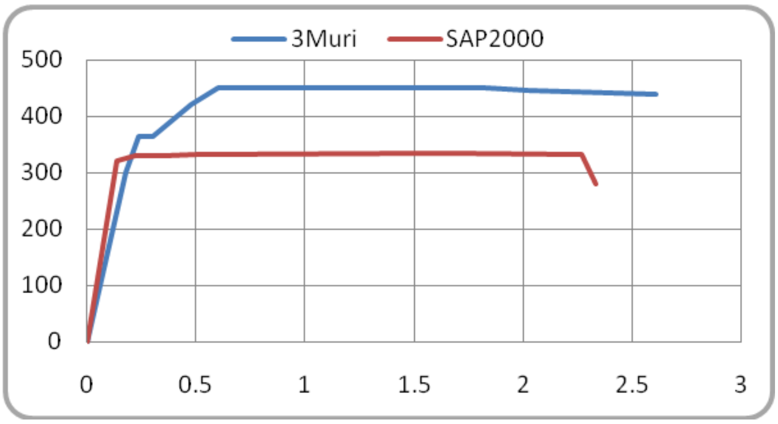

Figure 13. Pushover curves in Y direction from 3Muri and SAP2000.

Table 1. Comparison of results.

Software	SAP2000		3Muri software		Difference %	
Load pattern	Force	Ult. Disp.	Force	Ult. Disp.	Force	Ult. Disp.
Mode (X)	410 KN	2.26 cm	410 KN	2.16 cm	0 %	4%
Mode (Y)	335 KN	2.27 cm	450 KN	2.61 cm	25 %	13%

4. CONCLUSIONS.

The pushover curves show a good correlation between the two softwares. The pushover curve in X direction in SAP2000 is almost identical to corresponding 3Muri curve. Considering the fact that this software is validated with experimental tests, confirms that the approach presented in this paper is good enough for further application to more complex structures. It is obvious the 25% difference of the pushover curve in Y direction. In SAP2000 the modeling was the same for both directions and therefore the results should be reliable. If a logic interpretation is done it is possible to identify the trend of the results.

The hand calculated minimum shear strength is:

Σlength of wall without openings*width*shear max stress= Min shear capacity.

X-dir: (1.9+3.8+1.9)*2*0.38*60= 347 kN (3)

Y-dir: (5+5+2*1.9)*0.38*60= 315 kN (4)

So logically the Y direction capacity should be smaller than X direction capacity. In SAP2000 approach this is proved, but not in 3Muri. Further analysis is required for finding the reason for this result, but it is not the object of this paper.

This paper offers a unique solution to masonry capacity design with one of the most widely used software (SAP2000) and can be useful to engineers worldwide.

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[5] 3Muri analysis reference manual.

[6] SAP2000 analysis reference manual.