Proceedings of IOE Graduate Conference, 2019-Summer
Peer Reviewed
Year: 2019 Month: May Volume: 6
ISSN: 2350-8914 (Online), 2350-8906 (Print)

Non-linear Static Analysis of Unreinforced Masonry Building

Meera Chikanbanjar [a], Gokarna Bahadur Motra [b], Dev Kumar Maharjan [c]

[a] *Department of Civil Engineering, Thapathali Campus, IOE, Tribhuvan University, Nepal*
[b] *Department of Civil Engineering, Pulchok Campus, IOE, Tribhuvan University, Nepal*
Corresponding Email: [a] meerachikanbanjar5@gmail.com, [b] gmotra@ioe.edu.np, [c] dmaharjan.ess@gmail.com

Abstract
Unreinforced masonry is one of the oldest construction technology. It is composite material composed of masonry units (brick, stone and blocks) and mortar. Despite being the oldest construction material, its behavior is least understood. Its behavior can be determined by conducting experiments and structural analysis. Unreinforced masonry walls show highly non-linear behavior. This makes linear static analysis methods inadequate and inaccurate. Therefore, non-linear analysis of masonry buildings is preferable for both academics and practicing engineers. The choice of proper model to perform non-linear analysis of masonry structures is an important matter. Various modelling strategies are proposed in literature and codes for seismic assessment of masonry buildings, ranging from simplified models to equivalent frames, up to detailed finite element models. The detailed finite element model gives the comparatively precise results based on proper constitutive laws for the masonry components. But it is time consuming and requires the use of expensive and complex software. Other simplified models like equivalent frame approach allows the global analysis of building with a reasonable computational effort, suitable also for practice engineering aims. Thus, this study is done to gain better understanding regarding the nonlinear behavior of masonry buildings using different modeling techniques.
The main objective of this study is to apply static non-linear analysis to masonry building using different modeling approaches and then compare and discuss the results obtained. Two different modeling strategies have been adopted for this purpose. They are equivalent frame model and macro element model. Equivalent frame model is implemented in SAP 2000 code, and macro element approach is implemented by 3Muri. Three masonry building of same plan configuration but different number of storey are taken for this study.Each of these buildings are analyzed considering flexible floor and rigid floor separately.

Keywords
Unreinforced Masonry Buildings, Equivalent Frame Model, Macro Element Model, Pushover Analysis

1. Introduction

For many centuries and in different ways, unreinforced masonry is one of the most commonly used and important construction technology around the world. Unreinforced masonry structures suffered severe damages in various earthquakes. Many such structures lived through even large earthquakes. They still make up a substantial proportion of existing building stock in Nepal in the form of historic cultural heritages and residential buildings. They continue to pose large seismic risk, not only in Nepal but also in many parts of the world.In order to preserve the cultural heritages and reduce casualties and property loss due to damage in masonry buildings in earthquakes, it is necessary to understand the true behavior and response of these buildings in lateral loads which is possible through research and study in this field. Unreinforced masonry structures show highly inelastic behavior. The nonlinear behavior of unreinforced masonry can be determined by conducting either various experiments or structural analysis. The linear static analysis methods are inadequate and inaccurate as it cannot incorporate the non-linear characteristics of unreinforced masonry. Therefore non-linear analysis of masonry buildings is preferable for both academics and practicing engineers.

Several models, with different theoretical approaches, have been developed to date. Finite element models give accurate results but are time consuming and require the use of expensive and complex software. Many simple approaches are proposed in literature and codes. Such approach includes models that schematize the masonry wall as an equivalent frame.

The first frame model known as the POR method was proposed by Tomazevic [1] in Slovenia. Such a method assumes that the structural collapse occurs because of a storey mechanism. The failure is assumed to take place only in the piers, and no allowance for the possible damage of the spandrel beams is made. A more detailed approach, Simplified Analysis Method (SAM), developed by Magenes and Calvi (1997) and then modified by Magenes and Della Fontana (1998)[2], is an improvement of the POR method which considers spandrel as deformable element. In the SAM, the wall is schematized as an equivalent frame composed by: column element representing the piers; beam elements representing the spandrels; rigid offsets describing the joint panel [3]. The mechanical non-linearities are concentrated in particular cross-sections (plastic hinges) placed both in the middle and in the ends of the frames. Other simpler model, macro-element model, proposed by [4] describes the wall by a set of macroscopic no tensile elements, which represent piers, spandrels and joints. The computational effort is reduced in this approach due to reduction of degrees of freedom.

Generally, elastic analysis for the structural behavior of masonry is adopted using rather elastic parameters and strengths of masonry. Such analysis can give wrong and misleading results. Hence nonlinear behavior of the masonry structures should be accurately taken into account in analyzing the ultimate behavior of masonry buildings. This study is carried out to find out the non-linear behavior of unreinforced masonry building. The primary objective of this study is to apply non-linear static analysis to unreinforced masonry building using various modelling approaches and discussing and comparing the results obtained. In this work two modelling approaches are considered: the simplified analysis method based on the equivalent frame approach implemented in SAP 2000 code and the macro element approach implemented in 3Muri code.

2. Modeling of masonry building

Three unreinforced masonry buildings of one, two and three storey of brick in cement mortar masonry building is taken for this study. Two types of floors are considered. One floor consists of wooden floor with mud covering which is considered flexible while other is concrete slab which is considered rigid. Each building is analysed for flexible and rigid floor separately. The architectural plan of all the buildings is same as shown in Fig. 1.

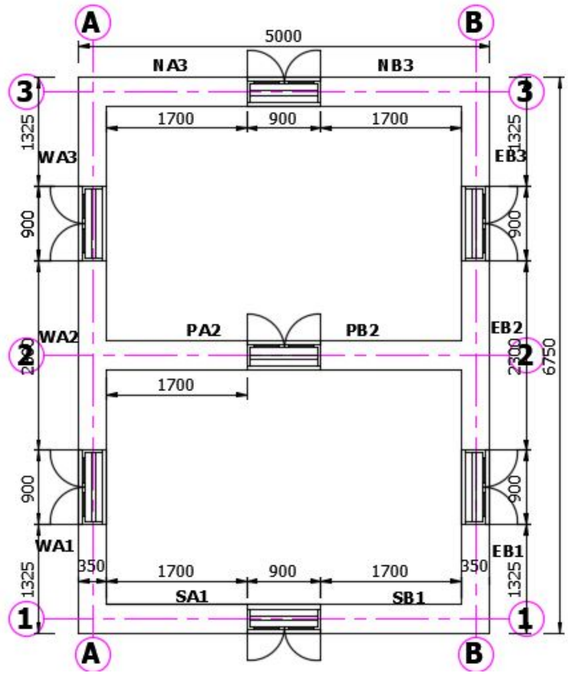

Figure 1: Plan of considered building

The mechanical properties of the masonry are shown in table 1. The loads considered for this study are self-weight of walls, self-weight of floor and roof as dead load and live load on floor. The floor consists of wooden beams, joists and planks with floor covering of mud in flexible floor type and concrete slab for rigid floor type.

Table 1: Material properties used in study

Description	value	unit
Unit weight of masonry (ω)	19	KN/m^3
Modulus of elasticity (E)	2237	MPa
Shear Modulus (G)	895	MPa
Compressive strength (fm)	4	MPa
Poisson's ratio (ν)	0.2	
Friction coefficient (μ)	0.5	

2.1 Equivalent Frame Approach

SAP 2000 has been used for modeling the building by applying equivalent frame approach. In this method, the element is modeled as an equivalent frame having same dimensions of an actual element. The structure is modeled as an assemblage of horizontal and vertical members called spandrels and piers respectively. To define a connection between them rigid offsets are defined at the ends of piers and spandrels as per the criteria given by Dolce,M. [5] as shown in Fig. 2. The floors and roof are not modeled in SAP 2000 v 20 for this study instead only their loads are considered and applied as uniformly distributed load for flexible floor system while concrete slab is modeled for rigid floor system.

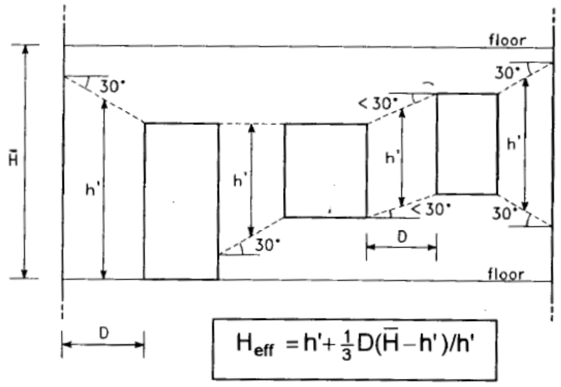

Figure 2: Effective Height determination offered by Dolce M. (1989) ([2])

The non-linear behavior of the elements is described by providing non-linear hinges whose force displacement properties are usually defined from experimental results. Two 'rocking hinges' at the end of the deformable parts and one 'shear hinge' at mid-height of the pier are introduced for the nonlinear analysis while only one "shear hinge was introduced at the mid span of spandrel [6]. The bending damage of spndrel is not taken into account assuming that both ends of lintels are restrained. The strength in terms of ultimate moment, diagonal shear and sliding are given in equations (1), (2) and (3) respectively.

$$Mu = \frac{\sigma o D^2 t}{2}\left(1 - \frac{\sigma o}{kfd}\right) \qquad (1)$$

$$Vuf = \frac{1.5 fvodDt}{\xi}\sqrt{1 + \frac{\sigma o}{1.5 fvod}} \qquad (2)$$

$$Vus = \frac{1.5 fvod + \mu \frac{\sigma o}{\gamma m}}{1 + \frac{3Ho}{D\sigma o} fvod} Dt \qquad (3)$$

Where, σ o is the mean vertical stress, D the pier width, t the pier thickness, k the coefficient taking into account the vertical stress distribution at the compressed toe (a common assumption is an equivalent rectangular stress block with k =0.85), fd the design compression strength, fvdo the design shear strength with no axial force; μ (friction coefficient)=0.4, ξ is the coefficient related to the pier geometrical ratio, Ho is the effective pier height (distance of the cross-section in which the strength criterion is applied from the point of zero bending moment), and γ m is the safety factor (assumed to be equal to 2).

The shear strength of spandrel is given by equation (4).

$$Vu = htfvod \qquad (4)$$

Where, h is the spandrel depth, t the spandrel thickness, and fvod the design shear strength with no axial force.

Fig. 3 shows equivalent frame idealization of front wall of two storey building analyzed in this study.

After calculating the strengths of the masonry pier and spandrel, three dimensional model of the buildings is constructed in SAP2000 v 20. Plastic hinges are assigned to each pier and spandrel for non linear analysis. Three dimensional model of two storey building in SAP2000 is shown in Fig. 4.

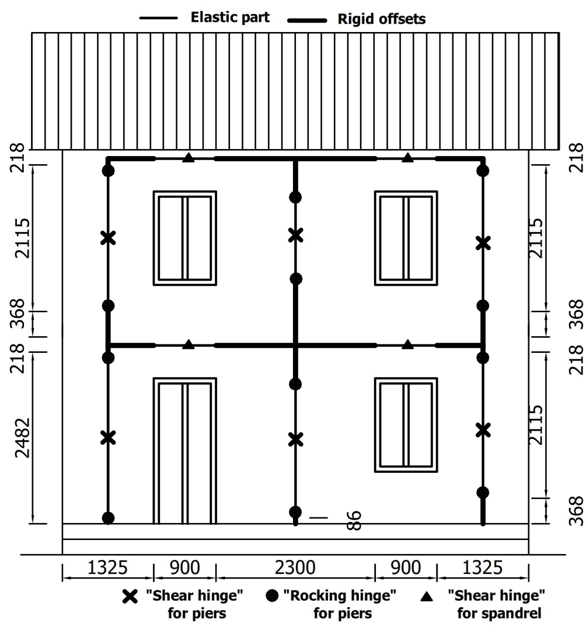

Figure 3: Plastic hinges location in the equivalent frame model of a wall of 2-storey building

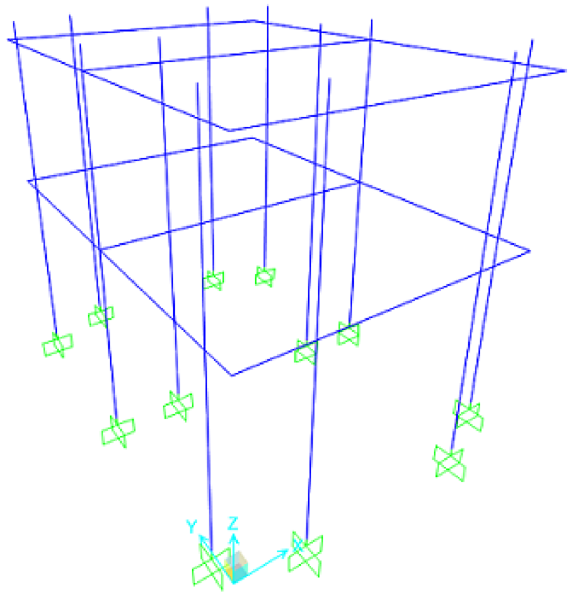

Figure 4: 3D model of equivalent frame of 2-storey builfig in SAP 2000

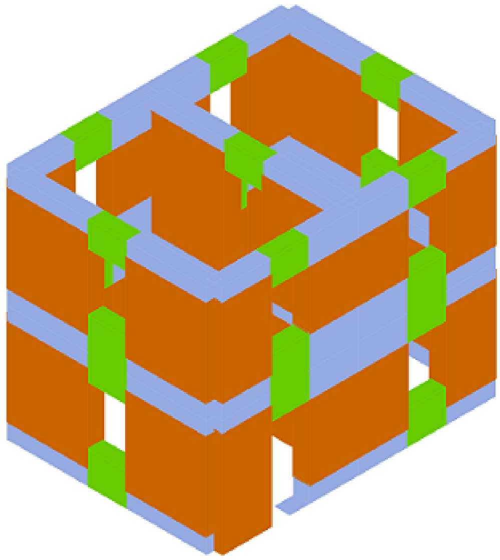

Figure 5: 3D Macro Element Model in 3Muri

2.2 Macro Element Approach

Macro- element model is implemented in 3Muri. and also used in this study for modelling purpose. 3Muri is specifically developed for dealing with masonry structures. The non-linear macro-element model, representative of a whole masonry panel, proposed by [4] permits, with a limited number of degrees of freedom, to represent the two main in-plane masonry failure modes, bending-rocking and shear-sliding (with friction) mechanisms, on the basis of mechanical assumptions [7]. Floor is modeled in 3Muri as one-way timber floor with single wood plank and the load from floor covering (mud) is input as load per square meter of area of floor for flexible floor while rigid floor system is modeled as rigid. The roof is not modelled and only its load is considered in the model. The 3D model of 2-storey building along with macro elements are shown in Fig. 5

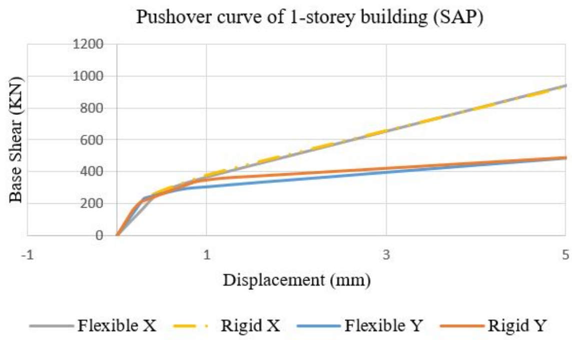

Figure 6: Pushover curve for 1-storey building (SAP)

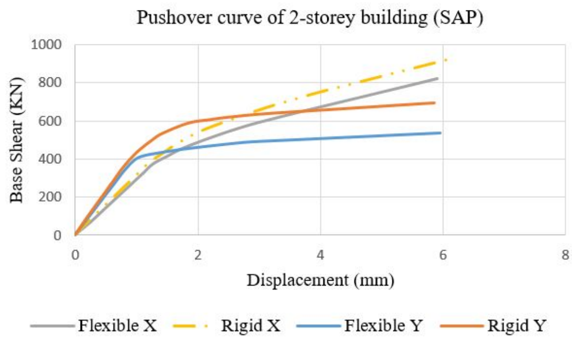

Figure 7: Pushover curve for 2-storey building (SAP)

3. Results and Discussion

Non-linear static analysis of one storey, two storey and three storey brick with cement mortar masonry buildings is carried out using two modeling approaches for two different floor types separately. In Fig. 6, the pushover curves of 1-stoery building determined from SAP2000 is shown. Similarly pushover curves for 2- and 3-storey buildings determined from SAP2000 are shown respectively in Fig. 7 and Fig. 8.

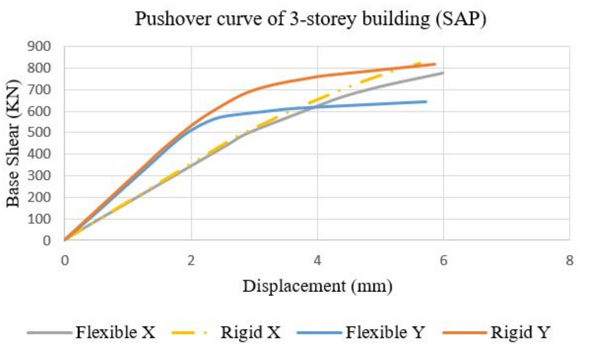

Figure 8: Pushover curve for 3-storey building (SAP)

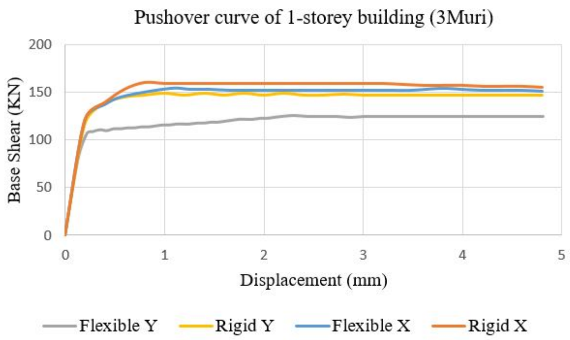

Figure 9: Pushover curve for 1-storey building (3Muri)

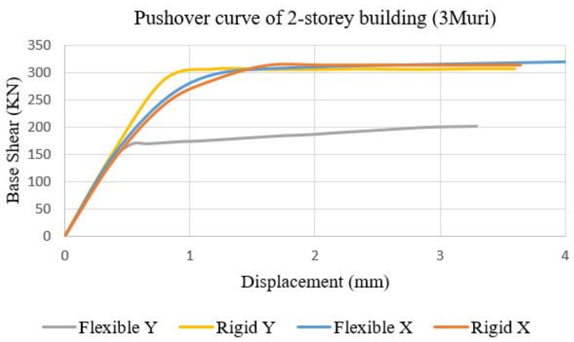

Figure 10: Pushover curve for 2-storey building (3Muri)

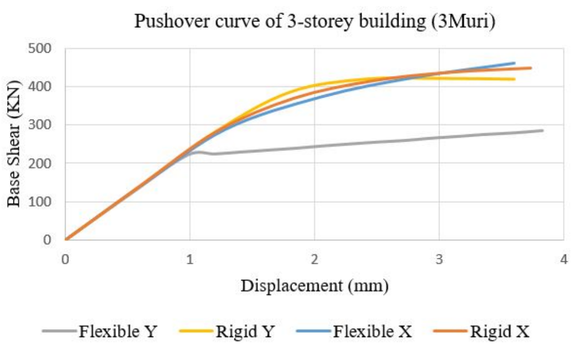

Figure 11: Pushover curve for 3-storey building (3Muri)

The pushover curves of the buildings determined from 3Muri for 1-storey, 2-storey and 3-storey buildings are given in Fig. 9, Fig. 10 and Fig. 11 respectively.

The nature of curves from both modeling approaches are similar. From the plots of base shear-displacement of one storey building, it is observed that there is not much variation in the behavior of one storey masonry building due to different floor type. But this variation in behavior for different floor type is significant for multi-storey masonry buildings. This shows that the influence of floor type on the behavior of multi-storey buildings is significant while the floor type does not effect much in the behavior of single storey building. It is seen that the capacity of unreinforced masonry building is enhanced in rigid floor in comparison with flexible floor.

Although the nature of the curves determined from both modelling approaches are similar, the variation in the quantity and post-yield behavior cannot be neglected. The variation is due to the difference in basic concepts of both the approaches. Equivalent frame idealization is being done in SAP 2000 for this study while 3Muri uses macro element model in which the elements are macro element panels. This makes stiffness idealization from both the approaches different which in turn affect the output from both approaches resulting in variation in output.

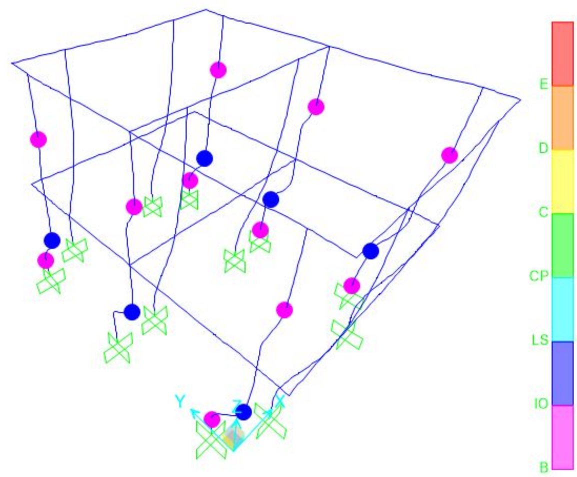

Figure 12: Failure Mechanism of 2-storey building at ultimate displacement (SAP)

Fig. 12 shows the failure mechanism of 2 storey building with flexible floor determined from SAP2000 and Fig.13 shows the failure mechanism for the same building determined from 3Muri. There are shear damage and shear failure in the piers as seen in 3Muri.

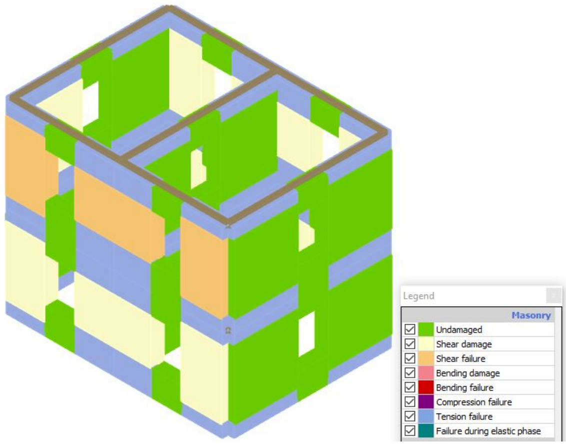

Figure 13: Failure Mechanism of 2-storey building at ultimate displacement (3Muri)

Similar behavior can be observed in the hinge formation pattern in SAP2000 where the shear hinges are formed in the corresponding piers showing the similar failure pattern as seen in 3Muri. So the governing damage pattern is also shear in Sap2000. This shows that equivalent frame method in SAP2000 can well represent the non-linear behavior of masonry buildings.

4. Conclusions

In this study, typical type of brick masonry buildings are modeled using equivalent frame approaches and then non-linear static analysis was done to find out the non-linear response of the masonry building for different floor type. It is seen from this study that the flexibility of floor has not much effect on the behavior of single storey building. But the influence of floor flexibility can be seen for multi-storey building. Unreinforced masonry buildings with rigid floor has high capacity in comparison to flexible floor because rigid floor creates box effect such that all the walls behave as one while in flexible floor walls tend to act individually.

Non-linear behavior of URM building is being ignored due to lack of understanding and limitation in availability of analysis tool. Equivalent frame method can be better solution to understand the non-linear behavior of unreinforced masonry buildings.It is a simple modeling method and analysis using equivalent frame model can be done in SAP 2000, which is more common among practitioners in Nepal. This method includes simple calculations, easy to understand and easy to implement. Non-linear analysis of masonry buildings using equivalent frame method is easy and fast. This makes it efficient and suitable for practitioners. This method can capture non-linear behavior of masonry buildings. However, it should be used with deep concept of the modeling approach.

The choice of appropriate modeling technique is an important matter for analysis of masonry buildings because different models have different assumptions and strategies which may give different output. But the results should be interpreted considering the assumptions and strategies being used in the modeling approach. So, appropriate modeling strategy should be chosen based on the deep knowledge of structure and modeling strategy and analysis requirement.

References

[1] M. Tomazevic. The computer program por. *Report ZRMK*, 1978.

[2] A. Della Fontana and G. Magenes. Simplified non-linear seismic analysis of masonry buildings. pages 190–195. Proceedings of the Fifth International Masonry Conference, 1998.

[3] Stefania Arangio, Francesca Bucchi, and Franco Bontempi. Pushover seismic analysis of masonry buildings with different commercial codes. *Built Heritage 2013 Monitoring Conservative Management*, pages 773–780, 2013.

[4] Luigi Gambarotta and Sergio Lagomarsino. On dynamic response of masonry panels. pages 451–462. Masonry Mechanics between Theory and Practice, (in Italian), 1996.

[5] M. Dolce. Schematizzazione e modellazione degli edifici in muratura soggetti ad azioni sismiche (simplification and modelling of masonry buildings under seismic loads). *L'Industria delle Costruzioni*, 242:44–57, 1991. (In Italian).

[6] Laurent Pasticier, Claudio Amadio, and Massimo Fragiacomo. Non-linear seismic analysis and vulnerability evaluation of a masonry building by means of the sap2000 v.10 code. *Earthquake Engineering and Structural Dynamics*, pages 467–485, 2007.

[7] Alessandro Galasco, Sergio Lagomarsino, Andrea Penna, and Sonia Resemini. Non-linear seismic analysis of masonry structures. page 843. 13th World Conference on Earthquake Engineering, 2004.