ANALYSIS OF MASONRY STRUCTURES: A REVIEW

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***Abstract*: The increasing interest in historic architecture heritage and preserving of the historical structures has led to continuous development in past 20-25 years of growing methods to analysis masonry structure. First Heyman applied plasticity method, which provided useful and easily comprehensible approach for the behaviour of masonry vault. The behaviour of masonry materials is not always agreeable to accurate treatment by the rigid-plastic simplification and the complexity of many vaulted masonry structures makes the application of rigid-plastic method difficult. These structures may subject to three dimensional effects that are not entirely addressed by the application of plastic or elastic analysis in dimensions. Progress has been made by making various formulations of three dimensional finite element analysis; including discrete element method and plasticity method which have also proven useful. Finite element analysis gives accurate prediction of the masonry structure response but on the other hand it requires very high computational skill and is time consuming. A better way of analysis could be the adoption of simplified model, such as equivalent frame approach. The equivalent frame model is not originally for the analysis of masonry structure, but the actual potentialities have not yet been completely studied.**

In view of wide-spread research carried out in this field, this paper attempts to present a comprehensive review of the work carried out in this field.

***IndexTerms*: Rigid Plastic Analysis, Finite Element Analysis, Equivalent Frame.**

I. INTRODUCTION

Masonry is the oldest building material that still finds wide use in today's building industries. Important new developments in masonry materials and applications occurred in the last decades but the techniques to assemble bricks and blocks are essentially the same as the ones developed some thousand years ago. Naturally, innumerable variations of masonry materials, techniques and applications occurred during the course of time. The influence factor was mainly the local cultural wealth, the knowledge of materials and tools, the availability of material and architectural reasons. The most important characteristics of masonry construction is its simplicity. Laying pieces of stone or bricks on top of each other, either with or without cohesion via mortar, is a simple, though adequate technique that has been successful ever since remote ages. Other important characteristics are the aesthetics, solidity, durability and low maintenance, versatility, sound absorption and fire protection. Loadbearing walls, infill panels to resist seismic and wind loads, prestressed masonry cores and low-rise buildings are examples of constructions where the use of structural masonry is presently competitive. However, innovative applications of structural masonry are hindered by the fact that the development of design rules has not kept pace with the developments for concrete and steel. The underlying reason is the lack of insight and models for the complex behavior of units, mortar, joints and masonry as composite material. Much of the world's architectural heritage consists of historic buildings in masonry. In addition to their cultural values, such monuments often have important economic value. Though many historic masonry buildings have survived for centuries, there is an acute need for new tools to analyze the stability and the safety of such structures. In particular, there is a need to assess the structural safety of large numbers of buildings quickly and accurately.

There are essentially two way of approaching analysis of masonry: the first one is processing, in which modelling aspect depends on large classes of masonry buildings (e.g. old masonry structures). The second one is more practical base and restricted to the mechanical description of very specific types of masonry (masonry structure of regularly arranged block). Both ways of approaching masonry analysis are completely different.

II. SIMPLIFIED UNIAXIAL MODELS

Stability of masonry structures is mainly depends on the axial force carrying capacity of structures. Therefore uniaxial modeling, which appears as the clue of structural interpretation behind the design of the great Architectural masterpieces of the past, was first rationally introduced by Heyman in 1966, with mile stone paper "the stone skeleton". According to Heyman's study all forward research on masonry structures is carried out as considering rigid plastic behaviour. Definitely there is possibility of modeling masonry structure as linearly elastic but masonry material is an elastic brittle material for very small stress and strains and the point is that the level of stress and strains at which masonry materials works in real structures, are usually higher. Typical uniaxial behaviour of all simplified models are shown figure 1.

Rigid No-Tension Model (RNT)

This uniaxial model that describes the material as indefinitely strong and stiff in compression but incapable of sustaining tensile stresses, was first rationally introduced by Heyman (1966). This material is rigid in compression and has a limited characteristic of admissible stresses and strains and show fractures in elongation. The behaviour of this model is shown in the figure 1(b). We can

also refer this model as Zero model because this model requires no material parameters since strength and stiffness in compression are assumed to be an infinite while they are completely neglected in tension [2].

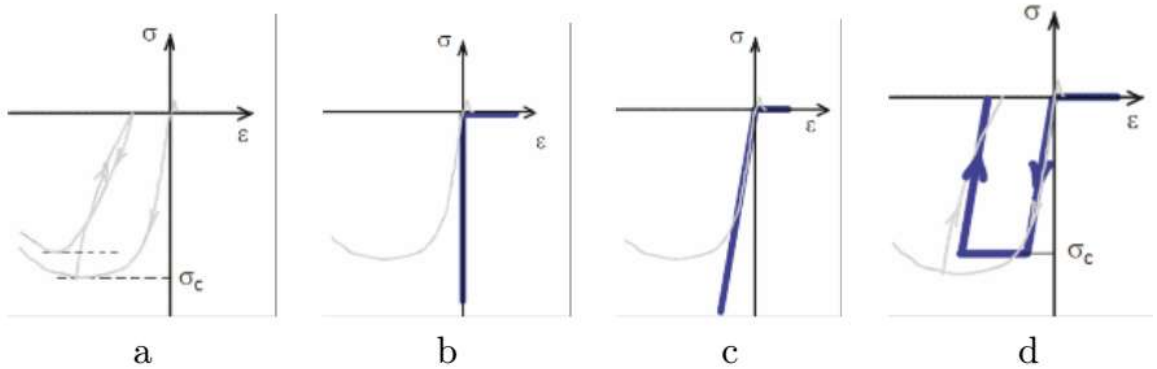

Figure 1: Typical uniaxial behaviour, (a), and simplified models: (b) rigid no tension model, (c) elastic no tension model, (d) masonry like model.

Elastic No Tension Model (ENT)

As first step into the closer modelling of masonry behaviour one can consider to add a finite stiffness in compression or we can say a linear ratio between stress and strain in compression is assumed. Another possibility would have been to add a limited strength in compression still assuming an infinite stiffness (rigid-plastic material). The behaviour of this model is shown in figure 1(c). In which we can see that the strain can be positive or negative, position strain being the fracture part of the deformation and negative strain the elastic part. Therefore this model is called as Elastic No-Tension model. The ENT material is globally elastic, in the sense that strain determines stress for any values of strain i.e. compressive stress is constititutive. This model requires only one material parameter i.e. the elastic modulus E, since strength in compression is assumed to be infinite, while strength and stiffness are completely neglected in tension [20]. For real application of this model we have to consider further parameter i.e. the Poisson ratio is required. For the simplifying assumption is that there is no sliding along the fracture lines [2].

Masonry Like Model (ML)

A further step can by adding the assumption of a limited strength σ_c in compression to ENT model. In this way the failure modes due to crushing can be modeled. The behaviour of ML model is shown in figure 1(d). But any attempt to enrich this model for real applications is usually disappointed by lack of sufficient confidence on the material properties of the real materials. From figure 1(d), it is assumed that the material behaves as perfectly plastic in compression, therefore the constitutive response becomes incremental and the actual stress state is path dependent, being determined by the whole strain history. Now we have to remark that this is an unusual perfectly plastic material since due to the different behaviour in tension (elastic fracture) and compression (incremental plasticity), the plastic deformations cannot be cancelled by reversing the strain. This model requires the setting of two material parameters i.e. the elastic modulus E and the strength in compression σ_c, strength and stiffness being still completely neglected in tension. For real application of this model, it is required to define a material function f, which is the limit surface in compression. The flow rule for the increments of crushing strain must be also introduced; for simplicity one can choose to adopt an associated flow rule, also if the frictional nature of sliding under compression would require the adoption of a non-associated law.

III. Refined Models

Masonry is a heterogeneous assemblage of units and joints. The large number of possible combinations generated by the geometry, nature and arrangement of units as well as the characteristics of mortars raises doubts about the accuracy of the term ”masonry”. An accurate modelling requires a comprehensive experimental description of the material, but due to variation of masonry there are difficulties in performing advance testing on masonry structures. Therefore most of the experimental research carried out in the last decades was concentrated in regular masonry structure such as brick block masonry. The behaviour of masonry is much dependent not only on the composition of unit and joints, but also on how they are arranged and treated. It is clear that the same surface with different treatments has different capacities. As said before the behaviour of masonry structures depends on the properties of mortar but as time passes the impact of mortar on masonry structures becomes inadequate. This phenomenon contributes to interlocking loss between irregular masonry units and masonry out of plane collapse in case of an earthquake and this phenomenon effectively is considered in Vasconcelos et al. (2009) [23]. Here, three different types of stone masonry walls with the same external geometry are tested under in plane cyclic shear, namely regular dry stone masonry, irregular mortared joints masonry and rubble masonry. Not only the strength and stiffness degradation of the walls is rather different but also the strength envelop found is much different, with a tangent of the friction angel varying between 0.4 (for dry stone masonry), 0.3 (for irregular masonry) and 0.2 (forrubble masonry).

Depending on the level of accuracy and the simplicity desired, usually the following representation are possible: (a) Micro-modelling, where the geometry of units and joints is directly considered and the constitutive laws are obtained experimentally; (b) Macro-modelling, where units and joints are smeared out in the continuum and the constitutive laws are obtained experimentally; (c) Homogenization, where the micro-structure is handled mathematically in terms of geometry and material data to obtain a smeared continuum model; (d) Structural component models, where constitutive laws of structural elements are directly provided in terms of internal forces such as shear force or bending moment, instead of stresses and strains, see Figure 2.

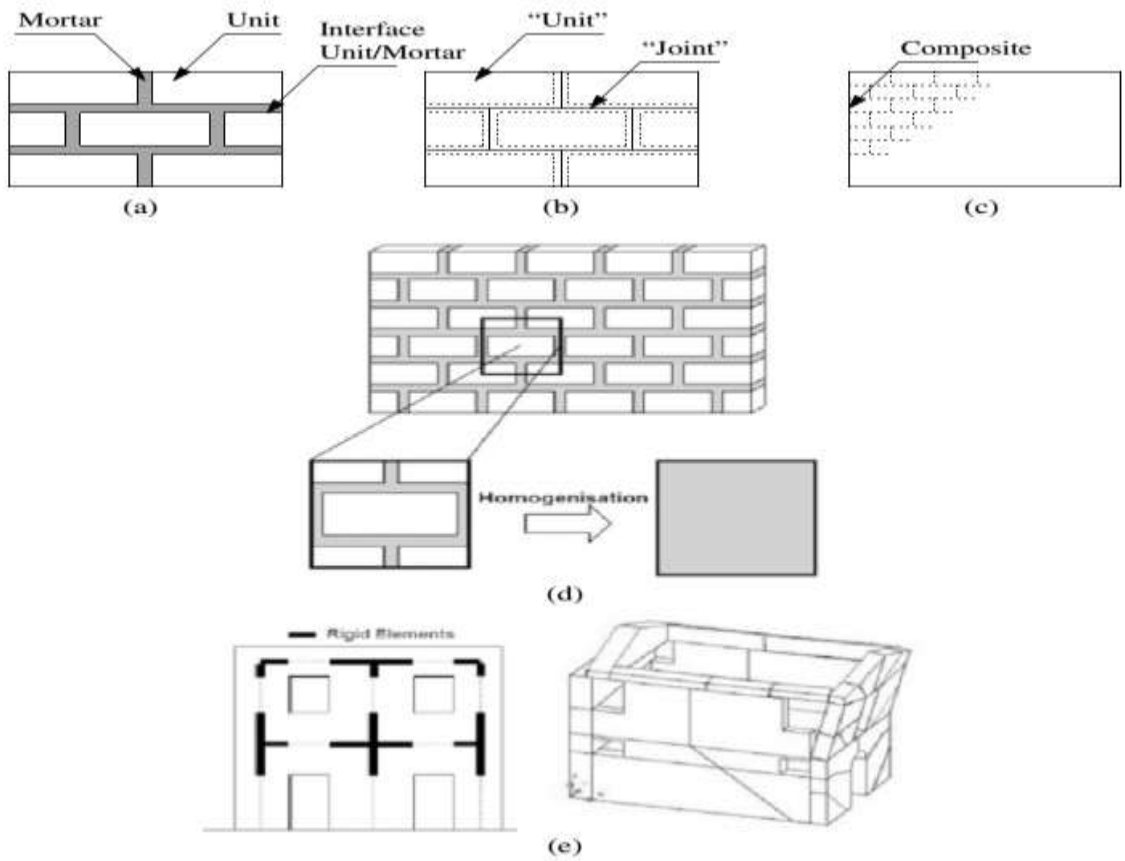

Figure 2: Modelling approaches for masonry: (a) representation of regular staggered or running bond masonry; (b) micro-modelling; (c) macro-modelling; (d) homogenization; (e) illustrative structural component models, with beam elements or macro-block.

IV. Micro-Modelling

Micro-models consider the units and the mortar joints separately. Each material used in masonry are characterized with different constitutive laws. The mechanical properties that characterize the models adopted for units and mortar are obtained through experimental tests conducted on single material. This approach leads to structural analyses characterized by great computational effort; in fact, in a finite element formulation framework, both the unit blocks and the mortar beds have to be discretized.

The adhesion between the mortar and the brick can play a fundamental role in the overall response of the masonry structure. Thus, the modeling of the response of mortar-brick interface can be necessary in order to reproduce the possible decohesion of the mortar from the brick. In the micro-modelling of masonry, at least two possible approaches can be distinguished

- The mortar and the adhesion surface between the mortar and the brick are modeled as a unique interface. In this case, the interface has zero thickness [13].
- The mortar is modeled as a continuum material, eventually characterized by nonlinear response, and the adhesion surface between the mortar and the brick is modeled by a specific interface [22].

Several models are presented related to interface and some of them have been developed to reproduce the gradual process of crack opening, in which the incipient separation of the two edges of the crack is constrained by cohesive stresses due to interaction and friction between aggregate or bridging phenomena. In order to model the behavior of masonry mortar joints, Lofti et al. (1994) [12] proposed a dilatant interface constitutive model capable of simulating the initiation and the propagation of interface fracture under combined normal and shear stress in both tension-shear and compression-shear regions. Gambarotta et al. (1997) [9] postulated the constitutive equation of interface model in term of two internal variables representing the frictional sliding and the damage occurring in the mortar joint because of cyclic load. Lourenco et al. (1997) [14] and Oliveira et al. (2004) [17] implemented a constitutive interface model, based on an incremental formulation of plasticity theory, able to simulate the cyclic behavior of the cohesive zone by reproducing the nonlinear response during unloading. The interface model was utilized by Fouchal et al. (2009) [7] to simulate the experimental behavior of the mortar-brick adhesion zones of the masonry structures, remarking that the decohesion between the constituents of masonry is mainly responsible for its nonlinear response.

V. Macro-Modelling

Masonry is a cohesive material characterized by softening response. Truly, his nonlinear behavior is due to the damage and plastic micromechanical processes. From a microscopic point of view the damage is linked to the growth of microcracks, leading to the formation of macrocracks which can induce the collapse of the structure. The available models adopted for structural computations are mainly based on macromechanical approaches using damage mechanics and plasticity theory.

Among the others, Lotfi et al. (1991) [11] developed smeared crack finite element analyses of masonry structures in order to assess the capability of this approach in capturing the strength and various failure mechanisms of masonry shear walls. They compared the numerical results with experimental data, investigating the objectivity of numerical results with respect to mesh size. Lourenco (1996) [13] presented an anisotropic continuum model based on multisurface plasticity, considering a Rankine type yield surface for tension and a Hill type yield surface for compression. The proposed model is completed with a computational algorithm which is used to perform comparisons between numerical and experimental results. Reyes et al. (2009) [21] presented a numerical procedure for fracture of brickwork masonry based on the strong discontinuity approach. The model, which takes into account the anisotropy of the material, has been implemented into a commercial code by means of a user subroutine. Comparison between numerical and experimental results has been provided, remarking that the proposed numerical procedure is able to accurately predict the experimental mixed-mode fracture for different orientations of the brick layers on masonry panels. Marques et al. (2011) [16] presented a simple design tool based on structural component models for investigating the seismic assessment of a two-storey masonry building using pushover analysis. They demonstrated that macro-modeling can provide adequate approaches for the seismic design of unreinforced masonry buildings, as the tool requires very low computational resources, allowing easy interpretation of results and provides satisfactory accuracy.

VI. HOMOGENIZATION FOR MODELING

The most of the popular simplified approaches that appeared in the past were for obtaining homogenized elastic moduli for masonry. The first idea presented byPande et al. (1989) [18], was to substitute the complex geometry of the basic cell with a simplified geometry. In particular, Pande et al. (1989) [18] presented a model in which a two-step stacked system with alternative isotropic layers was considered (Figure 3). In the first step, a single row of masonry units and vertical mortar joints were taken into consideration and homogenized as a layered system. In the second step, the intermediate homogenized material was further homogenized with horizontal joints in order to obtain the final material. Obviously, this simplification leads:

- To underestimate the horizontal stiffness of the homogenized material, since no information on the texture is considered. The inability of the model to consider the regular offset of vertical mortar joints belonging to two consecutive layered unit courses results in significant errors in the case of non-linear analysis;
- To obtain a homogenized material different if the steps of homogenization are inverted.

A different approach, proposed by Felice et al. (1997) [3] and Cecchi et al. (2002) [4], is based on the reduction of joints to interfaces. This idea arises from the observation that masonry units are generally much stiffer than mortar and joints show a small thickness if compared with the size of masonry units. Felice et al. (1997) [3] assumed also rigid masonry units in order to reduce further the complexity of the problem. Cecchi et al. (2002) [4] proposed a multi-parameter homogenization study for the 2D and the 3D in-plane case, removing the hypothesis of rigid masonry units (Figure 4(b)). The finite thickness of the joints was considered in an approximated way only in the constitutive relation of the interfaces. This approach comes with some disadvantages as listed below:

1. The reduction of joints to interface may reduce the accuracy of the results in presence of thick mortar joints.
2. A possible development of the method in the non-linear range can result in non-negligible errors with respect to finite element approaches and experimental evidences since the role of joint thickness is lost in the simplifications assumed.
3. Masonry behaviour can be quasi-brittle.

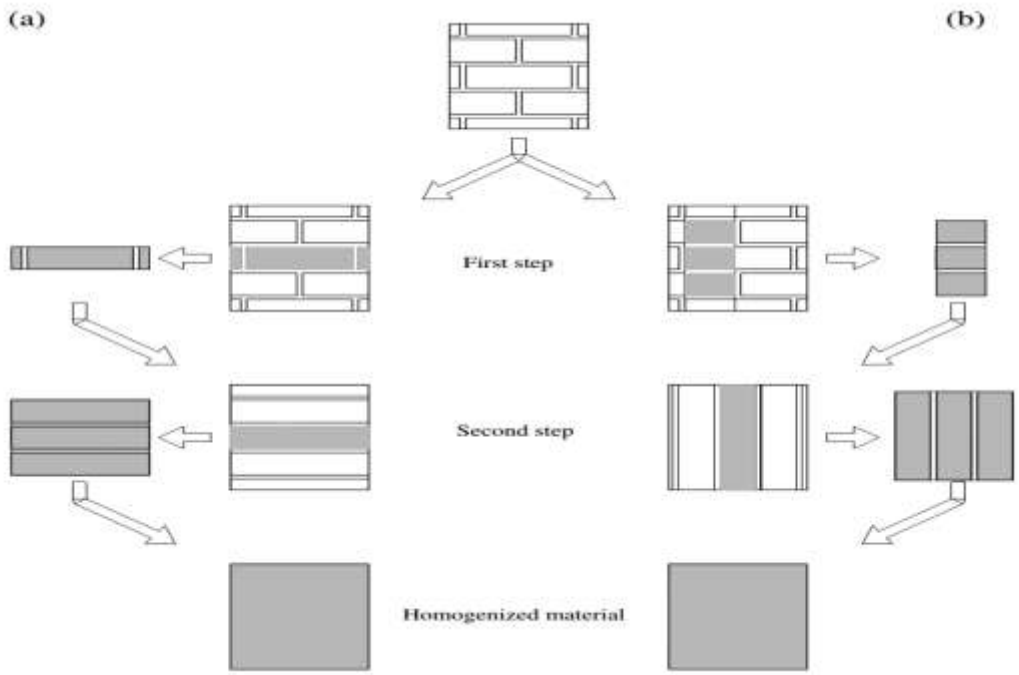

Figure 3: Two step Homogenization.

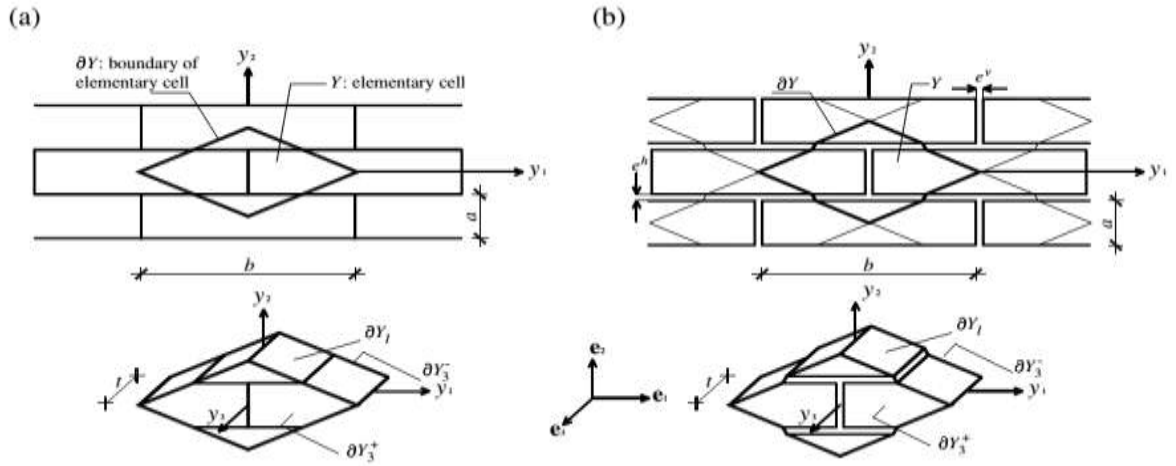

Figure 4: Unit cell utilized in Felice et al. (1997) [3] and Cecchi et al. (2002).[4] (a) Joints reduced to interface. (b) Actual thickness of the joints.

VII. Dynamics and Seismic Behaviour

In case of seismic loading on unreinforced masonry buildings, it is certain that non-linear behaviour is triggered at early stages of loading and linear elastic analysis is not an option. Alternative options seem to be push-over methods, as recommended in most codes for earthquake safety assessment. Another much relevant property in case of seismic loading is the presence of floors that provide diaphragmatic action and the so-called "box-behaviour". This possible feature is not usually present in ancient masonry buildings while being present in modern unreinforced masonry buildings, requiring different models of analysis. Modern masonry buildings usually adopt solutions for the slabs that provide considerable in-plane stiffness. This is done by using monolithic solutions for the floors, in concrete and steel, and also by establishing an effective connection between slabs and walls. The effect of floor diaphragms combined with the in-plane response of structural walls provides box behaviour to the buildings, which usually leads to good performance when subjected to earthquakes. The first assessment method for seismic analysis of masonry buildings was developed under this simple hypothesis. As result of research studies in former Yugoslavia and the 1976 Friuli earthquake, the POR method was introduced in the Italian region of Friuli-Venezia Giulia, to assess the seismic performance of existing masonry buildings [15]. Its limitations, namely the consideration of an independent storey mechanism, therefore there is need to consider the overall response of the masonry structures.

An improvement of the POR method is provided in the so-called 'equivalent frame method', which allows the user to carry out a global analysis of the building. In such a method, a higher number of possible failure mechanism occurring inside macroelement, such as shear with diagonal cracking, shear with sliding and rocking, can considered. The use of this approach is allowed by the FEMA 356 [6], the new Italian Seismic Code and the latest draft of the Europian Code (Eurocode 8). Both Italian and European Codes encourage the use of non-linear static push-over (SPO) analysis and require a control of the spandrels, which is not possible using POR method [19]. The use of suitable programs is therefore needed for the design of masonry building according to those regulations.

VIII. Conclusions

The main conclusion of the discussion on the different modeling approaches for masonry constructions is that all the approaches can satisfactory reproduce the response of specific masonry elements, there is no model that can be considered is absolute better than the others. On the contrary, each approach can be more appropriate for specific typologies of masonry structures. For instance, the micromechanical approach can be satisfactory adopted to reproduce the response of small size (laboratory) elements or of structures characterized by big blocks, in which the size of the blocks has the same order of magnitude of the size of the structural element. On the contrary, it is less suitable for the analysis of large structures because of the required great computational effort and for the difficulty in adequately describing the specific geometry of the whole masonry texture, i.e. the position of each brick or block in the structure. For large scale applications, macro-block approaches must be adopted and homogenization techniques represent a popular.

The possibilities of assessment of unreinforced masonry structures subjected to seismic loading are addressed using different techniques. It is recommended that linear elastic analysis can hardly be used, as masonry features have low tensile strength, and different models must be used in the presence or absence of adequately connected floors.

The non-linear static analysis could be a good and easily understood approach, because it is based on the simple evaluation of the requested deformation with respect to the displacement capacity of the building. Still, the results obtained from the non-linear static and dynamic analyses indicate quite different response of these structures to earthquakes. It is therefore concluded that non-linear pushover analysis does not simulate correctly the failure mode of masonry structures without box behaviour, even if higher modes are considered via modal pushover analysis [2].

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