Chapter

Modeling of Structural Masonry

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Abstract

Masonry is a composite material, and its behavior shows that its weaknesses lie in the minimum resistance of its components and the characteristics of the interfaces between them. Ceramic brick masonry has technological characteristics that make it suitable for housing and building functions. The bricks, of reduced dimensions and joined with mortars of variable characteristics, have the advantage of adapting to almost all construction projects considering the influence of the environment on their service life. The investigation of the structural behavior of masonry has had very significant advances in the laboratory during the last mid-century, which has allowed numerical modeling of the behavior of the material and validation of failure modes under seismic actions. The behavior of heritage masonry with thick walls differs greatly from simple masonry using conventional techniques and materials. These differences in behavior have only been confirmed through numerical simulation contrasted with experimental research. This chapter presents the numerical modeling used for simple and confined masonry with reinforced concrete and for very thick heritage masonry, using the finite element method validated with full-scale laboratory experiences.

Keywords: masonry modeling, earthquake, thickness, simulation, FEM

1. Introduction

Masonry is a material composed of natural or manufactured units, generally joined with mortar, which constitute the inventory of existing constructions in the world from the Egyptian civilization to the present. Architecturally, there is a wide spectrum of uses in walls, arches, vaults, domes, beams, and columns that exhibit simplicity and elegance, but the analysis of its structural behavior is complex in heritage masonry. The most investigated construction techniques correspond to the Greek and Roman buildings that have remained standing to this day. In Africa and Asia, the earliest masonry was made of stone or earth. In America, stone masonry has been used in the pre-Columbian era, earth or adobe masonry in colonial times, and fired ceramic masonry from the end of the eighteenth century to the present with different variants of arrangement and combination of layers of different materials (**Figure 1**) [1–3].

The conservation of heritage buildings requires knowledge to guide preservation strategies. Materials degrade over time when they are in contact with the environment, and this is a natural and unavoidable process, and it is necessary to determine

a) b)

c) d) e)

f) g) h)

Figure 1.
Examples of masonry in America (a) Machu Picchu (Perú) XV century, (b) Inca bridge and thermal hotel (Argentina) 1925, (c) chapel in Cuzco (Perú) 1598, (d) chapel in Córdoba (Argentina 1668), (e) king hovel's (Argentina-Chile) 1773, (f) interior Giol winery (Argentina), (g) Giol winery facade (Argentina) 1896, and (h) fader house museum (Argentina) 1889.

the rate of degradation, which is necessary data to estimate the service life of the construction in relation to safety and/or functionality. The presence of moisture that can come from the ground, rain, or faulty drainage services damage the masonry, especially ancient masonry. Interventions with new materials have often increased moisture problems in masonry [4, 5].

The effect of earthquakes has been devastating in unreinforced masonry constructions, but it has made it possible to summarize the problem of the damage generated by these horizontal vibratory actions [6, 7]. Earthen masonry has shown its lack of earthquake-resistant capacity over time in the different continents, even for low-magnitude earthquakes.

Repair and replacement materials are required to be chemically and mechanically compatible with the original materials. Environmental conditions require control of porosity and permeability to water vapor. There are records of damage to historic masonry due to failure to assess the compatibility of the repair material in terms of strength, density, and stiffness of the original material [8].

According to the available materials, the climatic conditions, and the functional requirements, a variety of types of masonry can be found, with traditional practices and local technologies that vary according to the different countries.

Masonry can be classified according to: the material (adobe, stone, brick, block), its location (country or city), its use (residential or public), the structural system (simple, confined, reinforced), time of construction (ancient, before the First World War, between the First and Second World Wars, after the Second World War, after the adoption of unified international codes) [2]. An important aspect to evaluate in the behavior is if the masonry resists the permanent and seismic loads generated by its own mass and the contributions of floors or ceilings supported on it [9].

Since the 1970s, studies and research have been carried out applying computational mechanics to achieve mathematical models that simulate the structural response of historical masonry due to its weakness under seismic actions. The complexity and uncertainty of the geometry of old buildings and the nonlinear behavior of masonry require an important contribution of computational analysis techniques.

2. Masonry modeling

Numerical modeling of masonry requires computational models that can capture the different failure modes and that are sufficiently accurate and simple to implement. There are several modeling techniques. The technique to be used starts from the desired level of precision and simplicity [10].

Finite Element Models (FEMs) and Structural Element Models (SEMs) represent the behavior of masonry at different scales, so predictions may differ significantly depending on the model chosen.

According to the current codes, the use of more complex models is not recommended due to the need for a great experience of the designer, high sensitivity of the parameters used, dispersion of the predictions, and the need for a better interpretation of the postprocessing to obtain results applicable [11].

Masonry exhibits different directional properties due to the influence of mortar joints acting as planes of weakness. Depending on the orientation of the joints and the directions of the stresses and, on the other hand, the level of normal stress applied, failure can occur only at the joints (bed joint sliding shear mode) or simultaneously at the joints together and bricks (bed joint slip shear mode or diagonal stress cracking). The significant number of influencing factors, such as the dimension and anisotropy of the bricks, the thickness of the joint and the arrangement of the bed and head joints, the material properties of both the brick and the mortar, and the quality of the coat site construction makes simulation of brick masonry extremely complex.

Masonry can be modeled as single-phase, bi-phase, or tri-phase material [11].

As a single-phase material, all the elements that make up the masonry: brick masonry + mortar + unit-mortar interface make up a homogeneous, isotropic or anisotropic continuum (**Figure 2a**), without differentiation of elements. This procedure is often preferred for the analysis of large masonry structures (macro-model), but it is not suitable for detailed stress analysis of a small panel, due to the difficulty of capturing all its failure mechanisms.

As a biphasic material, the expanded units are represented as continuous elements while the mortar joints and the unit-mortar interface are grouped into discontinuous elements (**Figure 2b**). This procedure is applicable to a wider range of structures because it reduces computational processing times (simplified micro-model).

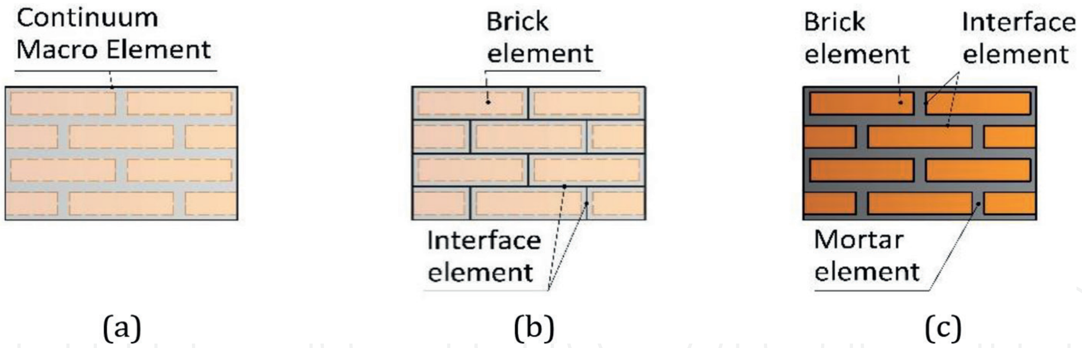


Figure 2.
Masonry modeling strategies: (a) macro-model, (b) simplified micro-model, and (c) detailed micro-model [11].

As a three-phase material, the masonry and the mortar joint are represented as continuous elements, while the unit-mortar interface is represented as a discontinuous element (**Figure 2c**). With this degree of mesh refinement, more accurate results can be obtained, but the availability of more powerful computational means is required (detailed micro-model), limiting its application to laboratory samples or structural details.

The boundary conditions that exist at the interface between the masonry and the surrounding frame in confined masonry have been modeled with springs or interface elements. The function of these elements is to represent the interaction between deformable structures, along surfaces where separations and sliding can occur.

Computationally, different commercial finite element packages have been developed for nonlinear, two-dimensional or three-dimensional static and dynamic analysis. All these software (ABAQUS, ADINA, ANSYS, ATHENA, and DIANA among the

Types of masonry	Details	Geometric Models	Macroelements	Blocks	Continuum Models
Unreinforced masonry	Single material	Static theorems Cinematic theorems	Equivalent frame Equivalent spring	Interface Contacts Texturized continuum Limit analysis Extended finite elements	Direct Homogenization Multiple scale
	Composed of various materials				
Confined masonry	Integrated masonry		Box behavior		
	Separate masonry		Equivalent structure		
Reinforced masonry	Vertical and horizontal bars included in masonry		Equivalent structure		

Table 1.
Masonry models.

most applied) incorporate libraries that include different finite element models and robust resolution strategies for different types of materials and load states, especially for brittle materials such as masonry and concrete. The use of these packages is required to resolve complex interfacial boundary conditions [6].

Table 1 presents a summary of the masonry models classified according to the structural system [2, 6, 9].

2.1 Modeling of unreinforced masonry

The classification proposed by D'Altri et al. [6] summarizes in a very complete way the investigations of the last 60 years in four types of generalized models for unreinforced masonry structures: models based on geometry, on macroelements, on blocks and as continuous material.

2.1.1 Geometry-based models

The masonry is modeled as a rigid body defined by the geometry of the structure. Structural equilibrium and collapse are studied through solutions based on limit analysis, which can be based on static or kinematic theorems (**Figure 3**).

Applications of the static theorem of limit analysis in real masonry structures are based on simple static schemes [13] suitable for the investigation of equilibrium states in arches, vaults, and domes, bounded between two extreme equilibrium conditions for static safety. In fact, if compression-only forces lines can be found within the confines of a vault, then the vault will remain in compression. Also, if the solution is within the middle third of the section, any stress (and thus any joints) will be present in the section.

There are different computational developments for the equilibrium analysis of masonry vaults, an analogy between the equilibrium of arches and hanging ropes (funicular model), the analysis of the thrust network that conceives vaults as membranes without tension. Few of these solutions have been able to incorporate the horizontal actions generated by earthquakes.

Kinematic theorems have been used in the last decades for an agile evaluation of masonry buildings. The Italian code has adopted the kinematic limit analysis approach, based on the decomposition into rigid blocks based on the failure mechanisms observed during earthquakes [14].

More advanced computational static theorem-based approaches have been developed to accurately assess the collapse multiplier and collapse mechanism of masonry structures. However, these approaches cannot provide the deformation capacity of a masonry structure, although they are very powerful to quickly and effectively assess the main vulnerabilities of a masonry building.

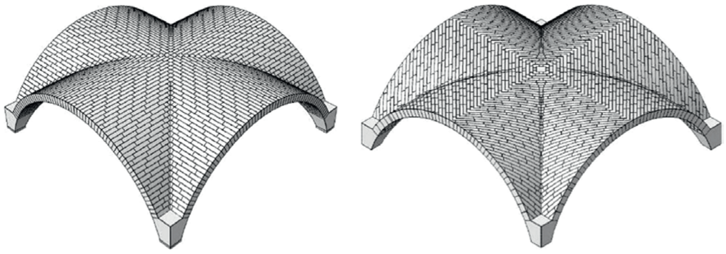


Figure 3.
Geometry-based model [12].

2.1.2 Macroelement models

When we refer of macroelement models, we mention a structure modeled in structural components at real or panel scale (1:1), considering a phenomenological effect or a nonlinear constitutive response, with the main structural elements being pillars and parapets. Observations of earthquake damage have shown that damage is concentrated on pillars and sills or lintels. With this structural idealization, the analysis of the global seismic response of the masonry construction is carried out.

Macroelement models are generally based on the assumption that any local failure mode activation, primarily associated with the out-of-plane twist response of masonry walls, is avoided. The seismic response is directly related to the shear capacity in the plane of the walls and to the load transfer due to the existence of diaphragms.

Both static and incremental dynamic global analyses are usually performed on 3D models, to consider load transfer between load-bearing walls due to horizontal action.

Columns are the vertical resistant elements that support vertical or horizontal loads. In contrast, spandrels or lintels are the horizontal portions of the structure between two vertically aligned openings, which couple the response of adjoining columns when loaded horizontally. Although the identification of masonry pillars and parapets can be easy in the case of masonry facades with regularly distributed openings, it becomes more complex when there are irregularly arranged openings, not being applied to very complex geometries.

Macroelement models are the most widespread modeling strategies used for the seismic evaluation of masonry structures due to their ease of computational application (also in 3D structures), together with the simple and fast definition of the model and the mechanical properties. The most used macroelement models correspond to equivalent beams and equivalent springs.

As application drawbacks, it can be indicated that this modeling has difficulties in solving structural details such as the indentation between orthogonal walls or the assumption of decoupling of the local failure mode, which requires experience when it comes to irregular arrangements [6].

2.1.2.1 Equivalent beam-based macroelements

The idealization of masonry panels as nonlinear beams represents the most common assumption in the so-called equivalent frame models. Tomaževič [2] proposed a model based on equivalent beams with basic mechanical assumptions where the in-plane damage of masonry facades is due to shear forces in the columns, while the beams and nodal regions are considered rigid and fully resistant. This simple mechanical description, based on simplified elastoplastic relationships, provides sufficient reliability only in the case of weak columns and strong spans. Improvements have been introduced successively implementing the flexibility and limited strength of masonry sills.

Other more advanced equivalent beam-based models have proposed the idealization of the masonry structure as a set of column beam and span beam elements, joined by rigid links representing the nodes between columns and spans (i.e., zones where the seismic damage is rarely observable). These models are based on the phenomenological nonlinear elastoplastic constitutive laws adopted for beam elements.

Another model considers a simple beam for nonlinear analysis of the masonry with two rigid displacements at the ends (simulating the rigid behavior of the intersection of columns and lintel) and a flexible central part. In the Tremuri software, a piecewise linear behavior is incorporated that allows the description of severe damage levels through the progressive degradation of the resistance in correspondence with the floor drift [15].

2.1.2.2 Equivalent spring-based macroelements

Various macroelement models have been formulated by implementing nonlinear springs, within a fictitious frame, to approximate the in-plane nonlinear response of masonry walls and facades (**Figure 4**).

Chen et al. [17] have adapted from reinforced concrete a model with nonlinear shear springs in series with rotational springs for in-plane masonry analysis. This updated model for masonry includes one axial spring, three shear springs, and two rotational springs to simulate failure modes (axial, bed joint slip, diagonal tension, and rocking/crushing) observed experimentally in masonry pillars.

Xu et al. [18] consider the masonry façade as an integral unit in a simple model, using two vertical springs and a nonlinear horizontal spring that governs the shear response of the wall. The hysteretic behavior depends on different parameters, such as the distribution of openings and/or confining elements, relative dimensions, material properties, and boundary conditions of the facade.

2.1.3 Block-based models

Block-based models represent the behavior of masonry at the scale of the main material heterogeneity, characterized by units assembled by mortar (or dry) joints, which governs the main aspects of its mechanical and failure response.

The first example of nonlinear block-based models corresponds to the work of Page [19], where the masonry is considered as an assembly (textured continuum) of elastic brick elements acting in conjunction with connecting elements that simulate the mortar joints that they have limited shear strength depending on the strength of the joint and the level of compression.

This type of model represents the actual union of masonry and structural details, using mechanical parameters obtained from small-scale tests, inclusion of anisotropy, a comprehensible representation of failure modes, and representation of 2D meshes (sheets) and 3D (solids) that allow in-plane and out-of-plane responses to walls and their interactions.

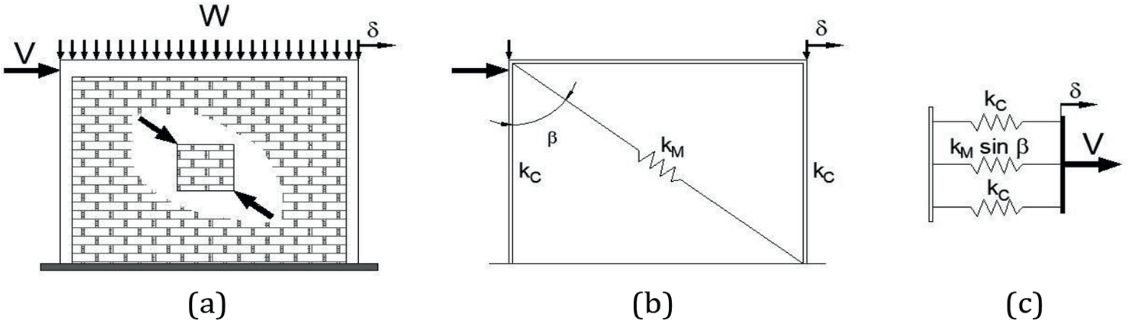


Figure 4.
Equivalent spring-based macroelements [16] (a) Masonry wall subjected to vertical and lateral load, (b) Macromodel, and (c) Simplified model of one degree of freedom with shear strain.

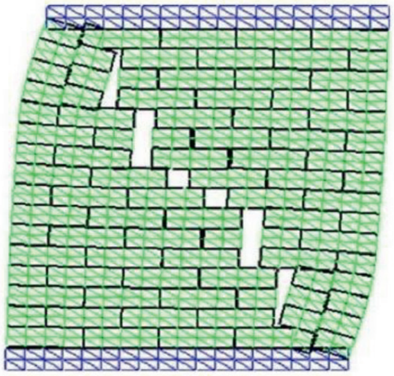


Figure 5.
Scaled deformed mesh obtained from the analysis [20].

The main problem with these models lies in their high computational demand, limiting their applicability at the panel scale. As the actual joint of existing masonry structures is often not fully known, block-by-block discretization could be approximated in those cases. Model assembly is usually a long and complex operation, which limits the use of these modeling strategies to academic studies and a very few high-level consulting groups [6].

Block-based models are classified according to how the interaction between blocks is formulated: on interface elements, on contacts, on textured continuums, on block-based boundary analysis, and on extended finite elements (**Figure 5**) [20].

2.1.3.1 Interface elements

One of the first nonlinear models based on interface elements to simulate the collapse behavior of masonry structures appears in Lofti and Shing [21], where mortar joints are modeled with interface elements of zero thickness and expanded units of masonry (which were considered expanded to take into account the geometry of the mortar joints) were modeled with cracked finite elements. The constitutive model is based on the plasticity of the dilatant interface capable of simulating the initiation and propagation of interface fracture under combined normal and shear stresses.

Lourenço and Rots [22] have developed a multisurface interface-based model in which all nonlinearities (including shear slip, tensile cracking, and also compressive crushing) were concentrated at the interfaces, increasing the efficiency of the model.

The proposal of a cyclic interface model in the mortar joint based on damage mechanics [23] shows a brittle response under tensile stresses and is characterized by frictional dissipation together with stiffness degradation under compressive stresses. In particular, the proposed constitutive equation is based on terms of two internal variables that represent frictional slippage and mortar joint damage. These models are applied for the analysis of 2D problems, which considerably limits the applicability of the modeling strategies to real problems.

2.1.3.2 Contact models

Modeling strategies are based on contact mechanics and are widely used for accurate modeling of masonry structures. Rigid or deformable blocks (linear or nonlinear) interact following a definition of frictional or cohesive-frictional contact. Although several in-house formulations have been developed and validated, three main families of contact-based approaches can be found [6].

1. Discrete Element Methods (DEM) are based on contact penalty formulations and explicit integration schemes implemented in the UDEC (Universal Distinct Element Code). Several applications have been made on actual masonry structures using rigid or linear elastic blocks.

2. An implicit approach that considers the deformability of blocks is Discontinuous Deformation Analysis (DDA). DDA complies with the constraints of no tension between blocks and no penetration of one block into another. Furthermore, Coulomb's law is satisfied in all contact positions for both static and dynamic calculations.

3. Non-Smooth Contact Dynamics (NSCD) method, developed by Jean [24] and characterized by a direct contact formulation, in its non-smooth form, implicit integration schemes, and energy dissipation by block impact. It is applied in dry stone masonry.

None of the approaches can adequately explain the crushing of the masonry, which can be, in some cases, crucial in the mechanical response of these constructions, so other models have been developed that consider the nonlinearity of the block in tension and compression (masonry units and mortar joints as a set of densely packed discrete irregular deformable particles bound together by zero-thickness contact interfaces) [6].

2.1.3.3 Textured continuum models

The main concept of continuous block-based textured models is to model in a context of nonlinear finite elements, masonry, and joints separately without any interface between them, This allows to determine deformations of the two materials, as well as the failure of the blocks, mortar, or mortar joints by adhesion [19].

A continuous block-based textured model discretizes both units and mortar joints with continuous elements, making use of a tension/compression damage model where the damage model has been refined to appropriately reproduce the nonlinear response under shear and to control dilatancy [6].

An innovative approach to mechanically model the nonlinear response of mortar joints from Addessi and Sacco [25], who proposed a micro-structured 3D composite interface formulation based on a multiplane cohesive zone model.

2.1.3.4 Block models based on limit analysis

The limit analysis in the block model allows to accurately and robustly predict the maximum load and its collapse mechanism in masonry buildings. 2D and 3D strategies have been proposed, generally based on limit analysis theorems, even though the effect of friction in calculations is often not an energy-conserving type.

Baggio and Trovalusci [26] proposed a solution of the analysis problem with friction in the interfaces between rigid blocks, that is, they consider the effect of nonlinearity with dilatancy in the solution of the problem.

Ferris and Tin-Loi [27] raised the calculation of the collapse loads of discrete rigid block systems, with unassociated friction and contact interfaces, as a special constrained optimization problem.

On the other hand, Sutcliffe et al. [28] developed a methodology to calculate the loads corresponding to the lower limit in unreinforced masonry walls subjected to shear actions, in plane deformation. Applying the Mohr-Coulomb criterion, the proposed numerical procedure calculates a statically allowable stress field using the finite element method.

Although block-based boundary analysis approaches have also been applied to actual structures such as masonry bridges, their computational demand seems particularly high, which precludes their use for large-scale masonry structures [6].

2.1.3.5 Extended finite element models

Abdullah et al. [29] propose a 3D model that includes a cohesive surface-based behavior to capture the elastic and plastic behavior of masonry joints and a Drucker-Prager plasticity model to simulate masonry crushing under compression.

In addition, XFEM (Extended Finite Element Method) is adopted to model the cracking behavior and compression failure of masonry in infill panels. The discrete interface element is used to simulate the behavior of masonry mortar joints and frame interface joints, showing these approaches as a powerful alternative analysis [30].

2.1.4 Continuum models

The masonry is modeled as a continuous deformable body. The mesh discretization does not have to describe the inhomogeneities of the masonry and can therefore have dimensions that can be larger than the block size. Although there are studies that present an approach at the micromodel level [31] that consist of modeling the masonry units and the mortar as continuous elements, while the masonry-mortar interface is represented by means of discontinuous elements, the scope of this is limited to the study of small specimens.

The computational cost of these continuous macromodel approaches is, in general, less than block-based approaches and much less than micromodels. But the complex behavior of masonry from a mechanical point of view presents a challenge in defining adequate homogeneous constitutive laws.

The parameters to be introduced in the constitutive models can be deduced from experimental tests, or through homogenization techniques, where the constitutive law of the material (considered as homogeneous in the structural scale model) is derived from a homogenization process that relates the scale of the structural model with the scale of a material model (which represents the main heterogeneities of the masonry). The homogenization process is generally based on refined modeling strategies of a representative volume element (RVE) of the structure (**Figure 6**).

2.1.4.1 Direct approach

Direct continuum models are based on continuum constitutive laws that can somewhat approximate the general mechanical response of masonry. Mechanical properties (elastic parameters, strength limits, etc.) can be obtained from experimental tests (**Figure 7**) or other data (for example, analytical or experimentally derived strength domains), without resorting to homogenization procedures based on RVE.

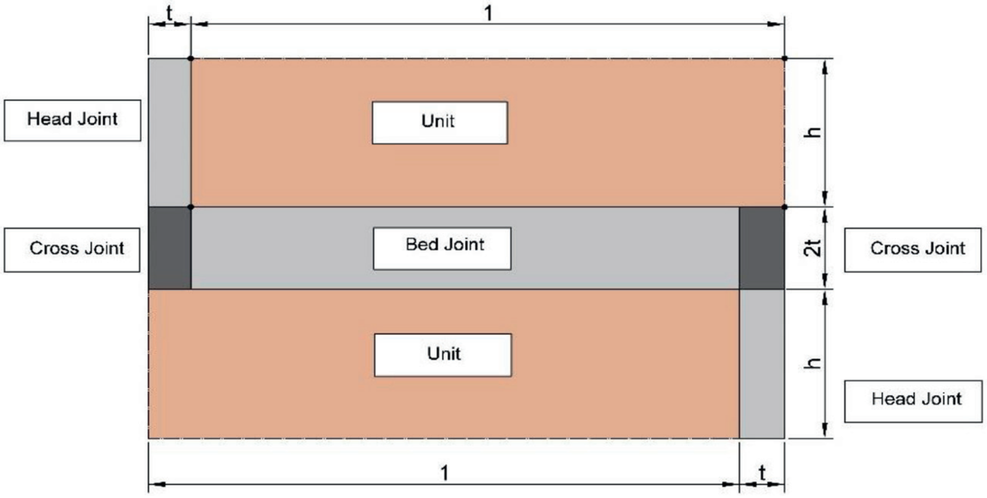


Figure 6.
Basic cell layouts (RVE).

Figure 7.
Preparation of masonry specimens [33].

A first direct approximation consists of an idealization of the mechanical behavior of the masonry. Masonry is conceived as a no-tension material. In general, a material that is not resistant to tensile stress implies an isotropic medium that is unable to withstand these stresses but is also linear elastic. This hypothesis has served as the basis for preliminary structural analyses and has been used in the stability analysis of masonry vaults and domes [13].

Although the cited non-tensile-resisting schemes represent elegant solutions for such a complex problem, their applicability to actual case studies is still limited, to 2D problems, and 3D stress-free structures have only recently been investigated. However, these approaches cannot simulate the post-maximum behavior of masonry structures, which is a strong limitation in the field of seismic evaluation of structures.

In addition, although the zero tensile strength assumption can be considered conservative in general, this could lead to failure mechanisms inconsistent with those observed experimentally, because the masonry tensile strength is not zero.

Other direct continuum models for masonry structures are based on continuous nonlinear constitutive laws based on fracture mechanics (smeared crack models), damage mechanics, or plasticity theory. Various models of smeared cracking [32–34], plasticity, continuous damage and coupled damage, and plasticity have been developed mainly for FEM analysis of concrete structures. However, its usefulness for simulating the collapse or near-collapse behavior of masonry structures has some limitations, mainly due to the multilevel anisotropy (elastic, strength, and brittleness anisotropy) of the masonry and its heterogeneity introduced by the mortar.

The constitutive model of Drucker Prager allows to represent in a simple and easy way the nonlinear behavior of the masonry as an elastoplastic material with dependence on the acting compression, being attractive since it requires the definition of very few parameters that can be determined from diagonal compression tests in the laboratory or the application of flat-jack in situ. To obtain masonry modeling parameters, laboratory tests can be performed on a 1:1 scale on samples of different thickness [35]. With the experimental results obtained, a finite element model is formulated using the ABAQUS software whose parameters allow to be obtained a behavior like that observed during the tests [36].

Although not fully consistent with masonry mechanics, smeared cracking, isotropic damage, and plastic damage models have been widely used to analyze masonry structures, mainly due to their efficiency, their spread in finite element codes, and the relatively few mechanical parameters to characterize the material.

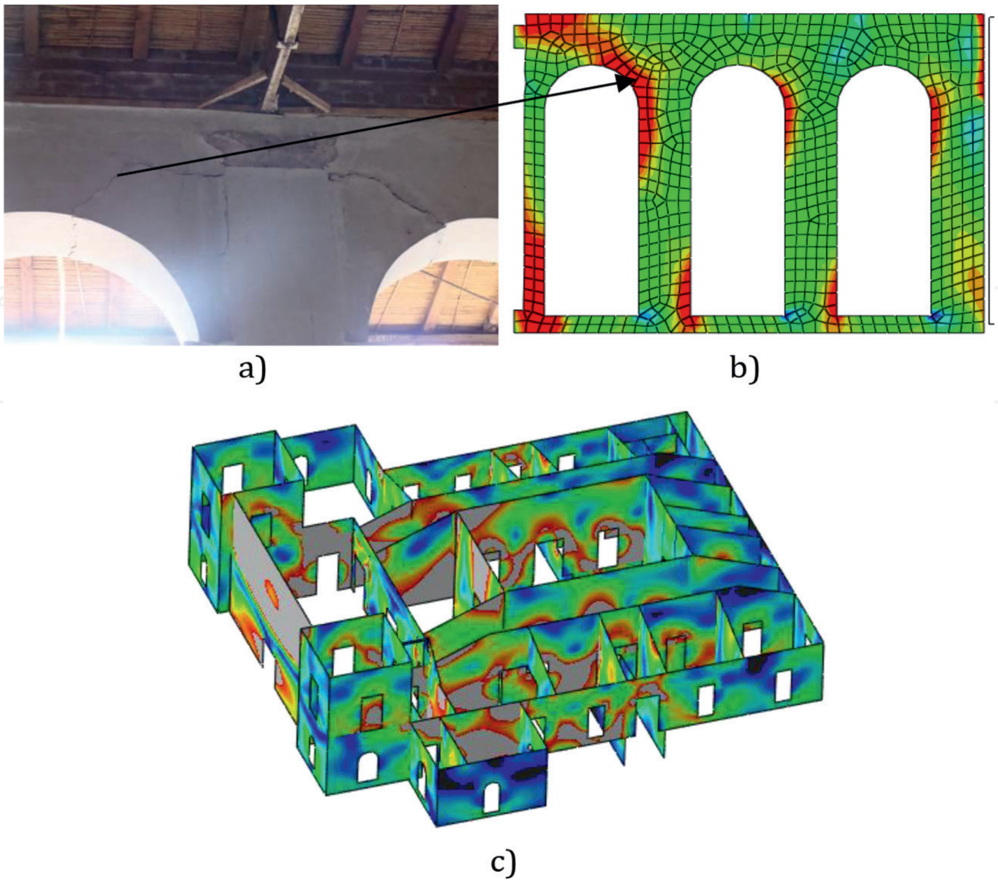
In particular, the use of these models with material nonlinearity has been found to be particularly suitable for the analysis of monumental heritage structures, given their limited computational cost and their ability to represent large-scale and complex 3D geometries. In addition, historic buildings often feature irregular, multilayered masonry, which is not possible to represent block by block and characterize mechanically, moreover, given the strict limitations for in-situ destructive testing of historic buildings of high heritage value [37]. In general, little information is available on the mechanical properties of historic masonry, which favors the use of nonlinear isotropic models.

Many applications with isotropic smeared crack models (isotropic plastic damage) have been carried out successfully in historical towers, churches and temples, palaces, and masonry bridges [6, 38, 39]. Most of the applications in monumental structures are based on 3D models (**Figure 8**), since the structural behavior can rarely be represented by 2D models due the complex and irregular geometries of these buildings.

Although every reliable damage model has to conceive a regularization of the fracture energy, which is normally normalized to a characteristic dimension of the element (characteristic length), very coarse meshes could lead to inaccurate results since their accuracy depends on the strain gradient, the damage pattern and consequently stresses redistribution. An improvement of the constitutive models could be represented using fracture mechanics algorithms, which originate from the analysis of localized fractures in quasi-brittle materials, which ensure mesh independence of numerical results and realistic representation of propagating cracks in the numerical simulation of fracture in quasi-brittle materials [6].

However, when dealing with periodically well-organized masonry, the assumption of a single tensile strength value (governing the tensile response in each direction) runs the risk of being overly simplistic. To this end, some orthotropic nonlinear constitutive laws have been developed and applied in masonry structures. Lourenco et al. have proposed a first example of an orthotropic plasticity model with softening and the ability of that continuous model to represent the inelastic behavior of orthotropic materials to reproduce the resistant behavior of different types of masonry [41].

In recent years, the effect of anisotropy has been introduced through fictitious spaces of isotropic stresses and strains. The properties of the material in the fictitious isotropic space are mapped to the real anisotropic space by means of a consistent


a) b)

c)

Figure 8.
Finite element model of the damaged structure [35, 40]: (a) Damage status, (b) stress state of the damaged sector, and (c) stress state of the masonry due to non-homogeneous settlements.

fourth-order operator. It has the advantage that classical plasticity theory can be used to model nonlinear behavior in anisotropic spaces [42, 43].

From this concept, an orthotropic damage model has been developed specifically for the analysis of masonry subjected to in-plane cyclic loading. Different elastic and inelastic properties are adopted along the two natural axes of the masonry (i.e., the directions of bed joints and head joints) also as principal axes of damage, since when stresses are reversed, the crack closes, and the material regains its stiffness.

Martín proposes an anisotropic damage model that decouples the behavior in tension and compression, in addition to contemplating the directionality of the damage [44].

Pelà et al. [45] have more recently proposed an orthotropic damage model for masonry analysis, in which the orthotropic behavior is simulated through mapping tensors that link the real anisotropic field with an auxiliary fictitious space. The model allows the simulation of orthotropic-induced damage, while accounting for unilateral effects, through a decomposition of the stress tensor into tensile and compressive contributions. The damage model has also been combined with a crack tracking technique to reproduce localized crack propagation in the FE problem [6].

Although direct continuum anisotropic approaches represent scientifically sound solutions, their application in real cases is scarce due to their computational cost and fundamentally to the number of properties of the material to be mechanically characterized, which is substantially higher than isotropic approaches.

2.1.4.2 Homogenization procedures and multi-scale approaches

A constitutive law of a homogeneous model at the structural scale that tries to represent the masonry can be deduced from the homogenization processes based on RVE. The definition of an adequate RVE is crucial, since it must be representative of the heterogeneity of the scale of the material under study, incorporating the characteristic heterogeneities of the material in a statistical way. Various RVE geometries have been proposed, to account for different periodic and non-periodic masonry patterns (**Figure 6**).

Given the mechanical complexity of masonry, in terms of anisotropy, three main families of approaches can be distinguished [6]:

- a priori homogenization where first an RVE-based homogenization is performed to deduce the properties of the material at the structural scale and then the homogenized mechanical properties are introduced into the model at the structural scale,

- step-by-step multi-scale where the general behavior at the structural scale is determined step by step by solving a boundary value problem (BVP) in the RVE for each integration point of the model at the structural scale and from that determination, an average response is estimated as a constitutive relationship in the step-by-step structural scale model.

- adaptive multi-scale, in which the material scale model is adaptively inserted and resolved into the structural scale model, thus establishing a strong coupling between the two scales.

2.2 Confined masonry modeling

In this case, there is a combination of elements of different materials with different physical-chemical-mechanical properties. In general, vertical and horizontal ties of reinforced concrete or steel are used, forming a framework resistant to vertical and horizontal loads, closing its openings with masonry.

The experiences obtained from earthquakes and from laboratory tests have shown a different behavior when the resistant framework has masonry than when it is not filled.

The interaction mechanisms between the infill masonry and the reinforced concrete frame system may require two design approaches [46]:

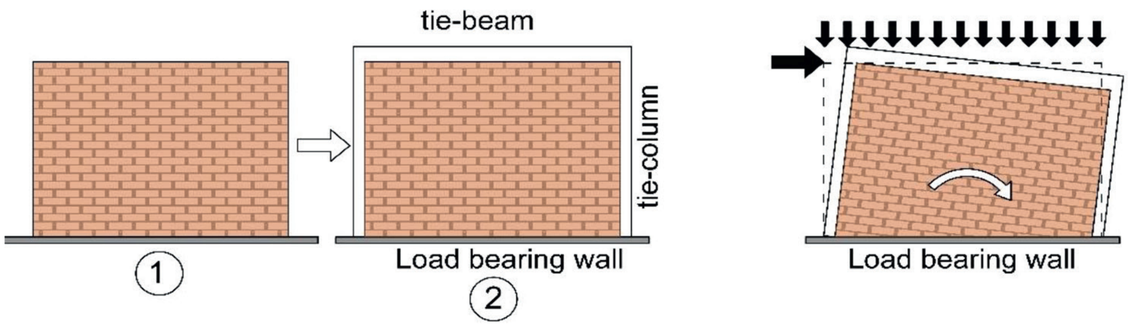


Figure 9.
Constructive process of confined masonry and behavior under seismic loads.

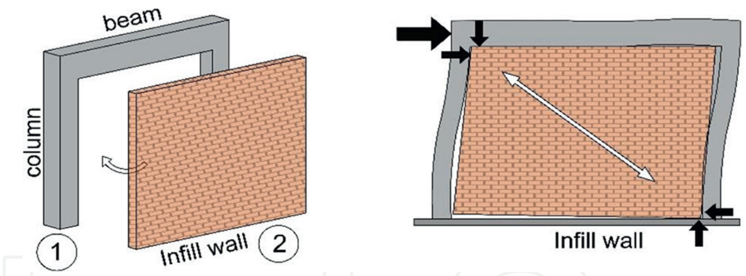


Figure 10.
Constructive process of filled confined masonry and behavior under seismic loads.

- The wall infill is constructed as a constituent part of the structural system. In this case, the effect of interaction of forces between the masonry filling and the reinforced concrete framework must be considered (**Figure 9**).

- The wall fill is built as a secondary structural element, separated from the main structure by means of suitable joints, allowing the main structure to deform freely during the earthquake (**Figure 10**).

2.2.1 Confined masonry with box behavior

Brick masonry buildings have a great mass and, therefore, large horizontal forces are generated during an earthquake, causing damage due to shear, tensile, and compressive stresses. A proper choice of structural configuration helps to minimize damage and prevent collapse. Earthquake evidence shows that confined masonry constructions with adequate wall density can withstand major earthquakes without collapse [46].

The most appropriate structural model is identified as “box action” that connects reinforced concrete beams and columns with masonry panels, floors, and ceilings. The horizontal beams at the plinth, parapet, lintel, and gable level support the masonry walls forming a unit. At ceiling level, flat or inclined reinforced concrete, ceramic, or wood slabs can also be used. Poorly connected roof or unduly thin walls are threats to good seismic performance.

The earthquake-resistant construction regulations have been incorporating the confined masonry design for use in social housing or buildings with symmetrical floors, considering the general shape and size of the building with limitations of slenderness and heights, the distribution of weight and elements resistant to lateral load in a regular and symmetrical way throughout the considered building [3, 14, 47].

2.2.2 Confined masonry with equivalent structures

Infill masonry significantly increases the rigidity of the structural system; therefore, to determine the interaction forces between the framework and its infill, it is necessary to know the contribution of the constituent elements to the lateral resistance of the assembly, as well as the change in the contribution with the increase in inelastic deformations of the assembly during the earthquake.

The investigations carried out by Zarnic and Tomaževič in the 1980s [2] have made it possible to evaluate this behavior, and their results have been incorporated into different regulations on earthquake-resistant constructions, especially for their application in the construction of social housing [47].

To model the inclusion of masonry in reinforced concrete frames, a fictitious compression diagonal can be used. Due to the complexity of the behavior of the structural system, the simplified numerical model must be based on the results of quasi-static and cyclic dynamic tests [3]. The layout of the compression diagonal is affected by location, size, and slope in such a way that it must be adjusted to achieve the combined structural behavior of the fill and the limiting structure.

The lateral stiffness in the plane of the filled frame is different from the sum of the independently interacting elements. Tests have shown that under seismic loads, the reinforced concrete structure separates from the fill, reducing the initial lateral stiffness due to nonlinear behavior of the system and reaching 60% of the maximum seismic load [3, 48].

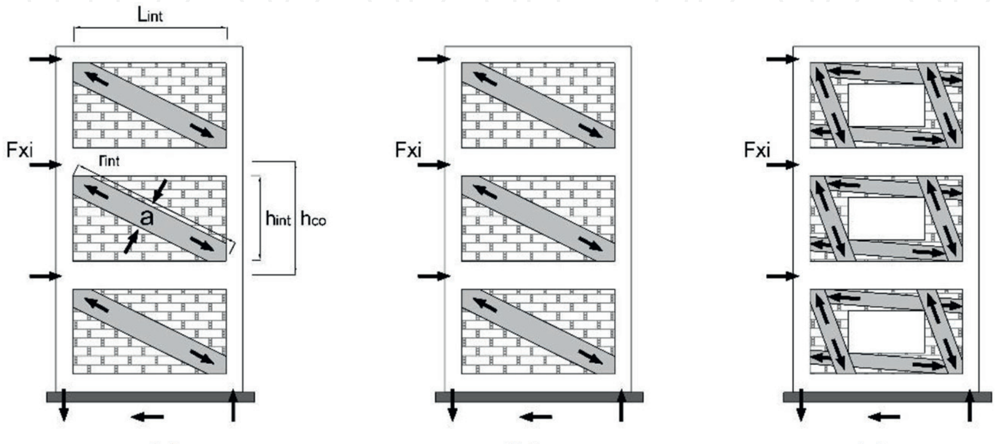
The American standard ASCE/SEI 41-13 guides on how to model the diagonal compression strut in the structural system with different arrangements: concentric (**Figure 11a**), eccentric (**Figure 11b**), at an angle of 45° (49), or in combination when they present openings (**Figure 11c**) [3]. The criteria for dimensioning the diagonals for the calculation model maintain the same thickness as the masonry panel as thickness and its height is a function of the width of the panel [47–49].

For undamaged infill panels, the arching effect of the masonry provides significant resistance to out-of-plane forces. This effect decreases when the filler is damaged due to in-plane forces. The exact mechanisms of deterioration cannot be reliably quantified, and therefore, the two actions are currently considered separately [5].

2.3 Modeling of reinforced masonry

Reinforced masonry with distributed reinforcement is one in which there is horizontal and vertical reinforcement distributed throughout the wall, placed in such a way that the masonry, mortar, concrete, and steel act together to resist the stresses. In this type of masonry, the placement of confined columns is not necessary (**Figure 12**) [46].

The presence of vertical and horizontal reinforcement in ceramic or concrete masonry units improves the resistance and ductility of the resistant wall. The vertical reinforcement is positioned in the hollow cores of the masonry unit where concrete is injected to anchor the reinforcement and protect it from corrosion according to the calculation of the reinforcement section necessary to absorb the stresses. The



(a) (b) (c)

Figure 11.
(a) Concentrically located compression strut analogy, (b) eccentrically located compression strut analogy, (c) compression strut analogy in infill walls with openings.

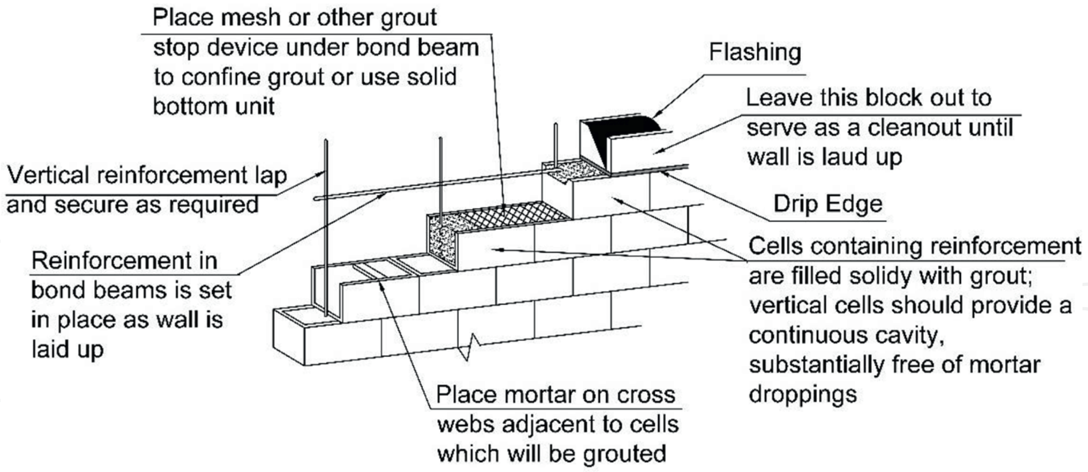


Figure 12.
Placing reinforcement in hollow bricks in a masonry wall [9].

horizontal reinforcement is located in the horizontal joints or in the connection beams of the floor and lintel. The amount of reinforcement is calculated as reinforced concrete based on the acting loads [3, 47].

3. Conclusions

The service life of well-constructed masonry structures over time indicates that it is a sustainable material due to its durability, adaptability, and maintainability. However, current construction practices of production with great speed and minimum amount of material impact the traditional image of this solid, durable, and sustainable construction material.

Finite element modeling has had a great evolution in applications to masonry structures, with different degrees of difficulty depending on the type of masonry, layout or rigging, edge conditions, data availability and tests, taking into account the objective of its application and experience level of the modeler.

Finite element method modeling for historical masonry structures is considered to have made great progress in the last decade, and the different software available adapts to the different conformations of the masonry structure. Improvements are still pending regarding connectors, sealants in joints and behavior of coatings under different environmental conditions.

Finite element models and structural element models represent the behavior of the masonry at different scales, therefore the predictions of the behavior of the masonry present differences, which in some cases can be significant.

Confined masonry modeling is based on field and laboratory experiences. The design guidelines present the current earthquake resistant regulations, either considering the box behavior or as an analogy of compression struts.

The modeling of reinforced masonry applies criteria of reinforced concrete macro-models.

Practical models of masonry structures available in masonry structure codes apply to current construction guidelines.

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