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Multiscale Seismic Vulnerability Assessment and Retrofit of Existing Masonry Buildings

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Abstract: The growing concern about the protection of built heritage and the sustainability of urban areas has driven the reoccupation of existing masonry buildings, which, in the great majority of the cases, were not designed or constructed to withstand significant seismic forces. This fact, associated with territorial occupation often concentrated in areas with high seismic hazard, makes it essential to look at these buildings from the point of view of the assessment of their seismic vulnerability and retrofitting needs. However, to be effective and efficient, such an assessment must be founded on a solid knowledge of the existing methods and tools, as well as on the criteria that should underlie the selection of the most appropriate to use in each context and situation. Aimed at contributing to systematise that knowledge, this paper presents a comprehensive review of the most relevant vulnerability assessment methods applicable at different scales, as well as the most significant traditional and innovative seismic retrofitting solutions for existing masonry buildings.

Keywords: seismic vulnerability assessment; large-scale vulnerability analysis; numerical modelling; seismic retrofit

1. Introduction

Devastating seismic events keep raising the awareness of scientific, technical and political community to the need of identifying assets at risk and developing more effective and cost-efficient risk mitigation strategies. The capacity to accurately assess the seismic vulnerability of these assets plays a fundamental role in this context, mainly because among the three factors that make up the standard formulation of risk (hazard, vulnerability and exposure), the vulnerability is the only factor in which engineering research can intervene. Nevertheless, and despite the significant advances in the field of seismic engineering and risk assessment, there is still much to be done, particularly with regard to existing buildings, most of them built without antiseismic provisions. Moreover, the wide variety of construction and structural systems, associated with the complex behaviour of their materials (raw earth, timber, masonry, steel and reinforced concrete), greatly limit the application of current codes and building standards to the existing building stock.

To tackle this global issue, it is fundamental to enhance the engagement between innovation and technical stakeholders towards the development and application of more sophisticated and reliable methods of analysis, as well as improved seismic retrofitting techniques compliant with buildings conservation principles, a goal that can only be achieved on the basis of a solid knowledge of the current state of the art. Based on this assumption, the present paper provides a general framework on the issue of the seismic vulnerability assessment of existing masonry buildings by reviewing the most relevant vulnerability assessment methods applicable at different evaluation scales (from large to building scale assessment) and the most successful traditional and innovative solutions used in the retrofitting of existing masonry buildings.

2. Seismic Vulnerability Assessment Approaches at Different Scales

The selection of the most appropriate seismic vulnerability assessment method to use must be made based on a proper balance between simplicity (of the tool) and accuracy (of the results), keeping always in mind that vulnerability outputs can be affected by several sources of uncertainty that should acknowledges and addressed, namely those related to the limitations of the model itself and to the inherent randomness of both the sample and the response.

Over the last decade, several European consortiums have been working on different aspects related to the assessment and mitigation of vulnerability and seismic risk, namely on the classification and categorisation of existing seismic vulnerability assessment approaches at different scales. According to their classification, methodologies can be grouped into three main categories taking into account their level of detail, scale of evaluation and use of data: (1) first level approaches, (2) second level approaches and (3) third level approaches (see Figure 1).

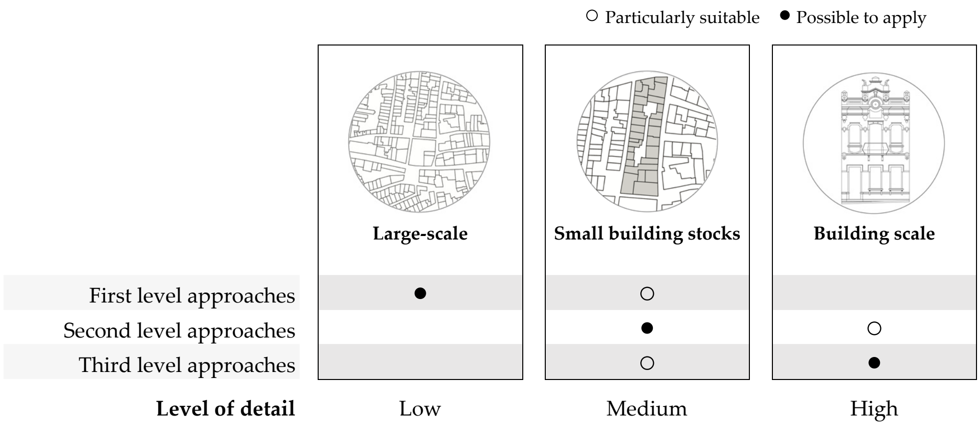


Figure 1. Analysis techniques versus assessment scales.

First level approaches are mainly based on the use of qualitative information and therefore they are ideal for the development of large-scale seismic vulnerability analysis. Second level approaches are based on mechanical models, which rely on detailed geometrical and mechanical information. For this reason, second level approaches are particularly suited to the assessment of small building stocks (aggregates or single buildings). Finally, third level approaches involve the use of complex numerical modelling techniques, which require a comprehensive and rigorous geometrical, material and mechanical characterisation of the building.

3. Large-Scale Seismic Vulnerability Assessment Methods

When assessing the vulnerability of a large number of buildings, the amount of information to collect and treat can be massive and thus the use of more expedite approaches is more adequate. Large-scale seismic vulnerability assessment methods, either at the national or urban level, should be based on few vulnerability indicators, which are usually defined from the statistical treatment of past earthquake damage data. The definition and nature of such methods (some of them are much more quantitative while others are more qualitative) naturally limits their methodological formulation and the level at which the assessment is conducted, from the expedite evaluation of an entire area based on the identification and characterisation of representative building typologies to the individual assessment of each building. Thus, and according to the scheme in Figure 1, some remarkable examples of the application of first and second level approaches are given in the following subsections, categorising them into four different groups of methods: typological, indirect, conventional and hybrid.

3.1. Typological Methods

According to typological methods, buildings are classified into different classes depending on a series of aspects (structural, construction, material, etc.) that either directly or indirectly influence their seismic response. In these methods, vulnerability is described as the probability of a structure to suffer a certain level of damage for a given ground motion intensity level, and damage probabilities are defined on the basis of past earthquake damage data and expert judgement. Since results obtained using typological methods are based on field investigation, they have to be considered in terms of their statistical accuracy. In this sense, they are valid only for either that particular area or for other areas with similar field conditions (in terms building typology and seismic hazard). A striking example of the use of a typological approach are the Damage Probability Matrices (DPMs) developed by Whitman et al. [1]. In this work, the authors have compiled DPMs for several building typologies according to the damaged sustained in over 1600 buildings after the 1971 San Fernando earthquake. According to different authors [2,3], one of the first European versions of a DPM was produced in Italy by Braga et al. [4] from the statistical treatment of the damage data collected after the 1980 Irpinia earthquake. The authors have used a binomial distribution to describe the damage distributions of each class for different seismic intensities. Buildings were separated into three vulnerability classes (A, B and C) and a DPM based on the MSK scale [5] was evaluated for each class [6]. The Italian National Seismic Service has processed the same Irpinia 1980 database, in order to obtain DPMs, see Di Pasquale et al. [7]. The main differences between this work and the original DPMs proposed by Braga et al [4] lies in the use of dwellings instead of buildings and in the quantification of the earthquake intensity in terms of MCS scale [8], instead of the MSK scale [5].

Although, as already referred, its origin goes back to the 1970s, the use of DPMs is still very popular. In 2003, as part of the ENSeRVES project (European Network on Seismic Risk, Vulnerability and Earthquake Scenarios), Dolce et al. [9] have derived DPMs for the Italian town of Potenza. An additional vulnerability class (D) was included by the authors in the formulation using the EMS-98 scale [10] in order to account for the buildings constructed after 1980 (i.e., buildings that have either been retrofitted or designed to comply with recent seismic codes) [2,6]. More recently, Lagomarsino and Giovinazzi [11] proposed a set of DPMs from the European Macroseismic Scale (EMS) aimed at providing a model for estimating seismic damages in five increasing and perfectly defined levels of damage.

3.2. Indirect Methods

Indirect methods involve the determination of a vulnerability index and the establishment of a series of relationships between damage and seismic intensity [6], which are generally supported by statistical studies of postearthquake damage data. As schematised in Figure 1, indirect methods have been applied extensively to assess the seismic vulnerability of large areas and/or building stocks. The "Vulnerability Index Method", originally proposed by Benedetti and Petrini [12] (see also [13]), is one of the most applied indirect methods, involving the computation of a vulnerability index (i.e., a building vulnerability classification system), which aims at traducing the physical and structural characteristics of the building into a quantitative form. According to this approach, each building is classified in terms of a vulnerability index related to a damage grade determined via the use of vulnerability functions. These functions enable the formulation of the damage suffered by buildings for each level of seismic intensity (or peak ground acceleration, PGA) and vulnerability index, see Figure 2. Indirect methods use extensive databases of building characteristics (typological and mechanical properties) and rely on observed damage after recent earthquakes to classify vulnerability, based on a score assignment. An adapted vulnerability index method has been developed and used to assess the seismic vulnerability of both unreinforced masonry and reinforced concrete building under the scope of "Catania Project" [14]. Following the guidelines of ATC-21 [15], a rapid screening approach was used in this project to define the vulnerability scores of the buildings.

Among the main advantages of indirect techniques, it is worth highlighting their ability to determine the vulnerability characteristics of the building stock under consideration, rather than base the vulnerability definition of a certain building typology considered as representative of the that building stock. Nonetheless, since they are based on vulnerability indices that are defined on the basis of empirical-based coefficients (weights), the uncertainty associated to the results is potentially high and should therefore be taken into account. Moreover, large-scale assessment using indirect techniques (at a regional or a national scale) must be based on data gathered from a large number of buildings, assumed to be representative of the building stock [16].

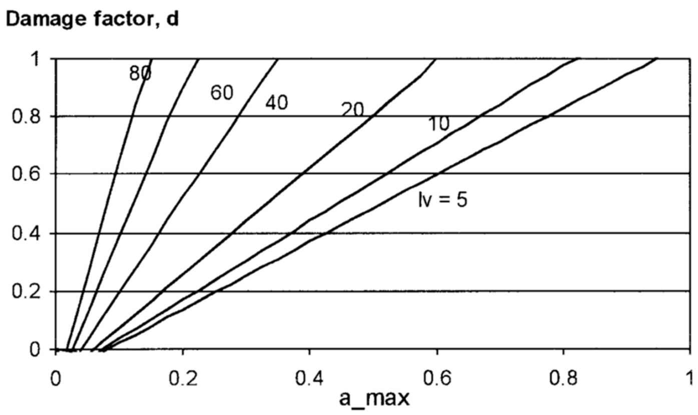


Figure 2. Unified relationships between vulnerability, damage and peak ground acceleration, adapted from Petrini [17].

3.3. Conventional Methods

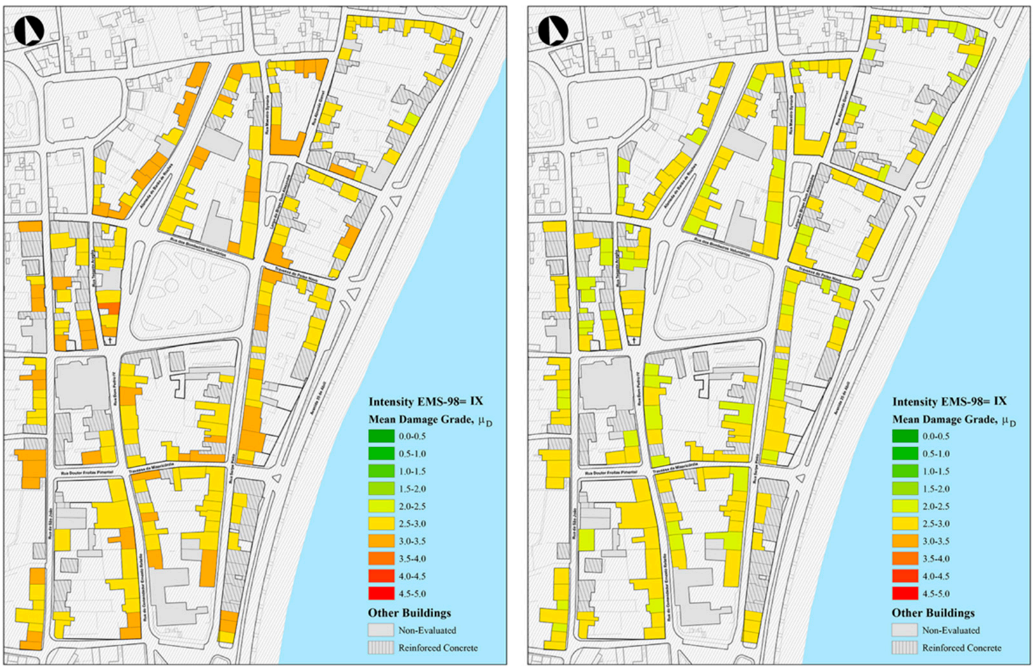
Conventional techniques are essentially heuristic, proposing a correspondence between a vulnerability index and a certain level of damage. According to Vicente et al. [18], there are essentially two groups of conventional approaches: the group that qualify the different physical characteristics of structures empirically and the group of those based on the criteria defined in seismic design standards for structures, evaluating the capacity–demand relationship of buildings. One of the best-known approaches of the first group is probably ATC-13 [19]. Damage probability matrices were defined therein based on the know-how of more than 50 senior earthquake engineering experts who were asked to estimate damage factors (the ratio of loss to replacement cost, expressed as a percentage) for Modified Mercalli Intensities [20] from VI to XII, and for 36 different building classes. Some large-scale risk and loss assessment works based on ATC-13 can be found in the literature [21–25]. As an example, Table 1 presents the damage factors for each damage state, computed by Eleftheriadou and Karabinis [22] for the city of Basel.

Table 1. Damage probability matrix (DPM) presented by Eleftheriadou and Karabinis [23] for Basel.

Damage Grade	CDF (%)	Intensity					
		V	VI	VII	VIII	IX	X
1	5	8	35	20	20	5	0
2	20	0	8	37	37	15	7
3	55	0	0	35	35	37	15
4	90	0	0	8	8	35	37
5	100	0	0	0	0	8	41
MDF		0.4	3	14	35	63	84

3.4. Hybrid Methods

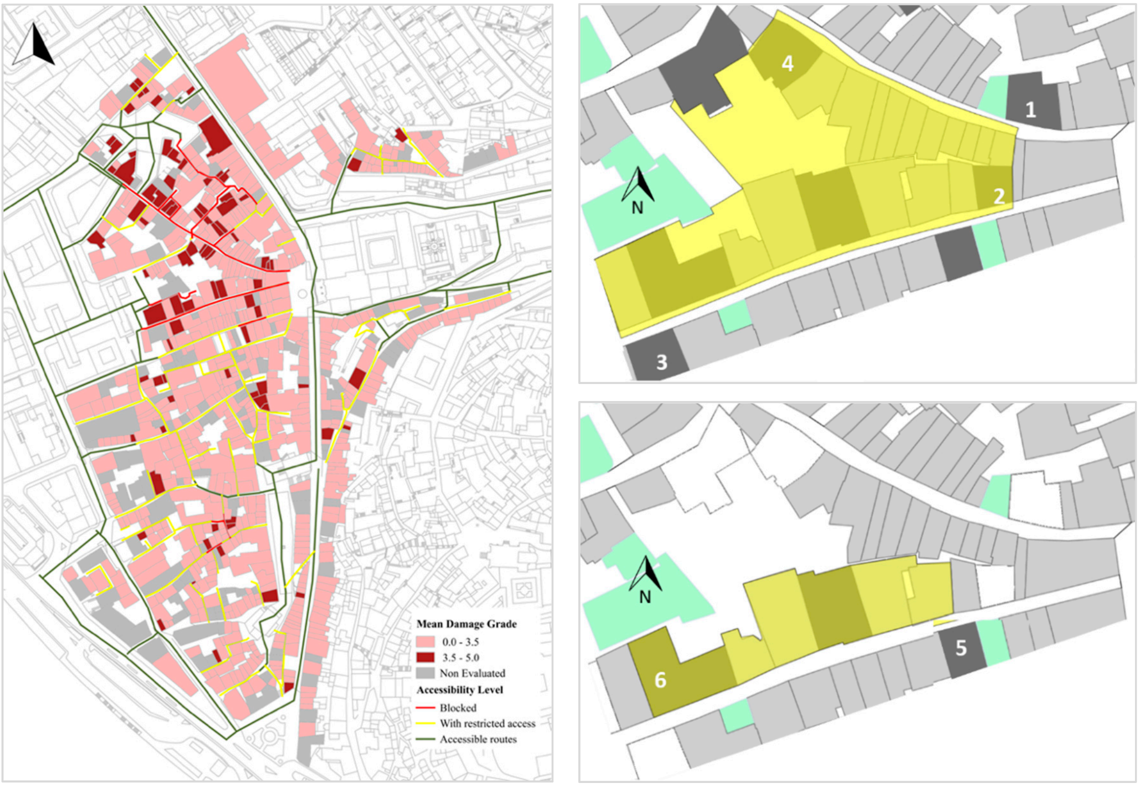
As its name suggests, the hybrid techniques combine features of the above-mentioned techniques. A representative example of a hybrid technique is the macroseismic approach proposed by Faccioli et al. [11], which combines the characteristics of the typological and indirect methods using the referred vulnerability classes and a vulnerability index improved by the use of modifier parameters. This macroseismic method, either in its original format or with some minor adaptations, has been widely applied for assessing the seismic risk of various urban areas, such as Barcelona (Spain) [21], Faro (Portugal) [26] or Annaba (Algeria) [27], just to mention some, as well as of neighbourhoods [28] and building aggregates [29]. An interesting example of the combined application of a hybrid approach and a GIS tool was recently presented by Ferreira et al. [30]. In that work, the authors make use of a simplified index-based approach to evaluate the impact resulting from the adoption of different large-scale retrofitting strategies, measured in terms of material, human and economic losses. In order to improve their interpretation, the results are mapped using a commercial GIS software, wherein georeferenced graphical information was combined and connected to a relational database containing the main structural characteristics of the buildings, see Figure 3. Various modules with different objectives were developed and integrated into the GIS, including vulnerability assessment, damage and loss estimation (number of collapsed buildings, casualty rate, number of unusable buildings and repair costs) for different macroseismic intensities, allowing for the construction of multiple physical damage and loss scenarios. With this discussion, the authors intended not only to demonstrate how simplified seismic vulnerability assessment approaches can be used to analyse the impacts resulting from the implementation of large-scale retrofitting programs (Figure 3a versus Figure 3b), but also to prove that investing in prevention strategies designed to mitigate urban vulnerability is one of the most effective strategies, both from the social and economic standpoint.



(a) (b)

Figure 3. Mapping of damage scenarios for the old city centre of Horta: (**a**) before and (**b**) after the application of seismic retrofitting strategies, adapted from Ferreira et al. [30].

In the same line, Aguado et al. [31] took advantage of a hybrid approach to discuss the potential benefit resulting from the application of different seismic retrofitting strategies, not only accounting for their effect on the reduction of individual and global damages resulting from different seismic scenarios, but also regarding their global impact in terms of civil protection and urban accessibility. For such, the authors applied a hybrid seismic vulnerability assessment approach for façade walls to obtain vulnerability and damage scenarios for the historical city centre of Coimbra. Resorting to a GIS tool, these scenarios were subsequently used to map evacuation routes with different levels of accessibility, see Figure 4a. Blocked, restricted access and free roads were plotted considering both the façade walls prone to partial or total collapse and the narrowness of streets. Moreover, the urban areas that may be potentially inaccessible in the case of a seismic event were also identified, as well as the number of people that, in consequence, may be affected. Finally, the author has analysed the impact, in terms of urban accessibility, of retrofitting the building façade walls that define the areas more prone inaccessibility, see Figure 4b. Due to its immediate and practical application, it is easy to understand that this kind of information is of major significance for decision-makers and civil protection agencies.



(a) (b)

Figure 4. Mapping of (**a**) evacuation routes and (**b**) configuration of the most critical urban area before (top) and after (bottom) retrofit, adapted from Aguado et al. [31].

4. Seismic Vulnerability Assessment at Building Scale

The seismic behaviour of existing masonry buildings is complex and depends on several aspects. The evaluation of the seismic response of this type of buildings can be divided in two main types of behaviour: (1) in-plane behaviour and (2) out-of-plane behaviour. In the last decades, several experimental and numerical studies on the in-plane and out-of-plane of existing masonry buildings were carried out, which allowed for significant improvement of the knowledge on its seismic performance. Furthermore, these studies helped develop new tools for the seismic assessment of existing masonry buildings. In the next sections, an overview on the numerical modelling approaches at material level, and the numerical modelling methods, the types of analysis and the assessment criteria for the seismic assessment of existing masonry structures at the building scale are presented.

4.1. Numerical Modelling Approaches at Material Level

Masonry is a composite material with units and joints. The units can be adobe bricks, fired bricks, ashlars, irregular stones and others. Two main types of joints can be distinguished, namely, dry joints and mortar joints. The mortar joints can be such as mud mortar, lime-based mortar and cement-based mortar, among others. The structural behaviour of masonry depends on several aspects: (a) material properties of units and joints; (b) geometrical properties of units and joints; (c) quality of the workmanship; and (d) conservation status. The morphology of the cross-section of the masonry element has also influence on the structural, since the masonry can present: (a) different types of unit bonds, such as uncoursed bond and coursed bond with stone units or the English bond and Flemish bond with brick units; (b) different number of layers/leafs that compose the masonry element (single leaf masonry wall, multileaf masonry wall and multilayered vault); and (c) different types of arrangement at the connections between the walls (with and without interlocking).

The strategy for the numerical modelling of existing masonry buildings can be defined based on the assumptions assumed at material level. At material level, three elements can be distinguished in the masonry with mortar (Figure 5a): units, mortar and interface unit/mortar. Two main approaches can be adopted to simulate masonry [32]: micro- and macromodelling. Micromodelling can be further divided into [32] detailed micromodelling and simplified micromodelling. In the macromodelling approach (Figure 5d), the units, the mortar and the interfaces unit/mortar are modelled together as a continuum and composite material. In the simplified micromodelling approach (Figure 5c), the units are expanded (unit and half of the thickness of the mortar) and they are simulated as continuum elements. The behaviour of the mortar and of the interface unit/mortar is modelled by discontinuous elements. The third approach (Figure 5b) corresponds to the most detailed approach, in which the units and the mortar are simulated by independent continuum elements and the behaviour of the interfaces unit/mortar are modelled by discontinuous elements. The mortar with dry joints can be simulated using a micromodelling approach, composed by continuous elements for the units and discontinuous elements to simulate the interfaces unit/mortar (infinite compressive stiffness and strength and no tensile stiffness and strength). In general, the most detailed modelling approaches provide simulations that are more accurate and can be more representative of the real behaviour. However, they are more complex, since they require a high number of material parameters and more computational effort. The number of material parameters is significantly high when the nonlinear analysis is adopted. Thus, the selection of the modelling approach at material level should be based on an equilibrium between the required precision in the results and the effort needed to prepare the model, run the analysis and analyse the results. In general, macromodelling is used to simulate entire buildings, while micromodelling is adopted to model small portions/elements of masonry. For examples of applications of the macromodelling, simplified micromodelling and detailed micromodelling see respectively Mendes and Lourenço, Kurdo et al. and Andreotti et al. [33–35].

4.2. Numerical Modelling Methods

In the numerical modelling of existing masonry buildings, four main strategies based on the following methods can be distinguished: (1) Finite Element Method (FEM); (2) Distinct Element Method (DEM); (3) equivalent frame method; and (4) method using rigid macroblocks taking into account the expected collapse mechanisms.

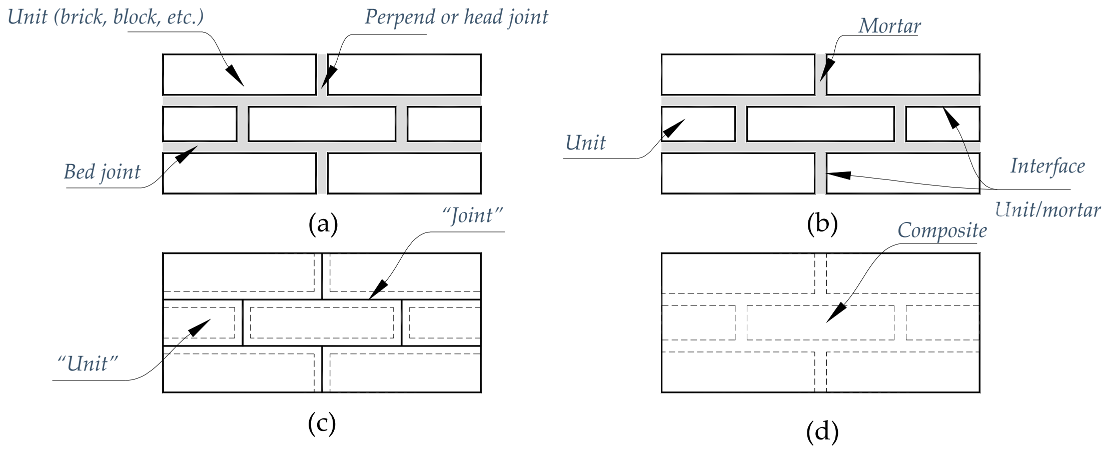


Figure 5. Modelling strategies at material level: (**a**) masonry sample; (**b**) detailed micromodelling; (**c**) simplified micromodelling; and (**d**) macromodelling, adapted from Lourenço [32].

In the Finite Element Method (FEM) (Figure 6b), the continuous domain is discretised by a mesh composed by elements connected by nodes. It is a method widely used to solve complex engineering problems, in which the problem is described by differential equations. In structural problems, first a numerical model, composed by elements, is prepared. Then, and after running the analysis, the results are obtained and evaluated. The FEM has several types of 1D, 2D and 3D elements based on different formulations that can be adopted to simulate structural problems, such as beams elements, shell elements or solid elements. FEM has also available other types of elements to simulate particular behaviours/characteristics of the structure, such as interface elements, springs elements, mass elements, boundary elements or reinforcement elements. This method can be used to solve static and dynamic problems, with linear and nonlinear behaviour. The nonlinear analyses can be adopted to simulate the nonlinear behaviour of the materials (e.g., cracking and crushing of masonry) or the geometric nonlinearity. The FEM models can consider also the anisotropic behaviour of the masonry. The standard FEM method to solve nonlinear problems is implicit, which requires an iterative method, more computational effort and provides an unconditionally stable solution. There are also FEM codes that provide the explicit method, aiming at reducing the computational effort associated to the convergence difficulties of the implicit method. However, this FEM method is unconditionally stable and small steps should be adopted. Several softwares to solve complex structural problems, including the behaviour of existing masonry buildings, are available, such as DIANA™ [36], ANSYS® [37] or Abaqus Unified FEA™ [38].

The FEM has been widely used to evaluate the structural performance of existing masonry buildings, including for the seismic action. Most of the FEM models of entire buildings are developed based on the macromodelling approach (Section 4.1), even for historic buildings, since it is the most simple and fast approach to prepare the models and run the analysis. In general, this approach is a good compromise between required accuracy and computational effort to evaluate the global seismic behaviour of an entire masonry building. There are several applications of the macromodelling approach based on the FEM to evaluate the performance of masonry buildings, taking into account the in-plane and out-of-plane behaviour of the walls, and to evaluate the efficiency of strengthening techniques [39–41]. The numerical models developed in the FEM based on the micromodelling approach (Section 4.1) are detailed, requiring more computational effort. Thus, this modelling strategy is not commonly adopted simulate the seismic behaviour of entire masonry buildings. It is mainly adopted to simulate a small portion of masonry or a masonry element, such a masonry wall (e.g., [42,43]).

The Distinct Element Method (DEM) (Figure 6a) was mainly developed to solve problems related to discontinuous materials, such as soils or masonry. Due to high computational effort required to run DEM models, this method was used mainly to simulate behaviour of small models. Nowadays, and to the recent advances in the computer hardware, the DEM is becoming more popular, even to solve problems of civil engineering, such the evaluation of the seismic performance of masonry structures. In the analysis of masonry structures or masonry components, two approaches can be adopted for DEM models: (1) DEM models developed with rigid or deformable blocks and (2) DEM models developed with spherical particles. The DEM models with spherical particles involve a high number of elements and they are not appropriated to simulate entire masonry buildings. In general, the masonry models based on DEM are prepared with blocks to simulate the units, in which the interaction between the blocks is defined by contact points. The normal and shear stress at the contact points are based on the relative displacement caused by applied forces. In this method, the accuracy is guaranteed if an enough number of contact points are adopted [44]. When the deformable blocks are adopted, the blocks are discretised into an internal finite element mesh (combined FEM/DEM method [45]). The DEM allows stimulating the collapse mechanisms at large displacement domains, which is useful to evaluate the behaviour of masonry buildings from the initial damage until near its collapse, including damage caused by the sliding mechanism. The solution is obtained from an explicit time-stepping algorithm, which allows to simulate the nonlinear interaction of a large number of blocks without high computational requirements or to use an iterative method. Thus, small steps should be used. The UDEC [46], 3DEC [47] and DEMpack [48] are examples of software based on DEM. In general, these softwares have also beam and cables elements to simulate strengthening of the structure.

The DEM can be useful to take into account the effect of the morphology of the masonry, using one block to simulate each unit, which require a high computational effort for large models. The computational effort can be reduced if the blocks simulate portions of masonry composed by several units. In this simplification, the discretisation should be carefully defined, taking into account the expected collapse mechanisms, since it can have influence on the response of the model. There are several applications of the DEM to evaluate the seismic performance of existing masonry structures, mainly for historic constructions [49–51].

In the equivalent frame method (Figure 6c), the main objective is to represent each type of member of the masonry building (piers, lintels, spandrels, etc.) by a specific structural element that simulate its behaviour (1D or 2D FEM element, macroblock, macroelements, etc.). In general, these structural elements are connected by rigid nodes, springs or interface elements. Thus, a 3D equivalent frame to the structural system of the buildings is created. This type of modelling strategy started to be applied by Tomaževič [52] in 1978, where the 1D macroelements were adopted to simulate the diagonal shear failure of the piers and assuming that the in-plane global behaviour of masonry walls is mainly controlled by this type of failure (POR method). In the last decades, new formulations based on this modelling strategy have been developed, aiming at including other types of behaviour and failures with influence in the global seismic behaviour of masonry buildings, such as both flexural and shear behaviour of piers and spandrels or the sliding failure of the piers. The analysis based on this numerical modelling strategy is significantly faster than the analysis carried out using the previous methods, since involves a very low number of degrees of freedom. Several software using the equivalent frame method are available for masonry buildings, such as 3Muri [53], PRO_SAM [54] and 3DMacro [55]. In general, this software allows users to take into account the contribution of other types of structural elements, such as timber floors or reinforced concrete floors. The analysis of existing masonry structures based on the equivalent frame methods can be also performed in software's that were not originally developed for masonry structures and more common in design offices, such SAP2000® [56], simulating the piers and the columns through beam elements with vertical and/or horizontal rigid offsets, connected by plastic hinges (spring elements to simulate the shear and the flexural behaviour) [57]. For examples of applications of this modelling strategy to existing masonry buildings see Lagomarsino et al., Magenes et al. and Penna et al. [58–60].

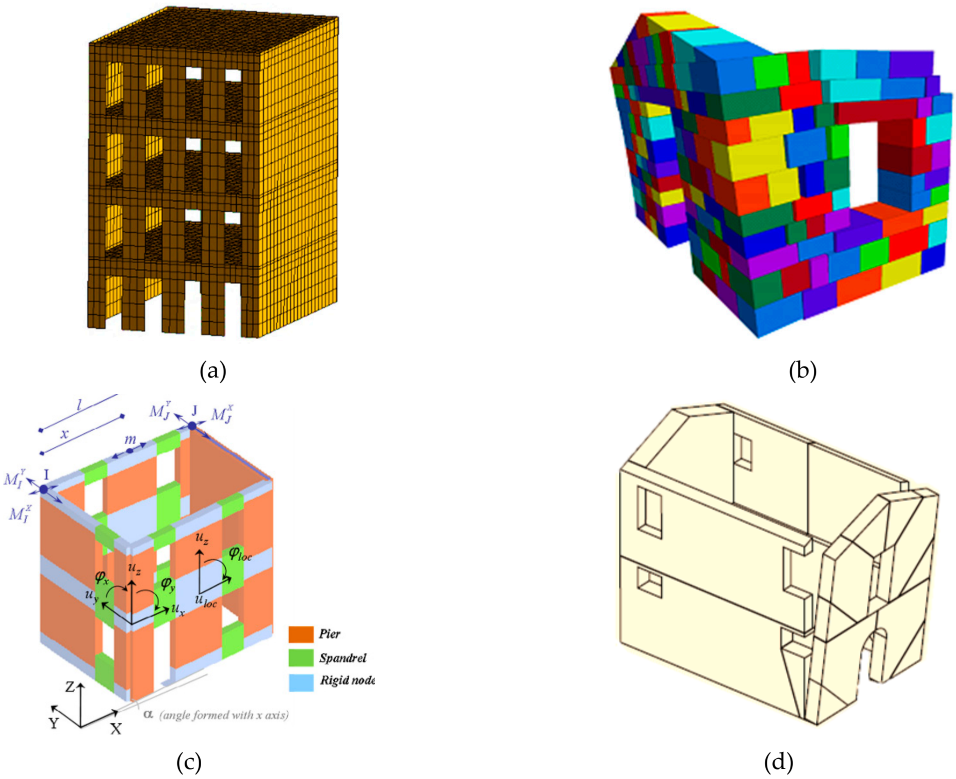


Figure 6. Examples of numerical model of masonry buildings using: (**a**) FEM [61], (**b**) DEM [50], (**c**) simplified equivalent frame method [62] and (**d**) method with rigid macroblocks taking into account the expected collapse mechanisms [63].

Finally, in last numerical modelling strategy (Figure 6d), the masonry building is discretised into several rigid macroblocks taking into account the expected collapse mechanisms. In general, and contrarily to the previous method of modelling, in this modelling strategy the macroblocks are defined by the failure lines and are larger than the structural components of the masonry walls, which reduces the number of elements and computational effort. The expected collapse mechanisms can be defined based on damage observed in postearthquake surveys, results obtained from experimental tests, numerical results obtained from analysis with FEM and DEM models and practitioner experience [64]. This means that the assumptions adopted for the discretisation of the structure can have influence on the evaluation of its seismic response, mainly when the collapse mechanism associated to the lowest load capacity is not considered. In general, the classic limit analysis (no tensile strength along the macroblock interfaces, infinite compressive strength for the macroblocks and the sliding failure is not considered) is used in modelling strategy, which makes it a practical and fast numerical tool to evaluate the seismic behaviour of existing masonry buildings. However, more advanced limit analysis with rigid blocks has been developed, for example, considering the crushing of the masonry and the sliding failure [65,66]. This numerical modelling strategy can be also adopted to evaluate easily the seismic capacity of local failures of masonry buildings using the static equilibrium equations (e.g., overturning of the façade with rotation at the base of the wall). For examples of application of this modelling strategy to masonry structures see Orduña [63] and Mendes [67].

4.3. Types of Analysis

The previous numerical modelling strategies can be adopted to perform different types of analysis to obtain the seismic response of existing masonry buildings. Five main types of structural analysis are highlighted: (1) limit analysis; (2) linear static analysis; (3) nonlinear static analysis (pushover analysis); (4) linear dynamic analysis; and (5) nonlinear dynamic analysis with time integration.

In general, the limit analysis, which can be based on the static or the kinematic approach, requires a low number of material properties and low computational effort. It provides results on the collapse mechanism and the load capacity of the structure. This type of analysis is a very useful tool for the evaluation of the seismic performance of existing masonry buildings [67].

The linear static analysis is mainly used to design new structures and, since does not considered the nonlinear behaviour of the masonry, it is not an analysis appropriated to evaluate the seismic behaviour of masonry structures near the collapse. This limitation is extended to the linear dynamic analysis, such as the modal analysis or the linear dynamic analysis with time integration.

In the evaluation of the seismic performance of existing masonry buildings, the nonlinear static analysis (pushover analysis) is the most used. In this type of analysis, the nonlinear behaviour of the masonry (e.g., cracking and crushing) is considered, and the seismic action is applied by using horizontal static loads. The horizontal loads can be proportional to the mass or to the shape of the fundamental mode of the structure and they are increased until the collapse of the building. In general, it requires the applications of several nonlinear parameters of the masonry and an iterative method to obtain the solution (implicit analysis), which can cause some convergence difficulties. Besides these aspects, it is a powerful tool to simulate the behaviour of masonry and a good compromise between accuracy of the results and effort computational. It provides results fundamental to evaluate the response of masonry buildings, such the capacity curve (applied force vs. displacement at the control point), where it is possible to know the inception of the nonlinear behaviour, the maximum capacity of the structure and zones of concentration of damage. Several procedures using the pushover analysis have been developed to estimate the seismic response of structures, such as the N2 method [68], the capacity spectrum method [69] or the displacement coefficient method [70]. It should be noted that the first nonlinear static approaches were mainly developed for regular concrete or steel structures with rigid diaphragms. Thus, more recent and advanced nonlinear static approaches have been developed or adapted for existing masonry structures, for example considering the effects of the in-plan and in-elevation irregularly of the building [71].

Finally, the nonlinear dynamic analysis with time integration is the most advanced type of analysis, in which accelerograms are applied at the base of the structure. However, it is not practical for the evaluation of the seismic behaviour of existing masonry building, since requires the applications of several nonlinear material properties of the masonry, including the damping ratios and advanced mathematical tools to solve the equation of motion at each time step. In general, the FEM uses the implicit solution with an iterative method by default and the solution for DEM is obtained using the explicit method. Although this type of analysis provides detailed and precise results on the dynamic response, it requires advanced knowledge on structural analysis, interpretation of results and high computational effort. For examples of nonlinear static and dynamic analyses carried for the evaluation of the seismic performance of masonry buildings see Mendes and Lourenço [61] and Chácara et al. [72].

4.4. Assessment Criteria

After the selection of the numerical modelling strategy to simulate the structure, the selection of the type of analysis, to obtain the numerical response of the building, and the seismic assessment can be carried out, comparing the capacity of the structure with the demand criteria. Three main approaches for the seismic assessment can be adopted: (1) Force-Based Approach (FBA), (2) Displacement-Based Approach (DBA) and (3) Energy-Based Approach (EBA).

In the FBA, the internal forces (e.g., axial forces, shear forces or bending moments) are compared with the demand forces defined in the codes for the seismic analysis of structures. This type of approach is widely used to design new structures, for the ultimate and service limit states. In the seismic assessment of structures based on the FBA and using the typical linear static analysis for design, a behaviour factor is adopted to take into account the inelastic cyclic deformation and the energy dissipation capacity of the structural system. However, the deformation is better related to the severity of the damage and the dynamic behaviour near the collapse. Thus, the DBA seems more appropriated to evaluate the seismic response of existing masonry buildings, mainly to evaluate the rocking mechanism. In this approach, the response in terms of deformation (e.g., displacements or drifts) is compared with the limit states defined in the seismic codes/literature, which are associated to the severity of the damage (e.g., no damage, minor damage, severe damage and collapse) [72]. Finally, the seismic assessment of a structure can be performed comparing the demand energy with the required energy to obtain the collapse of the building (EBA) [73]. Although this assessment approach is not commonly used, some research on the overturning of masonry walls based on the EBA has been performed [74].

5. Seismic Retrofitting Techniques for Masonry Buildings

When a building system or an existing structure are deemed unsafe under seismic loads or present evident limitations regarding these actions, improvement of the seismic behaviour is required to reduce the seismic vulnerability and to allow safe use. The awareness of the humankind to seismic risk occurred centuries ago and led to the development of several traditional seismic resistant building practices, which aimed not only at improving the local building processes, but also the existing buildings. The development of these practices was based on the empirical knowledge gained through time by the local populations struggling against the repeating destruction of several earthquakes. The most successful traditional practices are nowadays identified in many buildings around the world and are recognised as evidences of local seismic cultures [75]. On the other hand, the recent developments on earthquake engineering made the building practices and strengthening strategies become supported by a scientific background. These recent developments allowed also the proposal of innovative seismic retrofitting strategies based on advanced technologies and materials, which grant high structural efficiency.

In general, the traditional retrofitting solutions follow five main principles: (1) improvement of the connections between structural elements to allow a better global behaviour; (2) stiffening of the horizontal structural elements; (3) consolidation of the vertical structural elements; (4) use of redundant structural elements as backup for possible partial failure; and (5) construction of additional structural elements contributing to the resistance of the building to horizontal loads.

The innovative retrofitting solutions added two more principles: (1) improvement of the mechanical properties of the masonry walls to increase the loading and displacement capacities and (2) reduction of the dynamic effects induced by earthquakes.

The following sections present a brief discussion on the most successful traditional and innovative solutions used in the retrofitting of existing masonry buildings.

5.1. Traditional Solutions

Very frequently, ancient masonry buildings present timber floors and roofs, which are typically insufficiently stiff to provide to the structure the so-called "box behaviour". "Box behaviour" is responsible for promoting the structural collabouration between the masonry walls, meaning that in its absence the global seismic response of a building is considerably limited [39]. Furthermore, these buildings are also characterised by poor floor–wall, roof–wall and wall–wall connections, which do not allow the structure to develop a satisfactory monolithic "box behaviour" [76]. Thus, it is compressible that many of the traditional strengthening solutions are focused in the improvement of these limitations of ancient masonry buildings.

The introduction of ring beams between the walls and the roof is one of the most effective solutions to ensure the structural integrity of masonry buildings. Traditionally, ring beams are built using a pair of longitudinal planks joined together by transversal elements in a ladder-like configuration [77]. Nevertheless, they can be built using more rough timberworks, such as a grid of horizontal timber trunks or tree branches lying longitudinally and transversally [78]. In the last few decades, ring beams were also built using reinforced concrete, but this procedure introduces compatibility concerns, whose discussion is beyond the scope of this paper. The introduction of ring beams can lead to different types of improvement of the structural behaviour, namely enhancement of the "box behaviour" (increase of the loading and deformation capacity), prevention of out-of-plane collapse of the walls and tying of masonry leaves in multileaf walls. Thus, ring beams should be continuous around the entire building and present adequate connection at the intersections between walls and between the ring beam and the walls in order to provide the best performance. The main drawback of ring beams is its installation, since it may require removing and raising the roof.

Ties have been also extensively used for seismic strengthening of ancient buildings and are typically composed of timber tie beams or steel rods connecting walls in opposing façades (see Figure 7a). In this last case, steel anchor plates are used to fasten conveniently the tie rod to the masonry, meaning that this solution only works when the walls tend to move away from each other. Nevertheless, it enhances the "box behaviour" of the building by avoiding the out-of-plane collapse of the façades and by constraining the floors and roof. Thus, steel ties are typically introduced at the floor and roof levels, thus avoiding interference with the habitable spaces. The dimension of the anchor plates is another important aspect of this strengthening solution, as they should be sufficient large to avoid shear failure of the masonry. It should be noted that in buildings with vaulted masonry floors and roofs, ties are applied with similar purpose, namely to limit relative lateral movements of the abutment walls caused by seismic loads. This type of strengthening promotes the preservation of the geometry of the vault, avoiding its collapse.

(a) (b) (c)

Figure 7. Examples of traditional strengthening solutions: (**a**) steel tie, (**b**) installation of an anchor system and (**c**) buttresses.

The strengthening of connections of timber roofs and floors with the masonry walls is traditionally achieved with the use of timber wedges, which ensure a tight mechanical connection between the joists and the walls. In case of absence of this solution in existing buildings, its implementation requires sufficiently long resting lengths of the joists. In alternative, metal brackets, steel straps and ties can be more easily implemented to connect the timber floors and roofs to the walls [79]. Partial reconstruction can also be used to introduce or substitute timber wall plates, which ensure a better transition of the roof or floor timber elements to the walls. As referred previously, proper roof–wall and floor–wall connections are fundamental to promote the "box behaviour" of the structure.

The strengthening of masonry buildings by means of the improvement of the connection wall–wall is also frequently observed in existing masonry, namely at the corners. This type of improvement has been mainly implemented during the construction of these building by employing materials with better mechanical properties at these sections, which include high quality stones, bricks and timber elements. In existing buildings without these solutions, their implementation would require a large amount of reconstruction work, nevertheless the bond between original and new materials can be questionable. In this case, the strengthening of the wall–wall connection is more easily implemented by using anchor systems (Figure 7b), where a rebar is introduced in the masonry and is effectively bonded by means of grout injection and an anchor plate [80]. The additional tensile strength provided by this strengthening solution improves the load transmission capacity between intersecting walls, enhancing the "box behaviour".

Stiffening of floors and roofs made of timber is an effective solution to improve their diaphragmatic behaviour and, consequently, to improve the "box behaviour" of the existing structure. Floors and roofs can be stiffened by means of diagonal bracing, triangulation and by providing an additional layer of sheathing boards or timber planks placed perpendicularly to the existing ones [81]. Stiffening can also be achieved by substituting the timber floors with slabs made of reinforced concrete or mixed concrete clay blocks, which require building reinforced concrete beams on the walls to conveniently support the slabs. These beams should grant an adequate connection with the walls and provide uniform load transmission [82]. Nevertheless, this solution is highly intrusive, meaning that its use may be unacceptable.

Consolidation of the masonry walls (vertical structural elements) is a particularly used in multileaf walls. Under seismic loading, the masonry leaves tend to behave independently from each other if they are not properly connected, meaning that they are more susceptible to separation and thus to out-of-plane failure. The connection between leaves is typically assured by through-stones, which consist of long stones placed through the full thickness of the wall. These elements serve as connectors between leaves and allow an enhanced load distribution [51]. In multileaf walls without these elements, proper connection can be achieved by means of transversal ties, where a rod is introduced through the full thickness of the wall and is properly fixed with an anchor system and/or grout injection [83]. Consolidation of masonry walls also involves repairing existing cracks (e.g., postearthquake cracks) that debilitate the in-plane and out-of-plane performance of the walls. Cracks can be repaired by means of partial reconstruction, soft stitching and stapling. The first technique is very labour-intensive and intrusive, meaning that its use is only justified in the case of severe damage. Soft stitching consists in opening chases crossing the cracks, which are then filled with masonry units to create a mechanical bond. Stapling consists in applying staple shaped steel rebars transversally to the crack to connect the split sides [84]. Repointing (or deep repointing) is another technique employed to consolidate masonry and consists in removing the bed–joint mortar to substitute it by a better one. This procedure improves the accommodation between units and the bond in the masonry. In some situations, reinforcing rebars are also introduced with the mortar to mitigate other structural problems, such as creep damage [85].

Openings are clearly weak points of masonry walls, which must be properly designed to avoid collapse during seismic excitation. In this regard, lintels are key elements that must grant proper redistribution capacity of the transmitted loads. Lintels can be constituted by single stones or timber elements with length longer than the span and/or by discharging masonry arches. Thus, strengthening can be achieved by reinforcing the lintel resisting elements or by substituting them by stronger ones. Another option to reduce the seismic vulnerability associated with openings is to reduce their span or, as a more drastic solution, close them permanently [75].

Providing redundant structural elements to an existing building allows avoiding full collapse, even if partial collapse of the most vulnerable structural elements occurs [86]. Thus, this strategy is not efficient to mitigate damage. Rather than that, it allows to preserve the life of inhabitants by avoiding falling parts of the building to the interior. To this purpose, an additional structure made of timber, reinforced concrete or steel is built inside the existing building, which nowadays may constitute an intervention excessively invasive and likely unacceptable.

The construction of buttresses is a strengthening solution that serves to help the walls of a building counteracting the horizontal loads induced by earthquakes. Buttresses are massive masonry walls with typical triangular shape (see Figure 7c), which limit the out-of-plane movement of the adjacent walls due to the contribution of their heavy weight and additional shear stiffness and strength. Thus, buttresses and adjacent walls should be properly connected with cross ties in order to avoid an independent behaviour when both move apart, as undesirable impact damage may occur [78].

5.2. Innovative Solutions

The development of innovative seismic strengthening solutions originated new approaches for interventions in existing masonry buildings. Despite structural strengthening efficiency being the main motivation associated with these solutions, in their initial proposal, not all cases respected the main principles established in the conservation charters. Nevertheless, further experience and scientific studies helped improve many aspects of some of these solutions, among which the fulfilment of compatibility requirements was a main focus. The following paragraphs present a brief discussion of the main innovative strengthening solutions developed for existing masonry buildings, namely grout injection, externally bonded composites, base isolation and energy dissipation.

The strengthening of multileaf masonry walls with grout injection consists in filling their inner voids and cracks with a fluid mortar (see Figure 8a), which after hardening provides continuity and bond to the material [87]. Thus, the connection between leaves, and the overall stiffness and strength of the walls are significantly increased [83], leading to an improved seismic behaviour [88]. The capacity of grouts to penetrate into small pores also enables this solution to be used in the repair of cracks [89]. Despite the advantages of grout injection, it presents important drawbacks, such as the unpredictability of the required grout volume and the irreversibility of the solution. This unpredictability compromises the cost control of the intervention due to the impossibility of measuring adequately the ratio and interconnectivity of the voids, which, in general, represent an important percentage of the total wall volume (as high as 30%). Thus, the complete injection of the walls in the building can be a costly operation, meaning that its use in large buildings may be prescribed only for the most vulnerable walls. The irreversibility of grout injection also raises concerns on the selection of the grout, thus the use of poor compatibility grouts should be avoided. In this regard, past interventions evidenced that epoxy- and cement-based grouts may introduce durability problems in ancient masonry walls. Nowadays, several commercial grouts specifically developed for this type of masonry are available and are mainly composed of lime and pozzolanas, which provide enhanced compatibility.

(a) (b)

Figure 8. Examples of innovative strengthening solutions: (**a**) grout injection and (**b**) textile-reinforced mortar (TRM).

The strengthening of masonry with externally bonded composites has been also used to reduce the seismic vulnerability of masonry buildings, especially in Italy, where these solutions were mainly based on fibre-reinforced polymers (FRP). The popularity of FRP-based strengthening was driven by its ease of application and high efficiency in increasing the tensile strength and ductility of masonry walls, while increasing negligibly the weight (high strength and stiffness to weight ratio). Nevertheless, it presents several drawbacks related with the use of organic matrixes (epoxy-based), such as poor fire resistance, lack of vapour permeability, low reversibility, high-cost and poor compatibility with masonry substrates [90,91]. Thus, alternative composite solutions have been developed by integrating matrixes with enhanced compatibility, namely cement-, lime- or clay-based mortars. The adequate embedding and bond of these mortars also required substituting the sheet textiles by mesh textiles or steel grids with adequate aperture sizes (Figure 8b). These alternative composites are known as Steel Reinforced Grout (SRG), Fibre-Reinforced Cementitious Matrix (FRCM) or Textile-Reinforced Mortar (TRM) [92,93]. Nowadays, several commercial TRM systems are available in the market, as provided by companies such as Ardea Progetti, BASF, Kerakoll, Mapei, Sika and Simpson Strong-Tie. These systems are constituted by meshes of different fibres (steel, glass, carbon, basalt and polyparaphenylene benzobisoxazole) and mortars of different composition; nevertheless, they are in general high mechanical performance materials. Recommendations for designing FRP-based strengthening solutions are sufficiently documented in ACI 440 7R-10 [94] and CNR-DT 200 R1/2012 [95] for concrete and masonry elements. These recommendations have also been used for designing TRM strengthening systems for masonry, nevertheless they lack comprehensive instructions, in particular for what concerns application procedures, quality assurance of the materials, durability verification, laboratory and field testing methodologies and the effectiveness of the installation. More recently, the American Concrete Institute published the ACI 549.4R13 [96] to fill this gap.

The use of antiseismic devices to reduce the vulnerability of existing masonry buildings is not frequent, but in the last few years has been gaining attention, especially in the seismic protection of buildings with significant cultural value. Several types of devices have been proposed, among which the most interesting for masonry buildings are base isolators and passive dampers.

Base isolation consists in isolating the structure from the seismic vibrations by introducing an interface with low horizontal stiffness and sufficient capacity to support the vertical loads. This interface modifies the modes of the structure, namely increases their fundamental period and changes their configuration. Furthermore, the increase in horizontal flexibility, introduced by the base isolators, results in a reduction in the accelerations of the structure (by avoiding resonance) and a total displacement increase. Nevertheless, the structure behaves as a rigid body, meaning that the relative displacements of the structure are reduced and thus the associated damage. It should be noted that the total displacements concentrate at the interface of the system, which constitutes a limitation to the use of this solution if they may affect nearby buildings. Base isolation devices can be classified as elastomeric bearings and sliding bearings. Lead–rubber bearings are among the most established devices, whose installation in existing masonry buildings involves (1) construction of reinforced concrete beams at the base of the walls, (2) construction of the base of the devices, (3) installation of the devices, (4) lifting of the structure and transfer of its dead-weight to the devices and (5) construction of a rigid diaphragm at the level of the beams to promote a joint operation of the full system. The lifting–transfer phase is the most critical of the process, as it requires limiting the induced differential settlements to avoid causing damage to the masonry walls and other structural elements. As is implicit, this strengthening solution has an intrusive implementation and especially it can be very costly due to the complexity of the implementation process. Despite this, base isolation has been successfully applied in the strengthening of notable masonry buildings, such as the Salt Lake City and County Building (USA) [97].

The installation of passive dampers presents as main objective the improvement of the structure capacity to dissipate the energy transmitted by an earthquake, which in turn allows to improve the its seismic performance and reduce the induced damage. Dampers can be classified as (1) viscous dampers, (2) viscoelastic dampers, (3) hysteretic metallic dampers and (4) friction dampers. Viscous dampers are constituted by a hollow metallic cylinder filled with a silicon-based fluid and a piston that forces the fluid to pass through its small holes at high speed. The movement of the fluid originates high forces that oppose to the relative movement of the damper and dissipates energy through heat due to interparticle friction. The resisting forces are proportional to the piston speed and depend on the viscosity of the fluid. The installation of this type of dampers significantly increases the structural damping, which, in case of an earthquake, allows a significant reduction of the induced deformations. Viscoelastic dampers are normally constituted by metallic sheets intercalated by deformable polymeric sheets. The shear deformation of the polymeric sheets due to relative movements of the damper extremities generates heat and dissipates energy. The dissipated energy is a function of the elastic deformation and deformation speed. In general, the installation of this type of dampers modifies the structural linear parameters for damping and stiffness. Hysteretic metallic dampers dissipate energy by exploiting the plastic deformation capacity of steel, which can be achieved by using low-yielding stress steels or cruciform cross-sections. Finally, friction dampers dissipate energy due to friction generated at the contact surface between two moving solid elements. These dampers are typically constituted by steel plates connected transversally by nuts and bolts fixed with a specific torque, which defines the friction force required to initiate energy dissipation. In general, passive dampers can be installed to strengthen specific structural elements, meaning that they constitute a solution less intrusive and costly than base isolation. The Siena Cathedral (Italy) is an example of a historical monument strengthened with dampers. In this case, two spring viscous dampers were installed to improve the out-of-plane behaviour of the tympanum of the main façade [98].

6. Conclusions

A comprehensive literature review of the main methods and techniques proposed in the last decades to assess and mitigate the seismic vulnerability of existing masonry buildings is presented in this paper. Before making some final remarks, it is worth noting that, despite the authors' efforts to compile a sample of works as relevant and comprehensive as possible, there are certainly several other important works that, due to space constraints or oversight, are not included herein.

From the review given in this paper it is possible to draw some important conclusions. The first regards the selection of the most appropriate seismic vulnerability assessment method to use. As it is mention is Section 2, and easily verifiable from the discussion included in Sections 3 and 4, the selection of the most appropriate method or technique to use must be made based on a proper balance between its simplicity and the accuracy of its results. In this sense, it is very important to stress that vulnerability results can be strongly affected by several sources of uncertainty, which, for this reason, must be acknowledged and addressed. Moreover, and perhaps not less important, in order to be effective, it is fundamental that vulnerability indicators can be easily understood and interpreted, not only by the technical and scientific community, but also by citizens and governmental and civil protection authorities [99]. GIS tools can play a particularly relevant role in this context, making it possible to manage and communicate vulnerability and risk results in a very simple but informative manner. As exemplified in Section 3, such tools can be actually very helpful for the development of strengthening strategies, cost–benefit analyses, civil protection and emergency planning.

The fundamental role of vulnerability assessment methods from the risk mitigation standpoint was also clearly demonstrated though the discussion presented herein. In fact, only on the basis of a comprehensive knowledge of the characteristics of the buildings and of their structural vulnerabilities it is possible to select and implement proficient mitigation strategies and to outline strengthening interventions that can contribute to reduce, in an effective and cost-efficient manner, their seismic vulnerability.

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