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Research Article

Damage and Interventions to Historical Masonry Buildings: Good and Ill Practices

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ABSTRACT

This paper presents typical damage observed during recent earthquakes in Türkiye and elsewhere, along with their qualitative interpretation revealing the main weaknesses of existing stone masonry buildings. Historical structural systems, having a stone masonry ground storey and upper storeys made of timber framed masonry are also included. Strengthening techniques, frequently applied to alleviate the inherent inadequacies of stone masonry buildings are commented on, while their rationale, their efficiency and the effect of their misuse are presented, based on field observations after recent earthquakes and/or experimental results. The paper focuses on good and ill practices with the purpose of opening the discussion on the selection of adequate intervention techniques that may ensure an improved seismic behaviour, thus protecting human lives and property and contributing to the preservation of the built cultural heritage.

Introduction

Earthquakes in several countries throughout the globe have repeatedly demonstrated the inherent weaknesses of old unreinforced stone masonry buildings. On the contrary, there is evidence about the satisfactory behaviour of some historical structural systems, e.g., buildings made of timber-laced or timber-framed masonry. In countries around the Mediterranean and elsewhere, heritage buildings present similarities in their structural system and, hence, they undergo similar damage due to seismic events. Consequently, similar interventions are adequate for their pre- or post-earthquake strengthening and improvement of their overall behaviour. The international engineering community is being quite active in this field in the recent decades, while several national and regional regulatory documents were or are being produced, providing guidance related to the selection of adequate intervention techniques, to the investigation of their efficiency, as well as to their design and application. A survey of the internationally available relevant research data and guidelines is obviously beyond the scope of this paper. The purpose of this work is to briefly identify the main weaknesses or strong points of historical structural systems, as revealed by in situ observations after several earthquakes. On this ground, and based on the effect of recent earthquakes, including the 2023 Türkiye-Syria earthquakes, this paper focuses on some frequently applied intervention techniques and offers evidence on their positive or negative effects on the seismic behaviour of stone masonry buildings.

The main weaknesses of stone masonry buildings

Unreinforced stone masonry is known to be a heavy, composite, anisotropic and brittle material, with mechanical properties of low value. The old Constructors, building using this material were frequently taking measures to ensure the survival of their constructions, especially in earthquake prone areas. Some of those measures are: Thick walls of significant lateral stiffness, limited length of openings (doors and windows) compared to the total length of the building, strengthening of the perimeter of the openings (e.g., arched lintels, elaborate construction using larger stones embedded to masonry piers, etc.), proper connection of perimeter walls at the corners of the building, etc. There are, however, some typical weaknesses of old masonry buildings, repeatedly revealed because of many earthquakes in the last decades. Those weaknesses, aggravated by non-repaired slight to moderate damage due to previous earthquakes, by ageing and decay, by the lack of maintenance, by the abandonment of rural areas, etc., can serve as a basis for the selection of adequate remedial measures to protect the lives and the property of the inhabitants and, indeed, the built cultural heritage. It is noted that the weaknesses mentioned herein have been repeatedly identified, and described in several publications (e.g., [1]), including those referring to damage due to the 2023 earthquake sequence in Türkiye-Syria (e.g., [2], [3] and [4]. The related typical damage is presented and interpreted.

Vulnerable Construction Typology of Masonry

There is a vast variety of construction typologies of masonry, both on the faces of bearing elements and within their thickness. Quite frequently, the exterior face of masonry is of more elaborate construction than the interior one and it remains unplastered. Therefore, within the thickness, there are two leaves of different construction typology either in contact between them (two-leaf masonry) or with a space between them (three-leaf masonry). That space may be of more or less solid structure, made of small stones and large mortar quantity. As a rule, the exterior leaves of masonry are not transversely connected, using header stones (Fig. 1).

Figure 1. Typical construction typologies of stone masonries in Greece, Italy and Türkiye

The seismic vulnerability of those construction typologies is two-fold: (a) The material filling the space between the two exterior leaves of masonry being of poor mechanical properties, the actual resisting thickness of the masonry elements is substantially smaller than their nominal thickness. Thus, the bearing capacity in compression, shear and out-of-plane bending is significantly reduced as compared to a solid wall of the same thickness. More importantly, (b) the weak bond between the exterior leaves and the filling material can be broken, either due to decay or due to previous even small to moderate earthquakes. Thus, with the masonry transversely delaminated, the bearing elements become more slender, the exterior leaves resist the seismic action separately from one another, both in- and out-of-their plane. The consequence of this behaviour was repeatedly observed after strong earthquakes (Fig. 1 and Fig. 2).

Figure 2. Delamination of three-leaf masonry and damage due to seismic actions in Amatrice and in Samos

Inadequate connection between cross walls

Although special attention was often given by the Constructors in the connection of walls at the corners of buildings (Fig. 3a), there are cases where this rule was not applied. Indeed, especially in case of three-leaf masonry, the transverse connection of the exterior leaves of masonry (by interlocking of the corner stones) was not always ensured. Furthermore, quite frequently, the perimeter bearing walls were constructed first, and the interior bearing walls were following, unconnected with the perimeter ones. The ensuing damages (Fig. 3b, c) are quite eloquent. The almost linear vertical crack in Figure 3b proves the lack of connection of the two walls, while in Fig. 3c, one may observe the large stones at the corner of the building, connecting the interior leaves of the two walls. The lack of connection between the interior and the exterior leaf is proven by the collapse of the latter, at the corner of the building as well.

Flexible diaphragms loosely connected to walls

Typically, floors and roof in unreinforced stone masonry buildings are made of timber (e.g., joists or trusses, and timber planking). The diaphragms, flexible in their plane, are connected only to the supporting them vertical elements, this connection being of limited fixity. Thus, the walls are subjected to largely different deformations during a seismic event. Furthermore, the overall lateral stiffness of the building is decreased (compared to a box-like building composed of well connected among them walls and diaphragms) and, thus, the deformations imposed to the walls are larger. This behaviour affects mainly the out-of-plane behaviour of walls, increasing the probability of damage and out-of-plane partial or total collapse. The situation is aggravated by the vulnerable construction typologies of masonry, typical for those buildings. The related damage is very frequent and illustrated also in the photographs of Figs 1 to 3.


(a)


(b)


(c)

Figure 3. (a) Solid connection of cross walls, (b) Almost vertical crack suggesting a deficient connection between walls, (c) Lack of connection between the exterior and the interior leaves of the three-leaf masonry walls.

Interventions to alleviate the weaknesses of unreinforced stone masonry buildings

The aforementioned typical construction characteristics of stone masonry buildings, leading to the repeatedly observed problematic seismic behaviour thereof, may guide the engineer to adopt the most adequate measures towards the improvement of this behaviour. Indeed, providing a monolithic behaviour to two- and three-leaf masonries, enhancing the in-plane stiffness of floors and roof and ensuring proper connection among all bearing elements (horizontal and vertical) would allot box-like behaviour to the building, reducing the deformations imposed to the bearing elements for the same input action, imposing practically equal deformations to all vertical elements, etc. Therefore, the following paragraphs focus on systemic schemes of interventions that may alleviate the seismic vulnerability of historical buildings and, hence, contribute to their preservation. It has to be admitted that there are cases where the difference between the targeted behaviour and that ensured by the aforementioned techniques is such that further measures (e.g., masonry or steel buttresses, new bearing system at the interior of the building, etc.) are to be taken. Those buildings are to be examined on a case by case basis. General solutions, applicable to the vast majority of buildings to be preserved, may not be sufficient.

Transversely connecting the leaves of masonry

This is an intervention of major importance, and it constitutes a precondition for the application and the efficiency of several other intervention techniques, as explained herein. The transverse connection of the leaves of masonry and, hence, the monolithic behaviour of masonry can be achieved through grouting and by using transverse (metallic or non-metallic) connectors. The development of grouts able to be injected (at low pressure) to historical masonries and to fill internal cracks and voids is a long process. So is the development of adequate equipment and sequence of mixing the grout constituent materials, as well as the application methodology.

While the first attempts were directed to grouts with high cement content, the current state-of-the-art [5], based on numerous experimental campaigns and applications, shows the preponderance of hydraulic lime-based or ternary grouts. Indeed, those grouts constitute a durable intervention, they ensure the homogenization of masonry (Fig. 4), while they provide significant enhancement of the mechanical properties of masonry [6], [7], [8].

Thanks to the improved bond of masonry materials within the thickness of the bearing elements, delamination of masonry is significantly delayed or avoided and the severe damages shown in Figs 1 and 2 are prevented.


(a)


(b)

Figure 4. A three-leaf masonry (a) before and (b) after the application of a hydraulic grout

Some documents (e.g., [9]) focus on the transverse connection of masonry leaves, using connectors. Those connectors may be steel bars, arranged at intervals, and bonded to masonry elements using a strong cementitious mortar. Alternatively, the steel connectors are positioned in drilled-through holes, they are bonded to masonry and anchored on the faces of masonry elements using steel anchorage plates. The recently approved Greek Code for the assessment and structural interventions of masonry structures [10] does not allow the transverse connectors to be the only technique applied to transversely connect the masonry leaves. Indeed, the positioning of such connectors at distances to a non-grouted masonry (like that in Fig. 4a) provides only local connection of masonry leaves and it does not prevent delamination and damage in regions between the anchors locations. The results of tests on three-leaf masonry walls (e.g., [11]) have proven that the application of transverse connectors does not increase neither their bearing capacity in compression nor their stiffness. The most efficient technique is grouting, while the combination of grouting and transverse connectors yields the best results in terms of transverse deformations of masonry walls. It is noted that the same techniques are adequate for the re-instatement or the improvement of the connection between bearing walls.

Enhancement of the in-plane stiffness of floors and roof

As aforementioned, the in-plane flexibility of timber floors and roofs of historical stone masonry buildings, and their loose connection to the vertical bearing elements are responsible for severe damage, especially, due to out-of-plane actions. This is more so, when flexible diaphragms are resting on vulnerable masonries liable to delamination. It has to be noted that any technique to enhance the in-plane stiffness of diaphragms should be applied to homogenized masonry elements and it should include the adequate connection of the diaphragms to the walls [10]. The examples presented and commented on herein prove the necessity of those measures.

Until few decades ago, the replacement of timber roofs by reinforced concrete slabs was a rather frequent intervention to existing masonry buildings. RC slabs were combined with the construction of an RC tie beam. The latter was usually cast on top of the walls, its width being smaller than or equal to the thickness of the masonry walls. At intermediate floors, casting a continuous RC tie-beam over a significant portion of the wall thickness is not feasible and, thus, the slabs replacing the timber floors did not extend to the outer face of the walls. It should also be noted that there are many cases, where the timber roof was preserved (or replaced by a new timber one, of the same geometry). In those cases, typically, a RC tie-beam was cast on top of the walls and underneath the roof, presumably ensuring diaphragm action at roof level. Nonetheless, simple mechanics may prove and, unfortunately, several earthquakes have evidenced that this assumption is far from being accurate. Another ill practice related to interventions at roof level is that no connection (using dowels) was provided between the RC tie beam and the walls. It was assumed that the friction between the concrete and the top face of the wall was sufficient for the transfer of actions from the roof to the walls. However, the vertical loads at the top of the building being of small value, the frictional force at that level may not be adequate. Modena [11] refers also to damage observed in strengthened buildings, following earthquakes in Italy. For example, a RC slab was cast monolithically with a tie beam at the level of an intermediate floor. The tie beam was cast on the interior leaf of masonry walls only, while the three-leaf masonry walls were not strengthened. The eccentric application of actions (due to the eccentricity of the tie beam), combined with the horizontal movement of the added mass of the RC slab with respect to the vulnerable three-leaf walls have led to the out-of-plane expulsion and collapse of the latter.

In another building, the stiff RC roof, seated on top of unstrengthened three-leaf masonry, has moved as a solid body by almost one meter out of the facade of the building. The inadequacy of replacing timber roofs by RC slabs and tie beams simply seated on masonry walls was observed also by Munari et al. [12], after the 2009 L'Aquila earthquake. Similar are the observations that can be made on the photographs of Fig. 5. The significant mass of the RC slab added at the top of unstrengthened masonry walls of vulnerable construction typology, without any connection to them, cannot prevent the out-of-plane failure of the walls and, thus, it does not offer any improvement to the seismic behaviour of the building. On the contrary, in cases where the slab loses support due to the collapse of the walls (e.g., Fig. 5 c, e and f), casualties or injuries of the inhabitants are imminent.

Although this work does not consider the case of mosques or churches, where typical damage is observed in arches and domes, as well as in minarets and belfries (e.g., [13], [14]), it is interesting to observe that, as reported in [15], based on observation and numerical work, interventions using RC, prior to the 2023 earthquakes, did not prove to be beneficial to the monuments, while in some cases their effect may be characterized as negative for the seismic behavior.

The purpose to enhance the in-plane stiffness of floors and roofs can be served by means other than the construction of RC slabs. Several techniques are studied (e.g., by Piazza [16], Valluzzi et al., [17] and [18]) and applied in historical buildings and monuments, namely, the addition of a second planking in floors and roofs (at an angle with respect to the original ones), the use of a system of steel ties (parallel, perpendicular, and diagonal with respect to the walls), etc. A non-negligible advantage of the alternative techniques is their application in-dry and the minimal increase of the mass of the building.

The application of those alternative techniques as well, is paired with the consolidation of masonry and the provision of adequate connection among the vertical and the horizontal bearing elements. Shake table tests on a two-story building model (scale 1:2), made of three-leaf stone masonry (Vintzileou et al., [19]), strengthened through grouting and enhancement of the diaphragm action of the floors (by double timber planking) have proven the adequacy of the interventions, as the box-action of the model was achieved, while the model was able to sustain significantly higher base accelerations than at its as-built state.

Enhancing the bearing capacity of stone masonry buildings

In addition to the systemic interventions applied to improve the overall behaviour of stone masonry buildings, interventions aiming at enhancing the mechanical properties of masonry (and, by way of consequence, of the masonry structural members) are often needed for the building to meet the requirements dictated by its new use, as well as by current seismic codes. In addition to grouting of masonry, deep rejointing of masonry is considered as an adequate and efficient intervention. This may be the case, provided that many conditions are fulfilled, namely, (a) the masonry is grouted (Modena, [11]), (b) the thickness of the masonry elements is limited (say, to 0.50m approx.), (c) the workmanship (meticulous removal of mortar from all joints, cleaning, application of the stronger mortar to completely fill all the joints) is of high quality, etc. Thus, deep rejointing is, in the majority of cases, an intervention of high cost and of limited efficiency. Last but not least, the new mortar cannot be of excessively higher mechanical properties than the replaced one. Otherwise, the concentration of stresses close to the outer faces of masonry -where the strong and stiff mortar is located- may lead to spalling of the masonry units and, finally, even to reduction of the pre-intervention mechanical properties of masonry, as observed by Vintzileou [20] for the compressive strength.

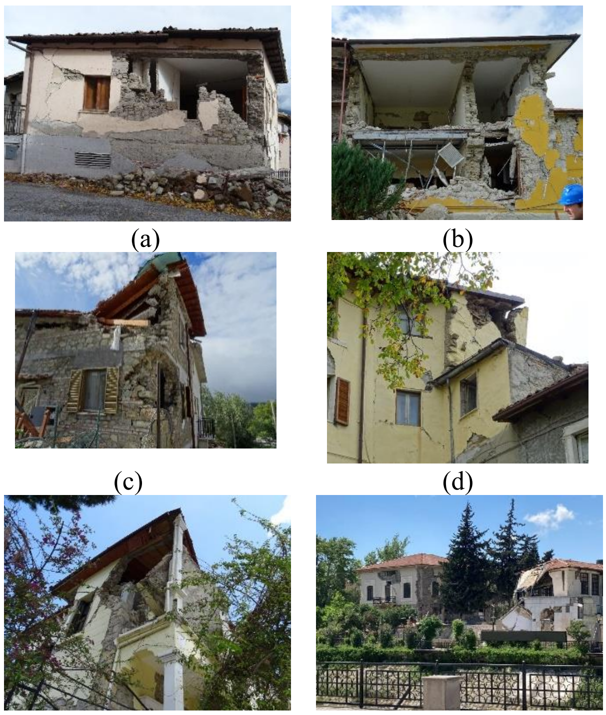

(a) (b) (c) (d) (e) (f)

Figure 5. The effect of RC slabs on top of unstrengthened masonry walls. (a) to (d) Italy, 2016, (e) and (f) Antakya, Türkiye, 2023.

Another technique, frequently applied in the past and currently prohibited by the competent authorities in several countries, is RC jacketing of stone masonry walls. In addition to the obvious reason of the harm caused by jacketing to the aesthetic and architectural values of historical buildings (Fig. 6), there are further reasons that justify the exclusion of this intervention, namely, the increase of the mass of the building, the radical change of the movement of moisture and vapour within walls enclosed in concrete (leading with time to the disintegration of masonry), the limited efficiency of one-sided RC jackets, usually applied in the interior of the building, etc. The need of bridging the gap between the targeted and the available bearing capacity can be served by alternative techniques (e.g., transforming partition walls to bearing ones, providing a new internal bearing system, constructing external buttresses, etc.) to be selected on a case-by-case basis. Last but not least, the new use of a historical building should be compatible with the potential of the structural system to safely host it, after due rehabilitation, respecting the values to be preserved.

Figure 6. RC jacket applications in listed stone masonry buildings in Greece

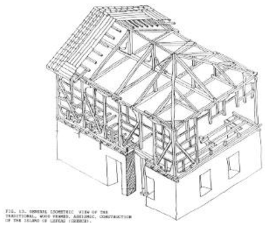
Mixed -stone masonry and timber-framed masonry- structural systems

In several earthquake prone areas, structural systems were developed to ensure improved seismic behavior and, hence, protection of human lives and property. A frequently met structural system is that of timber-framed masonry, presenting several alternatives in terms of materials, arrangement of timber elements, etc. In many locations, timber-framed masonry (in the upper story(ies)) is combined with unreinforced stone masonry in the ground story (e.g., Fig. 7a, and [21]).

A historical overview of this structural system is found in Vasconcelos et al. [22]. Timber-framed masonry is more or less elaborate. Indeed, there are cases where only vertical and horizontal timber elements are used, while in others, diagonal elements are also used (Fig. 7a). The connections among timber elements are simple (nails are used throughout the timber-framed masonry walls), while in other cases, special care is taken in the area of connection between walls and roof or floor, as well as in the corners of the building (Figure 7b).

Typically, the timber frames are filled with small size stones or bricks (fired or unfired), while the thickness of the walls is equal to the respective dimension of the timber elements. The main enemy of timber-framed masonry being the changes in moisture, the walls are typically protected either by the plaster (Figure 8) or by timber planking (Figure 7c).

The historical system combining stone masonry at the lower story and timber-framed masonry at the upper story is found in a number of buildings in Antakya (Figure 8). This structural system is reported to behave reasonably well after several earthquakes. For example, Bal and Vatan [23] report on the survival of buildings made according to the historical structural system, in contrast to modern buildings in the same area. This is confirmed by Gülhan and Güney [24], who have report on their study in Kocaeli and Sakarya, after the 1999 Marmara earthquake.


(a)


(b)


(c)

Figure 7. Island of Lefkada, Greece (a) Typical historical building, (b) Connections of timber elements, (c) Protection of timber-framed walls using timber planks (Vintzileou and Touliatos, [25]).

Similar are the observations after the recent strong earthquakes in Türkiye-Syria, 2023. Although statistical data on the percentage of buildings belonging to the historical structural system that has suffered significant damage or collapse are not available to the author of this paper, the in situ observations prove that many of those buildings have survived, thus offering to the inhabitants better chance to save their lives.

However, in several cases, the damage typical to this building typology were observed, namely, severe cracking or partial collapse of the stone masonry at the ground storey (Fig. 8b), loosening of connections between timber elements, damage to masonry filling the timber frames, etc. (see also [3]). It is admitted that the severity of damage depends on several parameters, such as the quality of stone masonry (quality of materials and construction typology), the level of elaboration of the timber-framed walls (in terms of arrangement of timber elements and their connections), as well as on the state of preservation (maintenance included).


(a)


(b)

Figure 8. The historical structural system of Antakya

Regarding the pre- or post-earthquake interventions to preserve the historical structural systems, one can distinguish between techniques to be applied to the ground story and those adequate for the rehabilitation of the upper stories.

Indeed, the aforementioned interventions aiming at transversely connecting the leaves of stone masonry, enhancing the bearing capacity of masonry walls, stiffening the floor on top of the ground storey, and providing a proper connection between vertical elements, as well as between walls and floor, are to be applied.

As for the upper storeys, adequate interventions are to be chosen, depending on the state of timber-masonry. Thus, extensive biological attack of timber elements or large residual deformations may lead to the need of partial or complete reconstruction. If the state of preservation is, in general, good, local damages of filling masonry may be repaired, loose connections are to be improved (e.g., using metal plates nailed on joints), etc. In other cases, e.g., in buildings like the one shown in Figure 8b, interventions may need to be limited to the lower storey.

Concluding remarks

The work of numerous researchers throughout the globe, and many seismic events that occurred in the last decades, have provided evidence on typical characteristics of masonry buildings that make those structures vulnerable to earthquakes. At the same time, the interpretation, in terms of Mechanics, of the observed damage shows the path to follow with the purpose of improving the seismic performance of masonry buildings.

In this paper, several systemic interventions are mentioned, aiming at alleviating the inherent weaknesses of stone masonry buildings. Those systemic interventions, aiming to improve the box-like behaviour of buildings, include consolidation of two- and three-leaf masonry elements through grouting (to avoid their delamination and to increase their mechanical properties), improvement of connection between walls (through stitching and/or using connectors), enhancement of diaphragm action of floors and roofs (to ensure almost equal displacements of all vertical elements) and adequate connection between horizontal and vertical bearing elements (to ensure the efficiency of the aforementioned interventions and the joint action of all structural elements).

Of course, there are further intervention techniques contributing to improved seismic behaviour. Those comprise repair and/or strengthening techniques.

It is noted that even when strengthening of the building is required, repair of damage should precede. Repointing, plastering, grouting or stitching of cracks, local reconstruction of heavily damaged regions, etc., aim at reinstating the pre-earthquake capacity of the structure.

Among the most commonly applied strengthening techniques are the reinforced plaster (preferably, double-sided and made of materials allowing masonry to breathe), the confinement of stone masonry piers and columns (using metallic or non metallic external reinforcement), filling of openings or the installation of (timber or steel) frames in the perimeter of openings, provision of struts and ties to reduce the detachment of walls from their transverse ones or -when installed to arches and domes- to resist the horizontal component of the thrust, constructing buttresses (adequately connected to masonry) to alleviate the out-of-plane vulnerability of long and high walls, etc.

Those and other techniques the Designer may apply are distinguished from the systemic ones. Indeed, the systemic interventions aim at improving the overall behaviour of the building, whereas the aforementioned techniques may be applied to a more or less limited number of bearing elements, when the systemic interventions prove not to be sufficient to bridge the gap between the available and the target margins of safety at the level of each distinct structural member.

It is noted that, if the state of the building or the required performance level are such that the combined application of several techniques cannot provide the necessary safety, the construction of a new internal bearing system may be sought. For such a new bearing system to efficiently protect the existing one against seismic actions, it has to be adequately connected to it, while the compatibility of deformations of the two systems (old and new) has to be ensured.

Some final remarks are needed here:

(a) In the common case of application of more than one intervention techniques, the final overall improvement in stiffness, resistance or ductility should not be taken as the sum of the contributions of all the applied techniques, as -up to now- there is no evidence (experimental or observed in situ after a seismic event) supporting this assumption.

(b) There are techniques applied to the existing masonry elements themselves (e.g., grouting, rejointing, etc.) and others applied to the exterior of them (e.g., reinforced plaster, buttresses, etc.). It is advisable to first consider those techniques that are applicable to the body of the existing construction and, only if those are not sufficient, to prescribe further external interventions.

(c) The in-time efficiency of the interventions constitutes a fundamental requirement, set in Codes and Guidelines. The selection of adequate materials, techniques, and application procedures satisfying the durability requirement is, therefore, of major significance.

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