

An Expeditious Tool for the Vulnerability Assessment of Masonry Structures in Post-Earthquake Reconstruction

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Research Article

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Abstract

Post-earthquake reconstruction activities need tools for assessing the vulnerability of structures, based on visual inspection and quick survey. So far, the public administrations in charge of granting the funds and monitoring reconstruction have adopted different methods taken from scientific literature or developed *ad hoc* for specific events. The time is ripe for a standard method to be developed, treasuring from the lessons learned in the field. This paper proposes an expeditious tool based on visual survey for the assessment of the seismic vulnerability of unreinforced masonry buildings, starting from available methods, whose parameters were reassessed and recalibrated, and scientific evidence from recent literature. The influence of the main structural features was considered to calculate a vulnerability index in the 0 ÷ 100 range. The effects of materials and arrangement of masonry were quantitatively evaluated through the masonry quality index, which represents an advancement with respect to current practice. The method was validated on a sample of 50 masonry aggregates and nearly 200 structural units of L'Aquila, Italy, where reconstruction is underway after a destructive earthquake in 2009, which is representative of the built heritage of other earthquake prone areas in Italy and many European Countries.

1. Introduction

The presence of historic centres in earthquake prone areas poses a number of challenges, which belong to collective memory but dramatically re-emerge after each severe seismic event. The high vulnerability of the building stock, especially of old masonry structures, has caused fatalities and structural collapses (Indirli et al., 2013; Penna, 2015; Dolce and Goretti, 2015; Sorrentino et al., 2019; Göçer, 2020), involving entire villages (Rapone et al., 2018; Sorrentino et al., 2019), ordinary buildings and aggregates (Penna et al., 2014; Vlachakis et al., 2020), and architectural heritage (Lagomarsino, 2012; D'Ayala and Paganoni, 2011; Cattari et al., 2014; Borri et al., 2019; Penna et al., 2019). It has also required many people to leave their own towns and move elsewhere, with further indirect troubles for the social identity and the economy of the communities (European Environment Agency, 2010).

The state of emergency immediately after the earthquake, during which people are rescued, dangerous buildings are secured and the safety of buildings is assessed, is followed by the much longer phase of reconstruction and structural retrofitting, which aims at repopulating places, restoring the beauty of architectural heritage, and restarting productive activities. At this stage, enhancing the safety level of the constructions in view of future earthquakes is a primary concern (Aguado et al., 2018; Mazzoni et al., 2018; Sisti et al., 2019). At the same time, it is of the utmost importance that the complex process of post-earthquake reconstruction progresses smoothly and it is completed with the available resources in a reasonable time (Di Ludovico et al., 2017).

In Italy, the institutions in charge of managing this process, together with research centres, universities and practitioners, have gained an outstanding expertise and developed effective procedures, such as the AEDES form for building usability (Baggio et al., 2007). On the other hand, after each of the recent earthquakes, the tools for damage survey and vulnerability assessment have been modified or re-

formulated from scratch. Even for the same event, if the territory struck by the earthquake depends on multiple administrative bodies different methods have (or are currently being) used. For instance, after 2009 L'Aquila earthquake, the reconstruction of the municipality of L'Aquila and that of the other municipalities of the earthquake area are managed by two offices, which do not share the same tools. Likewise, after the 2016–2017 Central Italy earthquake, four administrative Regions are managing reconstruction through four offices, adopting different procedures.

There is no shortage in the scientific literature of methods for vulnerability assessment of unreinforced masonry structures. D'Ayala and Speranza (2002) proposed one of the first ones, named Failure Mechanism Identification and Vulnerability Evaluation (FaMIVE), which identifies the most probable collapse mechanisms based on 42 parameters related to wall geometry, openings, connection with orthogonal walls, floors and roof, and presence of tie-bars and ring beams. An electronic form calculates the horizontal load that triggers the onset of the mechanism through limit analysis and estimates the seismic vulnerability of the construction. As the very final output, four vulnerability classes are defined, such as low, medium, high and very high.

The Italian Group for the Protection against Earthquakes (*Gruppo Nazionale per la Difesa dei Terremoti*, GNDT) developed a method based on 11 parameters, including type, strength and arrangement of the masonry, floors and roof, vertical and horizontal layout, non-structural members, and damage state. The scores attributed to such parameters are combined in a weighted sum to derive an index between 0 and 100 (Dolce et al., 2005). The method was initially conceived for isolated buildings and then extended to aggregates adding 5 more parameters accounting for interactions between adjacent structures (Formisano et al., 2011).

The Special Office for the Reconstruction of L'Aquila (*Ufficio Speciale per la Ricostruzione de L'Aquila*, USRA) adopted a method based on 9 main parameters (USRA, 2014). A score is assigned to each of them and an electronic sheet calculates a vulnerability index comprised between 8 and 57. Vulnerability is then classified as *low* if the index is ≤ 20 , *medium* if it is in the 21 ÷ 39 range, and *high* if it is ≥ 40 . The vulnerability class is used, together with the damage level according to the EMS98 scale (European Seismological Commission, 1998), to calculate the maximum permissible financial contribution per square meter. Finally, the Special Office for the Reconstruction of the other municipalities (all except L'Aquila) struck by the 2009 earthquake (*Ufficio Speciale per la Ricostruzione dei Comuni del Cratere*, USRC) is using a similar procedure, but with different scores.

All these methods share many of the parameters to be surveyed and collected in a form to evaluate seismic vulnerability. Indeed, despite the specificities of the building stock, which may change from territory to territory, the main features of unreinforced masonry constructions and of their seismic response generally recur (Taffarel et al., 2018). The time is ripe for developing a standard method, treasuring from the lessons learned in the past, recent scientific outcomes, and the experience gained in the field.

This paper proposes a tool for the expeditious assessment of the seismic vulnerability of unreinforced masonry structures, which can be used in post-earthquake reconstruction. The method originates from those adopted by USRA (2014) and by GNDT (Formisano et al., 2011), which have already been extensively used after recent earthquakes, and appear more suitable than others for the management of reconstruction activities. The parameters included in these two methods were reassessed and recalibrated. Information is to be gathered on 10 structural features, including the effectiveness of connections, the constructive details, the characteristics of floors and roof, the interaction with non-structural elements, and the quality of masonry. The role of this latter, which is accounted for only qualitatively in current practice, was evaluated quantitatively through the Masonry Quality Index (Borri et al., 2015), which considers constituent materials, size and shape of the units, thickness of the joints, and arrangement, and proves in good agreement with results of field tests. An expeditious survey is sufficient for a practitioner to collect required data on a building, which are combined to calculate a vulnerability index in the 0 ÷ 100 range. For calibration and validation, the correlation of such vulnerability index with an empirical damage index was calculated through a regression analysis on a sample of 50 masonry aggregates, including nearly 200 structural units, in the historic centres of L'Aquila and of the hamlets nearby. The sample was selected to be representative of the built heritage of the area as well as of many other earthquake prone areas in Italy, such as those struck by the recent 2016–2017 Central Italy earthquake (Penna et al., 2019; Sisti et al., 2019; Sorrentino et al., 2019) and in many other European Countries.

The paper is organized as follows. The proposed method is presented in § 2; the ten structural parameters to survey are listed together with the scores attributed to each of them, which are summed to calculate the Vulnerability Index. The parameters are described one by one in § 3, which also provides a brief roadmap for the evaluation of each of them, with the only exception of the quality of masonry, which is dealt with in depth later. Section 4 describes the sample of structural units selected for the calibration and validation of the proposed method in this study, its properties and the damage state of the buildings as reported in post-earthquake surveys. Section 5 describes the calibration of the scores attributed to the ten structural parameters and shows the correlation between the resulting vulnerability index (calculated for arch structural unit of the sample) and the corresponding damage index. Finally, the role of the quality of masonry and the use of the Masonry Quality Index (Borri and De Maria, 2009b; Borri et al., 2015; Borri and De Maria, 2019) for its quantification is discussed in § 6.

2. Proposed Method For The Expeditious Evaluation Of Seismic Vulnerability

The method proposed in this work requires an inspector to assess ten structural features of a building, listed in Table 1. The main information to survey, also including the presence of pre-existing damage and retrofitting systems, are briefly described in § 3. To this purpose, the expeditious inspection may include minor operations (e.g., removal of small areas of plaster) and the consultation of drawings, projects or

other documents, if available. On the other hand, structural calculations and experimental tests in the field are not required.

As the first outcome of the survey, a qualitative evaluation, such as low (L), medium (M), or high (H), is formulated on the contribution of each structural feature to the seismic vulnerability of the whole construction. *Low vulnerability* means that the parameter provides a low contribution to the seismic vulnerability of the construction, since it is associated with a good seismic performance. On the other hand, *high vulnerability* stands for weak behaviour in case of earthquake associated with that specific parameter. Clearly, *medium vulnerability* stands for a middle ground evaluation between *high* and *low*. This is not always possible, so, for some parameters, only L and H choices are available. The quality of masonry partially makes exception as it will be discussed later.

The method attributes a score to the evaluation formulated by the inspector (L/M/H) for each parameter (from #1 to #10), as listed in Table 1. In this work, the scores were tuned based on the relative importance of the parameter in the seismic vulnerability of the building (in Table 1, the parameters are sorted in descending order of importance). A sample of 50 masonry aggregates, including 192 structural units, belonging to the historic centres of L'Aquila and of the hamlets nearby (described in § 4), was considered to calibrate the scores and validate the method, as discussed in § 5. Noteworthy is that the quality of masonry (#2) is discussed separately in § 6, since its score is calculated from the Masonry Quality Index (Borri and De Maria, 2019).

As the final output of the assessment, all the scores are summed to calculate a Vulnerability Index (VI), ranging between 0 (minimum vulnerability) and 100 (maximum vulnerability). Finally, it may be useful in post-earthquake reconstruction activities (e.g., for granting funds, deriving statistics, filtering the database to extract a subset of it, etc.), to identify three vulnerability levels based on the correlation between VI and DI, such as *low* ($VI \leq 35$), *medium* ($35 < VI \leq 65$), and *high* ($65 < VI \leq 100$).

Table 1
Proposed parameters and scores for expeditious vulnerability assessment.

Parameter		Evaluations and scores		
		L	M	H
#	Description			
1	Connection between orthogonal walls	0	10	28
2	Quality of masonry	-	-	17.5
3	Connections between load bearing walls and non-structural components	0	8.5	17
4	Spacing between load bearing walls	0	5	9
5	Type of floors and their connections with walls	0	4	7.5
6	Horizontal offsets of load bearing walls (horizontal wall slenderness)	0	-	6.5
7	Regularity in elevation	0	-	5
8	Type of roof and its connection with walls	0	2	4.5
9	Vertical offsets of floors and vaults	0	-	4
10	Position and interaction of the structural unit within an aggregate	0	-	1
Vulnerability index (VI)		0		100

3. Structural Features

This section describes the ten structural parameters to assess for the calculation of the Vulnerability Index of a building. The main features to survey during an expeditious inspection are discussed and indications are provided for the formulation of the qualitative evaluation (L/M/H). A roadmap is traced for the inspector, even if the development of an actual guide is beyond the scope of this paper.

3.1. Connection between orthogonal walls (#1)

The seismic performance of an unreinforced masonry structure highly relies on its capacity to exhibit a box-type behaviour, which depends on the load transfer effectiveness at the intersections between orthogonal walls. On the contrary, insufficient connection leads to the separation between walls, especially of the perimeter ones, and promotes their out-of-plane overturning, which is one of the most frequent (and dangerous) seismic failure modes experienced by unreinforced masonry structures (Lourenço et al., 2011; de Felice et al., 2022).

This parameter depends on the arrangement of the units at the corners and on the presence of openings near the corners, which both need to be accurately surveyed, and/or on the presence of tie-bars, for which the number at each floor and the effectiveness of end plates need to be carefully evaluated. A number of

solutions have been proposed to improve the connections between orthogonal walls, ranging from traditional tie-bars and connectors (Ismail et al., 2010) to low-technological solutions using timber laces (Wang et al., 2019), crowning beam in reinforced masonry (Castori et al., 2018) and externally bonded reinforcements (De Santis and de Felice, 2021).

In the light of such observations, the inspector provides an overall evaluation, such as:

- *Low vulnerability* (0): squared units with regular arrangement at the corners, overlapped over the entire wall thickness, providing an effective connection that prevents crack development and wall separation at, and near, the corners. Tie-bars at all floor levels and at all wall intersections, provided with end plates ensuring adequate redistribution of the retaining effect on the front walls. Crowning beams in reinforced masonry, effectively connected with the masonry walls by vertical connectors with regular spacing, along the entire perimeter of the construction. Connectors inserted through the thickness of the façade at its intersection with orthogonal walls and externally bonded reinforcements at the corners may provide an effective connection even in absence of a sufficient number of tie-bars or of a crowning beam, or in addition to these latter ones.
- *Medium vulnerability* (10): both small and large units at the corners, with partial overlapping and moderate regularity of the arrangement. Tie-bars at most floor levels and wall intersections, with some lacks or some ineffective connections with the façade. Crowning beam only on top of some walls or ineffectively connected with the underlying masonry in some areas.
- *High vulnerability* (28): small units and weak materials, without intersections and overlapping, entailing ineffective connection at the corners. Insufficient number of tie-bars and/or ineffective connection with the external wall (due to small end-plates or extremely weak or damaged masonry near the end-plates). Absence of crowning beam and externally bonded reinforcements at the corners.

3.2. Quality of masonry (#2)

A masonry of low quality entails the possibility of the seismic response to differ from that of a nearly-rigid body, exhibiting instead leaf separation and/or disintegration (Vintzileou et al., 2015). This feature highly influences the overall structural vulnerability because such failure modes often activate at a lower seismic intensity than that producing the onset of rigid body mechanisms (de Felice et al., 2022). In the existing methods adopted in post-earthquake reconstruction, the properties of the masonry are assessed qualitatively exactly like all the other parameters. Given the importance of this feature, in the proposed method, the quality of masonry is instead quantitatively evaluated through the Masonry Quality Index (MQI), referred to the in-plane response of the walls (Borri and De Maria, 2019). The MQI ranges between 0 and 10 and is based on conservation state and mechanical properties of stone/brick units and mortar; size and shape of stone/brick units; wall leaf connection; characteristics of the horizontal and vertical joints. Once the MQI is calculated after survey, a conversion function is provided herein to convert it to the score, which contributes to the VI of the building (see Table 1). This score attains its maximum value

(17.5) for $MQI \leq 0.4$ and exponentially decreases to 0 for $0.4 \leq MQI \leq 10$. The reader is referred to § 6 for a deeper discussion.

3.3. Connections between load bearing walls and non-structural components (#3)

The presence of non-structural components and their connection with load-bearing elements may affect the overall seismic response of the construction and the safety of its occupants and activities (Perrone et al., 2019). First, protruding cornices, chimneys, balconies, stone or plaster friezes, false ceilings, doors and windows, etc. may fall and dangerously hit people, things, or structural elements. Second, their mass may promote the onset of collapse mechanisms, especially in case of heavy cornices or chimneys (Derakhshan et al., 2018). In both cases, effective connections may reduce the contribution of non-structural components to the seismic vulnerability. The parameter can be evaluated as follows:

- *Low vulnerability* (0): absence of non-structural elements sticking out of the contour of the building. Light cornices or chimneys effectively connected to load-bearing walls along their entire length (for cornices) or on all sides (for chimneys). Stone or plaster friezes connected to the masonry (e.g., by steel or composite connectors).
- *Medium vulnerability* (8.5): small cornices and chimneys with limited connections with structural members. Balconies supported by stone metallic girders effectively connected to the masonry. Friezes without connection with the masonry.
- *High vulnerability* (17): heavy cornices or chimneys, significantly protruding from the contour of the building, provided with no or limited connection with load-bearing walls. Balconies supported by stone cantilever elements.

3.4. Spacing between load bearing walls (horizontal wall slenderness) (#4)

The larger is the distance between two load bearing walls, the higher is the possibility for horizontal bending mechanisms to activate. Openings, interactions with floors and roof, and axial load may influence the shape of the mechanism (Candeias et al., 2017), which is often surveyed in post-earthquake inspections and significantly affects structural vulnerability. On the other hand, for this failure mode to occur, good connections at wall intersections are needed that prevent overturning, and leaf separation and disintegration need to be impeded by a relatively good quality of masonry. Therefore, with respect to parameters #1 and #2, the relative weight of this one is lower. Since the ultimate flexural capacity is associated with the thickness of the wall, this parameter can be evaluated based on the maximum wall slenderness $R = L/t$, L being the spacing between the intersections with orthogonal wall and t being the thickness of the façade (USRA, 2014). Nonetheless, the bending capacity can be significantly enhanced by applying strengthening systems to the external surface of the masonry wall, such as those comprised of composite materials (Bellini et al., 2017; Gattesco and Boem 2017; De Santis et al., 2019a). Low impact techniques have also been developed, using steel cords to repoint the mortar joints (Corradi et al.,

2016; De Santis et al., 2022), which preserve the fair face masonry of the façade, when the architectural value needs to be preserved. These strengthening systems may be more difficult to survey, but their presence should easily be detected by referring to available documents. The parameter can be evaluated as follows:

- *Low vulnerability* (0): $R < 10$ or presence of effective externally bonded reinforcements that enhance wall resistance under horizontal bending, at all floor levels and anchored at their ends.
- *Medium vulnerability* (5): $10 \leq R \leq 14$, limited number of tensile-resistant strengthening systems (e.g., not at all floor levels).
- *High vulnerability* (9): $R > 14$, lack of effective tensile-resistant strengthening systems on the surface of the wall.

3.5. Type of floors and their connections with walls (#5)

The type and materials of the floors affect the dynamic response of a masonry construction for a number of reasons. First, in case of earthquake, the horizontal loads they transfer to the walls are proportional to their mass, so light structures are preferable over heavy ones (Sisti et al., 2019; Sorrentino et al., 2019). Second, floors with high in-plane stiffness (provided with double boarding, concrete slab, metallic cross bracing) are able to redistribute the horizontal loads amongst the walls, avoiding local concentrations and providing the structure with a box-type behaviour, with beneficial effects (Senaldi et al., 2014; Boem and Gattesco, 2021). Finally, if the load bearing beams of the floors are effectively connected with the perimeter walls (e.g., by metallic pins), they can behave as tie-bars and contribute to constraining out-of-plane mechanisms. As for the vaults, in addition to the inertial forces, the thrust at the abutments may promote out-of-plane overturning/bending, in absence of tie-bars. These latter ones also contribute to constrain the relative movement of vault supports and limit deflections, which may cause collapse especially in slender vaults and in absence of backfill on top (Castori et al., 2016). Externally bonded composites, applied to either the extrados or the intrados of the vault barrel, possibly provided with end connectors at the abutments and/or with mechanical pins along the arch span, may highly enhance their capacity, reducing their contribution to the seismic vulnerability of the construction (Borri et al., 2009a; Cescatti et al., 2018; De Santis et al., 2019b). This parameter can be evaluated as follows:

- *Low vulnerability* (0): light floors (e.g., timber floors) transferring low inertial forces, provided with high in-plane stiffness and connected with perimeter walls, able to redistribute the loads and to provide box-type behaviour. Masonry vaults provided with tie-bars (which balance the horizontal thrust and constrain support movements) and tensile resistant strengthening systems.
- *Medium vulnerability* (4): light floors with high in-plane deformability (e.g. provided with single boarding layer) and/or not connected with perimeter walls. Masonry vaults provided with tie-bars and buttress walls, filled on top.
- *High vulnerability* (7.5): heavy floors (e.g., with concrete slab) not connected with the perimeter walls. Masonry vaults without tie-bars, without buttress walls, or without filling on top.

3.6. Horizontal offsets of load bearing walls (#6)

The presence of a load bearing wall with an offset with respect to the lower or the upper ones (that is, they are not vertically aligned) entails a concentrated mass within the floor or vault span, as well as an irregular stiffness distribution, which compromises the regular distribution of resisting mechanisms, with detrimental effects on the seismic performance of the construction (or at least of a portion of it). Note that thin walls, maybe conceived as partition walls, may have taken some load due to settlements along time, and should not be neglected a priori while assessing this parameter. The evaluation can be done as follows:

- *Low vulnerability* (0): no horizontal offsets or horizontal offsets in less than 10% of the surface of the building.
- *High vulnerability* (6.5): horizontal offsets over a surface equal or larger than 10% of the building.

3.7. Regularity in elevation (#7)

The seismic performance of the construction may be influenced by the interaction with adjacent structures, especially when these have different heights, and whether or not they belong to the same structural unit. Irregularity in elevation may cause local singularities of boundary conditions, which, in their turn, may promote the development of damage or the onset of collapse mechanisms (Lourenço et al., 2011). Both the portions of a structural unit (or of an aggregate) interested by a height mismatch, at least equal to the storey height, should be considered as irregular, so this parameter can be evaluated as follows:

- *Low vulnerability* (0): the structure is regular in elevation (the mismatches in height are absent or are lower than the storey height).
- *High vulnerability* (5): there is an irregularity in elevation interesting the interface with another portion of the same structural unit or that with another structural unit of the same aggregate, with the mismatch in height, even one side only, being at least equal to the storey height.

3.8. Type of roof and its connection with walls (#8)

As for inter-storey floors and vaults, the mass, the incline of the pitches, and the in-plane stiffness of the roof affects the thrust it transfers at the supports. Moreover, the connections with perimeter walls, if present, contribute to constraining out-of-plane mechanisms on top, also including those promoted by protruding cornices. This parameter can be evaluated as follows:

- *Low vulnerability* (0): light roof with high in-plane stiffness, provided by double boarding and/or metallic cross bracing (Boem and Gattesco, 2020), connected to the perimeter walls or to the crowning beam in reinforced masonry built on top of them, constituted by truss structures or provided with tie-bars, such that no horizontal thrusts are transferred to the wall.

- *Medium vulnerability* (2): light and highly deformable roof, weakly connected to the perimeter walls, transferring horizontal thrusts to the wall, partially balanced by tie-bars.
- *High vulnerability* (4.5): heavy roof (e.g., with concrete slab) or transferring horizontal thrusts to the wall without tie-bars.

3.9. Vertical offsets of floors and vaults (#9)

If there is an offset between two adjacent floors or vaults (that is, they are at different heights), the horizontal loads these transfer to the load bearing wall in the middle in case of earthquake are not (even partially) balanced by each other and may induce significant out-of-plane bending and in-plane shear loads. This parameter can be evaluated as follows:

- *Low vulnerability* (0): vertical offsets of floor and vaults absent or smaller than 1/3 of the storey height.
- *High vulnerability* (4): at least one vertical offset equal, or higher than, 1/3 of the storey height.

3.10. Position and interaction of the structural unit within the aggregate (#10)

A minor influence on the seismic performance of a structural unit belonging to a masonry aggregate is attributed to its position within the plan of the aggregate and to its interaction with the other portions of the aggregate (Senaldi et al., 2020). The lack of constraining offered by adjacent structural units may have some detrimental effects. On the other hand, due to the inherent discontinuous nature of unreinforced masonry structures, load concentrations at the edges of an aggregate caused by torsional effects are basically negligible. It may be useful to note this information in the survey, but its importance to the overall seismic vulnerability is lower than that of all the other structural features considered beforehand. This parameter can be evaluated as follows:

- *Low* (0): aggregate constituted by one structural unit. Structural unit placed in the middle of the masonry aggregate, near other structural units with similar properties (masonry type, wall thickness).
- *High* (1): structural unit placed in the edge or in the corner of the aggregate plan, or adjacent to other units with significantly different masonry type and wall thickness, which may cause localized damage.

4. Sample Under Study

This section describes the sample of masonry buildings selected for this study. The expeditious method described in § 2 was applied to all the buildings of the samples following the roadmap traced in § 3. By doing so, the structural parameters to survey and the scores attributed to the evaluation (L/M/H) formulated for each of them for calculating the VI, were determined following the validation and calibration process described in § 5 and § 6.

4.1. Locations and main features of the buildings

Within the reconstruction activities currently underway after the destructive earthquake of April, 6th, 2009, a form is filled for each building by the appointed practitioner, which reports the damage state and the data for the assessment of seismic vulnerability. Forms are submitted to USRA, which collects them in a database. For the aggregates, the form is comprised of more subsections, one per structural unit. The entire process includes two stages. In the first stage, USRA grants public funds for reconstruction/retrofitting works, whereas in the second one, the design is developed and submitted and works are carried out. In this phase, USRA is in charge of controlling and monitoring.

USRA made available its database for this study. It was analysed to select a sample of 50 old aggregates built in unreinforced masonry, 25 of which are in the historic city centre of L'Aquila and 25 in the centres of the hamlets around L'Aquila (Fig. 1). Information on all the buildings included in the sample was derived from the forms. Field surveys were performed when necessary to integrate this information and gather all the elements required for the application of the proposed expeditious vulnerability assessment method.

In the sample, 9/50 buildings were made of a single structural unit, whereas 41/50 aggregates were comprised of more structural units, defined as portions with homogeneous features (age of construction, type of masonry, type and height of the floors, etc.). In total, the sample included 192 structural units.

With regard to the age of construction, nearly 2/3 of the units were built before 1860, 1/5 even before 1700; 26% was built between 1860 and 1930, 8% between 1930 and 1960, and, finally, only 3% of them was built less than 60 years ago (Fig. 2a). Most of the oldest constructions are in the city centre of L'Aquila, whereas many of the more recent ones are in the hamlets.

As for the architectural value, almost the entire sample (98%) was made of valuable structures, either belonging to the historic urban fabric (8%), listed as high-quality building (38%), subject to urban protection (31%), or, finally, subject to direct architectural protection (21%, mainly in the city centre) (Fig. 2b).

Finally, regarding the materials, most of the structures were built in stone masonry (91%), the other ones had load bearing walls in brickwork (6%), concrete blocks (2%) or hollow bricks (1%) (Fig. 3a). As for the stone masonries, about 1/3 of them were in rubble stone masonry (34%), whereas 2/3 had roughly shaped stone units (65%); only a negligible number of stone walls (1%) had squared units (Fig. 3b).

4.2. Damage reported after 2009, L'Aquila earthquake

In the forms submitted to USRA, the intensity and extension of seismic damage was surveyed by the inspector for each structural and non-structural component of the building (USRA, 2014) and a damage level was determined, which varies from D0 to D5, according to the EMS98 classification (European Seismological Commission, 1998). As mentioned before, the method adopted by USRA provides a

vulnerability index in the $8 \div 57$ range, which is then converted to a vulnerability class, such as *low* (V1) if the index is ≤ 20 , *medium* (V2) if it is in the $21 \div 39$ range, and *high* (V3) if it is ≥ 40 .

Aiming at providing a picture of the damage state and estimated vulnerability of the buildings included in the sample, Fig. 4 shows the relationship between the vulnerability class and the damage grade based on the information extracted from the forms collected by USRA in its database. It is worth noting that, since the survey was carried out in a highly seismic territory after a strong earthquake, for most of the buildings the vulnerability was unsurprisingly assessed as medium or high and damage was classified from medium to severe. Moreover, as expected, the highest concentration of damage in the D2-D3 grades was found for buildings with medium vulnerability (V2), and that of damage in the D4-D5 grades for those with high vulnerability (V3).

On the other hand, there is a non-negligible scatter. Very few buildings, in spite of the low vulnerability, exhibited severe damage or collapse. Also, no or very limited damage was detected on some highly vulnerable buildings. Such relatively weak correlation between estimated vulnerability and surveyed damage may be due to the inherent limits of expeditious assessment tools, which lead to a limited number of classes (for both damage and vulnerability) starting from the features observed during a visual inspection, as well as to the possible effects of the interpretations of individual inspectors.

5. Calibration And Validation Of The Method

5.1. Calculation of an empirical damage index and preliminary application of USRA method

As a preliminary step, the damage level reported in the forms (classified from D0 to D5, as described in § 4.2) was verified and, when necessary, corrected. Then, it was converted into a damage index (DI) as follows: DI = 0 for damage level D0, DI = 0.1 for D1, DI = 0.3 for D2, DI = 0.5 for D3, DI = 0.7 for D4, and finally DI = 0.9 for D5, to obtain a quantitative, although extremely concise, measure of empirical damage (Dolce and Goretti, 2015). On the one hand, more refined methods to assess and express the global damage on a building exist (Hill and Rossetto, 2008; Lourenço et al., 2013). On the other hand, the approach adopted in this study was meant to be consistent with the expeditious nature of the assessment method, which necessarily requires a limited number of information to be surveyed by an inspector (De Martino et al., 2017). In this case, it is generally accepted that damage is evaluated empirically based on its level and extension on structural and non-structural components (De Martino et al., 2017).

Then, the method adopted by USRA was applied as it is to calculate the Vulnerability Index (VI) for each structural unit of the sample. Such VI, as mentioned before, ranges between 8 and 57. Its correlation with the empirical damage index was determined through a regression analysis with both a linear function and an exponential function. The resulting coefficients of determination (R^2) were 0.18 and 0.16,

respectively (Fig. 5a). Applying the GNDT method was not possible because some necessary information was unavailable.

5.2. Calibration of the proposed method

In order to calibrate the scores of the parameters listed in Table 1 and to validate the proposed method, each structural unit of the sample was analysed and its seismic vulnerability was estimated as described in § 2–3, based on the information included in the forms collected by USRA and of the attached documents (drawings, projects, photos), as well as by going in the field for inspections when necessary. The scores attributed to the structural parameters (Table 1) were calibrated as follows.

First, the correlation between damage (expressed through the damage index described in § 5.1) and each parameter taken individually was investigated through a regression analysis. For this purpose, each of the ten structural parameters was analysed and an evaluation was made for each structural unit of the sample. At this stage, the scores were normalized in the 0 ÷ 10 range (0 being associated with *low* and 10 with *high vulnerability*). The correlation between each parameter and damage index (DI) was expressed through the coefficient of determination (R^2) with linear and exponential interpolating functions. The score associated with *medium vulnerability* was tuned to achieve the best correlation, that is, the highest R^2 . The R^2 values of linear functions were higher than those of the exponential ones and varied between 9% and 75%.

Second, the relative importance amongst the parameters was estimated. To this aim, the parameters exhibiting the highest correlation (that is, the highest R^2 values) were considered as those mostly contributing to the overall seismic vulnerability of the construction. The scores were scaled accordingly, leading to a weighted sum of the contributions associated with the parameters. More specifically, the connection between orthogonal walls resulted the most important parameter. The highest weight was attributed to this parameter, which was listed as #1. The quality of masonry and the connections between load bearing walls and non-structural components followed, which had very similar correlation with damage and were listed #2 and #3. A lower importance was found for the other parameters (#4-#9). The less important feature resulted the position and interaction of the structural unit within the aggregate, which had a lower correlation with damage and was listed as parameter #10.

Finally, the scores were approximated to ½ point and scaled again to provide a vulnerability index (VI) in the 0 ÷ 100 range, resulting in those listed in Table 1. The vulnerability index (VI) calculated for all the structural units of the sample and the corresponding damage index (DI) are shown in Fig. 5b, in which the linear and the exponential regression functions are also represented together with their R^2 , which resulted 0.66 and 0.37 respectively. Comparing Fig. 5a and 5b shows that the correlation achieved with the proposed method on the selected sample resulted higher than that obtained with USRA method.

5.3. Remarks on the quality of masonry

Note that Fig. 5b still refers to an uncomplete version of the proposed method, since, in this phase, an evaluation was made for the quality of masonry, which was assessed as *high*, *medium* or *low* for each

structural unit of the sample. To this aim, the same features of USRA method (see § 6.1 for more details) were considered and the flow chart used by USRA was adopted (USRA, 2014). On the other hand, the scores attributed to these evaluations were set as 0 for *low*, 9 for *medium* and 17.5 for *high*, according to the outcomes of the tuning phase described in § 5.2 (and differently from USRA method). This step was necessary to identify the relative contribution of the quality of masonry with respect to the other parameters. The drawback associated with the use of discrete classes and the possible use of the Masonry Quality Index for quantitatively evaluate this parameter will be discussed in depth in § 6.

6. Quality Of Masonry

6.1. Analysis of the quality of masonry according to USRA method for the sample under study

The existing methods for the expeditious assessment of seismic vulnerability include the survey of the quality of masonry and the evaluation of its contribution to the performance of the construction. In particular, the method adopted by USRA requires that the following features are surveyed: (1) material (stone/brick/tuff/concrete); typology (units/bricks/blocks); (2) shaping (none/uncut/cut/dressed); (3) size of the units (small/medium/large); (4) presence of horizontal layers (no/yes); (5) presence of small units to fill gaps (no/yes); (6) strength of the mortar (low/medium/high); (7) type of mortar (hydraulic lime/aerial lime/cement); (8) presence of transversal connectors (no/yes); (9) running bond (no/yes); (10) cross-section (multi-leaf/one-leaf); and, finally, (11) general maintenance state (bad/medium/good). Based on this information, through a flow chart and without any quantitative calculations, the quality masonry results qualitatively classified as *good*, *medium* or *low*. The scores attributed to these grades are 4/15, 8/15 and 15/15, respectively (USRA, 2014).

The analyses on the sample selected in this study revealed that the masonry types included in each of the three classes of quality may significantly differ from each other. As the sake of an example, the pictures of six walls, taken from the forms filled by practitioners and submitted to USRA, are collected in Fig. 6. More specifically, masonries (a) and (b) were both classified as *low quality*. Nevertheless, the former is made of rubble stones and includes many small stones and thick mortar joints (with several voids where the mortar is lacking), and appears weaker than the latter, in which the stone units are bigger and roughly cut, and the joints are filled with mortar. Similarly, pictures (c) and (d) show masonries classified as *medium quality*, even if the latter appears stronger (cut stones, very few small units, relatively thin joints with mortar in good state) than the former (irregular size of the stones, thick joints and partially deteriorated mortar). Finally, masonries in pictures (e) and (f) were both considered as *high quality*, but the latter has a more regular running bond arrangement and thinner joints than the former. In summary, the comparisons of Fig. 6 suggested that differences amongst masonry types may be lost due to the discretization of the score interval in three quality classes. Therefore, it appeared more appropriate to quantitatively assess the role played by the quality of masonry in the overall seismic vulnerability through an index ranging within a continuous interval (thus avoiding discrete classes) to better reflect the

possible differences amongst masonry walls, while keeping the expeditious nature of the method, based on visual survey of a limited number of features. This can be done using the Masonry Quality Index as described in the following section.

6.2. The Masonry Quality Index (MQI)

The Masonry Quality Index (MQI) method quantitatively describes the attitude of a wall to exhibit a monolithic response or, on the contrary, to fail by leaf separation or disintegration. It was developed by Borri and co-workers in 2009 (Borri and De Maria, 2009b) and then updated more than once (Borri et al., 2015; Borri and De Maria, 2019). It is also known with the acronym IQM, from the Italian *Indice di Qualità Muraria*.

The MQI is determined on the basis of the presence, or lacking, of the “rule of the art” features, the set of proper construction rules that provide the wall with strength and solidity, and ranges between 0 (minimum quality) and 10 (maximum quality). To this end, the following parameters are considered: conservation state and mechanical properties of stone/brick units; size and shape of stone/brick units; wall leaf connection; characteristics of the horizontal and vertical joints of mortar; and mechanical properties of the mortar. Grout injections, strengthening systems applied to the external surface of the walls, such as FRCM (Bellini et al., 2017; De Santis et al., 2019a) or CRM (Gattesco and Boem 2017; De Santis and de Felice, 2021) overlays, reinforced repointing (Corradi et al., 2016) or transversal connectors (Giarretton et al., 2017; De Santis et al., 2019a; 2021) highly improve the response of the wall by preventing leaf separation and masonry disintegration and, therefore, need to be considered in the evaluation of the MQI.

The MQI method requires that a judgement is attributed to each “rule of the art” feature, such as fulfilled/partially fulfilled/not fulfilled, leading to a set of numerical values, which are combined in a weighted sum to obtain the MQI. In fact, there are three similar, but not identical, expressions to derive three indexes for vertical loads, horizontal in-plane loads, and horizontal out-of-plane loads (the reader is referred to the above cited papers for more details).

The method can be applied on the basis of a visual inspection (qualitative analysis), but quantitative criteria can also be adopted for some parameters, such as the wall leaf connection and the vertical joint characteristics, which can be evaluated through the *minimum path line* method (Borri et al., 2015). The MQI method is non-destructive and exhibits good correlations with theoretical mechanical properties of masonry (Marino et al., 2014; Borri and De Maria, 2019) as well as with destructive (Marino et al., 2014) and non-destructive (Van Eldere et al., 2019) field test results.

6.3. Relationship with double flat jack tests performed in the field

In order to validate the use of the MQI method for this study, the results of double-flat jack tests performed in 18 buildings of the database were compared to the in-plane MQI. This latter was considered because it is better associated with the global seismic vulnerability of the construction than the vertical

MQI (more relevant for axial loads and compressive strength related issues) and than the out-of-plane MQI (related to local collapse mechanisms).

A relatively good agreement was found both with the experimental compressive strength (f_m , Fig. 7a) and with the Young's modulus (E_m , Fig. 7b), as demonstrated by the R^2 values (0.60 and 0.56, respectively), confirming that the in-plane MQI is a reliable indicator of the properties of the masonry. It has to be noted that the subset considered for this comparison is limited (field tests are not mandatory in the first submission stage of USRA form) and a wider database may have led to more robust conclusions. Moreover, for this comparison, it was decided to consider only the masonry types for which both a good estimate of the MQI and a sufficiently complete description of test conditions and results were available.

6.4 Validation of the use of the Masonry Quality Index and complete version of the proposed method

In order to use the Masonry Quality Index in the proposed method, the in-plane MQI was first calculated for all the masonries of the sample. Both the qualitative method and the quantitative *minimum path line* method were used, which led to very similar outcomes, suggesting that the faster qualitative method could be used for the expeditious assessment of the vulnerability. For instance, the MQI values for the six masonries shown in Fig. 6 can be considered, which highlights the mismatch with USRA method and the non-negligible differences amongst types of masonry classified in the same quality grade according to this latter, as discussed in § 6.1.

Then, the conversion function shown in Fig. 5c was identified, which is an exponential law providing the score associated with the quality of masonry in the $0 \div 17.5$ range (the range identified in the calibration phase described in § 5.2). The higher is the MQI (meaning that the rule of the art was fulfilled) the lower is the contribution of the masonry to the seismic vulnerability. Conversely, the lower is the MQI (the masonry is estimated as highly prone to exhibit disintegration and leaf separation in case of an earthquake), the higher is the associated vulnerability. It is also assumed that the maximum score (17.5) is attained for $MQI \leq 0.4$.

By doing so, the quality of masonry was considered through the calculation of the MQI, which did not require longer time, nor more complex evaluations, than those required in USRA method. On the other hand, this provided an index within a continuous range ($0 \div 17.5$) overcoming the drawback of discrete classes.

Finally, the Vulnerability Index was calculated for all the structural units of the sample and the correlation with the empirical damage index is shown in Fig. 5d. A (slight) improvement of the correlation between DI and VI was found (compare $R^2 = 0.73$ for the proposed method including the MQI, shown in Fig. 5d, with $R^2 = 0.66$ for the same method, but with the discrete classes and without MQI, shown in Fig. 5b). On the

other hand, a non-negligible scatter still remained, which was due the expeditious nature of the method and to the simplified procedure for collecting information.

Conclusions

An expeditious method was proposed for the assessment of the seismic vulnerability of unreinforced masonry structures, which may be used in post-earthquake survey and reconstruction activities. The method originates from those developed by the Italian GNDT group and by USRA. It requires to gather information on ten structural features through visual inspection and fast survey. The contribution of each feature to the overall seismic vulnerability of the construction is evaluated as high/medium/low, based on the geometry, the materials and the constructive details of the structure, as well as on the presence of strengthening systems, including the innovative ones. Scores are attributed to these evaluations, considering their relative importance,

The quality of masonry is considered by evaluating the Masonry Quality Index (MQI) in the plane of the wall, which makes it possible to quantitatively account for its main properties (materials, arrangement, reinforcements), keeping the expeditious nature of the method.

Summing these scores leads to the calculation of a Vulnerability Index, ranging between 0 (minimum vulnerability, good seismic performance) and 100 (maximum vulnerability, weak seismic performance).

The method was calibrated and validated on a sample of 50 masonry aggregates, comprising 192 structural units, in the city centre of L'Aquila and of its surrounding hamlets. To this aim, a damage index was calculated based on the outcomes of post-earthquake surveys after the 2009 L'Aquila earthquake, to empirically (and concisely) represent the level and extension of damage on structural and non-structural elements, as in practice in expeditious methods.

The most important parameters resulted (i) the connection between orthogonal walls (responsible of the onset of out-of-plane overturning mechanisms), (ii) the quality of masonry (responsible of disintegration, leaf separation and in-plane shear cracking), (iii) the spacing between orthogonal walls and the slenderness of the façades (responsible of out-of-plane bending mechanisms), (iv) the type of floors and roof and their connection with the walls (responsible of horizontal thrusts and load redistribution), and (v) the presence and connection of non-structural members (responsible of local damage and dangerous collapses). After all, the seismic performance of a masonry building relies on few structural features, namely box type behaviour, load redistribution, horizontal thrusts, mass concentrations, strength and solidity of the masonry (fulfilment of the "rule of the art"). These parameters are related to general construction characteristics of the building, rather than to local details or geometrical irregularities, such as offsets, interaction with adjacent structures, for which a relatively lower importance was observed.

A regression analysis provided an improved correlation with the empirical damage level in comparison with USRA method. The use of the MQI to quantify the role of the quality of masonry, in the place of the classification in discrete quality grades, also proved beneficial.

On the other hand, the scatter between estimated vulnerability and surveyed damage remained relatively high, due to both the expeditious nature of the method, which relies on the fast assessment of a limited number of information, and on the extremely simplified representation of damage, taken as benchmark for calibration and validation. In principle, other validation strategies are possible, such as the structural analysis of each building, but this appears hardly feasible when a large sample is considered.

Moreover, since the method was applied and validated in an historic centre in which most of the buildings of the selected database were built in stone masonry and were assessed as unusable after the earthquake, a larger database, including a wider casuistry of masonry types and damage states, would allow deriving more robust statistics. The method cannot either be extended to other building typologies (e.g., reinforced concrete structures), for which other parameters should be clearly considered. Besides these limitations, the proposed method could already be used in the field, possibly implemented in an electronic sheet to facilitate practitioners and to draft reports. It may be useful for driving decision makers for ranking buildings and granting funds in the complex post-earthquake reconstruction phase. It could also be integrated in wider studies, such as the probabilistic based analyses of the seismic risk developed for ranking preventive retrofitting works at the scale of the urban centre.

Declarations

Compliance with ethical standards

Conflict of interest: the authors declare that they have no conflict of interest.

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References

1. [Aguado JLP](#), [Ferreira TM](#), [Lourenço PB](#) (2018) The Use of a Large-Scale Seismic Vulnerability Assessment Approach for Masonry Façade Walls as an Effective Tool for Evaluating, Managing and Mitigating Seismic Risk in Historical Centers. *Int J ArchitHerit* 12(7-8):1259-1275. <https://doi.org/10.1080/15583058.2018.1503366>.
2. [Baggio C](#), [Bernardini A](#), [Colozza R](#), [Di Pasquale G](#), [Dolce M](#), [Goretti A](#), [Martinelli A](#), [Orsini G](#), [Papa F](#), [Zuccaro G](#), [Pinto AV](#), [Taucer F](#) (2007) Field Manual for post-earthquake damage and safety assessment and short term countermeasures (AeDES). EUR 22868 EN, Joint Research Center, Ispra, Italy.

3. Bellini A, Incerti A, Bovo M, Mazzotti C (2017) Effectiveness of FRCM reinforcement applied to masonry walls subject to axial force and out-of-plane loads evaluated by experimental and numerical studies. *Int J ArchitHerit* 12(3):376-394. <https://doi.org/10.1080/15583058.2017.1323246>.
4. Boem I, Gattesco N (2021) The Roof Bracing as Minimum Intervention for the Reduction of the Seismic Vulnerability of Historical Industrial Buildings: Analytical and Numerical Simplified Strategies for the Assessment of the Performances. *Int J ArchitHerit* 15(2):274-288. <https://doi.org/10.1080/15583058.2020.1805817>.
5. Borri A, Casadei P, Castori G, Hammond J (2009) Strengthening of brick masonry arches with externally bonded steel reinforced composites. *J Compos Constr* 13(6):468-475. [https://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000030](https://doi.org/10.1061/(ASCE)CC.1943-5614.0000030)
6. Borri A, Corradi M, Castori G, Sisti R, De Maria A (2019) Analysis of the collapse mechanisms of medieval churches struck by the 2016 Umbrian earthquake. *Int J ArchitHerit* 13(2):215-228. <https://doi.org/10.1080/15583058.2018.1431731>.
7. Borri A, De Maria A (2009) L'indice di Qualità Muraria (IQM): Evoluzione ed Applicazione nell'Ambito delle Norme Tecniche per le Costruzioni del 2008. In Proceedings of 13th Italian national conference for earthquake engineering. Bologna, Italy 28/06-02/07/2009 (in Italian).
8. Borri A, De Maria A (2019) Il metodo IQM per la stima delle caratteristiche meccaniche delle murature: allineamento alla circolare n. 7/2019, In Proceedings of 13th Italiannational conference for earthquake engineering, Ascoli Piceno, Italy 15-19/09/2019 (in Italian).
9. Borri A, De Maria A, Corradi M, Castori G (2015) A method for the analysis and classification of historic masonry. *Bull EarthqEng* 14:2647-2665. <https://doi.org/10.1007/s10518-015-9731-4>.
10. Candeias PX, Campos Costa A, Mendes N, Costa AA, Lourenço PB (2017) Experimental assessment of the out of plane performance of masonry buildings through shake table tests. *Int J ArchitHerit* 11(1):31-58. <https://doi.org/10.1080/15583058.2016.1238975>.
11. Castori G, Borri A, Corradi M (2016) Behavior of thin masonry arches repaired using composite materials. *Compos Part B Eng* 87:311-321. <https://doi.org/10.1080/15583058.2016.1238975>.
12. Castori G, Corradi M, Sisti R, Borri A (2018) Database of structural behavior of reinforced masonry ring-beams. In Proceedings of 9th International Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering, CICE 2018.
13. Cattari S, Abbati SD, Ferretti D, Lagomarsino S, Ottonelli D, Tralli A (2014) Damage assessment of fortresses after the 2012 Emilia earthquake (Italy). *Bull EarthqEng* 12(5):2333-2365. <https://doi.org/10.1007/s10518-013-9520-x>.
14. Cescatti E, Da Porto F, Modena C (2018) In-Situ Destructive Testing of Ancient Strengthened Masonry Vaults. *Int J ArchitHerit* 12(3):350-361. <https://doi.org/10.1080/15583058.2017.1323243>.
15. Corradi M, Borri A, Castori G, Sisti R (2016) The Reticulatus method for shear strengthening of fair-faced masonry. *Bull EarthqEng* 14:547-3571. <https://doi.org/10.1007/s10518-016-0006-5>.
16. D'Ayala DF, Paganoni S (2011) Assessment and analysis of damage in L'Aquila historic city centre after 6th April 2009. *Bull EarthqEng* 9(1):81-104. <https://doi.org/10.1007/s10518-010-9224-4>.

17. D'Ayala DF, Speranza E (2002) An Integrated Procedure for the Assessment of Seismic Vulnerability of Historic Buildings. Proceedings of 12th European Conference Earthquake Engineering, London, UK, 9-13/09/2002. Oxford, England: Elsevier Science.
18. de Felice G, Liberatore D, De Santis S, Gobbin F, Roselli I, Sangirardi M, AlShawa O, Sorrentino L (2022) Seismic behaviour of rubble masonry: shake table test and numerical modelling. *EarthqEng Struct Dyn*. <https://doi.org/10.1002/eqe.3613>.
19. De Martino G, Di Ludovico M, Prota A, Moroni C, Manfredi G, Dolce M (2017) Estimation of repair costs for RC and masonry residential buildings based on damage data collected by post-earthquake visual inspection. *Bull Earthquake Eng* 15:1681-1706. <https://doi.org/10.1007/s10518-016-0039-9>.
20. De Santis S, AlShawa O, de Felice G, Gobbin F, Roselli I, Sangirardi M, Sorrentino L, Liberatore D (2021) Low-impact techniques for seismic strengthening fair faced masonry walls. *Constr Build Mater* 307:124962. <https://doi.org/10.1016/j.conbuildmat.2021.124962>.
21. De Santis S, De Canio G, de Felice G, Meriggi P, Roselli I (2019a) Out-of-plane seismic retrofitting of masonry walls with Textile Reinforced Mortar composites. *Bull EarthqEng* 17(11):6265-6300. <https://doi.org/10.1007/s10518-019-00701-5>.
22. De Santis S, de Felice G (2021) Shake table tests on a tuff masonry structure strengthened with composite reinforced mortar. *Compos Struct* 275:114508. <https://doi.org/10.1016/j.compstruct.2021.114508>.
23. De Santis S, Roscini, de Felice G (2019b) Retrofitting of masonry vaults by basalt-textile reinforced mortar overlays. *Int J ArchitHerit* 13(7):1061-1077. <https://doi.org/10.1080/15583058.2019.1597947>.
24. Derakhshan H, Lucas WD, Griffith MC (2018) In-situ seismic verification of non-structural components of unreinforced masonry buildings. *Australian J Struct Eng* 19(1):44-58. <https://doi.org/10.1080/13287982.2017.1370963>.
25. Di Ludovico M, Prota A, Moroni C, Manfredi G, Dolce M (2017) Reconstruction process of damaged residential buildings outside historical centres after the L'Aquila earthquake: part II - "heavy damage" reconstruction. *Bull EarthqEng* 15:693-729. <https://doi.org/10.1007/s10518-016-9979-3>.
26. Dolce M, Goretti A (2015) Building damage assessment after the 2009 Abruzzi earthquake. *Bull EarthquakeEng* 13:2241-2264. <https://doi.org/10.1007/s10518-015-9723-4>.
27. Dolce M, Martinelli A (2005) Inventario e vulnerabilità degli edifici pubblici e strategici dell'Italia centro-meridionale, Vol. II - Analisi di vulnerabilità e rischio sismico, INGV/GNDT Istituto Nazionale di geofisica e Vulcanologia / Gruppo Nazionale per la Difesa dai Terremoti, L'Aquila, Italy (in Italian).
28. European Environment Agency (2010) Mapping the impacts of natural hazards and technological accidents in Europe. EEA Technical report No 13/2010. Luxembourg: Publications Office of the European Union.
29. European Seismological Commission (1998) European Macroseismic Scale 1998, EMS-98, Gruntal, G. Editor, Subcommittee on Engineering Seismology, Working Group Macroseismic Scale.

30. Formisano A, Florio G, Landolfo R, Mazzolani FM (2011) Un metodo per la valutazione su larga scala della vulnerabilità sismica degli aggregati storici. In Proceedings of 13th Italian national conference for earthquake engineering. Bari, Italy 18-22/09/2011 (in Italian).
31. Gattesco N, Boem I (2017) Out-of-plane behavior of reinforced masonry walls: Experimental and numerical study. *Compos Part B Eng* 128:39-52. <https://doi.org/10.1016/j.compositesb.2017.07.006>.
32. Giaretton M, Valluzzi MR, Mazzon N, Modena C (2017) Out-of-plane shake-table tests of strengthened multi-leaf stone masonry walls. *Bull EarthqEng* 15(10):4299-4317. <https://doi.org/10.1007/s10518-017-0125-7>.
33. Göçer C (2020) Structural evaluation of masonry building damages during the April 24, 2014 Gökçeada earthquake in the Aegean Sea. *Bull EarthqEng* 18(7): 3459-3483. <https://doi.org/10.1007/s10518-020-00833-z>.
34. Hill M, Rossetto T (2008) Comparison of building damage scales and damage descriptions for use in earthquake loss modelling in Europe. *Bull EarthqEng* 6:335-365. <https://doi.org/10.1007/s10518-007-9057-y>.
35. Indirli M, Kouris LAS, Formisano A, Borg RP, Mazzolani FM (2013) Seismic Damage Assessment of Unreinforced Masonry Structures After The Abruzzo 2009 Earthquake: The Case Study of the Historical Centers of L'Aquila and CastelvechioSubequo. *Int J ArchitHerit* 7(5):536-578. <https://doi.org/10.1080/15583058.2011.654050>.
36. Ismail N, Oyarzo V, Ingham J (2010) Field testing of URM walls seismically strengthened using twisted steel inserts. In Proceedings of 10th Chilean Conference on Seismology and Earthquake Engineering. Santiago, Chile.
37. Lagomarsino S (2012) [Damage assessment of churches after L'Aquila earthquake \(2009\)](#). *Bull EarthqEng* 10(1):73-92. <https://doi.org/10.1007/s10518-011-9307-x>.
38. Lourenço PB, Mendes N, Ramos LF, Oliveira DV (2011) Analysis of masonry structures without box behaviour. *Int J ArchitHerit* 5(4-5):369-382. <https://doi.org/10.1080/15583058.2010.528824>.
39. Lourenço PB, Oliveira DV, Leite JC, Ingham JM, Modena C, da Porto F (2013) Simplified indexes for the seismic assessment of masonry buildings: International database and validation. *Eng Failure An* 34:585-605. <https://doi.org/10.1016/j.engfailanal.2013.02.014>.
40. Marino M, Neri F, Borri A, De Maria A (2014) Experimental data of friction coefficient for some types of masonry and its correlation with an index of quality masonry (IQM). In Proceedings of Second European conference on earthquake engineering and seismology. Istanbul, Turkey 25-29/08/2014.
41. Mazzoni S, Castori G, Galasso C, Calvi P, Dreyer R, Fischer E, Fulco A, Sorrentino L, Wilson J, Penna A, Magenes G (2018) 2016-2017 central Italy earthquake sequence: Seismic retrofit policy and effectiveness. *Earthq Spectra* 34(4):1671-1691. <https://doi.org/10.4430/bgta0170>.
42. Penna A (2015) Seismic assessment of existing and strengthened stone-masonry buildings: Critical issues and possible strategies. *Bull EarthqEng* 13(4):1051-1071. <https://doi.org/10.1007/s10518-014-9659-0>.

43. Penna A, Calderini C, Sorrentino L, Carocci CF, Cescatti E, Sisti R, Borri A, Modena C, Prota A (2019) Damage to churches in the 2016 central Italy earthquakes. *Bull EarthqEng* 17(10):5763-5790. <https://doi.org/10.1007/s10518-019-00594-4>.
44. Penna A, Morandi P, Rota M, Manzini CF, da Porto F, Magenes G (2014) Performance of masonry buildings during the Emilia 2012 earthquake. *Bull EarthqEng* 12:2255-2273. <https://doi.org/10.1007/s10518-013-9496-6>.
45. Perrone D, Calvi PM, Nascimbene R, Fischer EC, Magliulo G (2019) Seismic performance of non-structural elements during the 2016 Central Italy earthquake. *Bull EarthqEng* 17:5655-5677. <https://doi.org/10.1007/s10518-018-0361-5>.
46. Rapone D, Brando G, Spacone E, De Matteis G (2018) Seismic vulnerability assessment of historic centers: description of a predictive method and application to the case study of Scanno (Abruzzi, Italy). *Int J ArchitHerit* 12(7-8):1171-1195. <https://doi.org/10.1080/15583058.2018.1503373>.
47. Senaldi I, Guerrini G, Comini P, Graziotti F, Penna A, Beyer K, Magenes G (2020) Experimental seismic performance of a half-scale stone masonry building aggregate. *Bull EarthqEng* 18(2):609-643. <https://doi.org/10.1007/s10518-019-00631-2>.
48. Senaldi I, Magenes G, Penna A, Galasco A, Rota M (2014) The Effect of Stiffened Floor and Roof Diaphragms on the Experimental Seismic Response of a Full-Scale Unreinforced Stone Masonry Building. *J EarthqEng* 18(3):407-443. <https://doi.org/10.1080/13632469.2013.876946>.
49. Sisti R, Di Ludovico M, Borri A, Prota A (2019) Damage assessment and the effectiveness of prevention: the response of ordinary unreinforced masonry buildings in Norcia during the Central Italy 2016/2017 seismic sequence. *Bull EarthqEng* 17(10):5609-5656. <https://doi.org/10.1007/s10518-018-0448-z>.
50. Sorrentino L, Cattari A, da Porto F, Magenes G, Penna A (2019) Seismic behaviour of ordinary masonry buildings during the 2016 central Italy earthquakes. *Bull EarthqEng* 17(10):5583-5607. <https://doi.org/10.1007/s10518-018-0370-4>.
51. Taffarel S, da Porto F, Valluzzi MR, Modena C (2018) Comparing expeditious procedures for the seismic vulnerability assessment on the European territorial context: reliability, feasibility, cost, and time consumption. *Int J ArchitHerit* 12(7-8):1150-1161. <https://doi.org/10.1080/15583058.2018.1503375>.
52. USRA Ufficio Speciale per la Ricostruzione del comune de L'Aquila(2014) Manuale di Istruzioni della Scheda di Accompagnamento ai Progetti di Ricostruzione del Comune de L'Aquila (in Italian).
53. Van Eldere H, Ramos LF, Verstryngge E, Shetty N, Van Balen K, Barroso CE, Oliveira DV (2018) The Application of Sonic Testing on Double-Leaf Historical Portuguese Masonry to Obtain Morphology and Mechanical Properties. In *Proceedings of Structural Analysis of Historical Constructions Conference SAHC 2018, Cusco, Perù, 11-13/09/2018*. Springer International Publishing.
54. Vintzileou E, Mouzakis C, Adami CE, Karapitta L (2015) Seismic behavior of three-leaf stone masonry buildings before and after interventions: Shaking table tests on a two-storey masonry model. *Bull EarthqEng* 13(10):3107-3133. <https://doi.org/10.1007/s10518-015-9746-x>.

55. Vlachakis G, Vlachaki E, Lourenço PB (2020) Learning from failure: Damage and failure of masonry structures, after the 2017 Lesvos earthquake (Greece). *Eng Fail An* 117:104803. <https://doi.org/10.1016/j.engfailanal.2020.104803>.
56. Wang M, Liu K, Guragain R, Shrestha H, Ma X (2019) Shake table tests on the two-storey dry-joint stone masonry structures reinforced with timber laces and steel wires. *Bull EarthqEng* 17(4):2199-2218. <https://doi.org/10.1007/s10518-018-00528-6>.

Figures

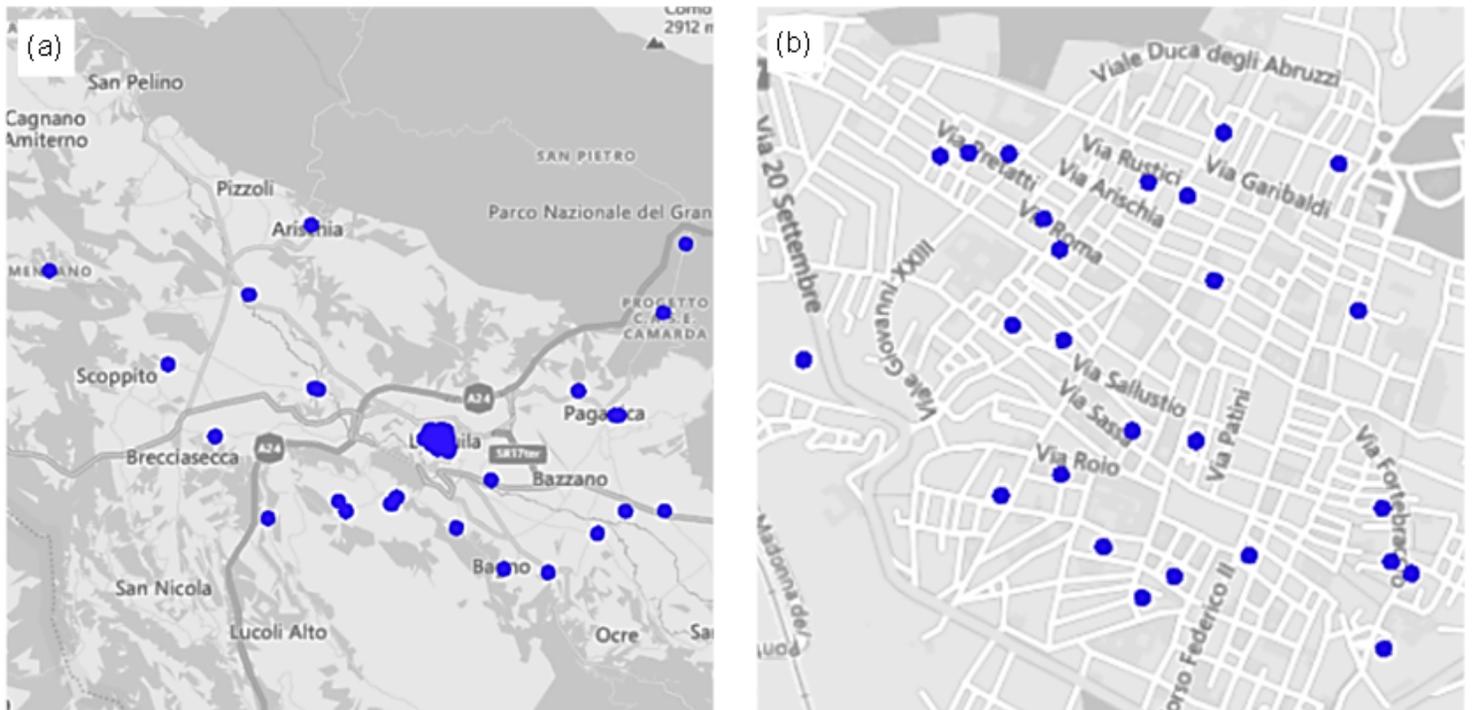


Figure 1

Locations of the aggregates included in the sample.

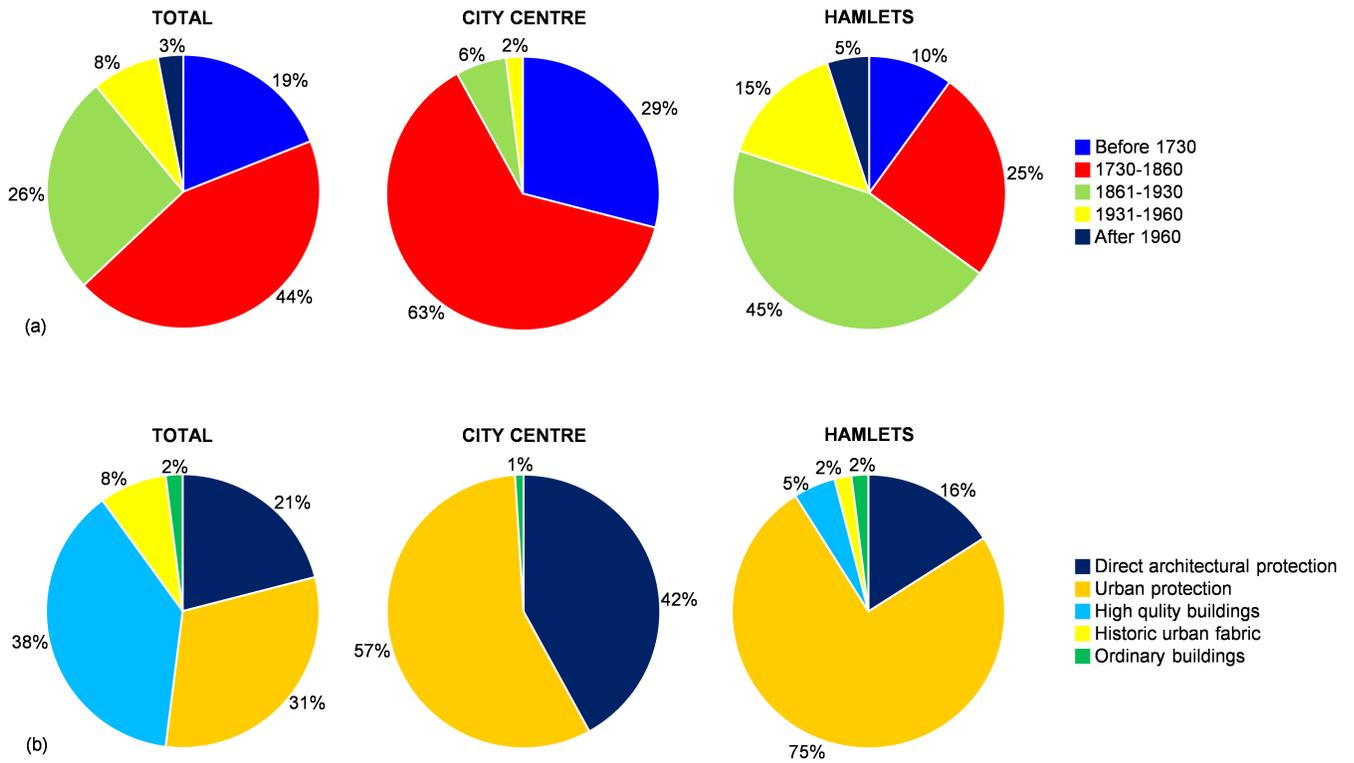


Figure 2

Sample under study: age of construction (a) and historic and architectural value (b).

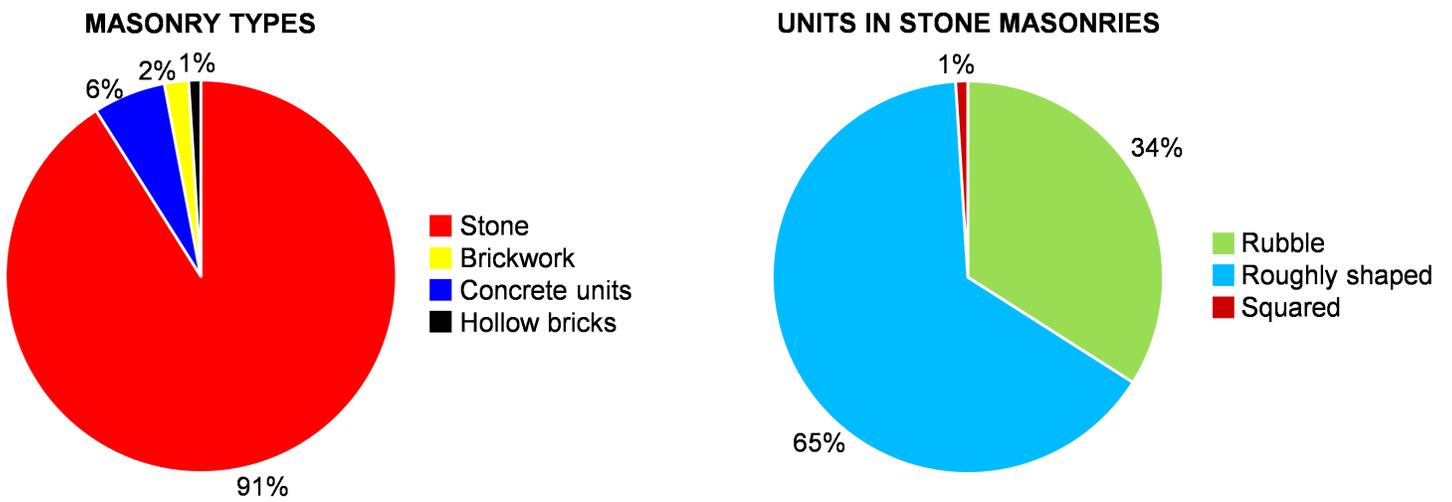


Figure 3

Sample under study: masonry types (a) and squaring level of units in stone masonries (b).

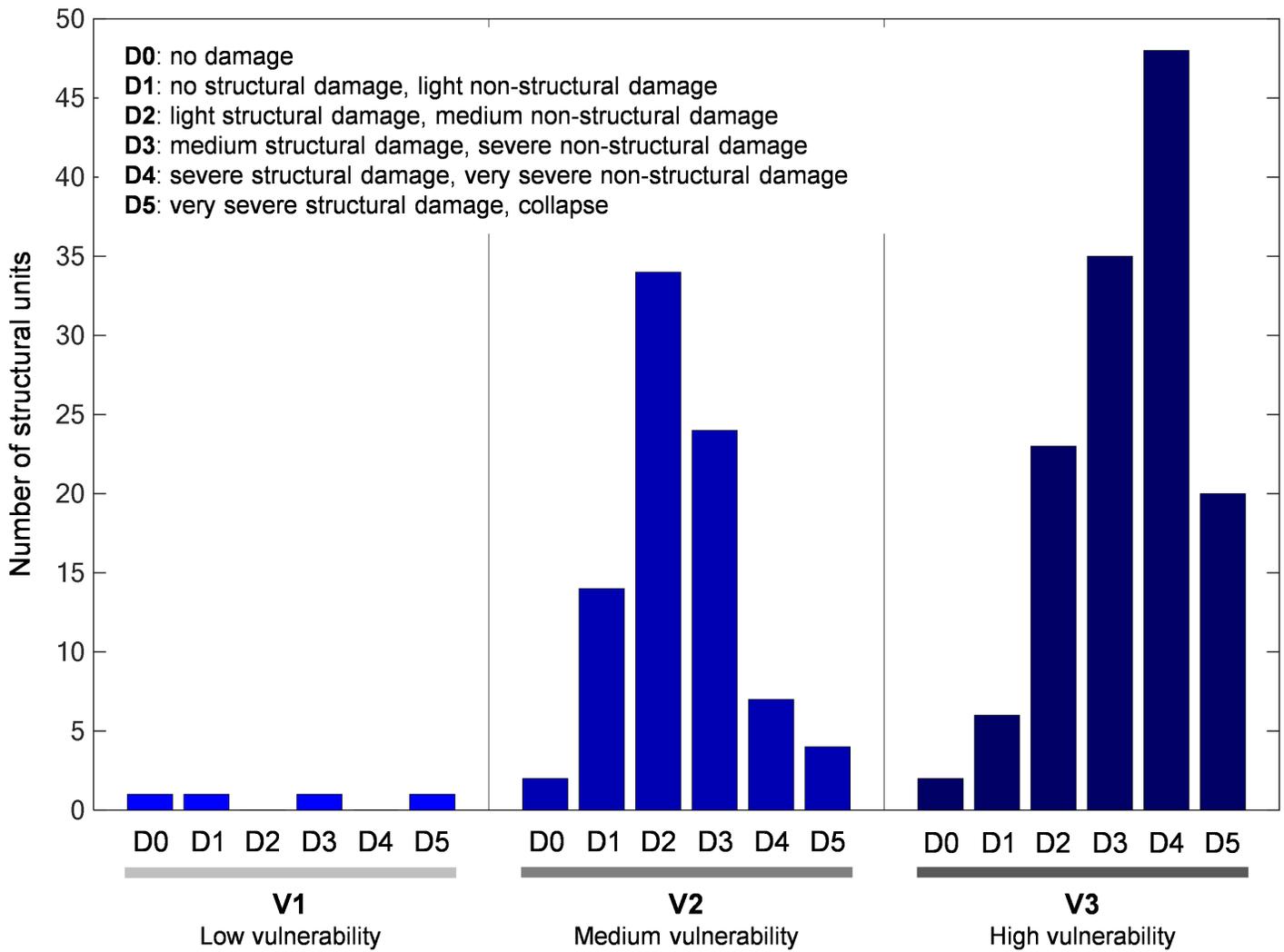


Figure 4

Relationships between damage and vulnerability detected during post-earthquake inspections on the structural units included in the sample. Information extracted from the forms submitted to USRA.

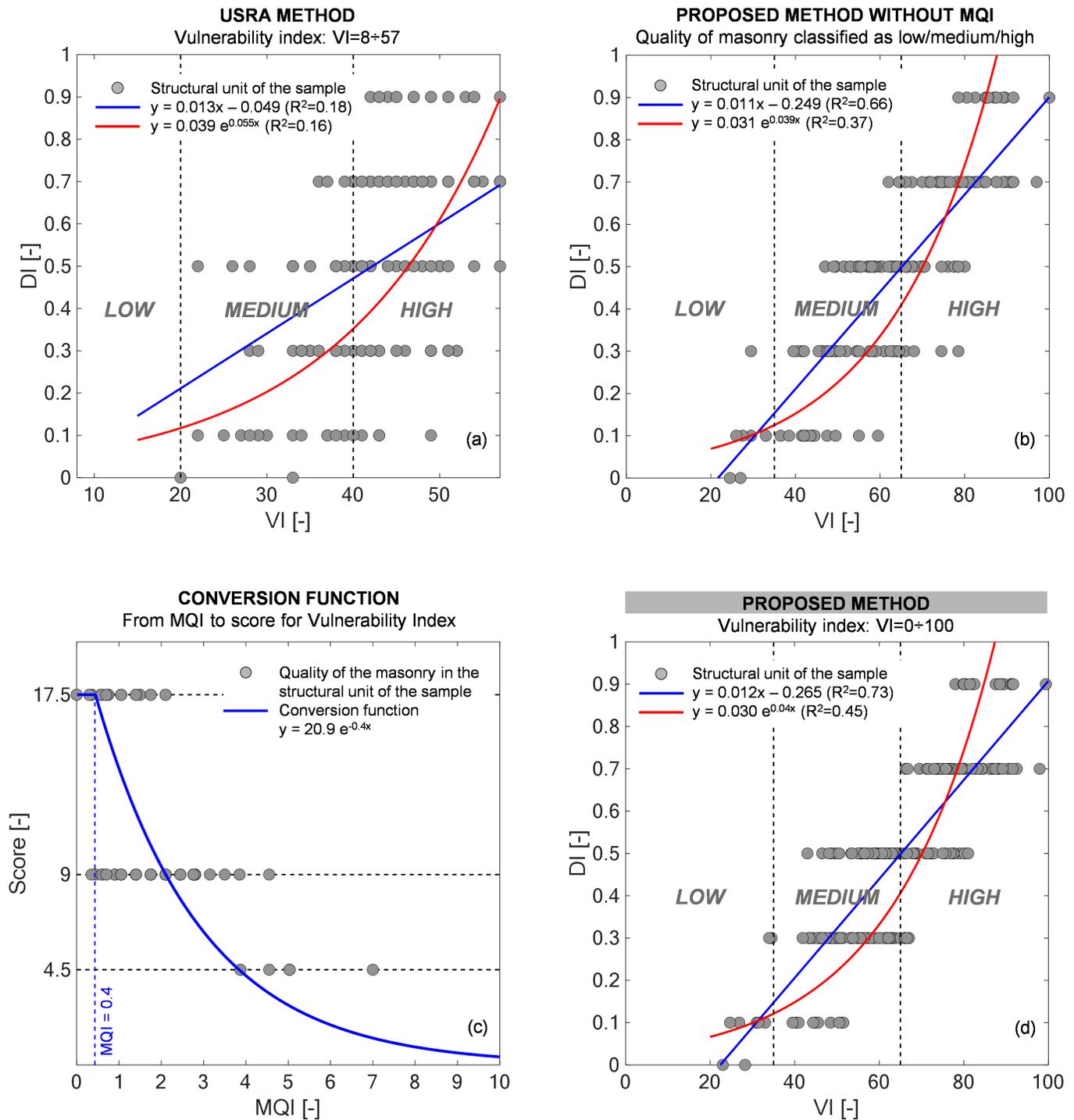


Figure 5

Relationships between damage index and vulnerability index provided by USRA method (a) and by the proposed method without MQI (b), conversion function to calculate the score associated with the quality of masonry from MQI (c) and relationship between damage index and vulnerability index provided by the proposed method with MQI (d).

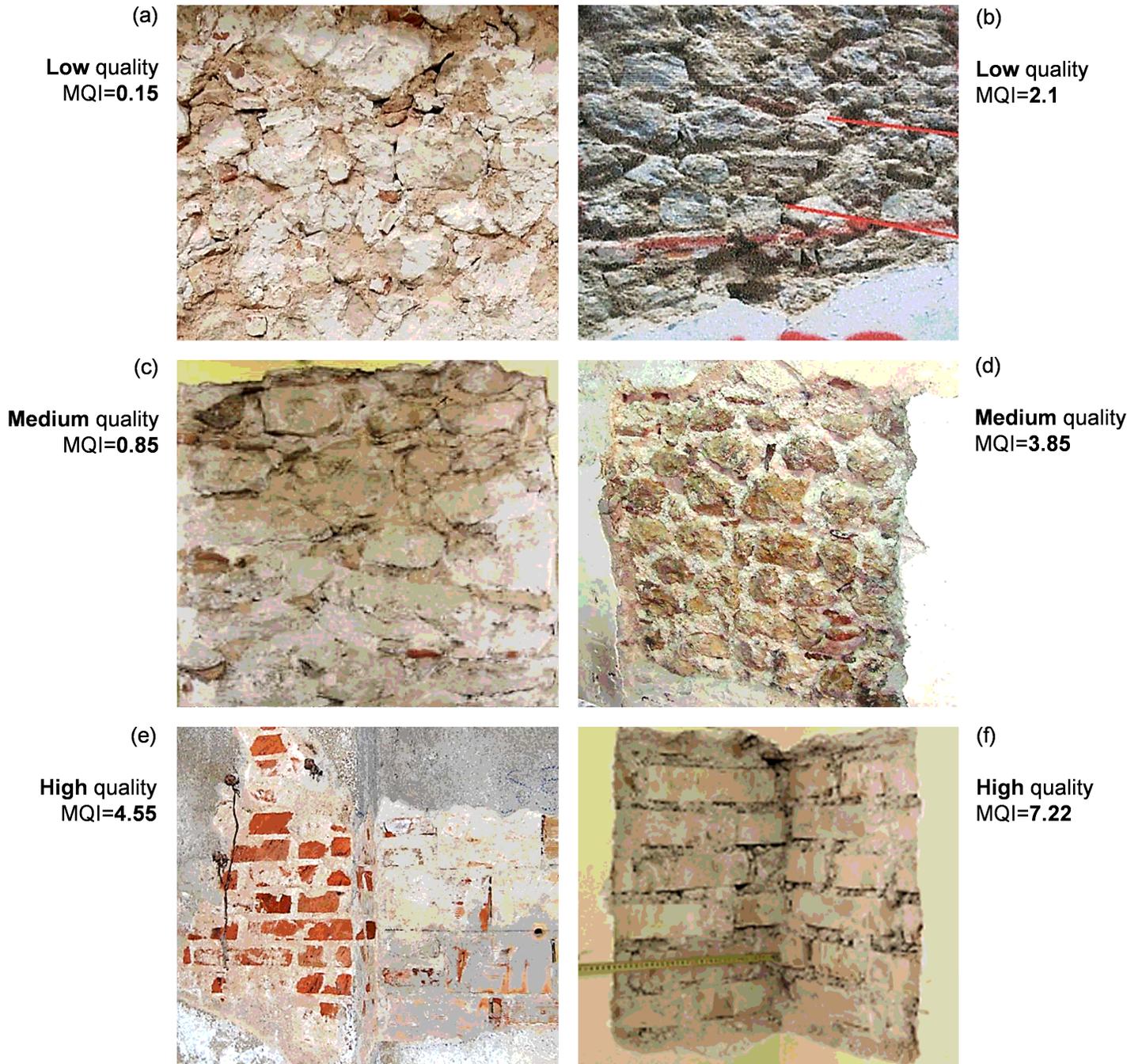


Figure 6

Masonry types from the sample classified as *low* (a,b), *medium* (c,d) and *high* (e,f) *quality* and corresponding values of the Masonry Quality Index.

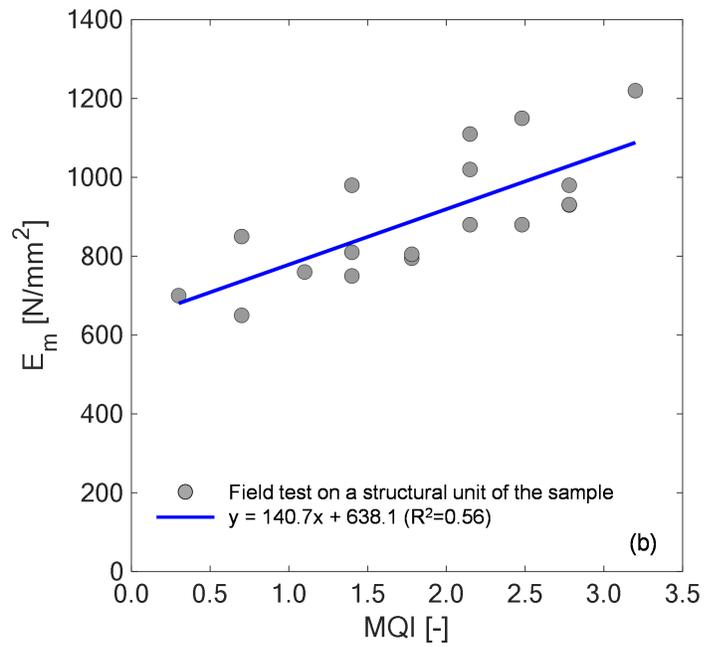
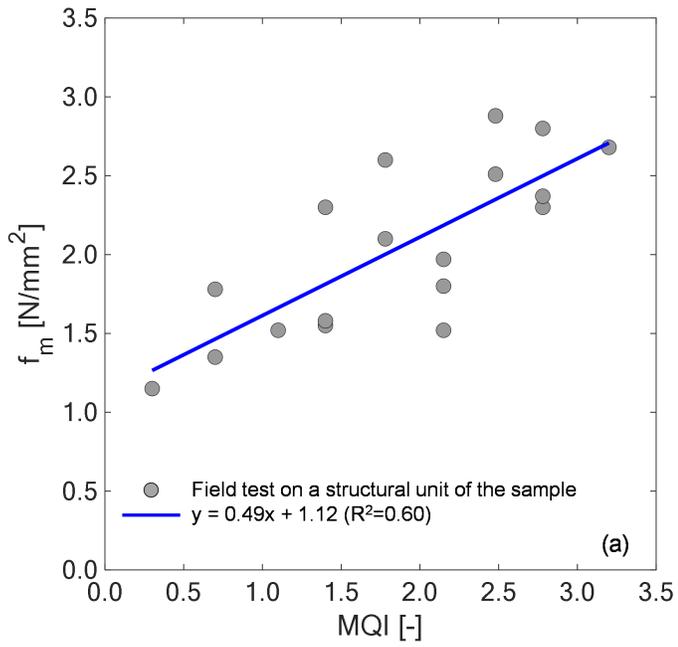


Figure 7

Relationship between in-plane Masonry Quality Index and masonry compressive strength (a) and Young's modulus (b) (double-flat jack tests available for a subset of the database).