

Simplified survey form of unreinforced masonry buildings calibrated on data from the 2009 L'Aquila earthquake

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Abstract The 2009 L'Aquila earthquake in southern Italy affected a rather large number of buildings, which experienced macroseismic intensities between V and IX on the Mercalli–Cancani–Sieberg scale. Almost sixty thousand unreinforced masonry constructions were officially inspected and almost half of them ended up losing their usability status temporarily, partially or completely, where the term usability refers to the suitability of a building for habitation or occupancy after a seismic event. A fairly detailed damage and usability form was compiled thanks to the work of a large number of volunteers. However, when pre-event surveys are carried out, data collection needs to be confined to the most relevant information in order to save time and manpower. The main aim of this article is, thus, the definition of a simplified form for pre-earthquake territorial-scale surveys of buildings, one containing fewer usability parameters and categories than the form compiled after the earthquake in L'Aquila. Analysis shows similar usability for buildings with more than two storeys above ground, those with construction timespans after 1962, and structural types with a specific combination of vertical and horizontal structures. Therefore, a simplified tool is recommended, one with just three categories for number of storeys instead of the thirteen in the current form, five construction timespan categories instead of eight, four structural classes instead of the current thirty. Other parameters, such as the presence of isolated columns or of mixed structures, have been removed altogether.

Keywords Seismic vulnerability · Usability assessment · Building inventory · Building types · Vulnerability classes · Rapid visual screening

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1 Introduction

In recent decades, great losses have been caused by natural disasters. As regards earthquakes, in particular, every year many cause significant economic and social losses, having a great regional impact on areas affected both directly by the earthquake and indirectly by the economic and social disasters that follow. Economic and social consequences are frequently related to loss of building usability, i.e. no longer being habitable or fit for occupancy after a seismic event (Stannard et al. 2014). Consequently, a model for the assessment of vulnerability, and for the evaluation of related economic and social losses, would allow not only to estimate possible future losses, due to the occurrence of earthquakes that can affect a given region, but also to prepare and to implement measures to mitigate this risk (Calvi et al. 2006).

In Italy, 57% of existing residential buildings have unreinforced masonry (URM) structures (ISTAT 2011), thus constituting a very large share of the construction portfolio. In the past, pre-event vulnerability was assessed according to rather detailed survey forms (e.g., GNDT-SSN 1994), requiring complete access to buildings and large resources, thus restricting application to limited areas because of the necessary effort. Productivity was even lower than for surveys taken after recent Italian earthquakes when teams were able to inspect about seven buildings a day on average (Goretti and Di Pasquale 2004; Dolce and Goretti 2015). The aim of this research is to completely change the situation as it now stands with the GNDT form (GNDT-SSN 1994) so as to speed up surveys, extend them to large areas, and perform them within the limited resources available to the small municipalities of the most seismic prone areas in Italy. This goal can be achieved only if the number of visual survey parameters is reduced.

As an alternative to the GNDT form (GNDT-SSN 1994), large scale vulnerability analyses have been carried out either involving the disaggregation of the inventory into building classes or by computing a vulnerability index for each building. An example of building class definition comes from the surveys performed after the 1980 Irpinia earthquake in southern Italy, when about 600 military engineers and architects inspected 36,000 buildings, using a basic form, to record damage and allocate funds. Considering damage to vertical structures, which was then associated with damage to other structural elements, Braga et al. (1982) defined three vulnerability classes for URM buildings, based on the presence of horizontal and vertical structures rather than other building features. The classes suggested by Braga et al. (1982) were later used to interpret observed damage after several earthquakes (Goretti and Di Pasquale 2004; Dolce and Goretti 2015) and for scenario analyses (Dolce et al. 2006). Damage probability matrices were derived, using Medvedev–Karnik–Sponheuer macroseismic intensity as a ground motion intensity measure. Barbat et al. (1996) computed a seismic damage scenario for URM buildings using the Monte Carlo method to generate damage probability matrices, fragility curves and vulnerability functions. Fragility curves for a larger number of vulnerability classes than in macroseismic scales were proposed by Kappos et al. (2006), involving a combination of damage survey data and numerical analyses to fill the gaps in post-earthquake inventories, especially for high intensities. Peak ground acceleration was used as an intensity measure, which was also chosen by Erberik (2008), who derived fragility curves for 120 Turkish masonry structural types, and compared predictions with damage surveyed on 140 buildings affected by the 1995 Dinar earthquake. Analytical fragility curves were derived from a mechanism approach by D’Ayala (2013), which also contains a broad review of available international procedures for vulnerability estimation.

On the other hand, Benedetti and Petrini (1984) introduced a vulnerability index that went beyond the simple listing of just a few building classes and took into account possible strengthening strategies. The procedure is based on the attribution of category and importance scores to ten parameters, and the authors provided recommended values based on expert judgement and on physical tests on two different specimens. Despite the large number of parameters considered, one of which required some knowledge of the geometry and actual computations, comparison between vulnerability index and surveyed damage in about 2300 buildings highlighted significant scatter (Benedetti et al. 1988). The vulnerability-index approach was further developed for several risk or scenario analyses (Angeletti and Petrini 1993; Cherubini et al. 1999; Martinelli et al. 2008; Vicente et al. 2011), and additional parameters were suggested to account for buildings belonging to blocks or aggregates (Formisano et al. 2011). Alternative scoring systems, still based on rapid visual screening, have been proposed in several seismic-prone countries around the world, as discussed by Achs and Adam (2012).

As mentioned, both building class and vulnerability index methods are based on data calibration from past earthquakes. A number of procedures were developed in the past for post-earthquake surveys, some being used in several seismic events, others remaining limited to experimentation. Among the latter is a rather advanced approach for fast assessment of post-emergency safety, as proposed within the STEP project, involving the combined use of an inspection form (Dragomir et al. 2012) and a mobile unit capable of performing in situ tests and analyses (Casarotti et al. 2009). The shortcoming of this procedure is the need for several instrumentally equipped units within a single municipality. On the contrary, a well-established procedure based on fast visual surveys is described in ATC-20-1 (2005), where three colour-coded placards are employed: green for a safe to use building, yellow for limited entry (restricted use) and red for an unsafe building. In ATC-20-1 the main safety considerations for the evaluation of damaged buildings are risks of overall or partial collapse due to loss of structural strength, stability or stiffness, and risks of non-structural building elements becoming falling hazards. ATC-20-1 formed a very important basis for the Rapid Assessment Form to carry out Rapid Building Usability Assessments during a State of Emergency applied in New Zealand (Stannard et al. 2014). The purpose of the procedure is to quickly establish the usability of buildings and corresponding infrastructure where functions may be compromised by a hazardous event. Again, three placard choices, depending on the damage level, are possible: white, yellow or red, whose meaning is very similar to those of the USA approach.

After the 2009 L'Aquila earthquake in southern Italy, some 75,000 buildings were officially surveyed. This involved filling out a form which, as will be shown in the following section, is rather detailed as regards the description of construction characteristics. Dolce and Goretti (2015) analysed in-depth damage surveys after this earthquake, studying the performance of the overall building stock and formulating extensive considerations about emergency management. They also investigated the association between surveyed damage levels and usability, but focused little attention on URM buildings and their construction details. On the other hand, other works discuss only specific issues about URM building performance during the 2009 event, concerning a smaller number of buildings. Augenti and Parisi (2010) associated the most significant observed damage with the theoretical failure modes of both reinforced concrete (RC) and URM buildings. D'Ayala and Paganoni (2011) used the FaMIVE approach on a building sample of about 10% of the historic city centre of L'Aquila. Baiocchi et al. (2012) used high-resolution satellite images for rapid identification of building collapse mechanisms. Dolce and

Manfredi (2015) debated the evolution of reconstruction procedures for private buildings, proposed interventions and corresponding economic issues.

Given the size of the inventory of officially inspected URM buildings, and the shaking intensities that vary across a wide range, and considering that, as will be shown in the two next sections, constructions affected by the 2009 earthquake are representative of those built in several seismic prone areas in Italy, it makes sense to analyse these data thoroughly. The proposed survey form uses parameters and categories based on quantitative evaluations of impact on usability, rather than qualitative expert judgement, and its simplified nature could save time and effort in future preventive risk analyses.

2 The AeDES survey form

The data analysed in the following sections comes from “Level 1 Form for Post-Earthquake Damage and Usability Assessment and Emergency Countermeasures in Ordinary Buildings” (whose Italian acronym is AeDES). This form, designed for ordinary buildings, thus excluding large halls or monuments (Gizzi et al. 2014; Sorrentino et al. 2014; Marotta et al. 2017), is a 2008 marginal update of the 2000 edition (Baggio et al. 2000), based on the experiences of the 1997 Umbria–Marche and 1998 Pollino earthquakes in Italy, the first events where the AeDES tool was used (Colozza et al. 2000). The 2000 edition is based on preliminary versions developed in the two previous decades (Pinto and Taucer 2007). Initially, usability surveys were performed in Italy by means of vulnerability forms (Benedetti and Petrini 1984), and the first usability form was proposed around the mid-1980s (Gavarini 1985). The 2008 version was officially approved in 2011 (DPCM 2011), and is the one currently used.

The AeDES form is subdivided into nine sections (Colozza et al. 2000):

1. Building identification: address, building position within a block (also called structural aggregate);
2. Building description: number of storeys, storey height, storey area, construction timespan and possible structural modification timespan, exposure in terms of use, number of real estate units and occupants;
3. Building typology: structural material (URM, RC, steel). In the case of masonry constructions: roof type, presence of isolated columns, of mixed structures, of strengthening interventions. In the case of constructions other than masonry: presence of walls, plan and vertical regularity;
4. Damage to structural elements, both earthquake-related and pre-existing, described in terms of severity and extension, and previous provisional interventions;
5. Damage to non-structural elements and related previous provisional interventions;
6. External hazard due to other constructions and related previous provisional interventions;
7. Soil and foundation: description of features and damage;
8. Usability assessment: usable building (A), temporarily unusable building but usable provided that short-term interventions are carried out (B), partially usable, only a part of the building can be used safely (C), requiring more detailed investigation (D), unusable building (E), unusable due to external hazard (F). Suggestions for short-term countermeasures;
9. Notes.

Hereinafter special attention will be given to the association between building features (sections 1–3) and usability (section 8), but there will be no discussion of observed damage (sections 4–5). For the purposes of the analyses to be presented, F-tagged buildings have been placed with A-tagged buildings, because the non-usability of the former is related to an external hazard, although the buildings themselves are usable.

3 Description of the inventory

3.1 Macroseismic intensities recorded in the investigated area

Only a subset of the original database of approximately 75,000 buildings inspected after the 2009 event has been considered in the following analyses, not taking into account forms:

1. Related to RC, steel or unknown structures;
2. Where section 3 was not filled in,
3. Related to municipalities where less than ten buildings were surveyed,
4. Referred to localities for which no macroseismic intensity has been assigned.

The characteristics of the remaining 59,492 buildings in the inventory are presented hereinafter. The constructions belong to 90 municipalities (Fig. 1), and 63 of them are

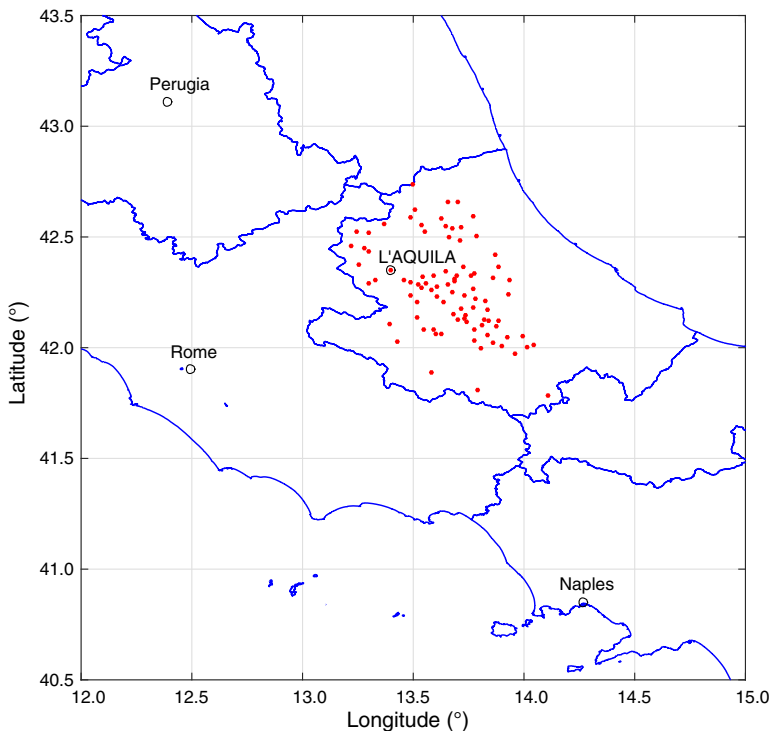


Fig. 1 Central and southern Italy: regional boundaries and location of the 90 municipalities affected by the 2009 L'Aquila earthquake considered in this study

subdivided into two or more localities. When the locality was not specified in the form, it was attributed on the basis of the address. The municipality of L'Aquila itself, where 16,599 inspected buildings are located, is subdivided into 61 localities.

The accelerometer network at the time of the mainshock was not dense enough to get an adequate resolution from ground motion records, thus hampering the use of ground motion parameters as intensity measures. Therefore, for the computations presented hereinafter, macroseismic intensity has been used. Moreover, in the past, earthquake data has been analysed in reference to macroseismic intensity and, consequently, comparisons are easier if this intensity measure is considered. Additionally, Italian seismic catalogues are fairly well documented, dating back to the 5th century B.C. (<http://storing.ingv.it/cfti4med/>), making it possible to define local seismic hazard in terms of macroseismic intensity. These catalogues make use of the Mercalli–Cancani–Sieberg (MCS) scale, and such intensities are available for a larger number of municipalities and a more detailed disaggregation of localities affected by the 2009 earthquake (Galli et al. 2009) compared to European Macroseismic Scale (EMS) intensities (Azzaro et al. 2011). Therefore, the following computations refer to MCS intensities, but it is worth mentioning that a mathematical relationship between the two intensity scales has been proposed in Margottini et al. (1987):

$$I_{MCS} = 1.17I_{EMS} - 0.76 \quad (1)$$

Macroseismic intensity has been attributed to each municipality and its localities according to Galli et al. (2009), and varies between V and IX–X MCS. Hereinafter intensities have been merged to integers, e.g., V and V–VI fall under V and so on, thus avoiding in the following analyses sub-samples with very limited populations. The distribution of these merged intensities is shown in Fig. 2a. Almost three quarters of the inventory, in terms of number of buildings, fall in the range from V to VI MCS, whereas 2% of the buildings experienced IX MCS. The buildings in L'Aquila, including the outskirts, underwent macroseismic intensities between V and IX MCS, whereas Dolce and Goretti (2015) considered the whole city experiencing intensity VIII MCS.

The inventory here considered is remarkable in terms of size and amplitude of experienced intensities, compared to previous Italian earthquakes (Braga et al. 1982; Goretti

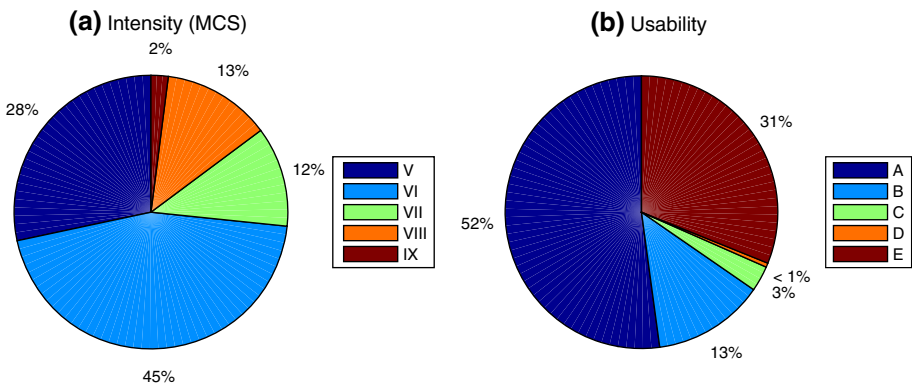


Fig. 2 Inventory distributions (number of buildings) according to intensities and usability assessment (A usable building, B usable building provided that short-term interventions are carried out, C partially usable, only a part of the building can be used safely, D requiring more detailed investigation, E unusable building). Total number of buildings: 59,492

and Di Pasquale 2004), and directly involves a medium-sized city, which has not been the case since the 1915 Avezzano earthquake in Abruzzi region.

3.2 Geometric and structural features recorded using the AeDES form

Given the size and the characteristics of the inventory, it is important to analyse how its features influenced usability. The disaggregation of the inventory in terms of usability is presented in Fig. 2b. More than half of the buildings in the sample are completely usable (A + F), more than 30% are unusable (E), about 13% are B cases, and about 3% C cases. Considering all types of structures, Dolce and Goretti (2015) report the following relative usability frequencies: 58% for A + F, 26% for E, 16% B – D. Thus, URM buildings, including mixed structures, show a slightly less satisfactory performance.

As for data in the first three sections of the form, a synopsis is presented hereinafter. The total number of storeys, including underground floors, varies between one and ten, however only one building out of fifty has more than four storeys, whereas almost nine out of ten have up to three storeys (Fig. 3a). Finally, only in 0.6% of the cases was this information not recorded. In almost two-thirds of the buildings there is no basement, whereas in more than one quarter of the inventory there is one underground storey (Fig. 3b). Considering the number of storeys above ground, i.e. the difference between total number of storeys and number of underground storeys, 14% of the inventory has just one storey, 46% has two storeys, 33% has three storeys, and less than 8% has more than three. The distribution of number of storeys considered here is similar to those in Celano, also in the Abruzzi region (Martinelli et al. 2008), Potenza, southern Italy (Dolce et al. 2006), and Catania, in Sicily (Faccioli et al. 1999), indicating that behaviours observed in the

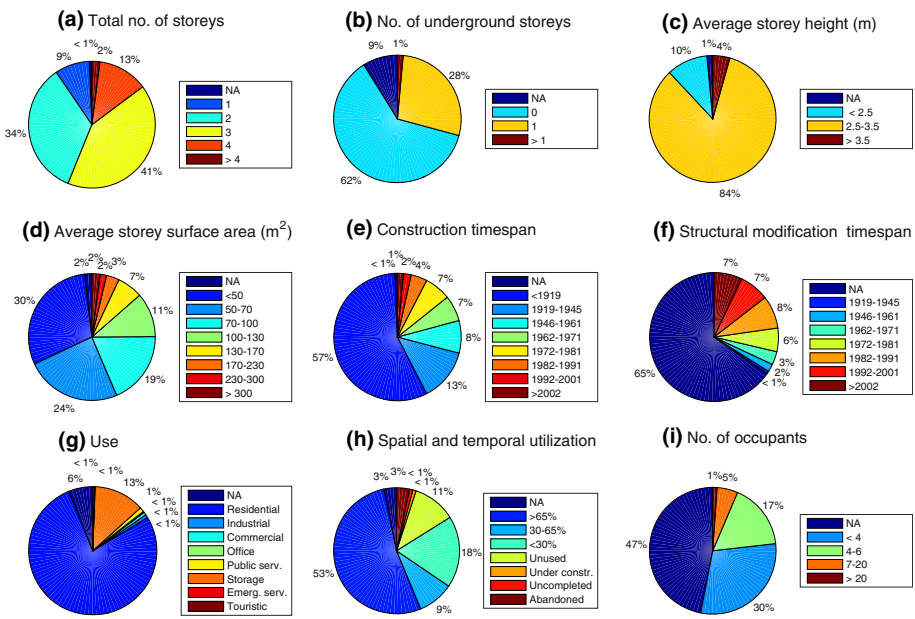


Fig. 3 Inventory distributions (number of buildings) according to building features in section 2 of the AeDES form. Total number of buildings: 59,492

L'Aquila earthquakes have the potential to be relevant to many Italian areas, with the only remarkable exception of very large cities such as Naples and Rome, which however are exposed to reduced hazard compared to previously mentioned cities.

Average storey height varies up to 5 m. However, in most of the inventory it is between 2.5 and 3.5 m (Fig. 3c). Average storey area varies up to more than 3000 m², but area larger than 230 m² covers about one in twenty-five buildings (Fig. 3d). Surface areas up to 70 m² make up more than half of the analysed buildings, and areas up to 130 m² almost another third. This result is consistent with data in Braga et al. (1982), who reported a storey surface area smaller than 100 m² as the most frequent.

As regards the age field, the AeDES form provides for up to two selections, one for construction timespan and another for possible structural modification timespan. Timespan ranges are those considered by the Italian Statistical Institute for Census (ISTAT), but they are modified in order to account for significant changes in structural standards, although not necessarily related to URM constructions. Construction timespan is given for all the buildings in the inventory, and about six out of ten fall within the first timespan (up to 1919), because a significant portion of URM buildings are located in historical centres. Less than one building out of ten in the inventory was built after 1981 (Fig. 3e). In the national census (ISTAT 2011), 25% of URM buildings fall within the first timespan, and another 16% in the second, hence the AeDES inventory is older, probably as a consequence of inspections being requested for more damaged buildings, which are typically older, a topic that will be discussed in a following section. Even newer are the inventories of Celano and Catania (Faccioli et al. 1999; Martinelli et al. 2008). Structural modification timespan is available for approximately one-third of the inventory. As may be expected, class distributions are concentrated in the most recent periods (Fig. 3f), also as a consequence of a M_S 5.8 earthquake which hit the province of L'Aquila in 1984 (Messina and Sposato 1985).

The building use field of the AeDES form provides for multiple selections. However, in approximately 85% of fields just one selection has been made, and only this subsample is presented in Fig. 3g. Residential use is predominant, followed at a great distance by storage. All other uses account for less than 4%. In agreement with previous relative frequencies, the status of 97% of the buildings in the inventory is private property. Spatial and temporal utilization is presented in Fig. 3h: in more than half of the cases utilization is almost full, and is partial in more than a quarter. One in ten buildings are unused and about one in thirty abandoned. Ranges in the number of occupants per building is presented in Fig. 3i. There are fewer than four occupants for almost one-third of the inventory, but 56% of the buildings for which information is available. Occupancy of up to six persons accounts for 88% of the buildings for which this form field has been filled out.

3.3 Structural typology according to AeDES data

Building typology is found in section 3 of the AeDES form. For URM constructions, the form provides for four types of vertical structures (B–E), based on the combination of two types of masonry and the presence or absence of effective connections. A fifth type (denoted by letter A in the AeDES form) is related to unidentified vertical structures. Similarly, five types of horizontal structures (2–6) are included, based on the association of vaults with tie rods, or floor stiffness. A sixth type (denoted by number 1 in the AeDES form) is related to unidentified horizontal structures. As already mentioned, the roof is described in a separate field. According to the form, tie rods can play two roles: enhancing the connections of vertical structures and reducing the thrust of vaults, hence it is possible

to have a building without (connection) tie rods but with tie rods at the springing of a thrusting horizontal structure. A combination of one type of horizontal structure and one type of vertical structure defines a structural type. If more than one structural type is present in a single building, the form asks for the two most predominant, but each combination of one type of horizontal structure and one type of vertical structure must be present at the same storey. Because some buildings are, indeed, of more than one structural type, the total number of surveyed structural types (78,418) exceeds that of the buildings (59,492). The relative frequency distribution of the AeDES structural types can be seen in Table 1. More than half of the vertical structures have poor quality masonry, which can be associated with natural stonework, they have no tie rods or tie beams, and most of them have vaults with no tie rods and flexible or semi-rigid slabs. About one-sixth of the vertical structures have good quality masonry, which can be associated with brick or blockwork, they have effective connections, and most of those structures are combined with stiff floors. Other structural types account for around 5% or less.

Previous structural types have been reported in parts of the Alps and along the Apennines mountain ranges, wherein the most seismic prone Italian areas are located. Moving from north to south, Benedetti et al. (1988) surveyed stone masonry buildings, with roughly dimensioned units, having vaults or timber floors, in Friuli and in a municipality of Umbria. Spence and D’Ayala (1999) described natural stone constructions in the regions of

Table 1 AeDES structural typology of URM buildings

Horizontal structures	Vertical structures					
	A	Unidentified			Good quality masonry of regular layout (blocks, bricks, dimensioned stone units,...)	
		Poor quality masonry of irregular layout (rubble stones, pebbles,...)		Without tie rods or tie beams	With tie rods or tie beams	Without tie rods or tie beams
	B	C	D	E		
Unidentified	1	1.2	2.1	0.5	0.7	0.5
Vaults without tie rods	2	0.4	14.6	2.3	1.8	0.4
Vaults with tie rods	3	0.1	1.0	1.6	0.2	0.5
Beams with flexible slab (timber beams with a single layer of timber boards, jack-arch slab...)	4	0.4	15.1	3.2	2.7	1.0
Beams with semi-rigid slab (timber beams with a double layer of timber boards, I-beams and hollow tile blocks,...)	5	0.5	14.8	5.2	4.7	3.4
Beams with rigid slab (RC floors, beams well connected to RC slabs,...)	6	0.5	2.9	2.9	3.3	11.7

Relative frequency of inventory distribution according to structural type, combination of one type of horizontal structure and one type of vertical structure at the same storey. Total number of structural types (up to two in a single building): 78,418

Umbria and Marche. In Molise, Decanini et al. (2004) discussed the seismic behaviour of natural stone buildings, having masonry vaults over basements or ground storeys, with timber floors above. In Irpinia, Braga et al. (1982) analysed URM buildings of stone or brick masonry with different types of horizontal structures, such as masonry vaults, timber, steel or RC floors. Similar constructions can be found in Mediterranean countries, such as in Greece (Kappos et al. 2008) and Turkey (Erberik 2008). Therefore, it is of some interest to investigate the performance of the types of buildings affected by the 2009 L'Aquila earthquake.

In addition to structural types, the AeDES form has fields relating to the presence of modifications and strengthening interventions, whether simultaneous or not. A first field is devoted to isolated columns, which are URM, RC, steel or timber elements that do not form a three-dimensional frame, which may be the consequence of renovation works, and may introduce additional vulnerability when two-dimensional walls are replaced by mono-dimensional columns. The AeDES form considers only three possible combinations of mixed structural systems in the same building: RC frame being a raised section above URM storeys (G1), URM storeys being a raised section above RC frame (G2), URM and RC structures at the same storey (G3). This classification represents a simplification of all possible mixed structures, which sometimes can be very complex (Cattari and Lagomarsino 2013). Mixed structure types are classified according to one of three categories. For example, a building with boundary URM walls and an internal RC frame, or a URM building with RC walls inserted (usually involving staircases or lift units) is classified as G3. However, confined masonry buildings are not accounted for in the form. As for strengthening interventions, the usability form envisages three possible categories: injections or unreinforced coating (H1); reinforced masonry or masonry with reinforced coating (H2); other or unidentified types of strengthening (H3). The occurrence of isolated columns, mixed structures and strengthening interventions in the inventory is shown in Fig. 4, with some of these features being simultaneously present in the same building. The most frequent observations are related to the presence of isolated columns and of lateral RC additions to the original URM building. Other cases are related to relative frequencies far below 5%. Nonetheless, it is possible that some strengthening interventions escaped the surveyor, because they are almost impossible to detect unless the owner mentions them.

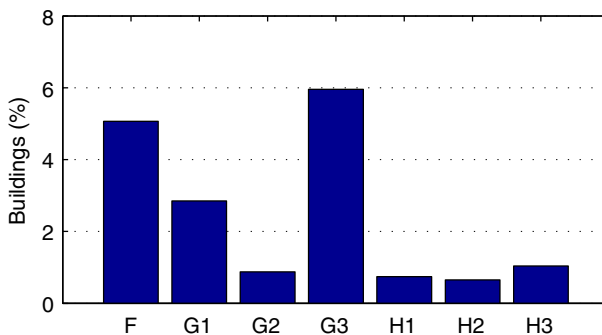


Fig. 4 Relative frequencies of buildings with isolated columns and/or mixed and/or strengthened structures (there may be more than one selection for the same building; percentages out of a total of 59,492). F = isolated columns; G1: RC frame above URM storeys; G2: URM storeys above RC frame; G3: URM and RC structures in the same storey; H1: injections or unreinforced coating; H2 reinforced masonry or masonry with reinforced coating; H3 other or unidentified strengthening

Four types of roof structures are included in the AeDES form as a result of the combination of static scheme and dead load (Fig. 5a). Sloped roofs are considered as thrusting on supporting walls if made of inclined rafters without tie beams (Sorrentino et al. 2008), and are considered as non-thrusting if made of horizontal joists resting on tympanum walls. In the target area, no use of vaults as roof cover has been observed. As for dead load, a metal or a timber structure is considered light, whereas a RC one is considered heavy. The most common roof type is non-thrusting and light, followed by non-thrusting and heavy. Thrusting and light roofs account for more than one out of five, whereas the last combination (thrusting and heavy) is much less common.

Finally, the building position within the aggregate recorded in section 1 of the form is depicted in Fig. 5b: isolated buildings account for more than one-fourth of cases, the end-of-row position another quarter, the corner position one-seventh of the inventory, and an internal position almost one-third of cases.

4 Number of buildings

The AeDES usability form is meant to be applied to a structural unit, the identification of which is based on construction homogeneity (e.g., materials) and geometry homogeneity (e.g., number of storeys). Interaction with adjacent units may take place, especially in historical centres where buildings are clustered, but does not require the application of a single form to a whole aggregate. No information is available about the degree of coverage of the AeDES form in the 90 municipalities. It is reasonable to expect that it is rather high where macroseismic intensity was high and damage widespread. On the other hand, much lower coverage can be expected in towns where shaking was light. If the total number of buildings is underestimated, the occurrence of non-usability will be overestimated, because computation is based on available forms alone. Moreover, the distribution of building characteristics in the sample will also be affected. Similar biases have been already reported in other building inventories (Walsh et al. 2014). Therefore, it is important to pursue a robust estimation of the actual number of buildings, and correct the distribution of parameters at low intensities by means of that at high intensities.

The most updated nationwide estimation of the number of buildings is that in the census, which was last carried out in 2011 (ISTAT 2011). The objectives of usability assessment are different from those of census (Zindato 2011). Hence, the definition of building is not the same and their total number is expected to be different as well. Use is a

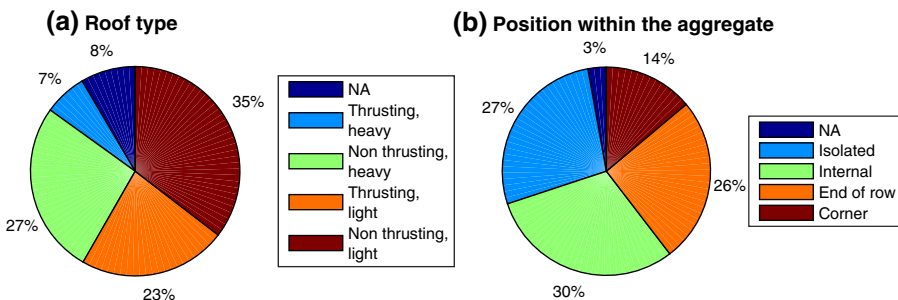


Fig. 5 Inventory distributions according to structural features in sections 3 and 1 of the AeDES form. Total number of buildings: 59,492

very important parameter for the census, which can lead to grouping buildings that are different structural units. For the same reason, some structures are not registered at all in the census, because they are scattered non-residential buildings or because they are annexes of main buildings (e.g., warehouses, stables, and so on). As shown in Fig. 3g, the latter category is not negligible. Similarly, buildings with a comparatively small foot-print area are not taken into account by the census, but such buildings can be present in historic areas. Finally, the census reports the structural material for residential buildings only, whereas the usability form applies to all structural units, irrespective of use, with the exception of large span and monumental buildings.

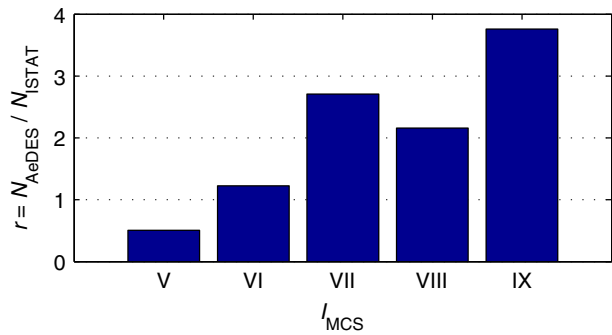
Another source of census underestimation of the number of buildings could be due to the fact that some constructions are not registered in the cadaster. In Italy, the current urban cadaster was established at the time of World War II (RDL 1939; DL 1948). The registration of a building potentially capable of creating an income is compulsory, and proof of registration is needed for habitability authorisation, renting or selling a real estate unit. However, if no such case occurred, owners tended to get out of registration to avoid paying taxes, and this phenomenon is more marked in small villages, where real estate values are lower and there is less interest in renovating the building stock. The existence of unregistered buildings is proven by the fact that current reconstruction grants are given also in such cases, provided that the owner rectifies irregular cadastral situations (USRC 2014a). A class of buildings that was exempted from registering in the cadaster is that of ruins (RDL 1939), defined as buildings that are damaged, lying derelict or lacking fundamental structural or utility elements (DMF 1998). Such buildings are present among URM structures, because a reduced grant is explicitly mentioned in reconstruction procedures for aggregates, including ruins (USRC 2014b), and because 3% of abandoned buildings have been documented in the AeDES database (Fig. 3h). Again, such cases are more frequent in small villages, where lower real estate values discourage the regeneration of these constructions. Despite the lack of cadastral registration, in both cases usability inspections have been performed, both because of safety issues and at the request of owners interested in getting a reconstruction grant. The impact of the lack of cadastral registration on census procedure is difficult to estimate. Theoretically, census surveyors should consider all the buildings they observe during their inspections (Zindato 2011). Nonetheless, it is possible that due to the lack of accurate cadastral maps some buildings evaded the census, thus contributing to an underestimation of their number.

For each locality of every municipality, the total numbers of buildings according to the usability form, N_{AeDES} , as well as the census, N_{ISTAT} , have been computed. The number N_{AeDES} is related to an inventory of 59,492 buildings, whereas N_{ISTAT} is related to URM residential buildings as defined above. The localities have been aggregated according to macroseismic intensity and the ratio r has been calculated for each intensity, I_{MCS} :

$$r|_{I_{MCS}} = \frac{N_{AeDES}|_{I_{MCS}}}{N_{ISTAT}|_{I_{MCS}}} \quad (2)$$

The results show $r < 1$ for $I_{MCS} = V$ (29% forms), whereas $r > 1$ for $VI \leq I_{MCS} < X$ (Fig. 6). The lack of a monotonic trend can be explained by the fact that in small villages (which experienced VII and IX MCS intensities) accessory structures (e.g., warehouses, stables, and so on) and unregistered buildings, neither recorded in the census, are found more frequently than in the historical centre of L'Aquila (which suffered a VIII MCS intensity). In the range $VI \leq I_{MCS} < X$, performing a mean weighted on the number of buildings experiencing the same macroseismic intensity, $r_{\text{weightedmean}} \approx 1.7$.

Fig. 6 Ratio r between number of buildings in the usability forms, N_{AeDES} , by number of residential buildings in the census, N_{ISTAT} , varying the macroseismic intensity



For the rest of the procedure, the distribution $D_{i,j}$, of i -th parameter in sections 1–3 of the form (building position within the aggregate, number of storeys, roof type, and so on), of the buildings that experienced the same j -th intensity, has been corrected obtaining $D_{i,j,corr}$, to account for incomplete coverage and overrepresentation of the most vulnerable elements of the distribution:

$$D_{i,j,corr} = \frac{N_{AeDES}D_{i,j} + \Delta N D_{i,mean}}{N_{bldgs}} \tag{3}$$

where N_{bldgs} is the estimated total number of buildings that experienced a j -th intensity:

$$N_{bldgs} = \begin{cases} N_{ISTAT} r_{weighted\ mean} & \forall I_{MCS} < VI \\ N_{AeDES} & \forall I_{MCS} \geq VII \end{cases} \tag{4}$$

$\Delta N = N_{bldgs} - N_{AeDES}$, and $D_{i, mean}$ is the average distribution of the considered parameter computed over the subset of buildings having $I_{MCS} \geq VI$, where $r > 1$.

In Eq. [4], it is assumed that, for $I_{MCS} \geq VII$, form coverage is sufficiently ample to be a robust representation of the actual building portfolio. Equation [3] corrects the distribution of the i -th parameter keeping a memory of the surveyed distribution, through $D_{i,j}$, but weighting this contribution through the number of surveyed buildings, N_{AeDES} .

5 Analysis of building parameters

In order to assess if a before-earthquake survey form can be obtained from a simplification of the post-event AeDES form and discuss which features are relevant for building performance, a discussion of the role played in usability by construction parameters (named variables in a statistical framework), noted in sections 1–3 of the current usability form, is presented in the following pages. Relative non-usability frequencies shown hereinafter are computed taking into account both temporarily/partially unusable buildings (B or C classification according to the form) and unusable buildings (E), by the total number of buildings sharing the same investigated parameter. All numbers are corrected as described in Sect. 4. Unusable (E) buildings are accounted for in full, whereas B and C buildings are both multiplied by a factor of 0.3. The same coefficient is used for both classifications because, in the reconstruction following the 2009 event, B and C buildings were granted the same contribution. The coefficient is equal to 0.30 because this is the average repair

ratio plus strengthening costs for B and C buildings by E buildings, computed considering contributions granted to almost 6,000 constructions (Dolce and Manfredi 2015).

Because of its expected relevance and in order to establish possible interactions with all other parameters, the first variable to be analysed will be the structural type, defined in the AeDES form as combination of one type of vertical structure and one type of horizontal structure (Table 1). Then, the order in the form will be followed (number of storeys, age, presence of isolated columns, of mixed structures, of strengthening interventions, roof type), the only exception being the position within the aggregate, considered at the end because it belongs to a section of the form different from those of all other parameters.

5.1 AeDES structural types and proposed structural classes

Figure 7 shows the disaggregation of the building sample between the six (1–6) types of horizontal structures and the five (A–E) types of vertical structures of the AeDES form, given the macroseismic intensity. The five subplots display a remarkable homogeneity and, despite being obtained after the correction of the number of buildings according to Eq. [4], confirm the general trends discussed with reference to Table 1.

The most noticeable deviations of the conditional relative frequency distribution of AeDES structural types are observed for intensity IX MCS where, compared to lower intensities, there is a reduction of good quality masonry with connections (type E), as well as a predominance of poor quality masonry without connections (type B), and of flexible floors (type 4). This behaviour is related to intensity IX MCS occurring in small rural settlements, displaying lower quality, and less renovated structures.

As mentioned in Sect. 3.3, the AeDES form allows for the indication of up to two structural types, each made of one type of horizontal structure and one type of vertical structure occurring at the same storey. Two structural types are present in a significant part (32.1%) of the sample, highlighting that it is common to have different structural elements in the same building. The correlations between the two structural types occurring in the same building have been investigated systematically, and Fig. 8 clearly shows that, in the eleven most frequent cases, the two coupled structural types share the same type of vertical structure. On the one hand, this phenomenon is the result of traditional construction techniques, preferring horizontal masonry structures for lower storeys and lighter structures for upper storeys (Giuffrè 1996). On the other hand, the same phenomenon reflects the renovation activity of replacing traditional timber floors with steel or RC diaphragms (Sorrentino and Tocci 2008).

Figure 9 shows the conditional relative frequency of having unusable buildings, given the structural type, combination of one type of vertical structure and one type of horizontal structure in the AeDES form, and the macroseismic intensity. As expected, the higher the intensity, the higher the relative frequency of unusable buildings, and the same trend can be observed for decreasing masonry quality. However, connections seem less relevant than masonry quality, so that moving from type B (poor masonry and poor connections) to type D (good masonry and poor connections) is more significant than moving from type B to type C (poor masonry and good connections). No systematic effects can be seen in horizontal structures, although a loose association can be observed between flexibility and vulnerability, as reported also by Rota et al. (2008), analysing several Italian earthquakes. In some instances, results are counterintuitive, e.g., for lower intensities and good masonry qualities, vaults with ties (type 3) induce higher non-usability occurrences compared to vaults without ties (type 2). This behaviour can be related to the comparatively small

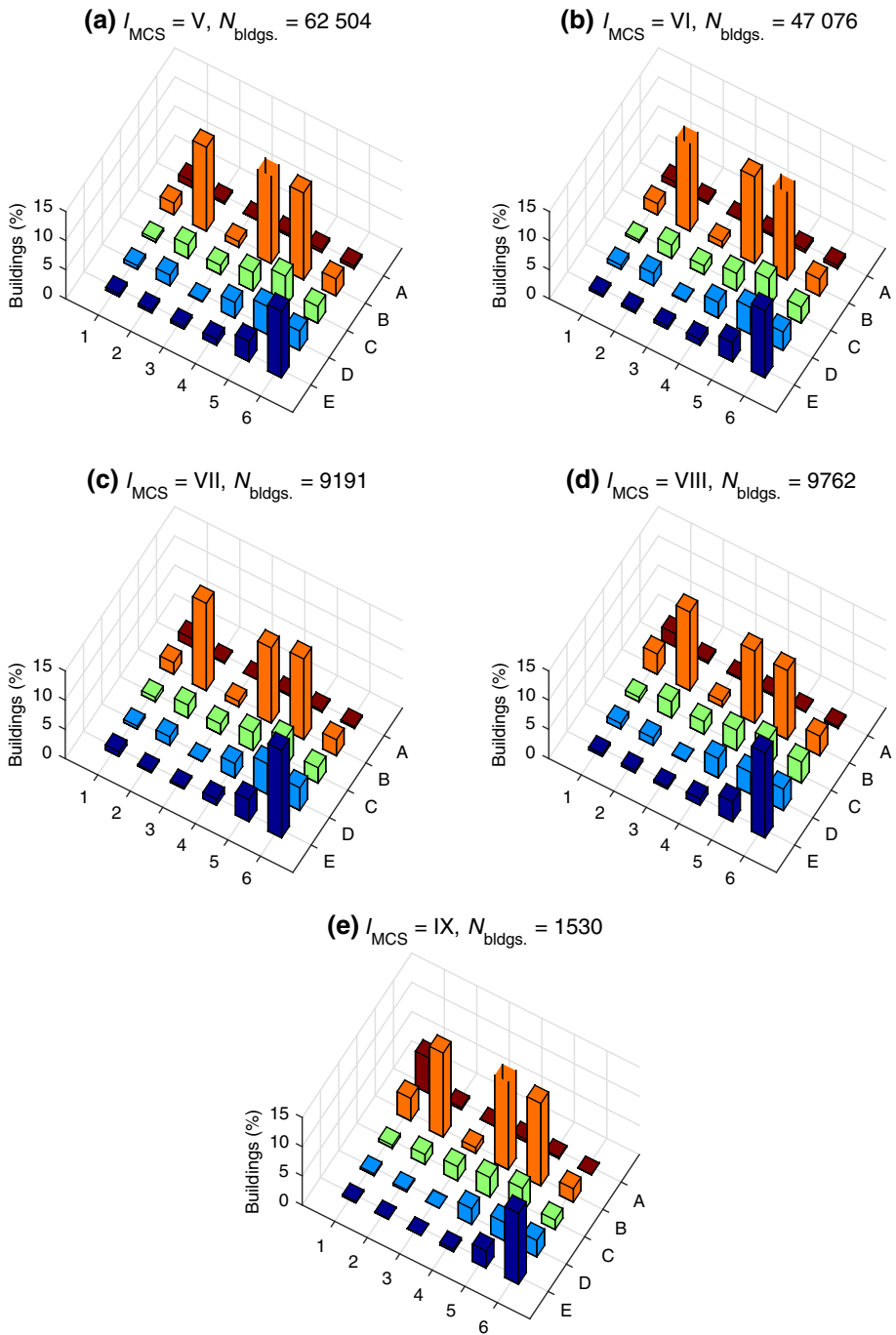


Fig. 7 Relative frequency distribution of AeDES six (*I*–6) types of horizontal structures and five (*A*–*E*) types of vertical structures (Table 1), given the macroseismic intensity. Percentages computed on the total number of buildings with the same intensity, after correcting the number of buildings (refer to Eq. [4])

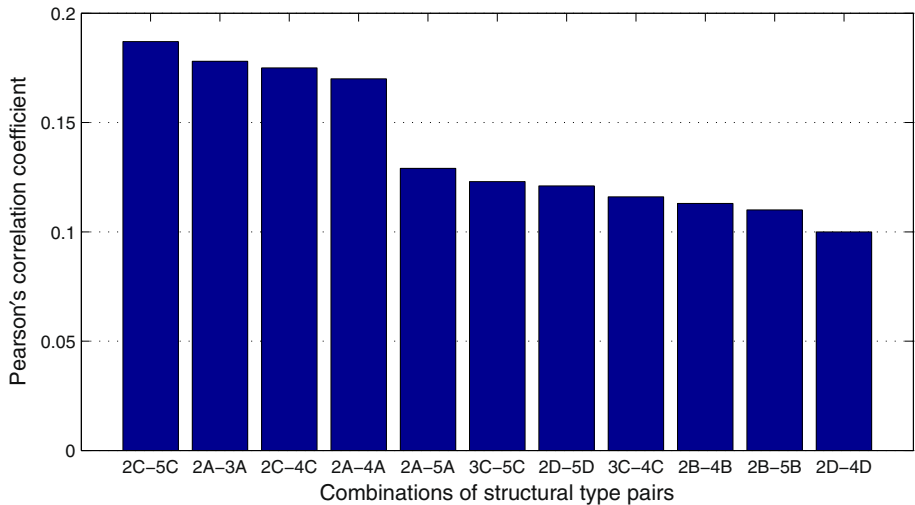


Fig. 8 Pearson's correlation coefficients for the most frequent combinations of two structural types present in the same building. Each structural type has one type of horizontal structure and one type of vertical structure at the same storey. Horizontal structure type range: *I–6*, vertical structure type range: *A–E* (refer to Table 1)

number of type 3 horizontal structures (Fig. 7), and to the interaction with other building features (e.g., construction timespan, roof type, and so on).

The higher relevance of masonry type is confirmed also in the analysis of unidentified horizontal structures (type 1, in Fig. 9), which shows decreasing vulnerability with increasing masonry quality. The lower relevance of types of horizontal structures is confirmed in the analysis of unidentified vertical structures (type A), where more haphazard trends are registered, as a consequence of different masonry qualities falling within a single type of vertical structure (type A).

The trends within each macroseismic intensity are reasonably consistent, hence the relative frequencies of non-usability have been summarized for all intensities in Table 2. Comparable values can be observed in several structural types, i.e. combinations of one type of horizontal structure and one type of vertical structure, and such correspondences are even stronger for $I_{MCS} \geq VII$ (not shown here for the sake of brevity). Hence, it makes sense to reduce the number of structural types in order to:

1. Get a limited number of classes, which can be compared more easily with the other parameters present in sections 1–3 of the AeDES form, as will be done in the following pages;
2. Obtain a simplified form, which can be used for preventive territorial-scale surveys.

The possible simplification is presented in Table 3. Based on this scheme, there are only two types of vertical structures and three types of horizontal structures. Their combination yields four structural classes (1 least vulnerable, 4 most vulnerable), based on good or poor (and unidentified) quality masonry, as well as on rigid slabs, or semi-rigid slabs, or vaults, flexible and unidentified slabs. Examples of the four proposed structural classes are shown in Fig. 10.

In the scheme of Table 3, the role of connections between walls and between walls and horizontal structures is disregarded. This choice does not mean that such connections are

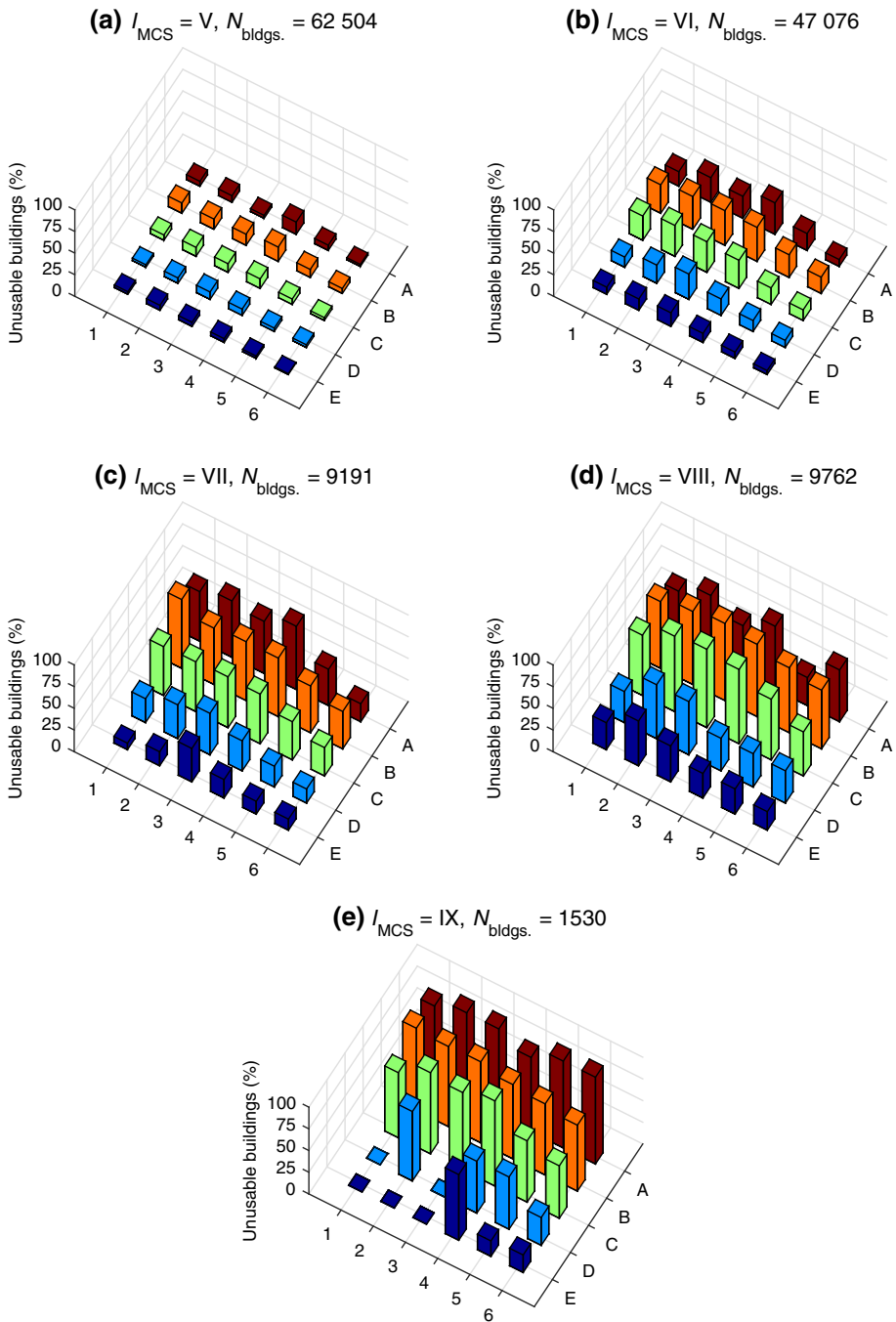


Fig. 9 Conditional relative frequency distribution of unusable buildings for AeDES six (I –6) types of horizontal structures and five (A – E) types of vertical structures (Table 1), given the macroseismic intensity. Percentages computed on the total number of buildings with the same intensity and structural type, after correcting the number of buildings (refer to Eq. [4])

Table 2 Relative frequency distributions of unusable buildings for AeDES structural types (refer to Table 1 for descriptions)

	Horizontal structures	Vertical structures				
		A	B	C	D	E
1		25	33	27	11	7
2		24	31	30	17	12
3		22	33	32	22	13
4		30	33	29	17	10
5		14	23	18	11	7
6		9	19	13	9	5

Percentages computed, for all intensities, on the total number of buildings of same structural type, after correcting the number of buildings (refer to Eq. [4])

Table 3 Correspondence between thirty AeDES structural types (refer to Table 1 for descriptions) and proposed four structural classes

	Horizontal structures	Vertical structures				
		A	B	C	D	E
1		Structural class 4			Structural class 2	
2						
3						
4						
5		Structural class 3			Structural class 1	
6						

not crucial, as clearly shown by both numerical (Prajapati et al. 2015; AlShawa et al. 2017), field (Sorrentino et al. 2017) and laboratory evidence (Tomažević et al. 1996; Magenes et al. 2014), but rather that identification in field surveys is difficult because such connections are frequently invisible to the naked eye.

Although Table 2 has been computed for the whole sample, the four classes show consistent behaviours with varying intensity, as shown in Fig. 11 where monotonic and non-intersecting trends can be observed. These plots are actually the fragility curves, in terms of usability, of the proposed structural classes, conditioned to MCS macroseismic intensity. An analogous simplification of structural types, based on damage (rather than usability), has been proposed by Braga et al. (1982), as well as Dolce and Goretti (2015). The three simplified classes suggested in the last work require the same detailed survey needed to fill in the AeDES form, and involve higher scatter of relative usability frequencies compared to the classes proposed in Table 3.

As mentioned, according to the AeDES form, buildings can present up to two structural types. No uncertainty in class attribution arises if both types belong to the same simplified structural class. Buildings with two AeDES structural types belonging to two different structural classes, as defined here, are rather uncommon, with the exception of buildings of structural types belonging to classes 3 and 4, occurring in approximately 13% of cases (Fig. 12). These two classes are similar in terms of usability and feature the same low quality vertical structures. Therefore, four classes seem enough to represent, also, buildings displaying two structural types, in which case the most vulnerable class is assumed.



Fig. 10 Examples of earthquake-damaged buildings belonging to the proposed four structural classes: **4** poor quality masonry and flexible slab, **3** poor quality masonry and rigid slab, **2** good quality masonry and flexible slab, **1** good quality masonry and rigid slab

5.2 Number of storeys above ground

The importance of the number of storeys has been pointed out by Rota et al. (2008) who, based on data from several Italian earthquakes, recognized a marked difference in

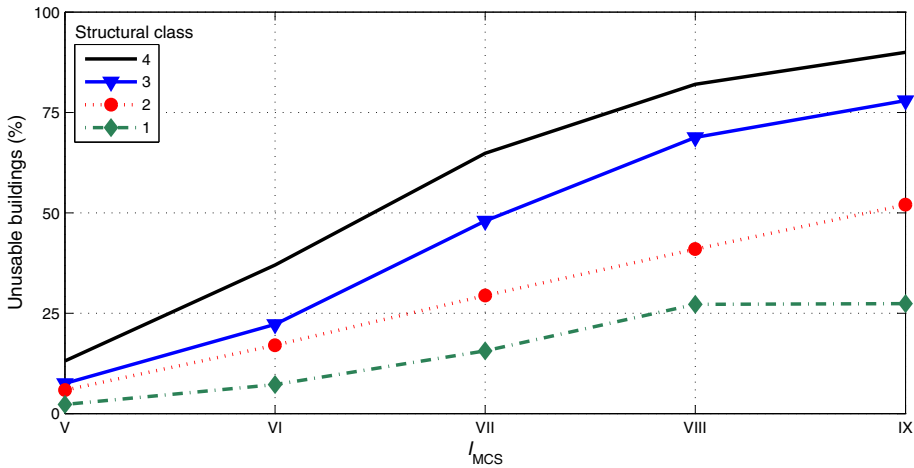
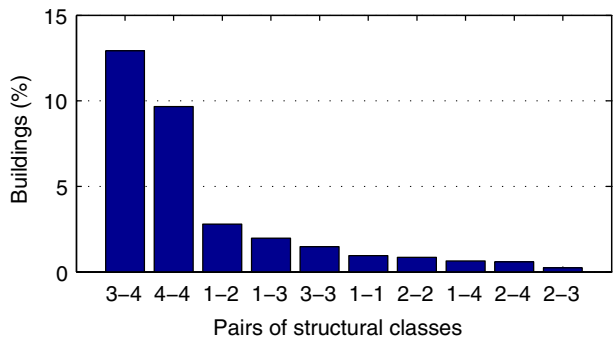


Fig. 11 Relative frequency distribution of unusable buildings given macroseismic intensity and structural class

Fig. 12 Relative frequency distribution of the most frequent combinations of AeDES structural types sorted according to respective structural classes (Table 3). Percentages computed on the total number of buildings (with and without two structural types)



earthquake performance in buildings having either up to two or more than two storeys. As mentioned in Fig. 3a, b, the AeDES form has two fields related to the number of storeys: (i) total number of storeys (including those underground), (ii) number of underground storeys. The association of usability with total number of storeys and number of underground storeys is not systematic, and is not presented here for the sake of brevity.

Consequently, Fig. 13 shows the conditional cumulative frequency distributions of unusable buildings for number of storeys above ground (= i–ii), given structural class and macroseismic intensity. Because there are no marked differences for taller buildings, only three curves are present in the plots. The number of storeys above ground is marginally relevant for structural class 1, moderately relevant for classes 2–3, and markedly relevant for class 4, the most vulnerable.

Hence, three categories are proposed in the simplified form for the number of storeys above ground and three values for the number of underground storeys. The number of storeys above ground is proposed instead of the total number of storeys, because this parameter seems a more obvious choice and can help reduce the number of possible selections in the form.

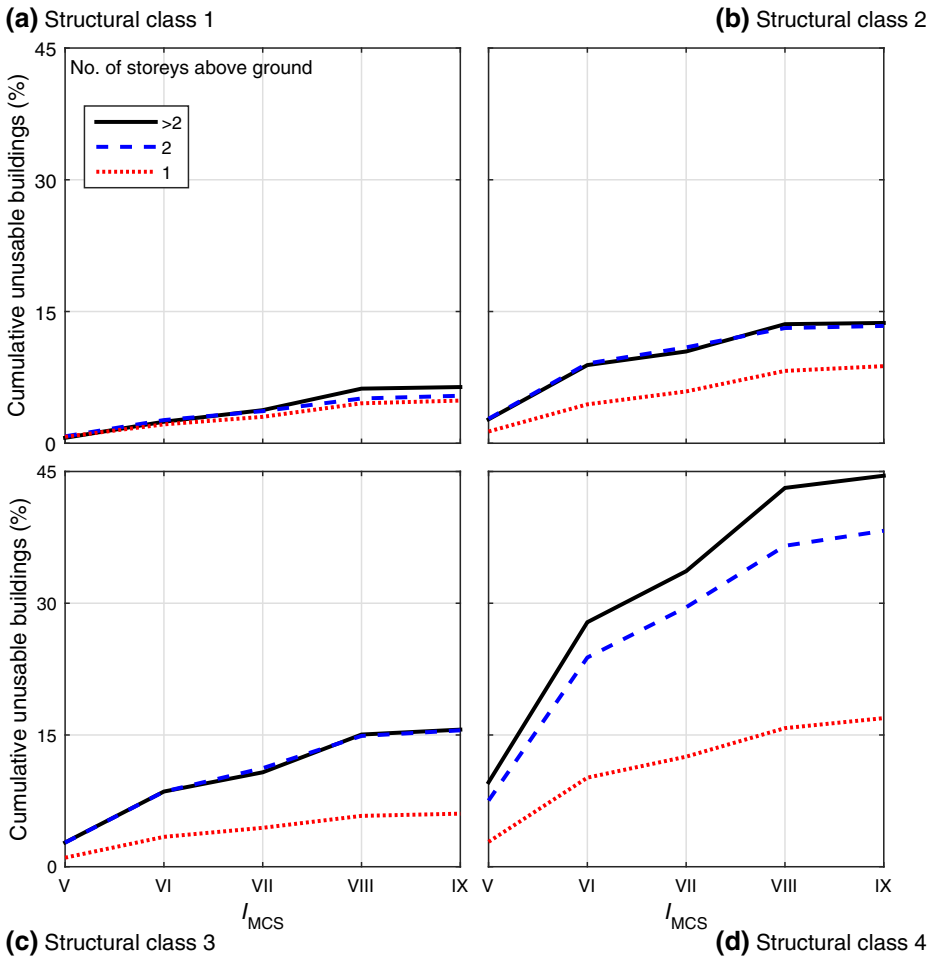


Fig. 13 Conditional cumulative frequency distributions of unusable buildings, given the number of storeys above ground, macroseismic intensity, and structural class. Structural classes defined in Table 3

5.3 Age

As for the field devoted to building age, the AeDES form provides for eight timespans, and allows for up to two selections in order to take into account construction and major structural modification. In Fig. 14a, the cumulative frequencies of buildings analysed based on construction timespans are disaggregated according to the four previously defined structural classes. It is worth mentioning that this piece of information is always available. In classes 3 and 4 the proportion of constructions built before 1919 is quite large, varying between 55 and 82% of the total for this class. On the contrary, class 1, the least unusable, has a larger preponderance of more recent buildings. Because of the eight construction timespans and the four structural classes, a disaggregation according to five macroseismic intensities would deliver very small sub-samples in some cases. Hence, in Fig. 14b, the structural classes have been merged. It is evident that the year of construction is a relevant parameter (the older the more vulnerable) for structures built up to 1961, whereas later,

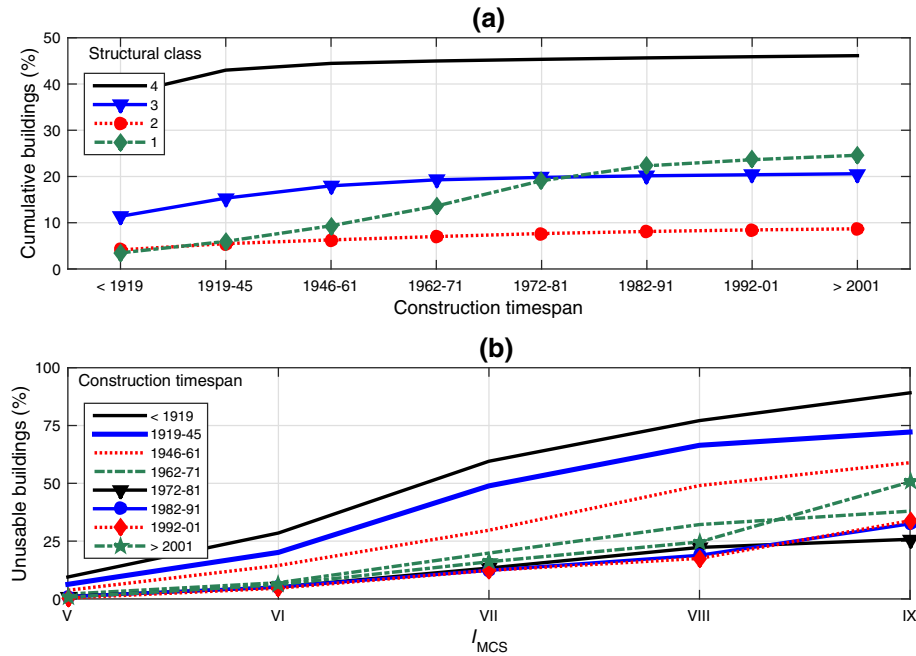


Fig. 14 Construction timespans for unusable buildings. **a** Cumulative frequency distribution of construction timespans, for each structural class (Table 3); percentages computed over the total number of buildings. **b** Relative frequency distribution of unusable buildings given macroseismic intensity and construction timespan. Subset of buildings for which the construction timespan is available

there is a much less pronounced effect. This trend is also observed if one disaggregates the structural classes, not shown here for the sake of conciseness, although in some instances quasi-zero values appear for the reasons already mentioned, especially for macroseismic intensity IX MCS. The “> 2001” construction timespan shows slightly lower usability rates than immediately preceding ones. This is due to comparatively higher relative frequencies of unusable buildings in classes 3 and 4 (not visible in the figure). This behaviour indicates that these classes are more vulnerable when more recent, due also to a higher incidence of unknown vertical structures (A in Table 1), compared to older buildings belonging to the same structural classes.

Considering the previous discussion, it makes sense to simplify the survey form, providing for five timespans: (1) < 1919, (2) 1919–1945, (3) 1946–1961, (4) 1962–2001, (5) > 2001. This choice is consistent with presented evidence, but allows for the identification of more recent buildings. In fact, in 2003 an important development took place in the Italian standard for earthquake-resistant constructions (OPCM 2003), with a significant change in the building code coming into force after the L’Aquila earthquake (DMI 2008), and this could have an impact on future performances. Similarly, the relevance of 1961 can be explained by a significant modification in the code (L 1962), which made transverse walls obligatory at a maximum spacing of 7 m, and reduced maximum height of buildings from previous standards (Van Riel 2004). This change is more relevant than the issue of a more modern seismic code, which came into force in the mid-1970s (DMLLP 1975), and which for the first time in Italy included a response spectrum (Sorrentino 2007). Quantitative computation for masonry structures became mandatory much later (DMLLP 1996),

and only when rules for simplified design were not respected. Otherwise, the seismic code prescribed just geometric limits and construction details for masonry buildings. Consequently, these code changes are not as relevant as the one in 1962 and it makes sense to propose a single construction timespan for the period from 1962 to 2001 in the simplified form.

No plot is presented for the structural modification timespan because data is limited, and because modification can take place in any of the previous construction timespans. Hence, this piece of information appears to be of limited usefulness, as will be further argued in the following sections.

5.4 Isolated columns

As already mentioned, the aim of the isolated column field in the AeDES form is to account for possible stress concentration as regards columns, which may increase building vulnerability (Baggio et al. 2000). Buildings with isolated columns present a 38% occurrence of a filled structural modification timespan field, almost the same relative frequency as of the general inventory.

Figure 15 shows the relative frequency distributions of unusable buildings as a function of macroseismic intensity, structural class and presence (or not) of isolated columns, but no systematic tendency can be recognized. For structural classes 1 and 2, the least vulnerable, the columns have a negative effect on usability at high intensities (VIII, IX MCS); class 3 involve a higher rate of usable buildings, while class 4 is rather irrelevant. The influence of isolated columns is not the same for the different structural classes and it is often the opposite of what AeDES form authors had expected. Hence, there seems to be no strong impact of isolated columns on usability and this field could be removed from a simplified form.

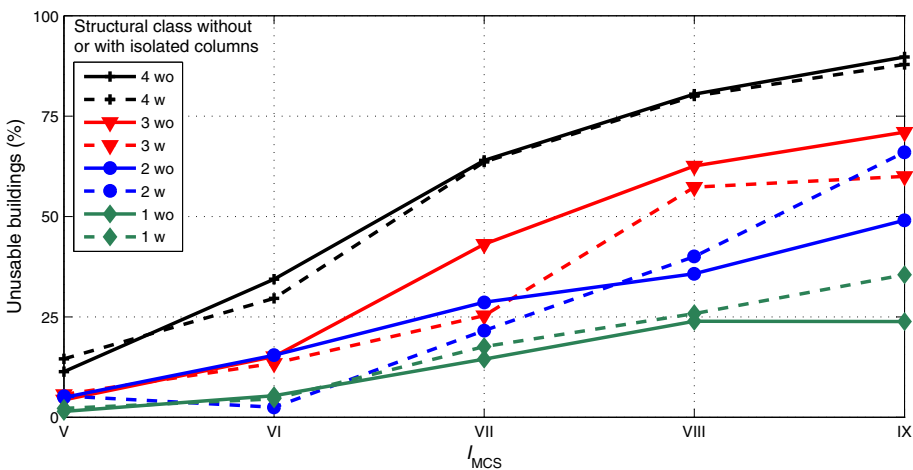


Fig. 15 Relative frequency distributions of unusable buildings given macroseismic intensity and structural class (Table 3), with and without isolated columns

5.5 Presence of mixed structures

As already mentioned in Sect. 3.3, the usability form envisages three possible combinations of mixed structural systems in the same building: RC frame above URM storeys (G1), URM storeys above RC frame (G2), URM and RC structures at the same storey (G3). Forty-four percent of buildings with mixed structures have a filled structural modification timespan field, 25% more than that of the general inventory, indicating that their presence, at least in some cases, can be linked to building renovation.

The analysis of the presence of mixed structures is potentially more complicated than that of isolated columns, because of the triple non-exclusive categories available. However, the simultaneous occurrence of two types of mixed structures is statistically negligible. Additionally, as already mentioned in Sect. 3, these combinations occur in a rather limited number of cases, especially for G1 and G2. Consequently, in the following analyses, either the macroseismic intensity or the structural class is disaggregated, in order to avoid zero-population bins.

In Fig. 16a, the relative frequency distributions of unusable buildings as a function of type of mixed structure and of macroseismic intensity is shown. Buildings presenting a mixed structure display a rate of usability higher than those of non-mixed structure, with URM above frame cases (G2) producing the best performance. The over-performance of mixed structures, compared to buildings made entirely of masonry, is not completely unexpected considering that it is stated in the AeDES manual that the mixed character of vertical structures is not necessarily an element of vulnerability, although it can imply a lack of homogeneity in structural response and possible local damage.

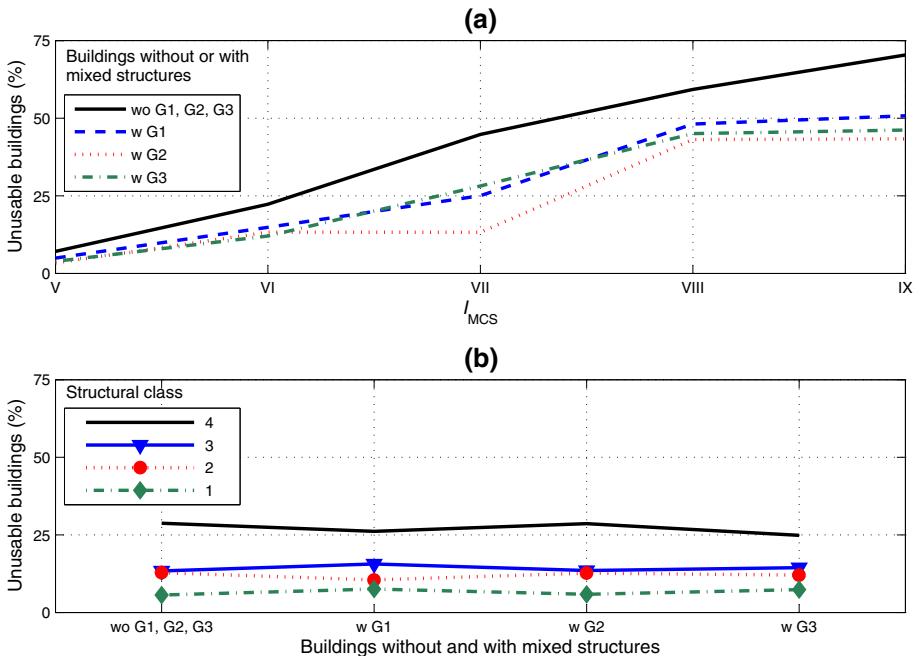


Fig. 16 Relative frequency distributions of unusable buildings given type of mixed structure and: **a** macroseismic intensity, **b** structural class (Table 3). G1: RC frame above URM storeys; G2: URM storeys above RC frame; G3: URM and RC structures at the same storey

In order to explain the observed behaviours, Fig. 16b shows the relative frequency distributions of unusable buildings as a function of type of mixed structure and of structural class. In this case, lower intensities affect the results more than higher ones, because a large share of the buildings experienced V and VI MCS shaking. The plot highlights that if the impact of the structural class is removed, behaviours are less systematic and the role of mixed structures becomes less relevant than one could expect. Thus, Fig. 16a is due to 46% of mixed structures belonging to structural class 1, whereas in the general inventory this relative frequency drops to 24%. Finally, the occurrence of mixed structures does not affect usability performance as much as structural class. Thus, if the latter is appropriately defined, the former could be dropped from the form.

5.6 Strengthening interventions

As shown in Sect. 3.3, strengthening work is reported in the form according to three possible categories: injections or unreinforced coating (H1); reinforced masonry or masonry with reinforced coating (H2); other or unidentified strengthening (H3). The filling out of the strengthening field should be accompanied by a double selection in the age field, which would be related to structural modification. However, there is only a 56% occurrence of second selection in the age field among strengthened buildings, less than recorded for mixed structures, although still one and a half times the occurrence of the same double selection in the general inventory. The strengthening field is filled even less frequently than the one for mixed structures (Fig. 4), consequently, in the following either the macroseismic intensity or the structural class is disaggregated, in order to avoid zero population bins.

Figure 17a shows the relative frequency distributions of unusable buildings as a function of type of strengthening and of macroseismic intensity, highlighting the clear effectiveness of the interventions. In Fig. 17b the relative frequency distributions of unusable buildings are plotted as a function of strengthening type and structural class. It is worth mentioning that, contrary to what was noted for mixed structures, strengthening work does not occur more frequently in structural class 1 than in the general inventory. Strengthening occurs in a limited number of buildings in the first two structural classes, so statistics are not robust enough to draw conclusions other than general trends. The impact of unidentified strengthening interventions on usability (H3) seems negligible. The other two interventions show a similar impact on usability, more relevant for some classes than for others. In conclusion, information about the occurrence of generic interventions, such as injections, unreinforced or reinforced coating, reinforced masonry, is considered to be sufficient for a simplified survey form, without the need for further distinctions among them and without recording other or unidentified interventions.

5.7 Roof type

Roof has been reported as being important for earthquake performance of URM buildings (Benedetti et al. 1988). As already shown in Fig. 5a, the form considers four possible combinations of static scheme (thrusting or not) and weight (light or heavy). Heavy roofs occur more frequently in structural class 1 (least vulnerable), whereas light roofs are associated more frequently with structural class 4 (most vulnerable). Consequently, it makes sense to remove the effect of the structural class, when analysing the role of the roof. Hence, the conditional cumulative frequency distributions of unusable buildings of the four roof types are presented in Fig. 18, given structural class and macroseismic

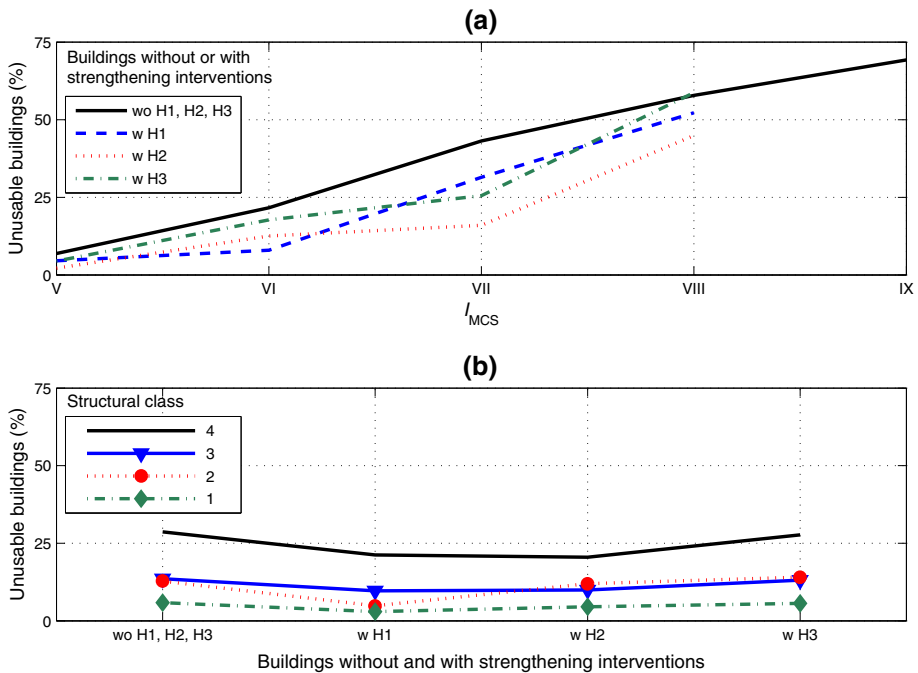


Fig. 17 Relative frequency distributions of unusable buildings given type of strengthening interventions and: **a** macroseismic intensity (data on strengthened buildings and intensity IX MCS not displayed because limited to less than 5 cases), **b** structural class (Table 3). H1: injections or unreinforced coating; H2: reinforced masonry or masonry with reinforced coating; H3: other or unidentified strengthening

intensity. Roof type is more important for classes 3 and 4 than for the other two classes. Moreover, the static scheme is more relevant than the weight of the roof, because thrusting roofs have a lower usability rate. However, for the same static scheme, a heavy roof makes the building less vulnerable than a light roof. This result shows that heavy top structures are not necessarily detrimental, but if timber roofs are replaced by RC roofs without the walls being properly strengthened, catastrophic collapses can take place, as observed in recent Italian earthquakes (Decanini et al. 2004; Valluzzi 2006; Augenti and Parisi 2010). These collapses are more frequent if roof replacement is combined with floor replacement because, in addition to an increase of mass, the insertion of a new floor involves performing deep chases in the existing vertical structures. Moreover, recent experimental research has shown that timber structures, properly strengthened and connected to walls, can guarantee satisfactory earthquake performance (Magenes et al. 2014). Additionally, one can highlight that heavy roofs are usually found on buildings that are newer than those where light roofs are used, another cross-association that explains the observed lower vulnerability. In conclusion, current roof types should also be included in a simplified survey form because they affect the usability rate.

5.8 Position of the building within the aggregate

Previous studies, based on expert judgement (Giuffrè 1996), have suggested that buildings belonging to aggregates have increased vulnerability with an increase in number of

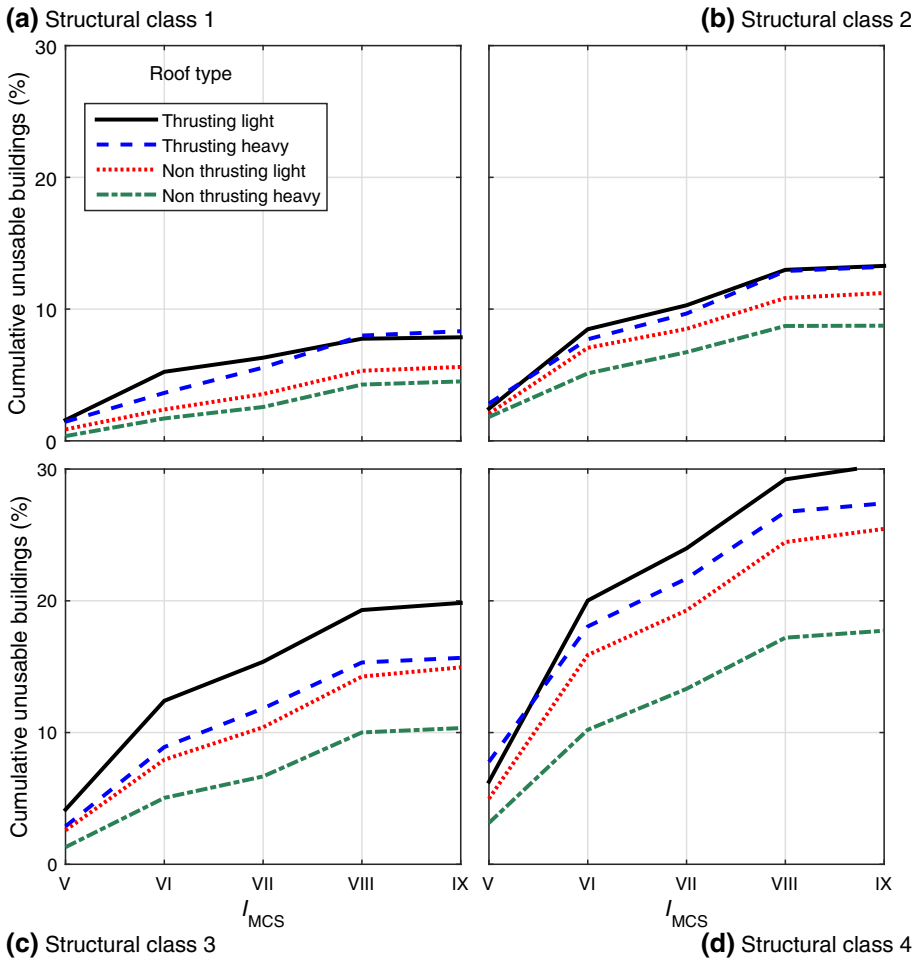


Fig. 18 Conditional cumulative frequency distributions of unusable buildings, given roof type, macroseismic intensity, and structural class. Structural classes defined in Table 3

façades: internal buildings are less vulnerable than corner buildings, and these are less vulnerable than end-of-row buildings. Comparing the numerical models of an isolated building and of the same building within a structural aggregate, Ramos and Lourenço (2004) found the latter condition to be beneficial, unless pounding phenomena take place. Formisano et al. (2011), again using numerical analyses, found similar results.

Figure 19 shows the conditional cumulative frequency distributions of unusable buildings for the four positions within the block, given structural class and macroseismic intensity. Subplot comparison shows that structural class is more relevant than position. The latter parameter is slightly relevant only at the highest intensities, but there is no systematic trend and performance of isolated buildings is slightly better. Therefore, numerical models are prone to emphasize differences that in actual buildings are downplayed by the cross-association of several other parameters. One of these parameters could be the higher maintenance of corner and end-of-row buildings, due to higher real estate values. Moreover, whereas the average number of above ground storeys is very similar in

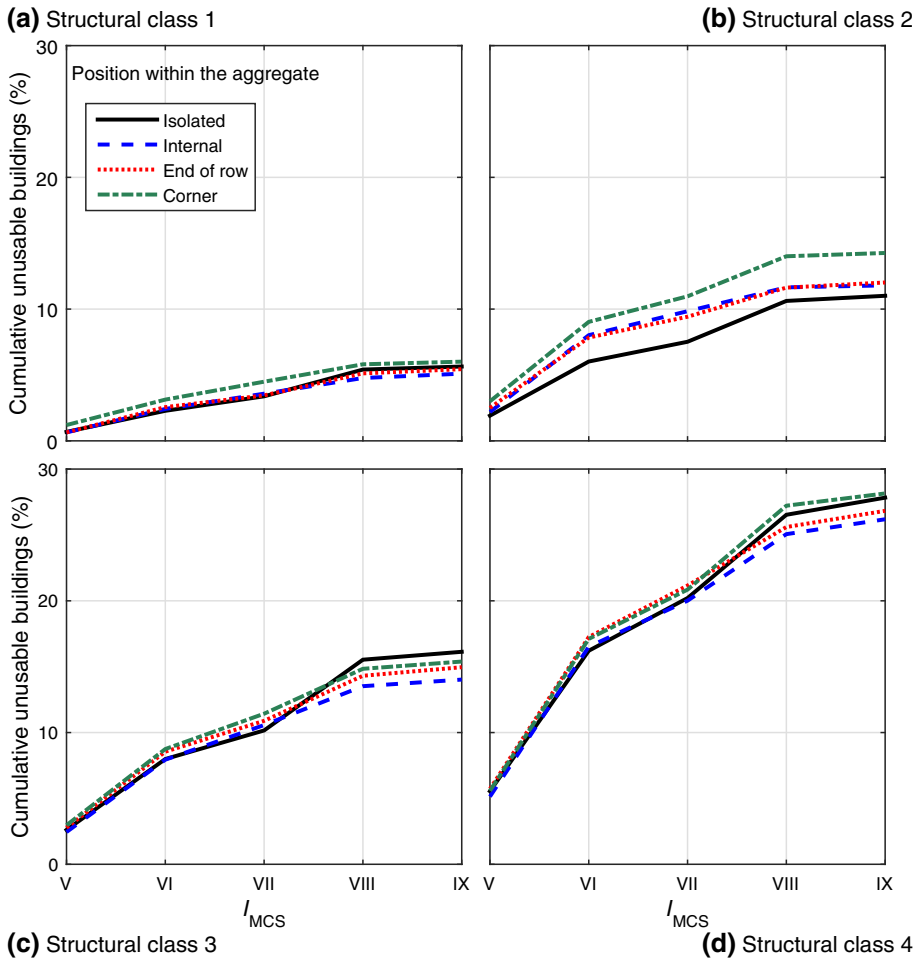


Fig. 19 Conditional cumulative frequency distributions of unusable buildings, given position of the building within the structural aggregate, macroseismic intensity, and structural class. Structural classes defined in Table 3

all positions, if mean construction timespan is considered, isolated buildings are newer than aggregate buildings, and end-of-row buildings are newer than corner and internal buildings. Despite the limited impact on usability, because the position of a building is quite simple and fast to survey, this field can be retained in a simplified form.

6 Simplified form

Based on previous considerations, a simplified form for pre-earthquake investigations is proposed in Fig. 20. The proposal is based on the three-page AeDES form but, in order to speed up large scale field surveys, it has been reduced to a single A4 sheet, divided into five sections: (1) building identification, (2) building description, (3) building type, (4) pre-existing damage to structural elements and (5) notes. The time necessary to survey a single

SURVEY FORM OF UNREINFORCED MASONRY BUILDINGS
IN SEISMIC PRONE AREAS

SECTION 1 Building identification		SURVEY IDENTIFICATION day month year	
Province: _____ Municipality: _____ Locality: _____ Address _____ _____ Number _____		Team [][] [][] Form n. [][] [][] Date [][] [][] [][]	
Geographic coordinates E _____ Time Zone _____ N _____		Region Istat _____ Province Istat _____ Municipality Istat _____ Aggregate No. _____ Building No. _____ Istat Hamlet code _____ Type of map _____ Istat Census code _____ Map No. _____ Cadastral data Sheet _____ Allegato _____ Parcels _____	
Position of the building within the aggregate <input type="radio"/> Isolated <input type="radio"/> Internal <input type="radio"/> End of row <input type="radio"/> Corner			

SECTION 2 Building description		Age	Exposure					
<i>Geometrical data</i>								
No. of stories above grade <input type="radio"/> 1 <input type="radio"/> 2 <input type="radio"/> > 2	No. of underground stories <input type="radio"/> 0 <input type="radio"/> 1 <input type="radio"/> > 1	Average storey height [m] <input type="radio"/> ≤ 2.50 <input type="radio"/> 2.50+3.50 <input type="radio"/> > 3.50	Average storey surface area [m ²] <input type="radio"/> ≤ 50 <input type="radio"/> 50 + 70 <input type="radio"/> 70 + 100	Construction <input type="radio"/> < 1919 <input type="radio"/> 19 + 45 <input type="radio"/> 46 + 61 <input type="radio"/> 62 + 01 <input type="radio"/> > 2001	Use <input type="checkbox"/> Residential <input type="checkbox"/> Storage <input type="checkbox"/> Others	Surface % [][] [][] [][]	Utilisation <input type="radio"/> > 65% <input type="radio"/> 30+65% <input type="radio"/> < 30%	<input type="radio"/> Not utilised <input type="radio"/> In construction <input type="radio"/> Uncompleted <input type="radio"/> Abandoned
		No. occupants [][]	Property <input type="radio"/> Public <input type="radio"/> Private					

SECTION 3 Building Typology				
Vertical structures Horizontal Structures	Not identified or poor quality masonry of irregular layout (rubble stones, pebbles,...)	Good quality masonry of regular layout (blocks, bricks, dimensioned stone units,...)	Strengthening	Roof <input type="radio"/> Thrusting heavy <input type="radio"/> Non thrusting heavy <input type="radio"/> Thrusting light <input type="radio"/> Non thrusting light
Not identified, vaults or beams with flexible slab (timber beams with a single layer of timber boards, jack-arch slab, ...)	<input type="radio"/> Structural class 4	<input type="radio"/> Structural class 2	YES <input type="radio"/>	
Beams with rigid or semi-rigid slab (timber beams with a double layer of timber boards, I-beams and hollow tile blocks, RC floors, beams well connected to RC slabs, ...)	<input type="radio"/> Structural class 3	<input type="radio"/> Structural class 1	NO <input type="radio"/>	

SECTION 4 Pre-existing damage to structural elements	SECTION 5 Notes																																																								
<table border="1" style="width:100%; border-collapse: collapse;"> <tr> <td rowspan="3" style="text-align: center;">Damage level - Extension</td> <td colspan="9" style="text-align: center;">DAMAGE⁽¹⁾</td> <td rowspan="3" style="text-align: center;">No damage</td> </tr> <tr> <td colspan="3" style="text-align: center;">D4-D5 Very heavy to destr.</td> <td colspan="3" style="text-align: center;">D2-D3 Moderate to heavy</td> <td colspan="3" style="text-align: center;">D1 Negligible to slight</td> </tr> <tr> <td style="text-align: center;">>2/3</td> <td style="text-align: center;">1/3 - 2/3</td> <td style="text-align: center;"><1/3</td> <td style="text-align: center;">>2/3</td> <td style="text-align: center;">1/3 - 2/3</td> <td style="text-align: center;"><1/3</td> <td style="text-align: center;">>2/3</td> <td style="text-align: center;">1/3 - 2/3</td> <td style="text-align: center;"><1/3</td> </tr> <tr> <td>Pre-existing damage</td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="radio"/></td> </tr> </table> <p style="font-size: small;">(1) - The damage extension must be filled only if the corresponding damage level is present in the building</p>	Damage level - Extension	DAMAGE ⁽¹⁾									No damage	D4-D5 Very heavy to destr.			D2-D3 Moderate to heavy			D1 Negligible to slight			>2/3	1/3 - 2/3	<1/3	>2/3	1/3 - 2/3	<1/3	>2/3	1/3 - 2/3	<1/3	Pre-existing damage	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="radio"/>	<table border="1" style="width:100%; border-collapse: collapse;"> <tr> <td style="width: 50%;">Section</td> <td style="width: 50%;">Notes</td> </tr> <tr><td> </td><td> </td></tr> <tr><td> </td><td> </td></tr> <tr><td> </td><td> </td></tr> <tr><td> </td><td> </td></tr> <tr><td> </td><td> </td></tr> <tr><td> </td><td> </td></tr> <tr><td> </td><td> </td></tr> </table>	Section	Notes														
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Pre-existing damage	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="radio"/>																																															
Section	Notes																																																								
The surveyors (block letters) _____	Signatures _____																																																								

Fig. 20 Proposed simplified form. Circles are used for single selection fields, boxes for multiple

building is reduced because only a few parameters are recorded and no systematic damage detection is required, as opposed to post-earthquake operations.

No map field is present in section 1, because geo-referentiation is possible today through most smartphones. The fields in section 2 are the same as those found in the AeDES form. However, the number of categories has been reduced, removing those

regarding very small occurrences, as reported in Fig. 3, or information loosely associated with building performance. As for the first field, the number of storeys above ground is preferred to the total number of storeys (including those underground), because in the experience of the authors the current definition of the AeDES form is sometimes misinterpreted by compilers. The age field is limited to construction, based on the observed negligible association between strengthening timespan and usability. The section provides for just three uses, the last being a collection of all marginally occurring uses. Strategic buildings, such as town halls, schools, barracks, will need to be investigated with more finely-tuned tools than a simplified survey form.

Section 3 is greatly simplified, the five types of vertical structures being reduced to just two, and the six types of horizontal structures again to two. No multiple selection is provided, and the most vulnerable structural class should be selected in the event that two or more are present within the same building. It is worth mentioning that the two masonry types in the proposed form are conditioned by the oversimplification of the AeDES form, which does not take into account the presence of continuous brick masonry layers (Dolce et al. 2012) or mortar quality (Liberatore et al. 2016). However, a different classification of masonry categories would make it rather difficult to use fragility curves calibrated from past data. Hence, conformity to AeDES is preferred. Similar considerations apply to roof categories. Information about isolated columns and mixed (RC, steel) structures has been removed, and no disaggregation is required for strengthening interventions, which are strictly limited to injections, unreinforced or reinforced coating, and reinforced masonry.

The only field in section 4 refers to pre-existing damage to structural elements, and it is organised in the same way as in the AeDES form, taking into account severity and extension in the building. Although there has been no discussion of this here, its importance has been highlighted in the past (Dolce and Goretti 2015). There is no section on soil morphology and damage, considering that first level microzonation has been carried out in most Italian earthquake-prone municipalities, and the information to be found there is far more detailed and robust than can be recorded in a simplified survey form (Baiocchi et al. 2011).

The proposed simplification of the form will speed up field surveys for pre-earthquake assessment, an operation that usually needs to be carried out with limited manpower. The need to react fast could suggest abridging also the post-earthquake form, as happened during the 2016–2017 central Italy seismic sequence when usability assessment was changed in a two-step process. In the first step, the mayor of a municipality can activate preliminary usability assessment through the so-called FAST form (Italian acronym for Post-Earthquake Synthetic Usability Survey for Ordinary Buildings), which can be filled by any chartered practitioner (PCM-DPC 2016). This form is extremely simplified, taking into account only storeys number, height and area, use, construction material (URM, RC, mixed or other structural materials), and if the building is habitable or not. In the first case, no further step is necessary. In the second case, temporary lodging will be arranged for dwellers and, as second step of the process, the AeDES form for the building will be filled in by practitioners who attended specific courses, in a procedure activated by national or regional civil protection organisations. From this brief description, it is self-evident that the FAST form cannot be used in badly damaged areas. Moreover, although filling in the FAST form is certainly faster than compiling the AeDES form, the survey time needed to exclude the presence of damage is the same and this time accounts for most of the effort. Hence, the main difference between these two post-earthquake tools is mainly administrative, in terms of activation and practitioners involved. On the other hand, as regards buildings that showed a satisfactory seismic response, valuable information about

construction characteristics and performance are lost, making the derivation of fragility curves or damage probability matrices from the AeDES database impractical.

7 Conclusions

Data on URM buildings derived from the “Level 1 Form for Post-Earthquake Damage and Usability Assessment and Emergency Countermeasures in Ordinary Buildings”, compiled after the 2009 L’Aquila earthquake in southern Italy, have been analysed to identify which building features need to be surveyed when territorial-scale risk assessments are performed. Forms concerning almost 60,000 URM buildings, belonging to 90 municipalities and subjected to macroseismic intensities varying between V and IX on the Mercalli–Cancani–Sieberg scale, have been studied. About one-third of the inventory is made up of buildings that completely lost their usability, i.e. the condition of a building being habitable or fit for occupancy after a seismic event, and one-sixth is made up of temporarily and partially unusable buildings.

The inventory was examined in terms of geometry, age, and exposure, deriving information that could be used for possible scenario and risk analyses. As for construction characteristics, more than half of the vertical structures show poor quality masonry without tie rods, usually associated with non-rigid horizontal structures. About one-sixth of the vertical structures have good quality masonry with effective connections, and most of those structures are combined with stiff floors. This range of techniques makes the inventory interesting for several earthquake prone Italian and Mediterranean regions. Isolated columns, mixed structures and strengthening interventions are found in about 5% or less of the inventory. The most common kind of roof does not thrust and is light, followed by the non-thrusting and heavy type. Finally, more than two-thirds of the buildings are part of a structural aggregate.

It has been shown that usability surveys have been carried out systematically in municipalities that have experienced high macroseismic intensities, whereas in low intensity areas they have been limited to the most damaged buildings. In order to avoid over-representation of the most vulnerable building features, estimates for the total number of buildings, for which the occurrence of non-usability has been computed, are based on the number of buildings in the census. However, this number has been adjusted to account for: the different definitions of building in the census and in the usability form, lack of cadastral registration, and abandoned buildings.

The occurrence and the usability of the thirty structural types in the AeDES form, consisting of the combination of one of five types of vertical structures and one of six types of horizontal structures, have been analysed. The proposal is for these to be simplified to just four structural classes, while as regards usability, fragility curves have been derived. Compared to previous definitions of vulnerability classes, those considered here show less scattered trends in terms of usability and a smaller number of parameters to be surveyed. This finding is related to the difficulty in identifying positive connections between structural elements due to the presence of plaster or other covers.

The four classes are associated with other parameters, highlighting how, at least for the 2009 earthquake inventory, they are able to explain a significant proportion of observed performances. The number of storeys have a negligible impact on usability in structural class 1 (the least vulnerable), but should be reported in a survey form because they are relevant for other classes. This result is in accordance with observations by other

investigators and related to the larger lever arm of inertia forces in taller buildings. The position within the structural aggregate, despite showing little impact on usability, being associated with different construction timespans, could be maintained in the form, because it is easy to record. The construction timespan is relevant up to the early 1960s, when an important change was made to the building code. Hence, the current eight categories could be reduced to five. The presence of isolated columns or mixed structures has no systematic impact on earthquake performance, possibly because associated with other renovation and strengthening work, and could be removed. Injections, unreinforced or reinforced coating, and reinforced masonry show a similar impact on usability, more relevant for some structural classes than for others. This can be due to the fact that some types of repair work might have escaped the surveyor's attention because they were plastered over or done within the masonry. As such difficulties are expected to be even more pronounced in pre-earthquake inspections, it is considered sufficient to record the occurrence of generic strengthening, without further specification. Roof type has a significant impact on usability rates for all structural classes, but more markedly for the most vulnerable ones. Thus, the roof field is retained in the proposed form.

Relevant parameters and categories have been identified herein, drawing on information contained in a large database regarding a specific Italian region. Hence, it is expected to be fairly reliable for other national areas with a comparable building inventory, such as most of the Apennine mountain range. For this territory to have a simplified form at its disposal would produce a marked increase in survey productivity.

Future research will involve deriving predictive equations for usability and damage based on the parameters in the simplified survey form proposed here. Such equations can be used to forecast building usability on a territorial scale and to estimate repair costs, as done after the 2009 event when public reconstruction contributions were allocated on the basis of usable, partially usable and unusable outcomes. The proposed form and corresponding predictive usability equations could then be compared with alternative vulnerability models and corresponding data collection forms. Furthermore, results obtained here for a specific area should be compared with those of other regional inventories. Finally, the same approach can be used for the analysis of data on reinforced-concrete structures.

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