Procedures and experiences in the post-earthquake usability evaluation of ordinary buildings

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ABSTRACT One of the most critical issues in a post-earthquake emergency is assessing the usability of buildings in order to recommence daily life in the stricken area while ensuring the safety of people returning to their houses. Generally, this is done by means of surveys based on usability forms filled out by expert technicians. Different countries adopt different forms, all that assess usability in terms of building damage. The Italian approach takes into account, in addition to the building’s damage, the vulnerability of the building. In this study, the data collected through the widespread survey performed in the aftermath of the L’Aquila (Italy) 2009 earthquake was analysed, showing that some buildings were judged not usable despite having no or very little damage. The role of other causes, including vulnerability, in the determination of unusability are discussed. Finally, a practical case faced by the authors during the usability survey in Emilia (Italy) after the 2012 seismic sequence highlights the role of vulnerability in the usability outcome.

Key words: earthquake emergency, damage survey, L’Aquila, Emilia.

1. Introduction

After an earthquake, usability of buildings definitely plays a major role in the recovery of the essential social and economic activities of the affected communities. Yet, usability of a structure represents a delicate calculation, involving the safety of individuals because of the possibility of significant aftershocks (Baggio et al., 2007).

In the aftermath of a seismic event, assessing the usability of buildings, both private (for their number) and public (for their function), is crucial in effectively managing emergency conditions.

On one hand, assessing usability determines if there is a significant risk to human life in using the affected and possibly damaged buildings, thus minimizing the risk which people could be subjected to when returning to their houses once the initial panic has ended. Considering this objective, being conservative in such an evaluation appears mandatory.

On the other hand, timely usability inspections are essential in order to minimize the number of homeless hosted in provisional or temporary structures. Too conservative evaluations can be detrimental, causing unnecessary discomfort, and therefore they should be avoided.

The social impact of this activity can be better understood by comparing the number of homeless before and after usability campaigns that followed past earthquakes. As an example,
during the 2002 Molise (Italy) post-earthquake, emergency temporary shelters were initially used for thousands of homeless before a wide campaign of building inspections by trained technicians started in the entire area. After the completion of the surveys, the number of homeless decreased from about 11,000 to 3,700.

In this study, after an overview of the survey forms adopted in several countries throughout the world, the form currently used in Italy for usability surveys (called the AeDES form) is described, especially focusing on those points that highlight the role of vulnerability in the final usability evaluation. An analysis of the extensive database of the L’Aquila 2009 earthquake usability surveys is presented, particularly discussing those buildings that were judged unusable despite having no or light damage. Finally, a case study analysed during the Emilia 2012 earthquake is reported.

2. The AeDES form for post-earthquake usability assessment

In the aftermath of a seismic event, a large number of survey requests need to be addressed in order to verify the usability of residential buildings. In order to give both rapid and sufficiently safe responses to these requests, a clear, simple, and standardized methodology is necessary. To this end, using a purposely set-up usability survey form that is able to effectively collect and analyse in-situ data through a guided path that leads the surveyor through checklists about the building, can speed up evaluations about the usability of buildings.

Until the mid-1990s, post-earthquake surveys in Italy were carried out using vulnerability forms prepared by the National Group for the Defence against Earthquakes (GNDT). These forms permitted the careful collection of vulnerability and damage data, without specific concern for building usability. For this reason, in 1997, a joint working group of the National Seismic Survey (SSN) and GNDT created a specific tool for damage assessment, short-term countermeasures for damage limitation, and evaluation of the post-earthquake usability of ordinary buildings (1st level AeDES survey form).

The rationale behind the AeDES survey form (DPC, 2000; Baggio et al., 2007), which reflects the usability procedures adopted in Italy, is pursuing a suitable balance point between the above-cited opposing objectives of safe and rapid recovery. To this purpose, clearly defining the distinctive features and objectives of usability is important. In DPC (2000) and Baggio et al. (2007) usability is defined as follows: “The evaluation of usability in the post-earthquake emergency is a temporary and rough evaluation - i.e., based on an expert judgment and carried out in a short time, on the basis of a simple visual inspection and of data which can be easily collected - aiming at determining whether, in case of a seismic event, buildings affected by the earthquake can still be used with a reasonable level of life safety”.

Usability surveys are first and foremost focused on the short-term use of the buildings under examination (Goretti and Di Pasquale, 2002). However, together with the usability survey, a global damage assessment can be done to provide data and directions useful in establishing long-term strategies on the affected building stock.

Actually, the AeDES form enables the collection of rough dimensional, vulnerability, and damage data through a strictly guided path that leads the surveyor to the final usability judgement.
The form is composed of the following nine sections arranged on three pages, plus a fourth page providing explanatory remarks on how to fill out the form:

Section 1 - Building identification;
Section 2 - Building description;
Section 3 - Typology;
Section 4 - Damage to structural elements and short-term countermeasures carried out;
Section 5 - Damage to non-structural elements and short-term countermeasures carried out;
Section 6 - External damage due to other constructions and short-term countermeasures carried out;
Section 7 - Soil and foundations;
Section 8 - Usability judgement;
Section 9 - Other observations.

The surveyor fills in the form, writing some information in predefined spaces and partially blackening some cells. The sections of the form that are mainly related to vulnerability and damage are 3 and 4, while Section 8 deals with the final usability judgement (DPC, 2000; Baggio et al., 2007). Section 5 is also noteworthy because it asks for information about the presence of damage to non-structural components like plaster, chimneys, parapets, and so on.

With respect to usability classification, six possible alternatives are considered in the form (DPC, 2000):

• A: Usable building. All parts of the building can be used without any threat to the inhabitants, without any short-term countermeasures;
• B: Temporarily unusable building (totally or partially), but usable with short-term countermeasures. The building, in its current state, is at least partially unusable, but it may be sufficient to implement short-term countermeasures in order to reduce the risk to the inhabitants to an acceptable level;
• C: Partially unusable building. The damage in some parts of the building could present an elevated risk to the occupants;
• D: Temporarily unusable building requiring a more detailed investigation. The building shows characteristics such that it is not possible to judge the building usability. A further, more detailed inspection is required;
• E: Unusable building. The unusability of the building is due to structural, non-structural or geotechnical risk;
• F: Unusable building because of external risk. The unusability is due to severe external risk, without any significant damage to the building itself.

The above classification system is designed to guarantee as much uniformity as possible in the procedure’s application by the surveyors, as well as to help in managing the data collected during the surveys.

In order to apply the above-mentioned definition of usability, three elements need to be identified, as widely discussed in Goretti and Di Pasquale (2002):

• the structural and non-structural building damage;
• the reference earthquake to which the building needs to resist (seismic scenario);
• the building vulnerability.

In selecting the reference earthquake, the knowledge of the maximum intensity expected at the site during the ongoing seismic sequence is required. This forecast is quite difficult to make in the
current usability procedures, because the reference event has not been yet codified. Generally, a seismic event corresponding to the maximum intensity experienced during the ongoing sequence is assumed (i.e., the shock that got the inspections underway), similar to the procedures used in other highly seismic areas, such as California and Greece. It is worth noting that thanks to this assumption the main shock that has been experienced, and therefore its effects, can be considered a meaningful test for the building in regard to possible future earthquakes. In other words, absence of significant damage after the main shock basically should lead to a positive judgement.

As a matter of fact, damage level, particularly on the load-bearing system, is crucial to the usability judgement. However, if there is a concern that future events could have higher intensity, the vulnerability of the building could also play a role in the judgement. In fact, even if the damage after the (assumed) main shock is slight or moderate, subsequent seismic events with lower intensity at the epicentre but local higher intensity can cause heavier damage - and therefore risk to human life - in highly vulnerable buildings. However, because it is very difficult to forecast whether the seismic sequence will have an increasing intensity, especially during the early phase of the sequence, accounting for high-vulnerability conditions can be helpful in the usability decision in any case.

Vulnerability (particularly for masonry buildings) can be roughly estimated on the AeDES form, thanks to the grey background of the cells in Section 3: darker grey colour means higher vulnerability, so different vulnerability levels can be assigned [e.g., class A, B, or C, in case of buildings without seismic protection, according to Dolce et al. (2003)].

The role of vulnerability in the usability judgement was pointed out in the previous version of the field manual for the compilation of the AeDES form (DPC, 2000), where in Section 5.2 (Risk evaluation), the following statement can be found: “In case of vulnerability indicators particularly elevated, they may induce to judge the structural risk as high, even in case of light damage or total absence of damage, if the reference earthquake has a higher degree than what felt by the building during this seismic crisis”. However, that vulnerability can be difficult to estimate, and it could inappropriately increase the number of homeless. In the current version of the AeDES Manual (DPC, 2014a), this recommendation has been removed.

3. Overview of usability forms

It is worth noting that specifically assessing and considering the role of building vulnerability in post-earthquake usability judgements is unique to the AeDES form, and therefore it can be considered unique to the Italian approach. In fact, in other countries such as Japan (Goretti and Inukai, 2002), Colombia (AIS, 2009), U.S. (ATC, 2005), New Zealand (NZSEE, 2009) and Greece (Dandoulaki et al., 1998), the usability judgement is dependent only on the observed damage.

Another peculiarity of the AeDES form is the clear and unequivocal evaluation of usability, which is different from other countries such as Japan, whose form gives general indications like safety, caution, or danger. Also, in Italy the recommendation of the AeDES survey becomes compulsory once accepted by the mayor of the municipality where the inspected building is located—not a simple recommendation or suggestion to the owner.

In Greece, a one-page post-earthquake usability form is used (Anagnostopoulos and Moretti, 2008), both for a rapid and a detailed usability evaluation. The rapid evaluation aims at identifying
those buildings clearly usable or unusable (Dandoulaki et al., 1998). Then, a detailed evaluation is carried out on the remaining buildings requiring a more detailed survey. Poor data on the structural typology and characteristics are collected, providing no vulnerability evaluation. Moreover, the damage evaluation does not provide a clear classification of the damage level, and therefore the decision of whether the building is usable, temporary unusable, or unusable/dangerous derives essentially from the expert judgement of the surveyor. Because the distinction between usable and temporarily unusable buildings is based on a rather low damage threshold, a tendency to frequently assign temporary unusability can be expected. As an example, after the 1999 Athens earthquake, 56% of the inspected buildings were judged usable, 41% temporarily unusable, and 3% unusable (Goretti and Di Pasquale, 2002).

The U.S. methodology for post-earthquake usability evaluation (ATC, 2005) provides for either a rapid or a detailed evaluation based on specific forms made up of one and two pages, respectively. The main difference between rapid and detailed evaluation resides in the damage description, which is much more accurate in the detailed one. In both forms, poor data is collected about the vulnerability of the inspected buildings, since only information about the main structural material and the lateral load-bearing system [e.g., steel frame, reinforced concrete (RC) frames, or shear walls, etc.] is required. The rapid evaluation form is suitable for surveying simple buildings, while the detailed evaluation is more appropriate for large buildings (e.g., tall buildings) and critical facilities (e.g., hospitals, lifeline utilities, emergency services).

The New Zealand methodology (NZSEE, 2009) is practically identical to the U.S. one, with procedures and forms based on the north American experience. The Japanese post-earthquake usability approach involves two phases. A first inspection is made in order to assess the possibility of short-term use. This kind of inspection can be quickly performed, surely faster than the inspections performed through the AeDES form, because only a rough evaluation of damage is requested. After the short-term usability assessment, a more accurate evaluation of damage is made to give directions about the long-term use of the building, as well as the need to repair, retrofit, demolish, etc. Recommendations made by the surveyors are compulsory only if public safety is involved (Goretti and Inukai, 2002). Signs indicating the usability classification are posted.

An approach similar to the two-step Japanese and Greek approaches has also recently been used in Italy, during the 2012 Emilia (Italy) earthquake, where early inspections were made very quickly by firefighters who performed more than 63,000 surveys in the very first days of the seismic sequence. Based on the results of these preliminary surveys, only damaged or “suspect” buildings (about 38,000) were subjected to later more accurate and time-consuming evaluations made by trained technicians using the AeDES form. Therefore, it can be computed that around 25,000 buildings with no or clearly negligible damage were considered usable just on the basis of the first fast survey, thus remarkably speeding up the reduction of the homeless number. Assuming that these preliminary surveys were correct, the only drawback of this approach is represented by the lack of structural information on the buildings not inspected with the AeDES form. This data, in fact, can be useful to later computations in terms of vulnerability, for example to prepare seismic risk maps and scenarios to be used for prevention purposes. However, after the experience of the 2012 Emilia earthquake, the Italian National Fire Department redesigned the form for first rapid assessments as “technical triage”. In the current revised form, elements related to type of structure are now organized into a systematic analysis of damage (Grimaz et al., 2016).
Whereas in many countries the civil protection system carries out post-earthquake usability surveys through a purposely developed form, in other countries a specific usability form is still not available. This is the case in Spain, as experienced during the May 2011 Lorca earthquake. The main shock had a magnitude $M_w=5.1$ with a 3-km depth, and peak ground acceleration ($PGA$) in Lorca equal to $0.37 \, g$. The earthquake caused 9 fatalities, about 250 injured people, and almost 15% of the building stock in Lorca suffered structural damage (Goula et al., 2011). About 4,000 buildings were inspected in the post-earthquake emergency in order to identify the usable buildings, thus allowing the population to go back home safely. The surveys were performed very quickly but without a specific form. Unfortunately, this resulted in usability outcomes which were sometimes disputed, thus causing a lack of confidence in the population. As a consequence, some inspections had to be repeated, and this caused a waste of time that could have been avoided if an appropriate form had been available.

4. Usability survey after the L’Aquila 2009 earthquake

On April 6, 2009, at 03:32:39 a.m. local time, a magnitude $M_w=6.3$ earthquake with shallow focal depth (10 km) occurred in the Abruzzo region (central Italy) very close to L’Aquila (the urban centre is less than 10 km away from the epicentre), the capital town of the region (Masi et
This event was the third strongest earthquake recorded in Italy after the 1976 Friuli (north-eastern Italy; $M_w=6.4$) and the 1980 Irpinia (southern Italy; $M_w=6.9$) earthquakes, and it is the strongest event providing recordings from accelerometric stations located very near to the epicentre. Specifically, four accelerometric stations (AQA, AQG, AQM, AQV) were located across the Aterno valley and recorded $PGA$ values up to 0.66 g. Specifically, the station AQK, located in the urban centre, recorded a $PGA$ value of about 0.35 g with a peak ground velocity around 35 cm/s.

In the first two days after the main shock, four earthquakes with $M_w \geq 5.0$ occurred. Among them, the first ($M_w=5.1$, April 6) and the third event ($M_w=5.1$, April 7) occurred nearby L’Aquila city. The second one ($M_w=5.1$, April 6) was localized at about 15 km NW of L’Aquila (Campotosto area), while the fourth one ($M_w=5.5$, April 7) was localized SE of L’Aquila, in an area where the main event practically destroyed the small village of Onna and caused extensive damage in other villages.

The April 6 main shock and the subsequent severe aftershocks caused heavy and extensive damage in the urban area of L’Aquila as well as in several surrounding villages, mainly located in the south-eastern part of L’Aquila province (central part of the Aterno valley), where MCS (Mercalli-Cancani-Sieberg) intensity values ranging from VI to IX degree were observed (Galli and Camassi, 2009). Conversely, intensity values generally did not exceed VI MCS in the area NW of L’Aquila town, as displayed in the map in Fig. 1. Five villages suffered intensities equal to, or greater than, IX-X MCS (i.e., Onna and Castelnuovo), four villages suffered intensities of IX (e.g., Sant’Eusanio Forconese), while two villages and the urban centre of L’Aquila town felt intensities of VIII-IX.

A total of 315 localities were classified with a MCS intensity equal to, or greater than, V, as displayed in Fig. 2, which reports the number of localities classified in terms of the assigned value of MCS intensity.

### 4.1 Analysis of the usability surveys database

In the first 60 days after the event, about 50,000 surveys were made in order to check the safety of buildings and evaluate their usability (DPC, 2014b). Until March 2010, about 80,000 surveys...
were performed on a total of 73,521 buildings. This means that up to about 6,500 buildings were surveyed two times. This work was performed by more than 5,000 voluntary technicians from all over the country. Final data reported from the National Civil Protection Department (DPC, 2014b) is displayed in Table 1.

Once the inspections were performed, the completed forms were taken to the DPC offices, where they were digitized. This operation allowed the building of a broad database that provides a clear picture of the surveyed building stock, from the structural typology, damage, and usability judgement points of view. Analysing this database can provide valuable hints for damage estimation that can occur in Italy due to future earthquakes.

Table 1 - Main results of the L’Aquila 2009 earthquake usability survey (DPC, 2014b).

<table>
<thead>
<tr>
<th></th>
<th>Private buildings</th>
<th>Public buildings</th>
<th>Cultural heritage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usable buildings (A)</td>
<td>52.0%</td>
<td>53.6%</td>
<td>24.1%</td>
</tr>
<tr>
<td>Partially or temporary unusable (B, C)</td>
<td>15.9%</td>
<td>25.2%</td>
<td>22.2%</td>
</tr>
<tr>
<td>Unusable (E) or Unusable due to external risk (F)</td>
<td>32.1%</td>
<td>21.2%</td>
<td>53.7%</td>
</tr>
<tr>
<td>Number of surveyed buildings</td>
<td>71302</td>
<td>2219</td>
<td>1800</td>
</tr>
</tbody>
</table>

While a comprehensive analysis of the survey database is reported in Dolce and Goretti (2015), in the present paper the L’Aquila database (AQ-DB) is analysed with the main objective of identifying the possible role played by vulnerability on the final usability judgement. To this end, due to the characteristics of the AeDES form, only masonry buildings are considered. In fact, Section 3 of the form assigns a vulnerability class to masonry buildings combining information relevant to their vertical and horizontal structure. Darker tonalities of grey indicate higher vulnerability. On the contrary, information collected on RC buildings is too scant to assign vulnerability, so they are not considered in the present study.

As stated in the manual of the AeDES form, data collected in Sections 3 (structural typology), 4 (damage to structural elements), and 5 (damage to non-structural elements) must be considered when assessing usability (Section 8).

Table 2 - Correlation between AeDES damage data and EMS98 damage grades (Augenti et al., 2004).

<table>
<thead>
<tr>
<th>Damage Level (AeDES form)</th>
<th>Damage Extension (AeDES form)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>&lt;1/3</td>
</tr>
<tr>
<td>D1</td>
<td>1/3-2/3</td>
</tr>
<tr>
<td>D2-D3</td>
<td>&gt;2/3</td>
</tr>
<tr>
<td>D4-D5</td>
<td></td>
</tr>
</tbody>
</table>

In order to identify the importance of vulnerability in the usability judgement, the AQ-DB is analysed with particular attention to the buildings that were judged unusable although affected by no or little damage. To this end, a more synthetic description of structural damage with respect to the one adopted in the AeDES form is useful, always based on the damage classification provided by the European Macroseismic Scale of 1998 [EMS-98: Grünthal (1998)]. In addition to no
damage (D0), EMS-98 damage grades range from 1 (D1, negligible damage) to 5 (D5, global collapse). Since the AeDES form evaluates damage in a different way, a correlation of the two different damage classifications is presented in Table 2, as proposed in Augenti et al. (2004). For our purposes, the maximum damage among vertical structure, floors, stairs, roof, and infill walls was taken into account, and the worst damage was considered when more than one problem was reported on the form.

Fig. 3 shows that masonry is the most diffuse structural type in the affected area, representing 70% of inspected buildings, as compared to 15% represented by RC frame buildings. Masonry is predominant even considering the volume data, although the difference with respect to RC buildings is lower.

![Structural types](image)

**Fig. 3 - Distribution of structural types in terms of number and volume.**

Among the several structural types, all those reported in Section 3 of the AeDES form have been considered. Buildings for which the horizontal and/or the vertical structure was unknown have been left out. Also, the masonry buildings with isolated columns or mixed structure (RC and masonry) have been discarded. In this way, only the buildings where the lateral load-bearing system is wholly made up of masonry have been considered, leaving out those buildings where the presence of additional structural elements could influence the seismic behavior. Looking at Section 3 of the AeDES form, combining 4 vertical with 5 horizontal structural types, a total of 20 building types results. The intersection of horizontal and vertical structure data determines the vulnerability class (A: high, B: medium, and C: low), as suggested by the grade of darkness of the grey background. These vulnerability classes are consistent with the classification given in the EMS-98 scale with respect to ordinary buildings without earthquake-resistant design (Dolce et al., 2003).

Fig. 4 shows that Class A is the most common, in terms of both number and volume of buildings, that is about two-thirds of the inspected buildings have high vulnerability. Class C is assigned to about 20% of the buildings, and Class B is at around 14%. Dealing with a single
structural type (i.e., masonry), there is little difference between the percentage in terms of volume and in terms of buildings; therefore, in the following only the number of buildings will be considered.

Over the last few decades, various authors studied the relationship between vulnerability and damage (Braga et al., 1982; Dolce et al., 2003; Masi and Vona, 2012; Masi et al., 2015), evidencing different damage frameworks depending on the characteristics of the building stock in the area where the seismic event occurred.

As stated, based on Table 2, damage data contained in the AeDES forms (Section 4) has been translated into a damage grade consistent with EMS-98 for each structural component.

After a damage grade coherent with the EMS-98 classification was attributed to each building in the database, the correlation between damage and vulnerability was first investigated. The main objective is to understand if, grouping buildings in zones with equal macroseismic intensity value (Galli and Camassi, 2009), those with higher vulnerability (assigned on the basis of their structural characteristics) suffered higher damage. In order to have a significant number of buildings in each group, three MCS intensity intervals have been considered, that is, MCS intensities from V to VI ($I \leq VI$, Fig. 5a), from VI-VII to VII-VIII ($VI < I < VIII$, Fig. 5b), and equal to, or higher than, VIII ($I \geq VIII$, Fig. 5c).

As expected, Fig. 5 shows that Class A buildings suffered damage much higher than buildings in Class C. Looking at the lowest MCS intensity values, Class C has a number of buildings with zero damage that is three times those of Class A. At the highest levels of damage (D4, D5), buildings with Class A are clearly prevalent.

Differences between the vulnerability classes tends to increase with the intensity values. For example, for $I \geq VIII$ the buildings of Class C with zero damage are almost five times those of Class A. In this case, not negligible percentages of Class C buildings suffered the highest level of damage, that is partial (D4, 4%) or total collapse (D5, 2%), while percentages for Class A are more than 20%.

![Masonry buildings](image)

**Fig. 4** - Distribution of vulnerability classes for masonry buildings.
Table 3 - Damage distribution in terms of number and percentage of buildings (grouped in zones with equal macroseismic intensity) for each vulnerability class.

<table>
<thead>
<tr>
<th>I (MCS)</th>
<th>Masonry</th>
<th>Damage grade (vertical structure)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>I ≤ VI</td>
<td>Class A</td>
<td>n.</td>
<td>3478</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>18.1</td>
<td>35.5</td>
</tr>
<tr>
<td></td>
<td>Class B</td>
<td>n.</td>
<td>1339</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>35.2</td>
<td>44.3</td>
</tr>
<tr>
<td></td>
<td>Class C</td>
<td>n.</td>
<td>2259</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>52.9</td>
<td>37.8</td>
</tr>
<tr>
<td>VI &lt; I &lt; VIII</td>
<td>Class A</td>
<td>n.</td>
<td>517</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>13.2</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Class B</td>
<td>n.</td>
<td>207</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>32.8</td>
<td>41.4</td>
</tr>
<tr>
<td></td>
<td>Class C</td>
<td>n.</td>
<td>333</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>56.8</td>
<td>34.1</td>
</tr>
<tr>
<td>I ≥ VIII</td>
<td>Class A</td>
<td>n.</td>
<td>968</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>11.5</td>
<td>16.1</td>
</tr>
<tr>
<td></td>
<td>Class B</td>
<td>n.</td>
<td>645</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>32.4</td>
<td>29.8</td>
</tr>
<tr>
<td></td>
<td>Class C</td>
<td>n.</td>
<td>2164</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>51.8</td>
<td>31.6</td>
</tr>
</tbody>
</table>

Fig. 5 - a-c) Distributions of damage levels (according to EMS-98 scale) for different vulnerability classes and MCS intensities; d) variation of ID_{med} values.
In order to examine and compare in a simple and concise way the damage distributions observed for the different vulnerability classes and macroseismic intensities, the mean damage index ($ID_{med}$), as defined by Dolce et al. (2003), has been used:

$$ID_{med} = \frac{1}{n} \sum_{i=1}^{5} d_i \cdot f_i$$

where:
- $d_i$ is the generic level of damage ($d_i = 1-5$);
- $f_i$ is the frequency;
- $n = 5$ are the levels of damage.

$ID_{med}$ can vary between 0 and 1 ($ID_{med} = 0$ means absence of damage, $ID_{med} = 1$ means total collapse). The diagram in Fig. 5d shows the variation of $ID_{med}$ with respect to the selected intervals of macroseismic intensity for each vulnerability class. The curves in Fig. 5d underline how the differences among the vulnerability classes increase at increasing MCS intensity values, both in terms of absolute values and in terms of trend, with the higher gradient displayed by the curve for Class A, while the curve relevant to Class C is almost insensitive to intensity variations.

The usability outcome is a strictly related consequence of the damage. In Fig. 6, all the results for the outcomes A-F are reported in absolute and percentage values (on the right), while in the diagrams on the left the percentages of usable (outcome A) and unusable (outcome E) buildings of the total of each vulnerability class, depending on the macroseismic intensity, are displayed.

As can be seen, for $I \leq VI$ (Fig. 6a), usable buildings of Class C are at almost 90%, while Class A buildings are at about 45%. For the higher intensity interval ($I \geq III$), the usable buildings of Class C are almost four times those of Class A. Percentages for Class B are always intermediate but closer to class C.

Looking at the diagram in Fig. 6b, which refers to the unusable buildings, higher differences between percentages of Class A buildings and both Classes B and C can be noted. As an example, for $I \geq VIII$, the ratio between the unusable buildings of Class A and Class C is about 6. Percentages for Class B are still intermediate and closer to Class C.

Although the unusability judgement is strongly correlated to damage severity and extent, analyzing the relation between vulnerability and unusability outcomes can provide hints to understanding if and how a significant vulnerability condition could drive the surveyor towards an unusability outcome, even if the building at hand does not show significant damage.

As expected, the share of unusable buildings is strongly associated with damage level (Fig. 7). However, it is worth noting that also for damage levels equal to 0 or 1, there is a certain percentage, even if low, of buildings judged unusable. In Fig. 7, the distributions of outcome E are provided in terms of both max damage found only in the vertical structures (D.vert, Fig. 7a) and maximum damage considering all the structural components (D.max, Fig. 7b), including infill walls and partitions. There is a significant correlation between them, with differences decreasing at increasing damage levels, pointing out that the role of damage in the vertical structures prevails at the higher damage levels.

The percentages in Fig. 7 are relevant only to outcome E, not including the cases where unusability was determined by external risk (outcome F) or when a high non-structural or
Post-earthquake usability evaluation of ordinary buildings

I (MCS) | Masonry | Usability outcomes | Tot.
Class A | 8970 | 2708 | 821 | 155 | 5698 | 835 | 19187
% 47 14 4 1 29 4 100.0
Class B | 2820 | 430 | 86 | 23 | 315 | 132 | 3806
% 75 11 2 1 8 3 100.0
Class C | 3739 | 261 | 49 | 13 | 114 | 93 | 4269
% 88 6 1 0 3 2 100.0

I ≤ VI
Class A | 1196 | 375 | 133 | 18 | 1809 | 382 | 3913
% 31 10 3 0 45 10 100.0
Class B | 383 | 65 | 16 | 5 | 83 | 79 | 631
% 61 10 2 1 13 12 100.0
Class C | 500 | 21 | 6 | 2 | 27 | 30 | 586
% 84 5 1 0 5 5 100.0

VI < I < VIII
Class A | 1502 | 782 | 158 | 61 | 5246 | 697 | 8446
% 18 10 2 1 61 8 100.0
Class B | 900 | 274 | 28 | 18 | 537 | 236 | 1993
% 46 14 2 1 26 12 100.0
Class C | 2902 | 505 | 45 | 27 | 427 | 273 | 4179
% 68 13 1 1 11 6 100.0

Table 4 - Distributions of usability outcome as a function of observed damage levels: maximum damage found in the vertical structures (on the left) and maximum damage considering all the structural components (on the right).

<table>
<thead>
<tr>
<th>Damage grade</th>
<th>Usability outcomes (vertical structures damage)</th>
<th>Tot.</th>
<th>Usability outcomes (max structural damage)</th>
<th>Tot.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>n. 13562</td>
<td>1085</td>
<td>155</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>% 83.2</td>
<td>6.7</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>1</td>
<td>n. 8544</td>
<td>2172</td>
<td>264</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>% 67.6</td>
<td>17.2</td>
<td>2.1</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td>n. 688</td>
<td>1429</td>
<td>342</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>% 16.6</td>
<td>34.5</td>
<td>8.3</td>
<td>1.9</td>
</tr>
<tr>
<td>3</td>
<td>n. 102</td>
<td>607</td>
<td>209</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>% 2.9</td>
<td>17.2</td>
<td>5.9</td>
<td>1.9</td>
</tr>
<tr>
<td>4</td>
<td>n. 3</td>
<td>82</td>
<td>142</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>% 0.1</td>
<td>3.4</td>
<td>5.9</td>
<td>0.6</td>
</tr>
<tr>
<td>5</td>
<td>n. 6</td>
<td>2</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>% 1.0</td>
<td>0.3</td>
<td>1.0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Fig. 6 - Percentage of usable (outcome A) and unusable (outcome E) as a function of the macroseismic intensity for each vulnerability class.
geotechnical risk was reported in Section 8 of the AeDES form. Therefore, the unusability outcomes found in damage levels D0-D1 could have been determined by high vulnerability.

In order to better understand the role of vulnerability, the percentages of unusable buildings (outcome E) have been analyzed for each vulnerability class, considering the damage levels from D0 to D3 in terms of D.vert (Fig. 8) and D.max (Fig. 9).

The diagrams in Fig. 8 (damage to vertical structures) show that an appreciable share of buildings is judged unusable even with low damage levels. Specifically, in the case of absence of damage (D0, Fig. 8a), there is a remarkable quantity of unusable buildings with vulnerability class A (5.4%), which is significantly higher than the percentage of classes B (1.0%) and C (0.6%), with a global percentage value of 2.8%. Similar results are found for damage grade D1 (Fig. 8b), with a total value of 4.2%. In other words, given the ongoing seismic sequence, it appears that the surveyors judged the building not safe enough to ensure human survival. For damage level D1, the percentage of vulnerability classes are comparable to that found for D0, with a low increase of unusability percentages. It is worth noting that damage D1 generally should not lead to an unusability outcome; therefore, vulnerability could still play a key role in the judgement.

When dealing with the maximum level of damage among all of the building components (Fig. 9), the percentage of unusable buildings for D0 and D1 damage grades significantly decreases with respect to the related percentages displayed in Fig. 8. This result shows that unusability frequently derives from damage found in building components other than vertical structure, for example damage to the roof. Specifically, about 1.0% of buildings (sum of Class A, B, and C) with damage grade D0 are judged unusable (Fig. 9a) while maintaining similar proportions among the vulnerability classes in comparison to those shown at Fig. 8a. In other words, out of the 394 Class A buildings judged unusable despite having no damage to the vertical structure (table on the right of Fig. 8a), only a small proportion (i.e., 78, equal to 20%) remains unusable when considering all the building components. The total percentage of unusable buildings remains almost constant in damage grade D1, considering all building components (Fig. 9b).

Percentages increase in damage grade D2 (not necessarily implying an unusability determination) and D3. Nonetheless, the higher percentages of unusable buildings are still found for vulnerability Class A.

Summarizing, the results show that only in a few cases, the building vulnerability (as assigned a posteriori by the surveyor) could have determined an unusability outcome in the case of little
Fig. 8 - Unusable buildings as a function of vulnerability class damage levels on vertical structures.
Fig. 9 - Unusable buildings as a function of vulnerability class and maximum damage levels among all the building components.
or no damage, particularly when the maximum observed damage on all the building components is considered. However, it is worth noting that, comparing the percentages of outcome E relevant to the same damage grade, the larger percentage of buildings judged unusable are always in the highest vulnerability class (A). This result suggests that vulnerability, although not explicitly, had a role in the usability outcomes related to undamaged buildings. It is worth noting that, in some cases, non-structural damage is responsible for the unusability outcome but, since it cannot be quantified (Section 5 of the AeDES form does not provide a non-structural damage grade), these cases have been excluded from the analysis by discarding the buildings with high non-structural risk (Section 7 of the AeDES form).

5. The Emilia 2012 earthquake: an example of considering vulnerability in the usability judgement

The 2012 Emilia earthquake struck the northern part of the Emilia-Romagna region (centre-north of Italy). Its epicentre was located in the Emilia region, about 30 km to the west of the town of Ferrara. The local magnitude of the first event, on May 20, was $M_L 5.9$. A second main shock occurred more than 20 km to the west of the first one, with local magnitude $M_L 5.8$, causing more damage in the affected area and the deaths of 19 people out of a total of 27 fatalities (Dolce and Di Bucci, 2014).

The macroseismic survey, which was updated after the second strong event, involved about 190 localities. The maximum intensity derived from the cumulative effects of the two main events was equal to VII-VIII MCS. The second shock of May 29, along with the main aftershocks that followed the earthquake of May 20, significantly increased damage in the western part of the stricken area. In addition, significant co-seismic effects were observed, such as soil liquefaction phenomena (Di Manna et al., 2012), especially in the villages of Mirabello, San Carlo, and Sant’Agostino.

About 3,000 expert technicians were employed to carry out a total of more than 40,000 usability inspections on ordinary buildings using the AeDES inspection form. During the period of maximum activity, the damage and usability survey involved about 180 teams per day (with a maximum of more than 200 teams). The maximum number of inspections per day ranged between 1,000 and 1,200 (Dolce and Di Bucci, 2014). As a result of the usability inspections, 37% of the surveyed buildings were judged usable (outcome A) and almost the same percentage were judged unusable (36%, outcome E), while the remaining buildings were distributed among the other usability outcomes (B, C, D, and F) but mainly attributed to B (building usable after short-term countermeasures).

As stated, the Emilia 2012 seismic sequence showed a significant migration of epicentres, as also observed in other sequences in the past (e.g., Friuli 1976, Umbria-Marche 1997).

Observing the position of the epicentres during the sequence, displayed in Fig. 10, it can be noted that they are located almost at the same latitude but with a remarkably different longitude. During the seismic sequence, the epicentres migrated to the west, with epicentral distance between May 20 and June 3 events equal to about 23 km.

The migration of epicentres during the seismic sequence increases uncertainty on the selection of the reference earthquake to be considered in the post-event surveys for usability evaluation.
Large distances among the epicentres of different events during the same seismic crisis make it possible that urban centres where rather low seismic intensities were felt during the early events could experience higher seismic intensities due to closer aftershocks. In such cases, very vulnerable buildings could suffer slight damage during the first events, but damage could become heavier during later events, even later events with lower epicentral intensity.

In the Emilia seismic sequence, several villages located at an epicentral distance in the range of 10-20 km during the May 20 event, were found to be at an epicentral distance of less than 10 km during the May 29 event (e.g., the villages of Camposanto, Cavezzo, Medolla, etc.)

During the post-earthquake emergency, immediately after the second shock (May 29, 2012), the authors carried out many usability surveys on school buildings in the framework of a collaboration between the ReLUIS Consortium (the Italian Network of University Laboratories of Seismic Engineering, www.reluis.it) and the Emilia-Romagna Regional Authority. Most of the inspections were performed in towns located far away from the epicentre (i.e., around 20 km or more), and therefore the surveyed buildings generally showed little damage. As a consequence, in some cases the need to take vulnerability into account when assessing usability was clearly brought out. An example is shortly described in the following.

The example refers to a primary school located in the municipality of Cento (Province of Ferrara) built at the beginning of the 20th century without seismic criteria. As for the main structural characteristics, it is a two-storey brick masonry building having an inter-storey height
of 4.6 m and a floor plan area of about 1400 m$^2$. Slight structural and non-structural damage was found, a condition that should imply a positive usability judgement.

However, very high, thin partition walls were found. Specifically, partitions had height $H=4.6$ m with a thickness $t=0.12$ m, and therefore a ratio of $H/t=38.3$. In addition, in some cases partition walls were separated from the surrounding structure because of the presence of cracks at the interface caused by the ongoing seismic sequence (Fig. 11). Therefore, although the damage level was slight, there was a high risk of out-of-plane collapse of the slender and not adequately connected partitions. Due to the bad connection, partition walls behave like a cantilever, and therefore out-of-plane collapse is possible even with small seismic actions (Braga et al., 2011; Manfredi and Masi, 2014). Such a condition of high vulnerability suggested a negative usability judgement involving the zone of the building where those partitions were located.

Taking into account the uncertainty in selecting the appropriate reference earthquake (seismic scenario after the assumed main shock), the considered example showed how in the case of structures designed without seismic criteria and having poor structural and non-structural characteristics, and therefore high vulnerability, a negative usability evaluation could be advisable, at least, as in the case at hand, referring to the classrooms containing the highly vulnerable partitions.

6. Final remarks

In this paper, the Italian procedure for post-earthquake usability evaluation, based on the AeDES survey form, was analysed, highlighting some important differences with the procedures used in other countries.

Using the AeDES form, damage data is carefully collected so that the damage level and its extension to the whole structure and to the main structural and non-structural components, can be estimated and classified in accordance with the EMS-98 classification. Furthermore, unlike in
other countries, vulnerability data are also collected in the Italian form. This is intended to make data available for the reconstruction phase (e.g., in the management of the financial requests from the affected population), and, as discussed in the present paper, to be used in support of the usability judgement.

Indeed, a building that is lightly damaged and therefore normally judged as usable, could in the case of high vulnerability be judged as unusable if it is expected that the reference earthquake during the ongoing seismic crisis can have a higher intensity with respect to the previous shocks that caused the damage observed during the inspection. However, it is quite unlikely that the authorities managing post-earthquake emergencies would have data to forecast the evolution of the ongoing seismic crisis. Therefore, it is an established practice to assume that the intensity of the reference event in the usability inspections is equal to that of the event that triggered the inspections. Under these premises, vulnerability should be discarded as a potentially useful factor in the usability evaluation.

To better understand this issue, the broad usability of the L’Aquila 2009 earthquake database was analysed in the paper. Few buildings with no or little damage that were judged unusable are found, showing that the surveyors accounted for the role of building vulnerability only in some cases, presumably only when it could have a quite clear influence on the building response to aftershocks.

The role of vulnerability (assigned *a posteriori*) in support of the usability judgement should increase when a migration of epicentres can be expected. This feature of earthquake sequences makes it possible that aftershocks, even of decreasing magnitude, can cause higher local intensities in some urban centres far from the epicentre of the main shock. As a result, in some cases, vulnerability may be an additional factor potentially useful in the usability evaluation.

To briefly illustrate and discuss how the presence of vulnerability factors along with the uncertainty related to the reference earthquake can influence the usability evaluation, a case study relevant to the inspection carried out on a primary school building during the 2012 Emilia seismic sequence was reported. Although the building suffered only slight damage, it was judged partially unusable due to the high non-structural vulnerability deriving from very slender partition walls.

In conclusion, it should be stressed that having a clear and well-founded procedure to follow during the inspections is essential, although the use of expert judgement is crucial to effectively apply the official procedures when one works on such a sensitive matter as the usability judgement. In this regard, some remarks reported in the foreword of the current version of the AeDES manual are noteworthy: “The activities during an emergency phase always proceed along a narrow line, along a boundary where the rapidity of the expected answers and the capacity in providing effective assessments based on poor judgment factors sometimes have difficulty in finding the right balance. The surveyor stands in the middle of it: only guarantee strictly derives from his/her technical competence and ability to fully operate on the basis of professional ethics”.

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